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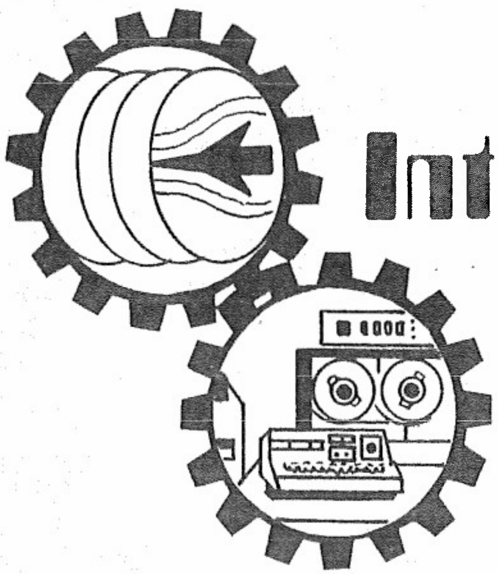

Integrating Wind Tunnels And Computers

VOLUME II

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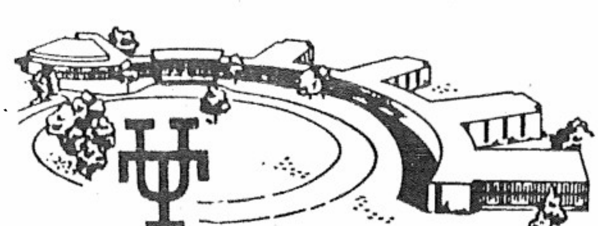

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A summer design study group consisting of twelve participants and a technical director studied various aspects of the present and future interaction of wind tunnels and computers. This study was conducted under the sponsorship of the Air Force Office of Scientific Research at the University of Tennessee Space Institute with the support and assistance of the Arnold Engineering Development Center and its operating contractor, ARO, Inc. Guidance was provided by a government/university steering committee selected by AFOSR.

The study group's procedure on this broad topic was the following:

A. Technical presentations by specialists from UTSI, AEDC, and ARO for basic background information.

B. In-depth presentations by technical specialists from
1. The Aerospace Industry
2. The Computer Industry
3. Government
4. Universities

C. Detailed discussions with these speakers by one or more of the three working panels into which the summer design group was divided
1. Experimental Facilities Panel
2. Computational Fluid Dynamics Panel
3. Computer Design Panel

D. Extensive literature search and development of a large bibliography collection, review and summary of a mass of reports.

E. Regular discussion activity by the individual working panels and the design group as a whole to produce a written report of the findings.

F. Several meetings with the steering group to provide review and guidance.

The scope of the investigation was narrowed in order to proceed in greater depth. The subject of propulsion tests was excluded. Emphasis was given to the subsonic and transonic regimes at the expense of the supersonic regime and the near exclusion of the hypersonic region. Considerable emphasis was given to the following areas:

A. Understanding the areas of agreement and disagreement between theoretical and experimental activity in the areas of:
1. Boundary-layer modeling
2. Determination of transition location
3. Separated flow phenomenon

B. Progress and potentials of new techniques for improvements in flow qualities of wind tunnels by a synergic application of computer closed-loop controls, mechanical adjustments of tunnel physical parameters, and new noninterference methods of measurements.

C. The present and future potential for the fast-developing field of computational fluid dynamics

In the course of the study a number of conclusions and recommendations were reached, and these are summarized in a separate section of Volume I and are presented in detail together with the supporting information and references within a body of the main report in Volume II.

It is concluded that this study of wind tunnels and computers was very worthwhile, that the activity was of great value to the participants, and that the results will be of value and interest to the sponsor.

VOLUME II

DETAILS OF SUMMER DESIGN STUDY

USAF/OSR/ASEE

SUMMER DESIGN STUDY PROGRAM

on the

INTEGRATION OF WIND TUNNELS AND COMPUTERS

by

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Tullahoma, Tennessee

AFOSR Grant No. 77-3289 August 1977

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ABSTRACT

A summer design study group consisting of twelve participants and a technical director studied various aspects of the present and future interaction of wind tunnels and computers. This study was conducted under the sponsorship of Air Force Office of Scientific Research at The University of Tennessee Space Institute with the support and assistance of the Arnold Engineering Development Center and its operating contractor, ARO, Inc. Guidance was provided by a government/university steering committee selected by AFOSR.

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D. Estimates of computer requirements to support the various integration activities and investigation of future potentials for advanced high-speed computers.

In the course of the study a number of conclusions and recommendations were reached, and these are summarized in a separate section of Volume I and are presented in detail together with the supporting information and references within a body of the main report in Volume II.

It is concluded that this study of wind tunnels and computers was very worthwhile, that the activity was of great value to the participants, and that the results will be of value and interest to the sponsor.

COMMENTS BY THE STEERING COMMITTEE

This report is the result of an unusual educational experiment: a set of young people in academic positions ranging from mathematics to engineering spend the summer months at UTSI for the purpose of arriving at a common point of view on the interrelations between computers and wind tunnels. Their task was not easy: they had to become fast experts in a field of strongly held and divergent opinions. A large amount of factual information presented by lecturers from the engineering and computing communities had to be absorbed, put into context, and synthesized into a coherent picture. We feel that this task was well accomplished and that their report will prove useful to others in understanding the relative rolls of, and constructive relationships between, computers and wind tunnels. We take this opportunity to commend the members for their quick assimilation of facts and philosophies about a complex relationship, and for the long hours they devoted to preparing their report, resulting in a very respectable contribution. The task would have been much more difficult, if not impossible, without Professor Bernard Marschner whose untiring efforts to coordinate and guide the study were crucial for its success. Last but not least, the contribution of Dr. Robert Young, Associate Dean of the University of Tennessee Space Institute, should be acknowledged. He was the guiding spirit in getting the study under way and in providing the appropriate academic setting for its execution.

Dr. Hans W. Liepmann, Chairman
Steering Committee
November 14, 1977

1.0 INTRODUCTION

1.1 STATEMENT OF THE DESIGN PROBLEM

The design problem that was selected was the general area of the interaction between developments in computers and the obtaining of design data from wind tunnels. The rather broad scope of this topic made it necessary to restrict the consideration of the study to the following areas:

1. Control of the Tunnel Parameters for Wind Tunnel Tests
2. Control of Model Parameters
3. Improvements in Tunnel Similation Qualities
4. Computational Fluid Dynamics in the Design Cycle

Even in the consideration of these four elements, certain compromises were made since the basic aim was to attempt a rather in-depth review of the literature and to study a restricted subset of the problem rather than to try to cover all aspects of the field. Consequently, the area of propulsion testing was not covered. The emphasis on the flow regimes was directed toward the subsonic and transonic regimes at the expense of the supersonic regime and to the almost total exclusion of the hypersonic regime.

The selection of the participants was done by national advertisement under the aegis of the American Society for Engineering Education in conjunction with programs that the association conducts on an annual basis with NASA, and with a complementary program that the association conducts with the Air Force and The University of Tennessee Space Institute. Abbreviated vitae of the participants and the technical director are presented in Appendix IV.

The individuals in the Summer Study Group came from backgrounds ranging from experimental aerodynamics to mathematics. The experience level of the participants varied considerably.

1.2 STEERING COMMITTEE

The Air Force Office of Scientific Research selected a Steering Committee comprised of the following individuals:

*Dr. Hans Liepmann, Chairman . . . . Director, Graduate Aeronautical Laboratories
California Institute of Technology
Pasadena, CA 91125

*Dr. Gary T. Chapman . . . . Aerodynamic Research Branch, Code FAR
NASA-Ames Research Center
Moffett Field, CA 94035

*Dr. Wilbur Hankey . . . . Air Force Flight Dynamics Laboratory AFFDL/FXM
Wright-Patterson AFB, OH 45433

*Dr. David McIntyre. . . . . Air Force Weapons Laboratory/AD
Kirtland AFB, NM 87117

*Dr. Richard Seebass . . . . Department of Aerospace Engineering
University of Arizona
Tucson, AZ 85721

1.3 OBJECTIVES

The objectives of the study were agreed upon between the sponsor, the Steering Committee, and The University of Tennessee Space Institute. An outline of the objectives is presented below:

1. To provide a design study experience on a realistic and pertinent engineering subject for the faculty participants.
2. To ascertain the current status of experimental aerodynamic facilities and test methods and the current status of aerodynamic computational methodologies and computer systems.
3. To prepare an estimate of future developments in experimental and computational aerodynamics consistent with projected design needs, with special emphasis on the impact of the next generation of experimental and computational facilities.
4. To explore means of obtaining and improving aerodynamic data by developing concepts for integrated use of computers and wind tunnels.
5. To prepare the faculty participants to make future contributions in the area of experimental and computational aerodynamics

1.4 METHODOLOGY: An outline of the methodology is presented below.

1. A review of current literature in the following three areas will be made:
   a. Experimental facilities and methodology for wind tunnel testing of advanced military air vehicles
   b. State-of-the-art in computational fluid mechanics and aerodynamics
   c. Design trends of computer architecture and computer implementation techniques as they pertain to computational aerodynamics and wind tunnel testing.
2. Material will be presented by contributors in the three fields under consideration to aid in the understanding of computational and experimental aerodynamics.
3. A brief written assessment of the current status of three areas will be prepared.
4. A written estimate will be made of future trends, capabilities, and limitations for the interaction between computational aerodynamics, experimental aerodynamics, and advanced computer design and implementation.
5. Study participants will present reviews of current technical reports in the three areas.

Careful understanding of the methodology is important to the understanding of the preparation of the report. During the report period no new research was accomplished. The basic working method of the project was to have presentations from a wide variety of representatives in the field, collect a large bibliography, obtain a rather large collection of reports, and read, summarize, and review a large cross section of these reports. From this activity the write-up was based on 1) a synthesis of remarks from many sources, 2) the general impression which was left by a number of the speakers, and 3) an overall assessment by the panel.

The final report of the summer design study is presented in two volumes. The first of these is a summary report, and the second contains the details of the work accomplished by the design panel. The majority of the write up of the individual sections of the report was done in a concentrated fashion by the use of a working panel arrangement.

Section 2.0 of Volume II was written by the Experimental Design/Wind Tunnel Working Panel, which consisted of:

1. Frank G. Collins, Chairman - Associate Professor, Aerospace Engineering
2. Salvador R. Garcia - Professor, Engineering Systems
3. Michael H. Jones - Assistant Professor, Engineering
4. Carlos Tirres - Assistant Professor, Engineering

Section 3.0 of Volume II was written by the Computational Fluid Dynamics Panel, which consisted of:

1. Sin-I Cheng, Chairman - Professor of Aerospace Sciences
2. Donald A. Chambless - Assistant Professor, Mathematics
3. James L. Jacocks - ARO, Inc.
4. Vireshwar Sahai - Associate Professor, Engineering Science

Section 4.0 of Volume II was written by the Computer Systems Panel, which consisted of:

1. William A. Hornfeck, Chairman - Assistant Professor, Electrical Engineering
2. L. Eugene Broome - Professor, Mathematics
3. James R. Cunningham - Assistant Professor, Mathematics
4. Gregory M. Dick - Assistant Professor, Division of Engineering Technology

Each of the sections 2.0, 3.0, and 4.0 begins with a tutorial type of presentation in order to provide the reader with appropriate background material which will place each panel's presentation in the proper perspective. Readers who are specialists in a given area may skim this material with ease. It was felt a review of the present status of wind tunnels was necessary in order to ascertain the future role of computers in this field. Similarly, a review of the present state of computational fluid dynamics was conducted in order that an assessment of its role in the design cycle could be made.

2.0 WIND TUNNEL TESTING

2.1 INTRODUCTION

2.1.1 Historical Perspective

Aerodynamic wind tunnel test facilities are used extensively for the development of aeronautical systems. Since the Wright Brothers constructed their tunnel in 1901, the development of wind tunnel facilities has usually preceded improved flight vehicles (Ref. 2.58). Wind tunnels are the best simulators (analogue) of the Navier-Stokes equations and provide the primary data for predicting flight performance. Furthermore, wind tunnel data are very repeatable, and their quality is continually upgraded. However, the existing wind tunnel capabilities are now being taxed to their limits as closer design margins are demanded for the development of new aeronautical systems. Moreover there is in a sense a false confidence in the simulation accuracy of wind tunnel data; but this situation can be greatly alleviated by integration of computers and wind tunnels.

Currently computers used with wind tunnels have increased the degree of sophistication available for testing new aeronautical systems (Refs. 2.23, 2.48, and 2.67). Both quantity and quality of data have been increased to meet the new demands. These current integrated tunnel/computer systems are discussed in detail in Section 2.4. In addition, there is a great potential for further integration that should provide significant improvements in aerodynamic test capabilities and simulation accuracy. This potential is discussed in more detail in Section 2.7.

In assessing the value of wind tunnel data in the design process, one must consider the cost of the wind tunnel test relative to the cost of the total system. For example, the total R & D cost for an aircraft can be divided into the itemized costs for airframe design, airframe wind tunnel testing, propulsion design, propulsion testing, avionics, etc. It is estimated that the cost for wind tunnel tests for the typical aircraft is only about 2 percent of the total R & D cost, and this percentage decreases compared to the total cost as the number of aircraft produced increases. Although this cost is small relative to the total system cost, it is a critical item which plays a vital part during the embyronic stages of the new aircraft (see Section 2.2). Therefore, aerodynamic test facilities, integrating wind tunnel and computers, will continue to provide vital design information for aeronautical systems of the foreseeable future.

2.1.2 Overview

This chapter will lay the foundation for the requirements and recommendations on future integration of wind tunnels and computers. The current status, current requirements, planned developments, and future needs for integrated wind tunnels and computers are discussed. Recommendations, observations, conclusions, summaries, or position statements are given in italics in each section of this chapter when appropriate. Much of the material in Sections 2.2 through 2.4 is tutorial and may be omitted if the reader is familiar with the current wind tunnel situation. The following sections are included in this chapter:

- 2.2 Impact of Tunnel Testing on the Design Process
- 2.3 Current Status of Experimental Aerodynamic Facilities and Test Methods
- 2.4 Current Use of Computers in Wind Tunnel Testing
- 2.5 Future Developments in Experimental Aerodynamic Facilities and Test Methods
- 2.6 Calibration and Benchmark Experiments
- 2.7 Future Integrated Use of Computers and Wind Tunnels

2.2 IMPACT OF TUNNEL TESTING ON THE DESIGN PROCESS

2.2.1 Overview

Since the time of the Wright Brothers, the wind tunnel has been the place where aeronautical systems have been developed. The number of testing hours required in a wind tunnel has increased steadily with the growing complexity and sophistication of aeronautical systems (Fig. 2.1). More data and test points have been required for each new system. This trend obviously cannot continue unabated or the next generation of aircraft will never be developed in time to be useful. The apparent need for more test data will be addressed later in this section. The fact remains, however, that tunnels have been the most important of all tools for aircraft design and development.

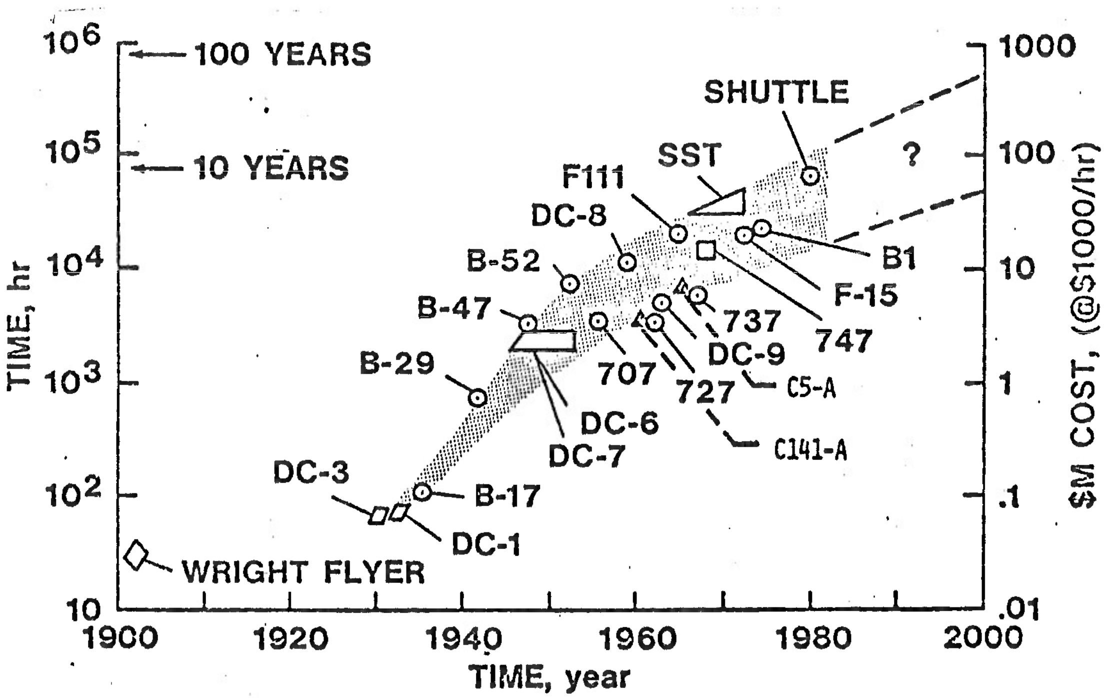


Fig. 2.1 Total Wind Tunnel Test Hours for Development of Various Aircraft (Ref. 2.141)

The computer, by contrast, has not had an impact on aerodynamic design until recently. For example, the C-141 was designed with 5,375 hours of tunnel testing and 1 hour of computer wing design, and the C-5A was designed with 14,000 hours of tunnel testing and 5 hours of computer wing design (Ref. 2.141). In the future however, the computer will make a continuously increasing contribution to the design process and will have a decided impact by reducing the number of required tunnel tests. This will take place as more computational techniques are validated and computer speeds and sizes are increased.

The tunnel testing costs, although very high, are small compared to the total aircraft R & D or fleet costs. Tunnel aerodynamic (not including propulsion) testing costs were 0.4 percent of the C-5A fleet cost (Ref. 2.193). The cost of propulsion testing is usually higher than that of aerodynamic testing, and the cost of flight testing is higher still. For example, 1,500 flight test hours are required to certify a commerical transport (Ref. 2.30).

Although tunnel testing costs are small compared to total development costs, the tunnel tests are of great importance for proper vehicle design. The benefits from testing usually far outweigh their cost. It has been estimated that a reduction of one drag count through geometric modifications suggested by tunnel tests could save an amount equal to the total testing costs for the C-5A (fuel cost savings over the life of the fleet) (Ref. 2.193). More emphasis will be placed on fuel savings in the future (Ref. 2.102), and the wind tunnel will be used to find ways to reduce aircraft drag.

The steady increase in tunnel testing is really dictated by the desire of the government to obtain a weapon system with performance in the "last 5 percent possible." The possibility of failing to meet initial performance goals is therefore great. The survey results of Mitchell (Ref. 2.115) reveal a number of important facts concerning the origin of the test plan for a system development.

As shown in the survey, the test plan (number of tests, type of tests, models, facilities to be used, measurement accuracy required) is usually prepared by a potential contractor as a part of his proposal. Test plan details are not emphasized when a bid is evaluated, but a contractor does not want to appear deficient by requesting too many tests in an area where problems are expected. Those who did respond to Mitchell's survey indicated that they thought that a decrease in the number of tunnel tests would increase the technical risk of the proposed development, but that the number of tests was nevertheless decreased to lower the bid price. However, it was also thought that the test plan was not important for awarding the contract. This method of determining the test plan leads to an inefficient use of tunnel testing; too few tests are run in problem areas which arise as the development program proceeds, too many tests are run in other areas, and probably not enough testing is accomplished early in the program.

An additional point of interest is the fact that a company with their own wind tunnels was agreed to have a competitive edge over companies without tunnels. However, there is a trend toward the use of government facilities.

Mitchell (Ref. 2.115) examined 35 aircraft development programs. Eighty-four percent of these aircraft experienced deficiencies in the flight evaluation. The respondents agreed that more and earlier testing could have prevented these problems. Although the respondents' comments reflect the desire to lessen the ultimate design risk, their proposed solution must be challenged. Certainly a more judicious test plan will yield a better designed aircraft, but this can be done with fewer tests, not more. Also, some of the program failures can be related to a lack of simulation accuracy (not repeatability) in the tunnel. *The use of computers for test planning, intelligent wall, and tunnel controls will assist in lessening the probability of failure to meet aircraft design goals in the future.*

The risks involved from poor tunnel test results cannot be over-emphasized. For example, uncertain scale effects (lack of Reynolds number simulation) such as occurred in the C-141 program (Refs. 2.71 and

2.185) cause conservative design and limit potential aircraft advances in performance and efficiency (Ref. 2.77). Bowes (Ref. 2.30) comments that "...the ability of the designer to promise a performance capability and of the airplane to meet this promise has been a dominant factor in the success or failure of individual programs." Proper simulation in the tunnel is mandatory for a successful program (Ref. 2.185). *Because of the importance of tunnel testing in the eventual success of a program and the relatively small testing cost, every effort should be made to continuously improve the tunnel simulation accuracy.* Simulation improvement should also assist in reducing the number of needed tests. Even with the increasing use of the computer for analysis there will continue to be a need for tests in a high quality wind tunnel (see Section 2.7).

Success or failure of a flight vehicle can depend upon how well the wind tunnel data can be extrapolated to flight conditions to predict the actual performance. Extrapolation procedures are validated by comparison with previous tunnel/flight test correlations. Therefore, new designs are frequently only incrementally different from previous ones where the tunnel/flight correlation is well known.

An example of the success of incremental testing is the series of aircraft that began with the B-47. This aircraft was the beginning of a line of aircraft that changed in an evolutionary manner. Each aircraft had a performance greater than the previous, as measured by the transonic range parameter ML/D (Ref. 2.30). Incremental testing is very valuable for improving the performance of existing aircraft. Only incremental differences from an existing model need to be determined by tunnel tests; thus, only tunnel test repeatability (i.e., precision) is required.

Incremental testing is essentially conservative and can lead to the continuation of low design standards, nonoptimal performance, and bad tunnel measurement practices (Ref. 2.32). Also often nonincremental advances need to be made (e.g., the B-52 to the B-58). *In the future there will be less requirement for incremental testing and more for determining absolute measurements.* This will require improvements in tunnel simulation accuracy (see Section 2.3.4) and elevated standards of test design, execution, and analysis (Ref. 2.32).

Computational techniques, validated by well performed experiments, will play an increasingly important role in the aircraft development process. Computational techniques are particularly suited for optimization procedures and can perform much of the task formerly done by incremental testing. This will occur particularly as designers gain confidence in the techniques (Ref. 2.42). This possibility is discussed in Section 2.7.3. There will be a desire to minimize the design risk by utilizing a balance between computations and experiment. Computations will not be able to handle all geometries in the near future, and some important design aspects, such as the wing-fuselage interaction, will continue to be examined in the tunnel (Ref. 2.139). In addition there will be an ever-increasing need for the use of model/flight test correlations to measure the simulation accuracy in wind tunnels. *Computations, however, will make a significant contribution by allowing more design by analysis.*

2.2.2 Preliminary Design Phase

The development of an aerospace vehicle can be divided into three phases (Ref. 2.139): the preliminary design phase, the project definition phase, and the flight test phase. As will be demonstrated, the wind tunnel plays an important role in each phase.

In the initial phase of a vehicle development program, the design is presently based primarily on empirical methods resulting from accumulated tunnel and flight data obtained on a variety of similar configurations, with parametric corrections to account for variations between the configurations. The tunnel/flight correlation results are highly proprietary and become a significant part of a company's "know-how" (Ref. 2.30).

Fast performance estimates for engineering outlines which are lacking in detail are needed at this stage. However, the techniques used must be accurate enough to allow correct evaluation of the alternative configurations. In particular, this requires very careful and complete flight tests so that the effect of various vehicle components and their mutual interference can be ascertained. This type of flight testing is very expensive (see Ref. 2.30 for a more complete discussion).

Semiempirical numerical codes are sometimes used at this stage, especially for supersonic aircraft and hypersonic reentry vehicles (Ref. 2.205). The primary design tool is the tunnel and the computational results are presently used to verify or extend the tunnel results (see Section 2.4.4). Reentry vehicles must be designed to great accuracies and are now pushing simulation accuracy improvements in the wind tunnel (Ref. 2.205). More complete numerical codes will be used in the future.

There appears to be a definite need for the development of vehicle components (airfoils, for example) and concepts independent of any particular weapon system. Such work would add another source of data upon which the preliminary design of a vehicle which is not incrementally related to any previous vehicle.

Although this stage presently relies primarily upon previous tunnel tests and flight test correlations, computational techniques are already having an impact on the optimal design of individual components, such as wings. *Use of computational techniques will increase, and thereby help eliminate the reliance upon experience obtained from previous tunnel and flight tests on geometrically similar vehicles.*

2.2.3 Project Definition Stage

This stage involves intensive computational and experimental research and development on selected main design aspects, using models generally representative of the proposed design. There is concern with accuracy (of the final design prediction) from this point onward in the program (Ref. 2.30). Any design modifications tested in the tunnel before the vehicle reaches the flight test stage provide benefits usually far exceeding the tunnel costs (Ref. 2.193).

Only a finite amount of tunnel testing time is specified in the test plan (see Section 2.1.2), and it invariably happens that the period of testing has expired before the design has been optimized. Because of the time required to make model modifications, only several configurations can really be examined (Ref. 2.42). Therefore, means must be used to optimize the configuration quickly and early in the development program.

Also, more flexibility is needed in the text plan. Mistakes found at this stage are of much less consequence than those found in the flight test stage. *In the future, computational techniques can assist by determining most of the performance characteristics, leaving the tunnel to verify the computations and to examine critical performance areas.*

While it is relatively easy to examine various configuration geometries on the computer, it is very difficult to do so in the tunnel. An exception is through the use of wax models, aided by oil flow visualization, in low-speed wind tunnels or water tunnels. Because many aspects of separation are qualitatively the same at all Mach numbers (Ref. 2.187), the technique has been used with great success for reducing the drag of transonic transports and with somewhat less success on fighters. For example, the C-5A drag was reduced by 57 counts using this technique (Ref. 2.68).

The results of the tunnel tests must be corrected for tunnel interference effects (wall interference, buoyancy, flow nonuniformity, equivalent Reynolds number, etc.) and extrapolated to flight Reynolds numbers to obtain a performance prediction for the preliminary vehicle design. The correction and extrapolation procedures must be very accurate because the corrections are large, and errors in their magnitude will invalidate the comparison of the projected vehicle performance and the contracted performance. (Examples of typical wall corrections are given in Ref. 2.131 and Ref. 2.139 shows that the extrapolation correction for the drag coefficient, C_D , of the C-5A was 20 percent of the measured C_D). Tunnel and extrapolation corrections are primarily obtained from semi-empirical procedures which have been validated by careful tunnel/flight test correlations. This again points to the need for good simulation accuracy of the tunnel tests.

The desire to eliminate mistakes at this stage is very great, and it is estimated that 15 percent of the tunnel tests are performed to verify data of questionable quality (Ref. 2.115). These verification data are obtained in tunnels different from the ones which obtained the original data. *An improvement of simulation accuracy of the tunnels would eliminate the necessity for verification of previous tests, improve the final product, and reduce the development cost and time.*

The important problem of how to integrate the power plant smoothly to the airframe will not be discussed in this chapter. However, it is recognized to be one of the largest sources of uncertainty for the final configuration. Problems connected with it are discussed in Refs. 2.30, 2.32, and 2.139.

2.2.4 Flight Test Phase

Even after the design has been frozen and the first vehicle has been built and tested, the need for wind tunnel tests is not over. There is almost always a need for corrective action after the first flight test of a new aircraft (Ref. 2.30). Large risks are involved with the development of new vehicles, and many perform badly during the first test; nevertheless the record clearly indicates that the final product is good.

When problems occur at the flight test stage, then the program goes back to the tunnel to find the cause. Eighty-five percent of the corrective tests use flow visulation to discover the flow problem (Ref. 2.69), indicating that they are due to interferences (which cannot and will not be capable of being computed for many years).

Some planes, such as the F-111, had more tunnel tests after the first flight than before, whereas some others, such as the C-5A, had very few at all. Commercial aircraft companies immediately initiate tunnel studies of the final configuration not only to eliminate any problems that have arisen but also to improve the vehicle performance and keep the competitive edge. Incremental testing is used especially to reduce drag (and thus increase range). For the Boeing 707, for example, range was increased by 35 percent, of which the engine accounted for 19 percent and the airframe for 16 percent (Ref. 2.30).

The tunnel is also used to modify existing aircraft for new missions. At times these modifications are needed quickly so that existing aircraft can be changed. Only tunnel testing has been able to respond with the needed speed.

In conclusion, the wind tunnel presently is involved in all aspects of an aeronautical vehicle design. As the vehicles become more complex and sophisticated and perform in new flight regimes, an increase in simulation accuracy is demanded of the wind tunnel to reduce the design risk and improve the final vehicle performance.

2.3 CURRENT STATUS OF EXPERIMENTAL AERODYNAMIC FACILITIES AND TEST METHODS

2.3.1 Wind Tunnel Test Facilities

Experimental aerodynamic data for the design of aerospace systems are generated from wind tunnels, aeroballistic ranges, vacuum chambers, sled tracks, etc. However, this report will consider only the wind tunnel and its integration with computers for aerodynamic testing. Furthermore, propulsion test cells and thrust stands will also be excluded from the report. Specifically, the following discussion will pertain only to subsonic, transonic, and supersonic aerodynamic test facilities and testing techniques.

Wind tunnels experienced a steady growth during approximately the first half of the century. The number of facilities of a given type (i.e., subsonic, transonic, or supersonic) fluctuated with national needs, but in general a steady growth continued until the mid 1960's. The number of facilities has declined sharply since that time. It appears that the decrease in number of wind tunnels is related to the decrease in the number of aerospace companies and the number of systems developed.

According to Pate (Ref. 2.138), the number of supersonic and hypersonic wind tunnels has decreased by about 50 percent since 1965. Consequently, an appropriate increase in productivity of the remaining wind tunnels has been required to serve system development test needs. An example of increased productivity through facility improvements for AEDC tunnels A, B, and C for the period 1960-1977 is shown in Figure 2.2 (Ref. 2.138). This trend will probably continue as the cost of tunnel testing increases. In addition, the number of research wind tunnels of very high quality flow have become nearly nonexistent. The decrease in the number of production facilities appears to be a healthy trend because it has forced the remaining facilities to become even more efficient. Furthermore, effective integration of wind tunnels and computers should significantly accelerate the improvement of both productivity and quality of data (see Section 2.7). However the trend of decreasing research facilities is counterproductive, because these facilities are essential for developing wind tunnel testing techniques and computational

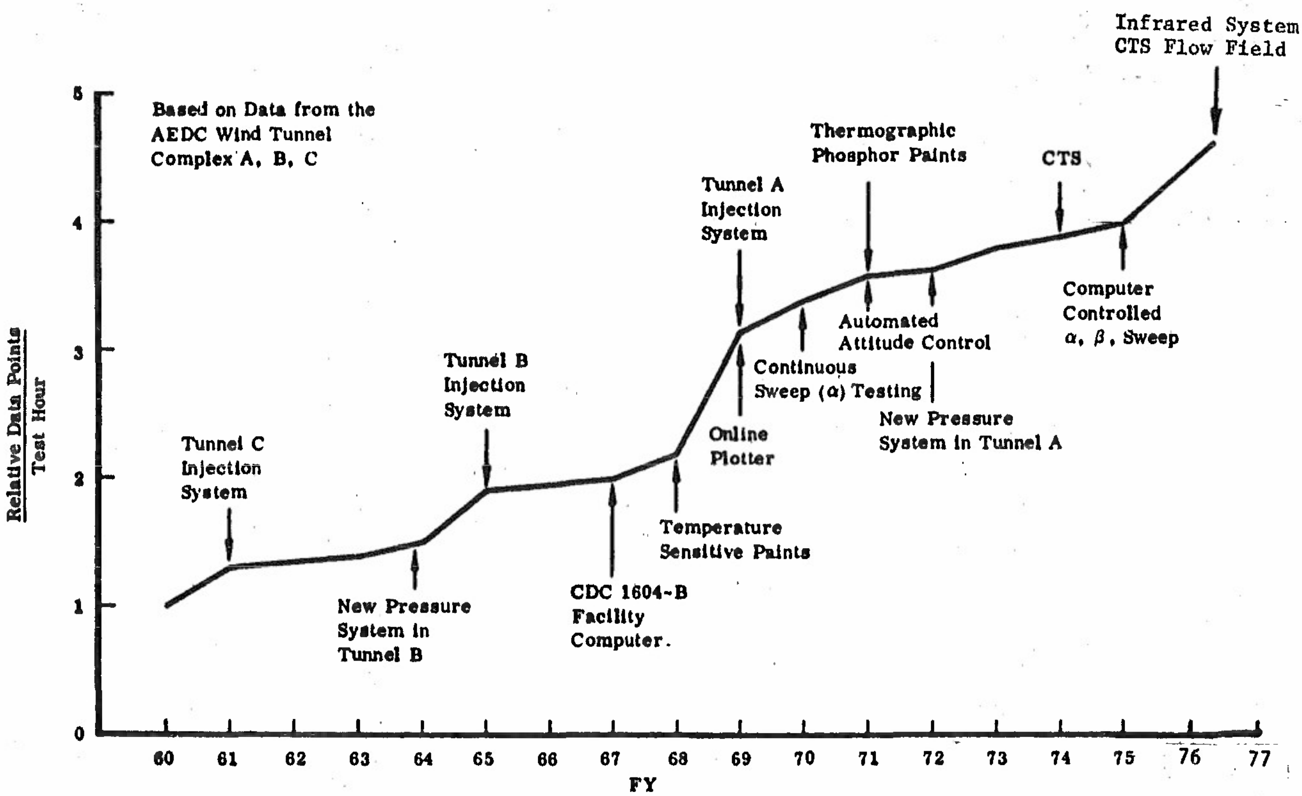


Fig. 2.2 Examples of Increases in Data Productivity
(Ref. 2.138)

techniques. Research facilities are needed to provide understanding of certain flow fields and benchmark data for the verification of computer codes, which are discussed in Section 2.6.

The most recent inventory of the major aerodynamic wind tunnel test facilities is described in Refs. 2.145 and 2.178. Many of the facilities described in Ref. 2.145 are no longer operational.

2.3.2 Recent Wind Tunnel Facility Improvements

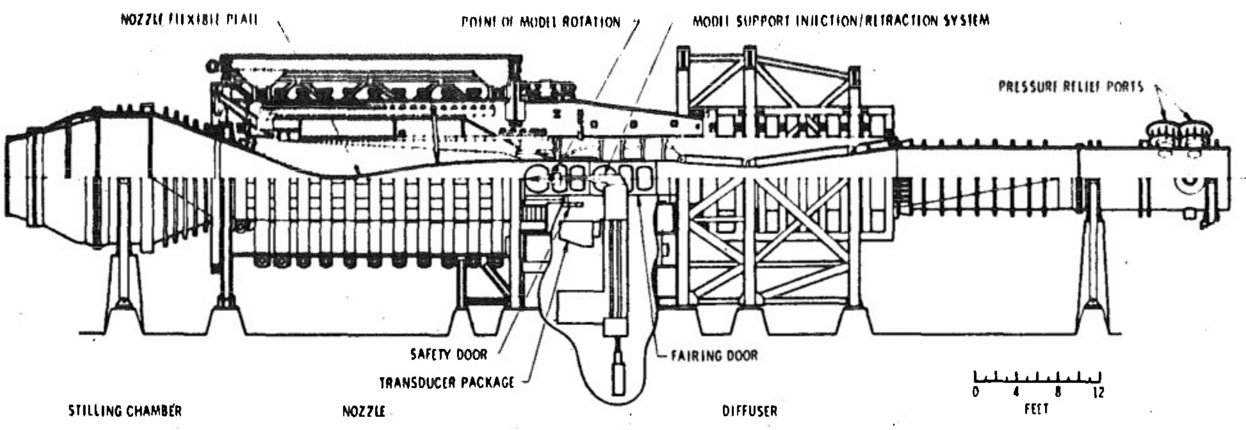
The demand for improved full-scale vehicle performance and accuracy of performance prediction has led to a sustained effort to improve the accuracy of test data from existing wind tunnel facilities. In addition, the decrease in number of production facilities has emphasized the need for improved productivity. This has resulted in wind tunnel facility improvements that have not only improved the accuracy of test data but in many cases have also increased facility capability as well as productivity. Some of the major improvements of the past years are summarized herein.

Model Injection System

The model injection system permits the insertion and removal of the model into or out of the test section without having to shutdown the tunnel. The system is controlled by direct computer commands (see Section 2.4). Figure 2.3 shows the model injection system used at AEDC in tunnels A, B, and C. The system increases the productivity of these facilities by allowing faster model configuration changes while maintaining tunnel conditions. This is accomplished by a set of interlocking doors that isolate the test section from the model installation chamber. The system also provides easier and faster access to model and onboard instrumentation for repairs. The major advantages of the system are increased productivity and added test capability and flexibility.

Captive Trajectory System (CTS)

The CTS is an electromechanical six-degree-of-freedom model support used for separation simulation (Fig. 2.4). It provides aerodynamic coefficient data for online computer generation of the trajectory of a body as it is staged or separated from another body. The primary reason for dual or multibody testing is for simulation of flow-field interference on



Tunnel A Assembly

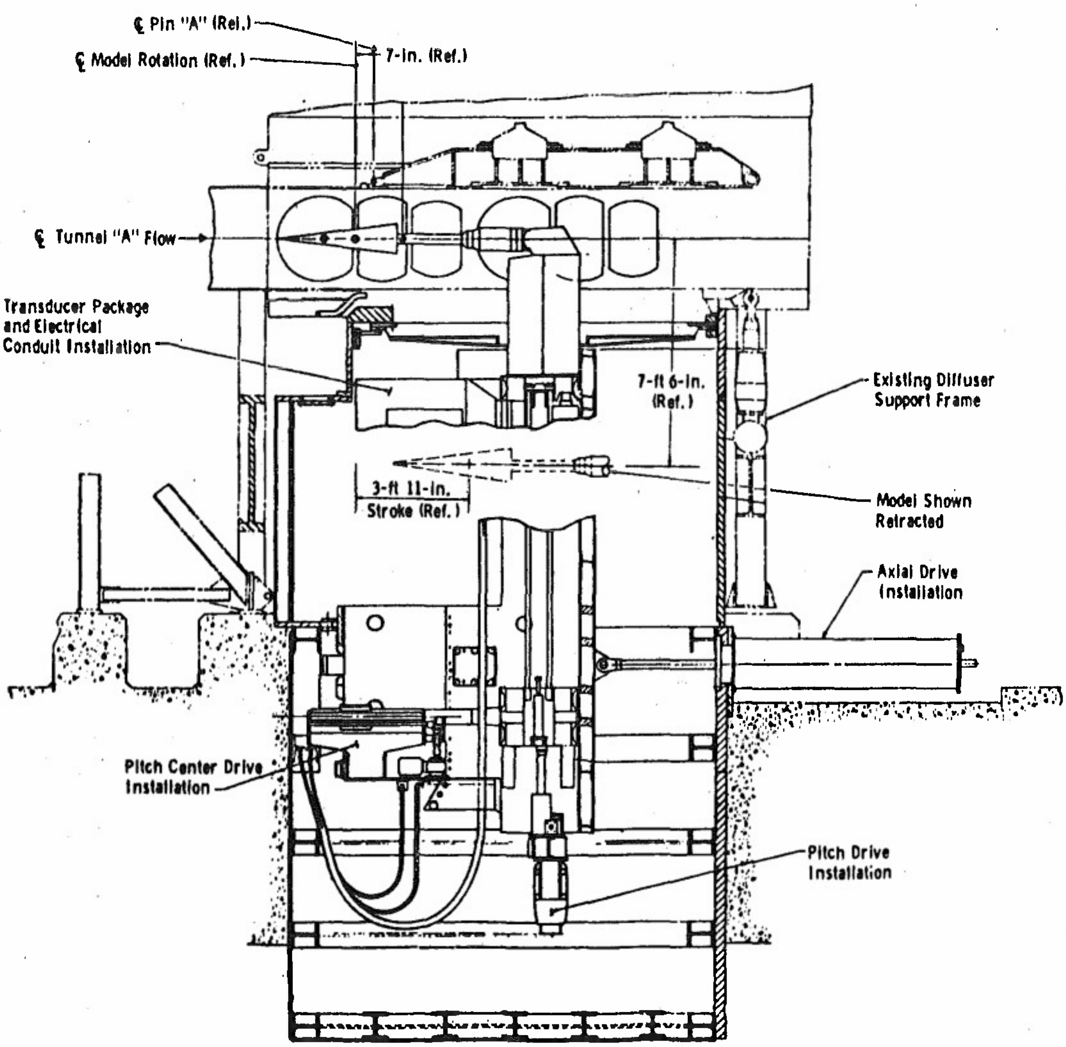


Fig. 2.3 The AEDC Tunnel: A Model Injection System (Ref. 2.178)

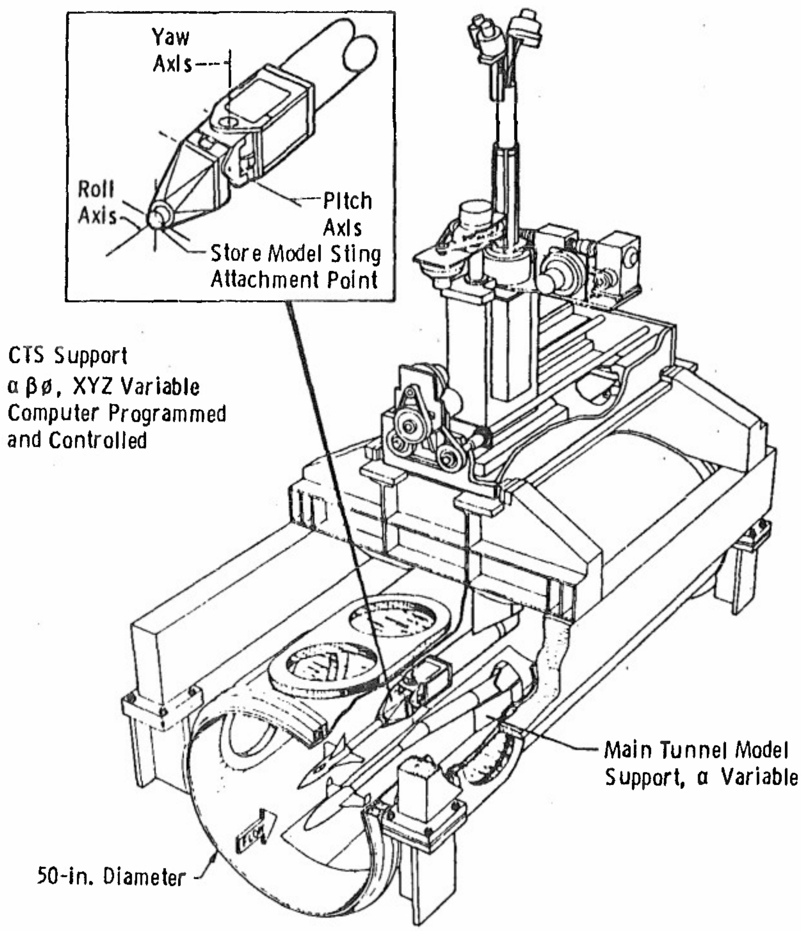


Fig. 2.4 The AEDC Tunnel B: Captive Trajectory System
(Ref. 2.178)

on both the primary and secondary bodies. The CTS is also used for flow field studies where the survey probe is computer-controlled via the secondary body (or CTS) support (Ref. 2.138). This capability is available in wind tunnels throughout the speed range (i.e., subsonic, transonic, supersonic, and hypersonic) (Refs. 2.23 and 2.178). This system provides both added capability and increased productivity in existing wind tunnels.

Captive Aircraft Departure System (CADS)

The CADS provides information on the maneuver behavior of an aircraft in the wind tunnel (Ref. 2.23). With the wind tunnel used as an analog data source for the required static aerodynamic data, the Euler equations of motion for the aircraft are solved by an online digital computer. The solutions of these equations are used to control the orientation of the model in the airstream. This system provides added capability.

Variable Porosity Walls

Variable porosity walls such as those used in AEDC tunnel 4T (Ref. 2.178) are used to alleviate interference. The test flow environment is improved by adjusting the wall porosity and wall angle as a function of Mach number. The wall porosity is varied uniformly by sliding the outer wall over an inner wall (Fig. 2.5). This improvement provides improved data accuracy.

Computer and Wind Tunnel Interfacing

Current use of computers in wind tunnel testing will be discussed in detail in Section 2.4. However, it should be noted here that although computer and wind tunnel interfacing came into extensive use only within the past three years, nevertheless it represents a very significant improvement to aerodynamic testing in production wind tunnels. For example, the model injection system, CTS, CADS, and variable porosity walls are all computer controlled. These improvements and others discussed in Section 2.4 provide increased productivity, added capability, and improved data accuracy.

2.3.3 Simulation Requirements

The primary function of production wind tunnels is to simulate the aerodynamic characteristics of the full-scale vehicle in free flight by testing a scaled model of the prototype. The simulation is accomplished by using basic aerodynamic similarity variables that relate the tunnel model values to flight values. These variables are Mach number, Reynolds number, Prandtl number, stagnation enthalpy, and wall temperature ratio. Wind tunnels provide very good information in incremental parametric tests. However, existing facilities are unable to simulate all the required aerodynamic similarity variables; therefore, they are unable to predict vehicle performance in absolute terms.

The major factors limiting the aerodynamic simulation are airframe/engine interference, wall interference, low Reynolds number, poor flow quality, model deformation, and model support interference. Other factors that could add to the simulation error if not carefully controlled are poor wind tunnel calibration, poor instrumentation precision, and poor model surface finish. These other factors are mentioned only because they continue to surface in the literature; they will not be discussed any further in this report. On the other hand, the major factors will be discussed in some detail.

Airframe/engine interference is of primary concern to the aircraft designer, particularly on airplanes having close-coupled or highly integrated propulsion systems. Predicting the proper thrust minus drag requires careful testing in the wind tunnel to determine the interactions between airframe and propulsion system (i.e., inlet and nozzle afterbody). Current thrust-drag prediction methods are discussed by Bowes (Ref. 2.30) and Paterson, et.al (Ref. 2.139). However, the success of these prediction methods is not known because, according to Bowes, "The answer to this question is a highly qualified one, and since it may perhaps involve a legal as well as a technical concern, the data is understandably hard to come by." News reports of conflicts between engine and airframe

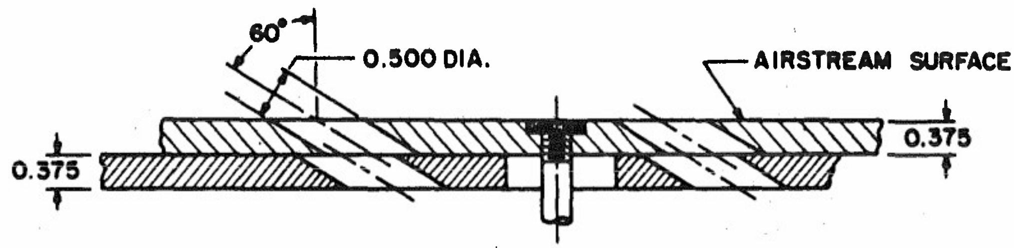


Fig. 2.5 The AEDC 4T Variable Porosity Wall
(Ref. 2.22)

manufacturers indicate that major deficiencies exist in the current simulation techniques for airframe/engine interference testing. Therefore, *the need for a substantial research effort in airframe/engine interference is indicated, including correlation studies of flight and wind tunnel data. Perhaps existing test techniques could be improved by intelligent integration of wind tunnel and computer in such a way that a large data base and mathematical models are available online to improve the quality of simulation.*

A major deficiency of aerodynamic simulation in wind tunnels is attributed to boundary interference. This deficiency is of considerable concern at all free-stream Mach numbers, but is particularly severe at transonic speeds where model-induced normal shocks are reflected from the wall back onto the model. Moreover, when the model is embedded in a large supersonic region the flow field is grossly distorted by the wall resulting in significantly compromised test data. The effects of tunnel wall porosity on the drag-rise characteristics and on airfoil pressure distributions are given by Paterson (Ref. 2.141) in Figures 2.6 and 2.7, respectively. These results indicate that wall interference effects in transonic wind tunnels could be more detrimental to the aerodynamic simulation than most of the other effects such as low Reynolds number, poor flow quality, etc. Research in this area has experienced a modest but sustained effort in three major areas: (1) wall interference corrections for test data (Refs. 2.21, 2.22, 2.74, 2.92, 2.116, 2.124, and 2.144), (2) modification of existing wall configurations to reduce or eliminate wall interference (Refs. 2.20 and 2.132) and (3) development of an intelligent wall for interference free performance (Refs. 2.12, 2.13, 2.14, 2.50, 2.51, 2.60, 2.61, 2.62, 2.93, 2.100, 2.161, 2.162, 2.164, and 2.190). These results seem to indicate that wall corrections and modification of existing walls are not sufficient for all test requirements. *The intelligent wall appears to hold the best promise for success in reducing or eliminating boundary interference.* This approach will be discussed extensively in Section 2.7.2.

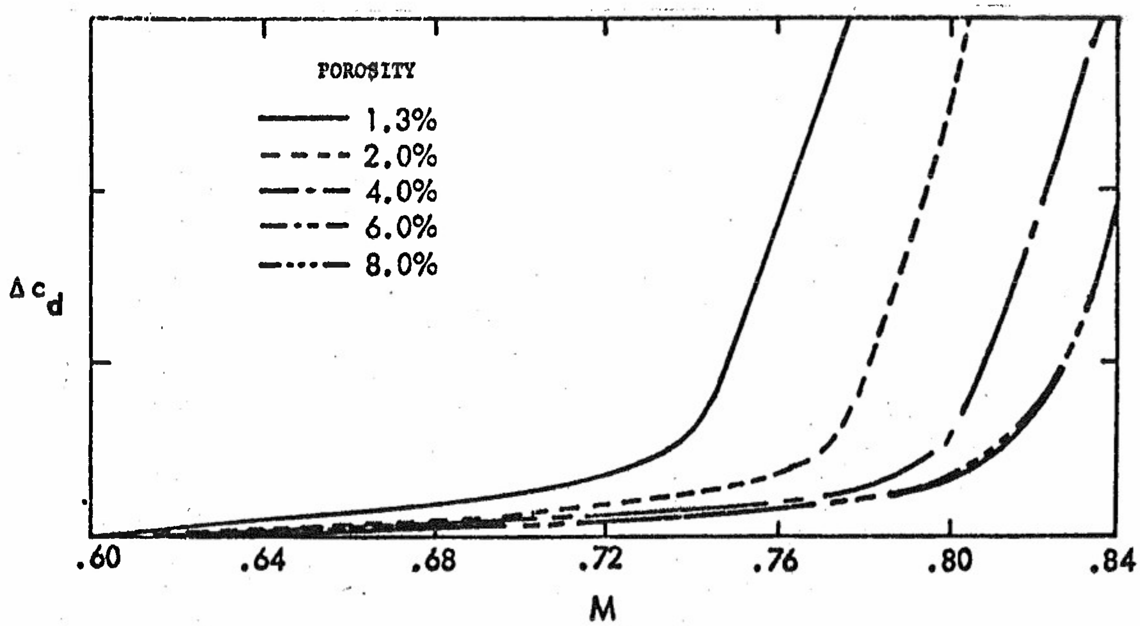


Fig. 2.6 Effects of Porosity on Drag-Rise Characteristics (Ref. 2.141)

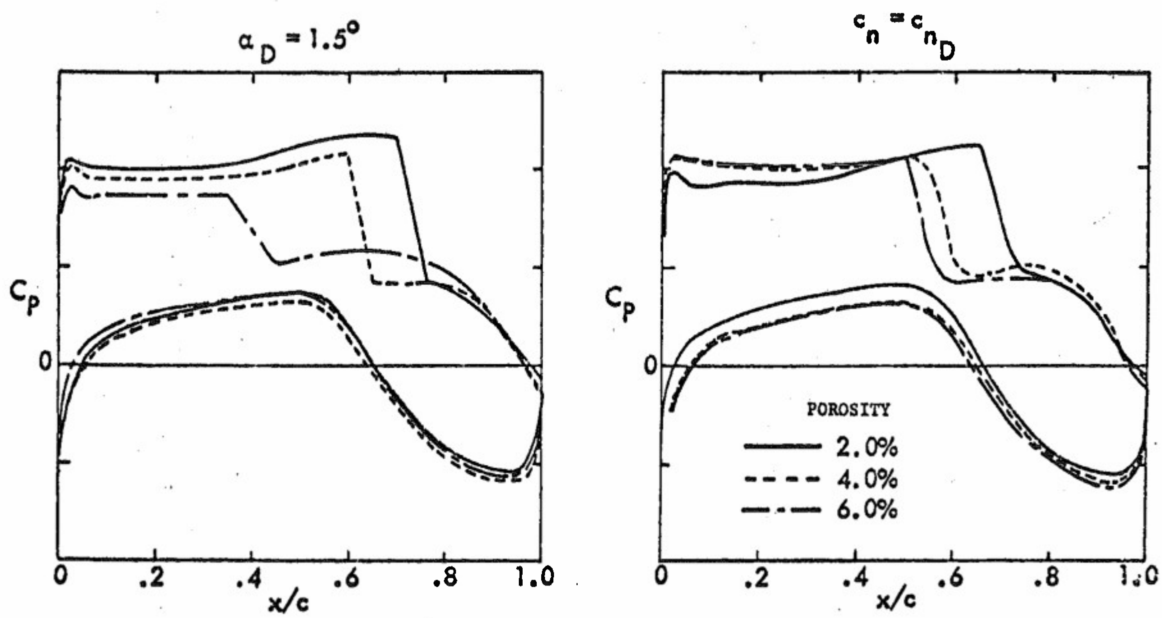


Fig. 2.7 Effects of Porosity on Airfoil Pressure Distribution at M=0.80 (Ref. 2.141)

The problems associated with the low Reynolds number (Re) capability of existing wind tunnels are well documented (Refs. 2.11, 2.184, 2.205, and 2.211). Existing Re capability in transonic and supersonic wind tunnels and the required values to match flight conditions on specific vehicles are illustrated in Figure 2.8. The planned National Transonic Facility (NTF) is the only wind tunnel to approach the Re level of 10^8 needed to match the flight values for large transport aircraft. The amount of information for justifying construction of this very high Re facility is overwhelming, but most of the data used as evidence in the justification are contaminated with the effects of wall interference, poor flow quality, and other kinds of interferences. Therefore, the "real" Reynolds number effects are neither quantified nor well known. In fact, investigators have observed negligible Re effects on flow fields that were previously believed to be Re sensitive (Refs. 2.98 and 2.191). However, there is no question of the need for a high Re facility to investigate specific flow phenomena sensitive to Reynolds number, such as skin friction, shock wave/boundary layer interactions, separated flows, etc. The NTF will provide solutions to these Re sensitive phenomena, but it will not be available until the early 1980's. Consequently, low Reynolds number production wind tunnels will continue to accomplish system development tests in the foreseeable future. Even after the arrival of NTF, system development tests will probably continue to be accomplished in low Re facilities because of their economy, productivity, and efficiency.

Integration of the low Reynolds number wind tunnel with a large dedicated computer could improve the Re simulation significantly by using a data base and appropriate math models. The NTF should be very useful for developing the appropriate math models.

The quality of flow in wind tunnels has been the concern of investigators since the turn of the century. For example, the Wright Brothers' tunnel was equipped with both wire screens and honeycomb for flow smoothing. The major problems associated with flow quality include turbulence,

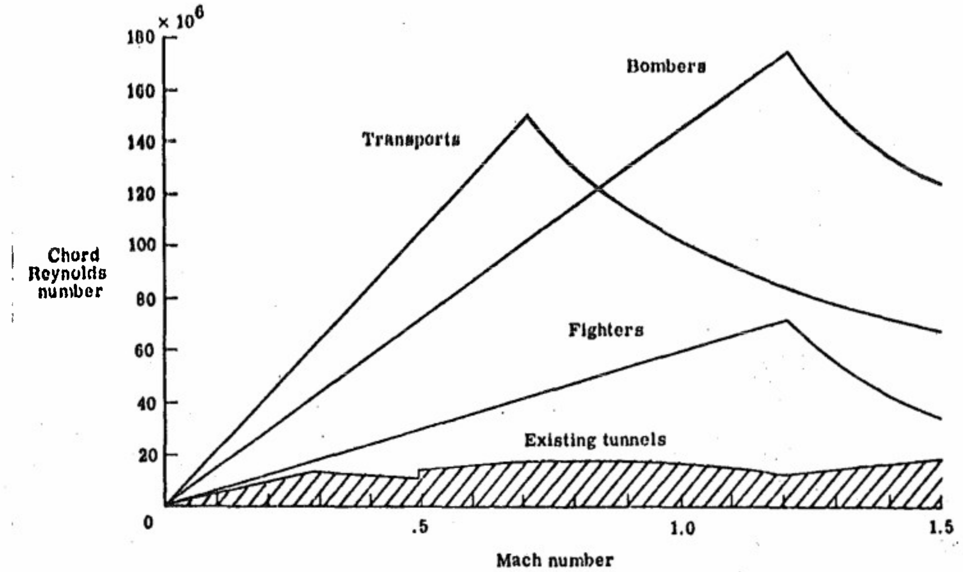


Fig. 2.8a Existing Reynolds Number Test Capability in Transonic Wind Tunnels (Ref. 2.11)

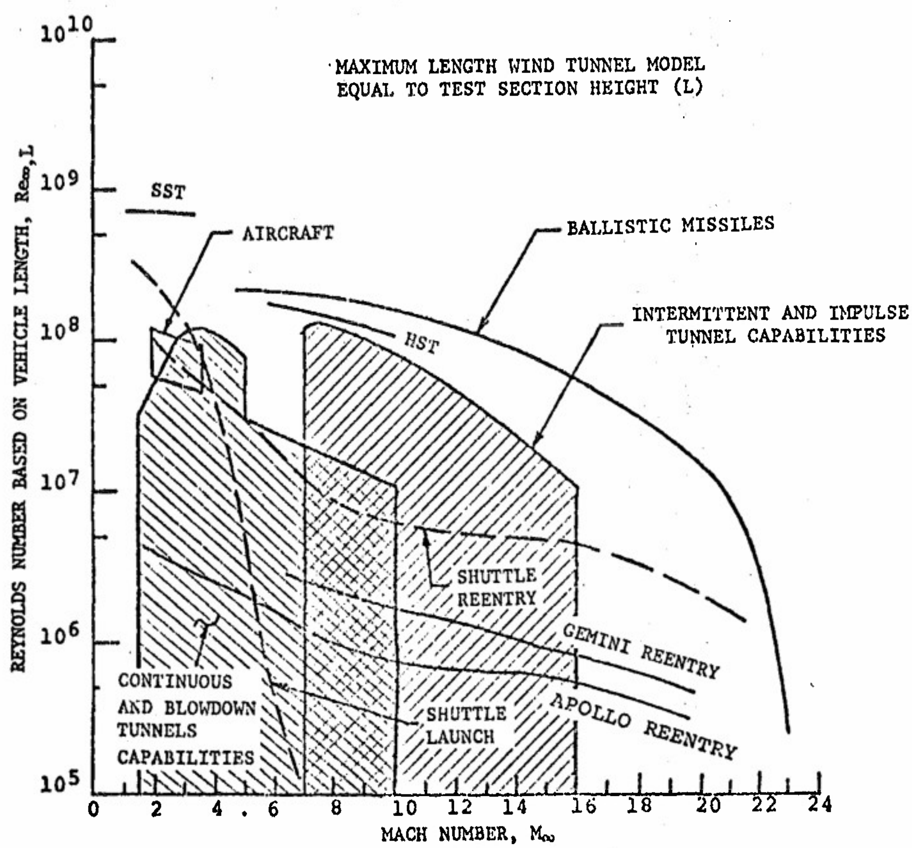


Fig. 2.8b Existing Reynolds Number Test Capability in Supersonic Wind Tunnels (Ref. 138)

acoustics, flow nonuniformities, and moisture. Turbulence and flow nonuniformities are corrected with screens and honeycomb, but with the penalty of pressure losses. Consequently, most production facilities do not use screens or honeycomb, and they suffer from flow nonuniformities and undesirable levels of turbulence. Air driers are effectively used to remove moisture from the test flow. However, instrumentation to monitor moisture levels is nonexistent, and unless the moisture is visible in the test section, the effects of moisture are not questioned. The effects of acoustics on test data have gained importance in recent years (Refs. 2.44, 2.46, 2.136, 2.137, 2.194, and 2.195). Dougherty evaluated several techniques to suppress edgetones from perforated wind tunnel walls and found methods to effectively eliminate the acoustic effects (Ref. 2.45). *Therefore, the technology to significantly improve flow quality in existing wind tunnels is in most cases well in hand; it is only a matter of allocation of funds to correct the problems, if one takes into account the trade-offs discussed above.*

Model deformation or aeroelastic effects are becoming significant in aerodynamic wind tunnel simulation of high Re conditions, As the test dynamic pressures are increased in an attempt to achieve high Re flows, the model wings bend and twist under load, resulting in erroneous local angles of attack. For example, the local angle of attack is reduced on a swept wing as it bends under load (Ref. 2.77). The simulation errors become more severe as test dynamic pressures increase. This problem, however, is reduced significantly with the NTF because high Re flows are achieved with a drop in temperature and no increase in dynamic pressure.

Model support interference can also introduce a significant amount of uncertainty, especially to the drag measurements. Typical model support systems are shown in Figure 2.9. All of these mounting systems will introduce interference, and at the higher test Mach numbers the errors due to interference effects can be very large. The interference

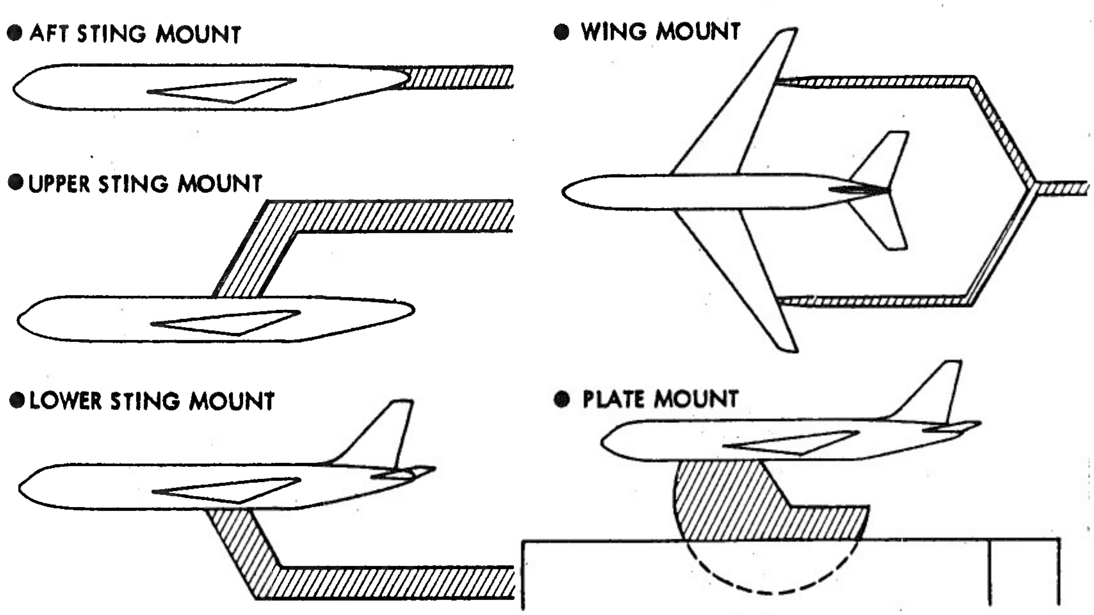


Fig. 2.9 Typical Model Support Installations
(Ref. 2.30)

can be determined by using various mounting systems and dummy struts. This technique has been used effectively for correcting interference effects caused by the model support system (Ref. 2.210). However, Bowes (Ref. 2.30) gives warning that some uncertainty always exists in this procedure because the corrections are determined from small differences of two large numbers. Perhaps the integration of wind tunnel and computer could alleviate this problem with proper modeling of the support system.

2.3.4 Accuracy and Measurement Requirements

Accuracy requirements for aerodynamic simulation are dictated by the mission of the new aeronautical system to be developed and are generally established by the successful bidder of the proposal. Wind tunnel testing plays a critical role in the development of the new system. It provides the system designers with the information to predict performance, optimize the design, determine loads data, and evaluate, identify, and correct operational problems with the vehicle. The wind tunnel data also allow the customer (government) to evaluate the performance of competing designs. Therefore, the accuracy of the performance prediction for the economic and operational aspects of the vehicle is very significant to both the customer and the designer. For these reasons it is highly important that accurate wind tunnel data be provided for aeronautical system development.

The quest for higher accuracies in simulation are motivated by the customer's needs. For example, the average effect of an error of one count of drag (approximately 0.4 percent) over all the guaranteed missions for a large transport aircraft, such as the C-5A, is equivalent to about 1000 lb. of payload (Ref. 2.201). Its value is estimated at $600,000 per aircraft, or $48 million for a fleet of 80 airplanes. Figure 2.10 shows an example of the trend in drag accuracy prediction for a transport aircraft during its development cycle (Ref. 2.30). Note that a ± 5 percent probable error is considered a very good prediction. However, this error is an order of magnitude larger than the one count of drag discussed above. Therefore,

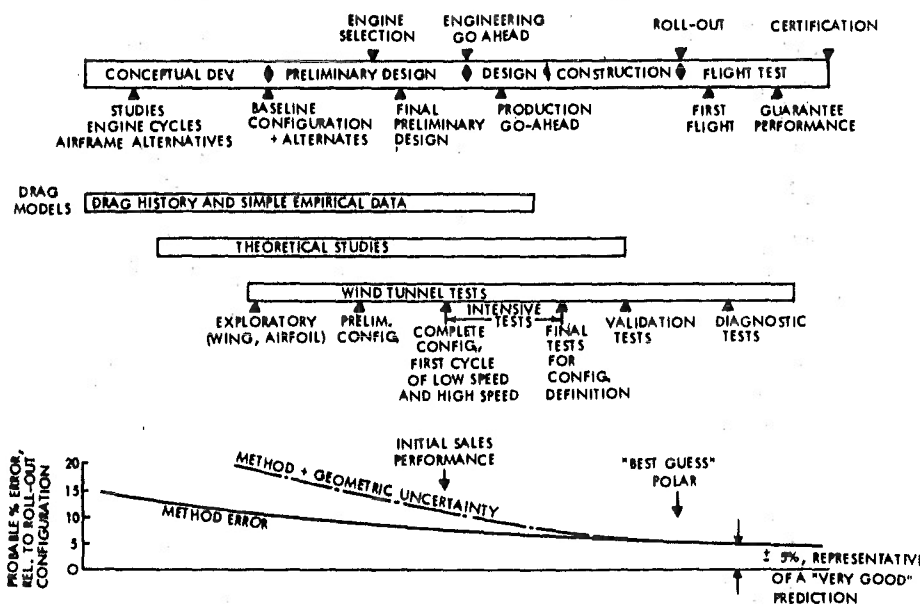


Fig. 2.10 Development Schedule for Transport Aircraft (Ref. 2.30)

the demand for one count of drag accuracy on transport aircraft development is not realistic and its specification could stand a complete review.

Accuracy requirements in fighter aircraft development also provide challenging demands in aerodynamic simulation. The higher accuracy demands are motivated by the need to "squeeze out" all the performance possible from a new system. Figure 2.11 shows a sketch of the accuracy requirements (or cost) as a function of performance. The 5 percent band is the area where the performance requirements must be met. The sensitivity of the fighter's effectiveness (advantage) because of its performance is illustrated in Fig. 2.12. These figures clearly show that the demand for a high degree of simulation accuracy is well founded. *Unfortunately, the existing wind tunnels fall short of meeting the required capabilities to provide aerodynamic simulation accuracy which is better than the 5 percent upper band where the performance requirements must be met on fighter aircraft.*

The best current-measuring capabilities available in wind tunnels are given in table 2.1.

Table 2.1. Summary of Hardware Component Accuracy (Ref. 2.143)

Component	Standard Deviation
Stagnation pressure	±0.5 psf or ±0.1 percent of range
Test section static pressure	±0.5 psf or ±0.15 percent of range
Stagnation temperature	±1 to ±3°F or ±2 percent of range
Angle of attack	±0.06 deg.
Internal balance	±0.35 percent of range
Model pressures	±0.1 percent of range
Data acquisition system	±0.03 to ±0.05 percent of range

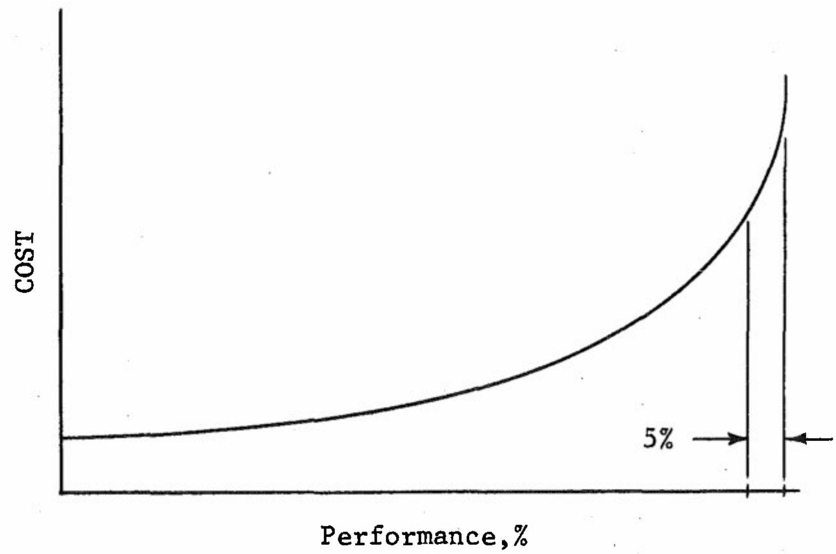


Fig. 2.11 The Cost of Performance on Fighter Aircraft

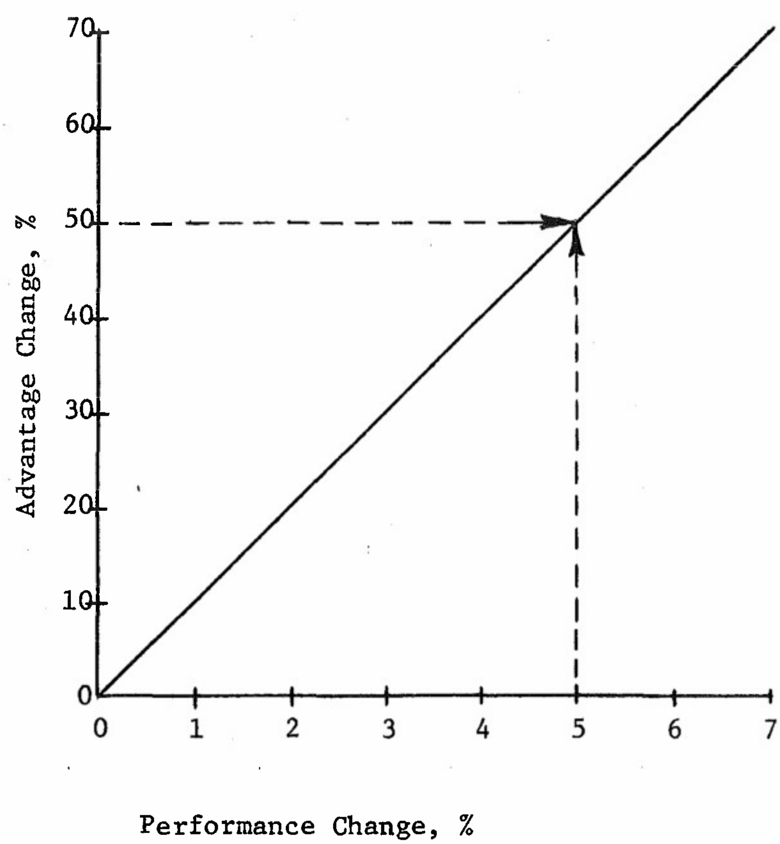


Fig. 2.12 Sensitivity of Advantage to Changes in Performance on Fighter Aircraft

Table 2.2 summarizes the wind tunnel data accuracy. These accuracies are based on regular tunnel calibrations, correlation of data with other facilities, and instrumentation analysis. The data are taken as one standard deviation errors in percent of range except where otherwise noted (Ref. 2.143). The acceptable tolerance levels for a given run are shown in Table 2.3. It should be noted that the tolerance levels given for Mach number and angle of attack are nearly equal to the uncertainty of their respective measurements. Also, the drag coefficient is larger than the desired one count of drag accuracy for the simulation.

Table 2.2. Overall Accuracy Measurements (Ref. 2.143)

Parameter	Standard Deviation
Stagnation Pressure	± 0.2 percent
Stagnation temperature	$\pm 2^{\circ}$ F
Static pressure (test section)	± 0.2 percent
Mach number	± 0.002
Dynamic pressure	± 0.5 percent
Reynolds number	$\pm 0.03 \times 10^6$
Angle of attack	± 0.06 deg.
Drag coefficient	± 0.005
Lift coefficient	± 0.008
Pitching-moment coefficient	± 0.006

Table 2.3. Acceptable Tolerance Level (Ref. 2.143)

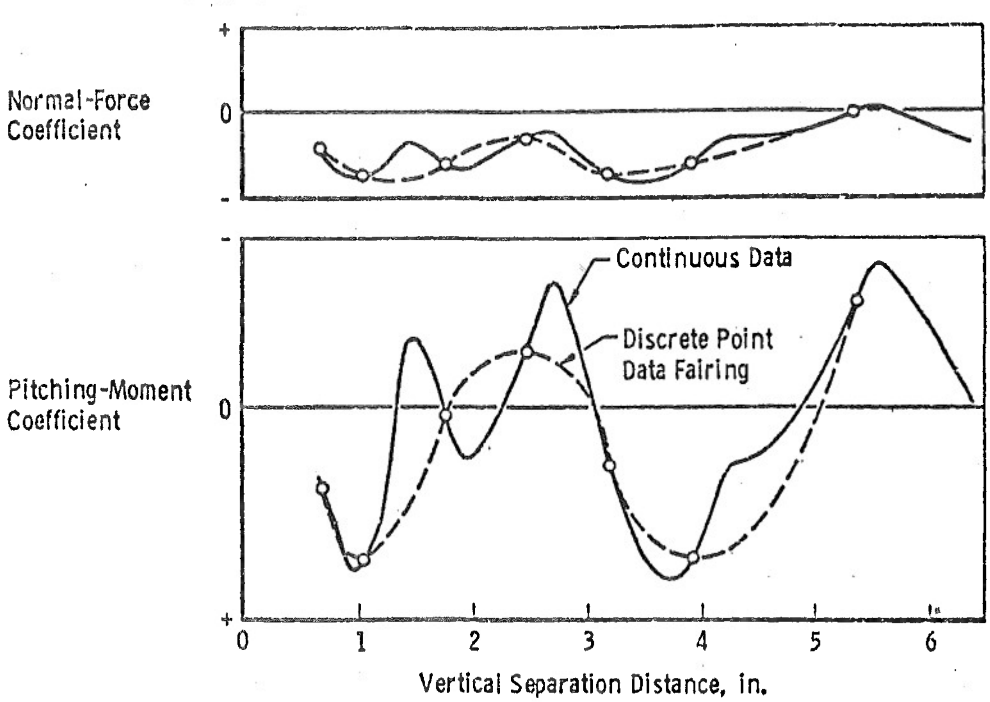
Parameter	Acceptable Deviation
Mach number	±0.003
Reynolds number	1 percent of value
Dynamic pressure	1 percent of value
Angle of attack	+0.05 deg.

The accuracies and tolerances in these tables are based on instrumentation precision, repeatability and correlation of data with other wind tunnels. They are not, however, a measure of the aerodynamic simulation accuracy.

The information presented in this and the previous sections shows the need for improved simulation accuracy and some possible solutions to achieve this goal. It appears that a new emphasis for upgrading wind tunnel facilities is urgently needed if our desire to keep abreast of the simulation accuracy demanded by current and future aeronautical systems is to be met. Integration of computers and wind tunnels should provide some solutions to these needs. *However, more effort in research and development of integrated wind tunnels and computer facilities is clearly needed.*

2.4 CURRENT USE OF COMPUTERS IN WIND TUNNEL TESTING

With the advent of the modern electronic computer, it has become possible to automate numerous tunnel and model controls and to automate the data acquisition/reduction and data verification techniques. At the same time that computers have become available for use in wind tunnel testing, the demand for improving the performance of air vehicles has created higher test data requirements. These requirements dictate an increase in the accuracy of the aerodynamic parameters measured in the wind tunnel. Ultimately, these test data requirements must translate into increased accuracy of similitude. Figure 2.13 illustrates how the quality of the data has been improved in a particular test where continuous data were taken.



COMPARISON OF CONTINUOUS DATA WITH DISCRETE POINT DATA ON A WEAPON DEPLOYED FROM THE B-1 BOMBER AT MACH NUMBER 2.26

Fig. 2.13 Data From the Computer-Programmed Position Control System (PPC) in AEDC-VKF Tunnel A (Ref. 2.138)

The productivity of wind tunnel testing has been increased over the last few years as more controls have become automated. Data handling effort has been reduced by an order of magnitude as a result of the concise, pertinent, and intelligible data points provided. As the cost of operating wind tunnels continues to increase, the demand for more and better use of computers in wind tunnel testing becomes paramount (Refs. 2.77 and 2.125).

The areas where computers are currently being used in wind tunnel testing include: tunnel controls, model controls, data automation, and data verification. The majority of controls in wind tunnel testing are direct command systems (open-loop), and these type of controls have been available for many years. Only a small number of controls are closed-loop and these are available in only a few facilities. However, these latter systems are still under development. Future improvements can be made by applying closed-loop techniques to more model and tunnel controls and to test planning optimization.

2.4.1 Tunnel Controls

With the increase in complexity of the aircraft under development, the control requirements placed upon the wind tunnel are accordingly increased. The free stream conditions must be maintained at precise and constant values. As suitable computing hardware and software become available more of the control features are incorporated into a computer control system. Because of their inherent simplicity and their well developed instrumentation, direct command controls, such as those listed in Table 2.4, have been extensively used. Closed-loop tunnel control, however, is currently available in varying degrees in only some facilities; in others, it is the subject only of research and development. Unfortunately, neither the application nor the study of closed-loop control is widespread.

The need for closed-loop automation of tunnel controls is clearly evident. Controls increase the test repeatability and reliability and have the additional benefit of improving the free stream flow quality.

Basically, all closed-loop control systems consist of one or more direct command controls that have been provided with error correction servo-mechanisms and the appropriate software.

MODEL SUPPORT SYSTEM	STAGNATION PRESSURE CONTROL
PLENUM EVACUATION SYSTEM	EJECTOR FLAPS CONTROL
FLOW FIELD PROBING	WALL ANGLE CONTROL
NOZZLE CONTROL	FUEL SYSTEM
SCANNIVALVE CONTROL	ROCKET PROPELLANT SUPPLY SYST.
OPTICAL RECORDING SYSTEM	ATMOSPHERIC DRYER SYSTEM
TEMPERATURE CONTROL	VACUUM SYSTEM
VARIABLE WALL POROSITY	HYDRAULIC & PNEUMATIC SYSTEMS

Table 2.4. Examples of Direct Command Controls Used in Some Production Wind Tunnels.

An example of a production facility using a modest degree of closed-loop automation is tunnel 4T at AEDC (Ref. 2.67). A mini-computer (PDP 8/E) automatically controls the tunnel stagnation pressure for most conditions and the Mach number in the range 0.2 to 0.9. Complete control is available for ejector flaps, porosity, and wall angle (see Fig. 2.14), but these are controlled by predetermined calibration information and position sensors. Pressures, temperatures, position, dynamic pressure, Mach number, and Reynolds number are continuously monitored and displayed.

Plans at AEDC call for extending automatic control of Mach number and stagnation pressure for 4T, ultimately providing automation (in closed-loop) for all test conditions within the range of the tunnel. Even with the moderate degree of closed-loop control presently used, tunnel 4T has increased its productivity by an estimated 5 percent due to the monitoring of test conditions, and an additional estimated 10

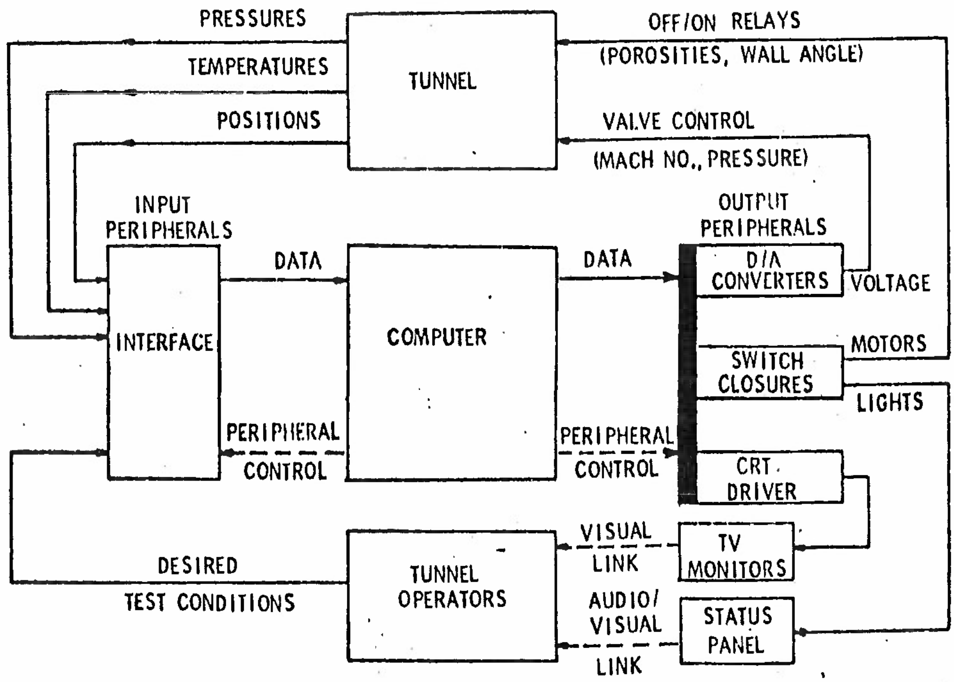


Fig. 2.14. The AEDC 4T Tunnel Real-Time Control and Display System (Ref. 2.67)

percent due to the position and process control. Efforts to further develop closed-loop control systems continue at AEDC.

Plans for the NTF include closed-loop control for the test section walls, reentry flaps, pressure, temperature for cooling water flow, liquid nitrogen, and drive speed (Ref. 2.66).

Most of the remaining closed-loop applications are of a research and development nature. One example is provided by the intelligent wall work of Judd at the University of Southhampton (Ref. 2.80). The studies involve the integration of the intelligent wall wind tunnel with an online computer. Such a set-up will provide the calculations required to set the walls, control the wall movement until minimum interference conditions are attained, and finally provide model data acquisition (see Section 2.7.2).

As the tunnels are required to provide control over more parameters, and thereby provide higher quality test conditions and test data, it is likely that computers which have faster computational speeds as well as larger memories may have to be dedicated to both direct command and closed-loop systems.

Various computer systems should be studied to determine whether one large or several small computers will accomplish the task better. Hawkins and Partridge of the RAE, for example, have reported (Ref. 2.70) that their facility would be best served by a system divided into a "number of modular packages each based on a small computer."

There is presently a lack of effort in the R & D of new closed-loop control techniques as well as a lack of application of existing closed-loop control technology to production wind tunnels. A more concerted emphasis needs to be made in the R & D of closed-loop controls as well as in the application of proven closed-loop control techniques to upgrade existing facilities. One area that definitely shows promise and appears to be reachable within the next few years is the automation of Mach number and stagnation pressure for improved continuous testing at varied test conditions.

2.4.2 Model Controls

Model controls have been significantly improved within the past decade and have become the central focus of computer and wind tunnel integration. At the present time, model controls are highly automated in most wind tunnel facilities, and these are frequently used in closed-loop systems. Pate (Ref. 2.138) refers to the automated model controls as one of the major advances in wind tunnel testing in the last 10 years.

Like the tunnel controls discussed in the previous section, model controls can be classified as either of two types: (1) direct command systems or (2) closed-loop systems. Direct command control systems currently being used at AEDC in model control include those listed in Table 2.5. Most of these systems control the model orientation, including maneuvering characteristics, probe position, and model engine inlet or mass flow.

a.	Adaptive Scanivalve Control
b.	Air Inlet Control System (AICS)
c.	"Closed-Loop" Air Flow Control (CLACS)
d.	Model Attitude Positioning System (AMAPS)
e.	Pitch and Roll Control
f.	Model Injection System
g.	Probe Position System
h.	Dynamic Stability Control

Table 2.5. Direct Command Control Systems Used in Model Control at AEDC.

The Model Injection System (Fig. 2.3) is one of the most significant advances in wind tunnel testing capabilities of the past 10 years. This system allows faster model installation and configuration changes, and thus increases productivity and test flexibility; it also allows various wall temperature ratios to be examined by cooling the model before injection.

While all of these direct command controls used for testing models are currently driven by a computer, some of them are also used in a closed-loop manner in some tunnels. Table 2.6 is a more complete list of closed-loop control systems used in model control.

a.	Captive Trajectory System (CTS)
b.	Computer-Programmed Position Control (PPC)
c.	Adaptive Scanivalve Control
d.	Vehicle Trim System
e.	Captive Aircraft Departure System (CADS)
f.	Constant Parameter Analysis*
g.	Self-Optimizing Flexible Wing*
*Under Development	

Table 2.6. Closed-Loop Control Systems used for Model Control

These controls are extremely effective in simulating a variety of flight conditions and are excellent time savers. A number of production wind tunnels are equipped with closed-loop control systems (Ref. 2.138 shows that the Captive Trajectory System (CTS) is available in four AEDC tunnels, two NASA tunnels, and in one tunnel each at General Dynamics and LTV). Figure 2.4 illustrates the CTS in one of the AEDC Tunnels.

Binion (Ref. 2.23) points out that the CTS is a great convenience to wind tunnels testing, in that it provides a separation simulator used for trajectory analysis of air-launched stores and a function generator for the aerodynamic forces experienced by both the stores and the parent aircraft. The closed-loop form of control allows the prediction of the store trajectory online using the aerodynamic forces and moments. A closed-loop slave vehicle control similar to the CTS system was reported by Titchener and Recover of the RAE (Ref. 2.180).

Closed-loop model controls used in wind tunnel testing have been significantly improved in the past decade, and improvement is continuing. Computer and wind tunnel integration is mostly developed in the closed-loop control of models, and this development has markedly influenced the integration of tunnel controls as well. The productivity of wind tunnels *has increased remarkably at no loss in quality during this past 10-year period and will probably continue to increase as the closed-loop control of parameters is improved in both model and tunnel environments.*

2.4.3 Data Automation

Current use of computers in wind tunnel testing provides a high degree of data digitization, storage, and reduction. Online data reduction allows data to be displayed on plotting and tabulating equipment within seconds after the read cycle is initiated. When the data require further analysis, they can be recorded and stored on magnetic tape for subsequent offline data reduction (ref. 2.178). Currently, most of the data reduction done in production wind tunnels is done on a mid-size computer or, in many instances, on a minicomputer.

Some recently developed measurement techniques such as infrared temperature scanning (IR) yield global data which must be digitized and analyzed on a computer in order to be efficiently utilized. This technique, also known as thermographic data, can be digitized into color patterns which are then displayed on a television monitor. Other new measurement techniques requiring digital data reduction include holographic interferometry, Moire' pattern pictography, and laser velocimetry. Sophisticated pattern recognition capability is needed to efficiently analyze the data from some of these techniques.

Data automation has also made possible real-time data analysis, which allows online CRT plotting and interactive graphics which, in turn, provide opportunities for test decisions and possible changes.

As test data requirements become more pronounced due to increased sophistication in measurement techniques and/or more complex air vehicle performance characteristics, larger and dedicated computers (or, perhaps, groups of minicomputers set up in modular systems) will be needed (Ref. 2.70). More use of interactive graphics will also be called for.

2.4.4 Data Verification

Large facility computers are frequently used to verify wind tunnel data by comparing them to results obtained through computational techniques. In some cases, tunnel users demand that the computations be done in advance of the wind tunnel test in order to gain confidence in wind tunnel data (Ref. 2.205). This type of verification is more commonly done in hypersonic testing with cone models at low angles of attack, though the practice extends to subsonic and supersonic regimes as well.

Computational codes in present use involve linear potential theory with corrections for the boundary layer plus semiempirical transition, shock, and separation location. Nevertheless, current computer codes have proven successful in providing reliable design and analysis criteria for three-dimensional weak boundary-layer interactions, two-dimensional transonic weak boundary-layer interaction, and three-dimensional transonic isolated wing calculations (Ref. 2.42 and 2.141). They have also been highly successful for hypersonic reentry vehicle computations (Ref. 2.205). Figure 2.15 illustrates where airfoil analysis by computer is in excellent agreement with experimental data. Figure 2.16 on the other hand, illustrates that there is disagreement between computational codes and experimental data in other flight regimes.

Present computational codes are semiempirical in nature and are not solutions of the Navier-Stokes equations; therefore, comparisons between the tunnel data and numerical computations are not a guarantee of the correctness of the data. The existing codes are small enough to fit on the common larger computers (e.g., CDC 6600).

Although progress is being made in computational fluid dynamics, and although codes seem to progressively agree with experimental data, it is unsafe to extrapolate beyond the area where the empiricism, upon which they depend, is obtained.

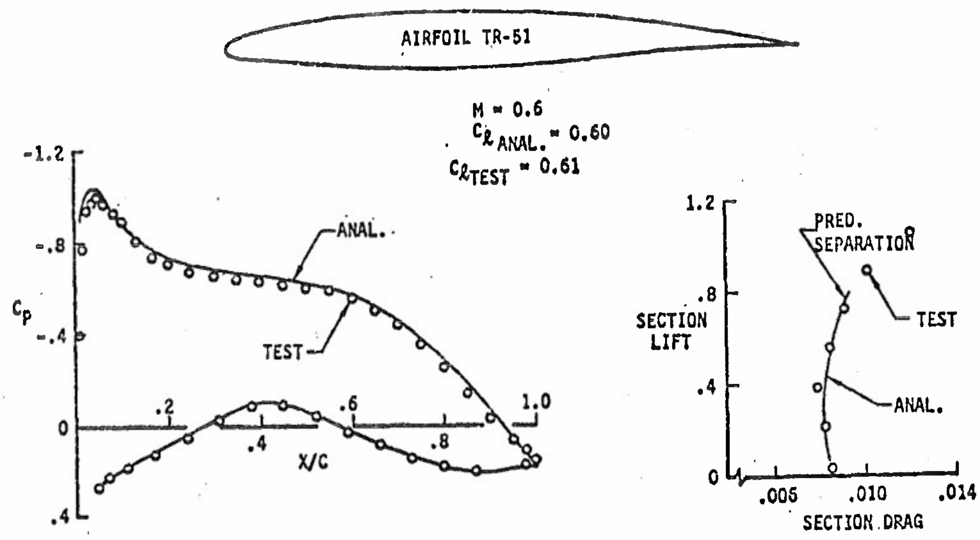


Fig. 2.15. Airfoil Analysis in Subcritical Viscous Flow (Ref. 2.42)

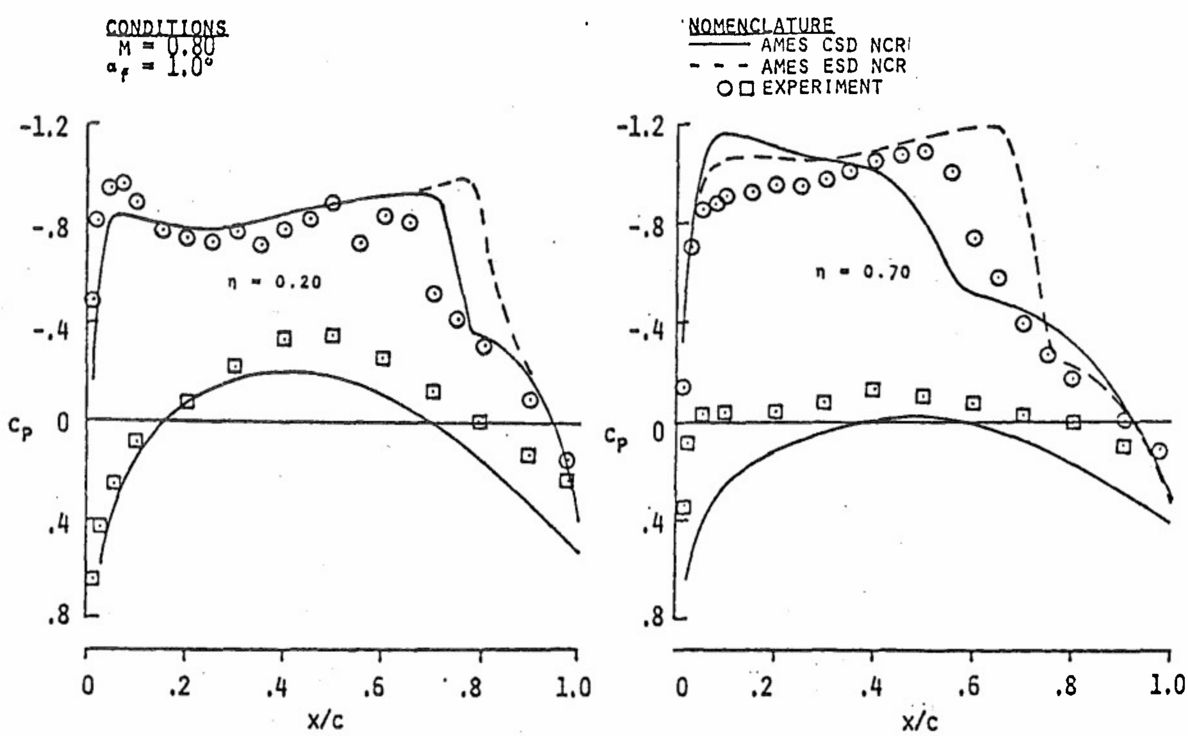


Fig. 2.16. C-5A Transonic Wing Pressure Correlations (Ref. 2.141)

2.5 FUTURE DEVELOPMENTS IN EXPERIMENTAL AERODYNAMIC FACILITIES AND TEST METHODS

2.5.1 Facility Planning Goals

In the future there will be fewer aeronautical weapons systems, but those used will be more complex and sophisticated. Testing facilities will have to be capable of examining these new systems as well as systems that will be developed using new emerging technologies such as V/STOL and supersonic and hypersonic cruise. There will be a continuing need for more and better design data with the reduction of the design risk as a major goal (see Section 2.2.1). Testing facilities can assist in reducing the design risk by improving simulation accuracy (see Section 2.3.4).

The facility planning goals can be summarized as follows (Refs. 2.2 and 2.154): 1) to improve simulation quality, 2) to improve data quality, and 3) to improve testing efficiency. These goals will be accomplished by constructing new facilities where it is obvious that existing tunnels will not meet the needs or by modifying existing facilities to extend their capabilities and improve their simulation quality. Except for the existing commitment for new facility construction (see Section 2.5.2), it is not known whether the other goals will be realized, since there is no assurance that the needed funds will be made available. It almost appears to be easier to obtain funding to build a new facility than to upgrade the quality of an existing one.

There is general concern for increasing the simulation Reynolds number and improving tunnel flow quality by reducing the facility sound and turbulence levels. Flow quality improvements are needed most urgently for the development of laminar flow vehicles but are also required to improve simulation accuracy for all vehicles.

Data quality will be increased by the use of more computer controls on the tunnel flow parameters, on model controls, and on data acquisition and analysis. This subject is covered in detail in Sections 2.4 and 4.0. New instruments and measuring techniques will also be used. More attention to flight test correlation will also assist in improving data quality. The goals and needs of future research facilities are discussed in Section 2.6.3.

There appears to be a desire to improve existing facilities, but improvements are given a considerably lower priority than the construction of new facilities. Funds should be made available for improvements in existing facilities, especially those improvements that will increase their simulation accuracy.

2.5.2 New Testing Facilities

The need has been demonstrated for new testing facilities which either extend current capabilities or provide testing environments for new technologies. The planning for a new facility takes many years, from the examination of various concepts to operation of the completed facility. (This is illustrated in Table 2.7 using the dates for the National Transonic Facility). Therefore, much foresight is needed to insure the availability of testing facilities for the development of future generations of weapons systems.

National tunnel construction programs exist in both the U.S. and in Europe (Refs. 2.2 and 2.202). Because of their large cost, great caution has been exercised in the selection of the facilities to be constructed (see Ref. 2.77). However, it must again be pointed out that facility construction and operation costs are small compared to the R & D cost of a new weapon system.

The wind tunnels which have been approved for construction are the following:

1. National Transonic Facility (NTF), to be built at NASA-Langley, at a cost of $85M (Refs. 2.82, 2.83, 2.11, and 2.84).

2. Full-scale subsonic wind tunnel, to be built as a modification of the 40 by 80-foot wind tunnel at NASA-Ames, at a cost of $83M (Ref. 2.122).

3. Quiet supersonic wind tunnel to be built at NASA-Langley (Ref. 2.15).

Table 2.7. National High Reynolds Number Wind Tunnel Planning (Ref. 2.77)

1966-1975	--Air Force design development of Ludweig tube facility (HIRT)
1969-1970	--NASA Study of hydraulic drive conventional tunnel
1969-1972	--NASA design studies of injector driven tunnels
1971	--NASA/DOD (AACB) approves HIRT to propose as a national facility
1972-1973	--NASA experiments with cryogenic low-speed pilot tunnel
1973	--AACB study recommends HIRT (development) plus cryogenic TRT (research)
1974	--Congress authorizes Air Force to build HIRT
1974	--Construction cost escalations result in Air Force decision not to go forward with HIRT and AACB to make a reevaluation of transonic facilities
1975	--AACB approves cryogenic NTF as single facility to be jointly operated by NASA and DOD for research and development testing
1976	--Congress authorizes construction of NTF by NASA. Appropriates funds.
1981	--Planned operational date

Two proposed facilities were deferred and will be considered at a later date. These are a large transonic wind tunnel at NASA-Lewis and a true temperature hypersonic tunnel at AEDC. Other governmental agencies, as well as aircraft companies, would like to construct new testing facilities, but there are no immediate plans to do so.

Plans also exist to make some modifications to existing tunnels. These modifications include anechoic and adaptive wall test sections (Ref. 2.2). Because these modifications will have to be funded from operational budgets, it is not known when they will be made.

A central computer facility is usually included in the plans for new tunnels. Although it is good to include the computer as part of the design and have it funded with the total tunnel, this method would result in the purchase of an out-of-date computer by the time the tunnel is finally operational. It would be better to defer the computer selection until completion of the tunnel in order to insure the purchase of a state-of-the-art computer that will not quickly become obsolete.

The new construction program will result in only one high Reynolds number transonic tunnel (NTF). This one tunnel will never be able to handle all of the high Reynolds number testing needs of the country. Furthermore, no prior consideration is being given to improvements in the test section wall (such as intelligent wall) or to the flow quality, although the option exists for making modifications once the tunnel is operational (Ref. 2.191). As pointed out previously (Section 2.3), it is very important that the best technology be used to lessen the effects of wall interference and flow disturbances, and it is unfortunate that this was not done for NTF.

The wind tunnel facilities which will be available for testing in the next five years are known. They are the existing facilities plus an additional three new facilities, which are deisgned to meet certain testing and research needs. The new tunnels will not meet all of the new testing needs; NTF will not be able to perform all the needed high Reynolds number tests.

The best technology for alleviation of wall interference effects and improvement in flow quality should be incorporated into all new facilities.

Computer systems which are included with new facilities should be selected during the final stages of facility construction.

2.5.3 Future Testing Needs

Military missions and commercial applications will continue to determine the majority of needs in testing, and these new systems will probably be significantly more complex than those currently in use. However, as noted in Section 2.3.1, probably no more than about 50 percent of the wind tunnels inventoried in the U.S. in 1965 are still in operation (Ref. 2.138). The combination of fewer tunnels and more complex systems to be tested dictates that more efficient testing techniques must be developed and employed. Hence, increasing the extent of tunnel interaction with computers will probably be necessary to upgrade test efficiency and the quality of data acquired. In addition to new systems, various modifications and adaptations of existing systems to extended roles will continue to require a substantial amount of wind tunnel test time (Ref. 2.115). With the past and present as a guide, the test information on these extended systems will be expected to be supplied in the shortest possible time period. In addition, for a few systems, inevitably there will be problems discovered during flight evaluation, requiring additional wind tunnel testing, the results of which will always be desired expeditiously.

There will be some special testing needs associated with basic research, and these must be dealt with as they arise and are identified. However, certain areas of testing which must be more thoroughly explored on a fundamental level before being upgraded to full production status are as follows:

High Angle of Attack (Refs. 2.188 and 2.189)
Unsteady Flows (Refs. 2.85 and 2.179)
V/STOL (Ref. 2.202)
Engine/Aircraft Interaction (Refs. 2.30, 2.125, and 2.139)

One particularly interesting example of data scatter associated with high angle-of-attack testing is shown in Figure 2.17. This illustrates the difficulties and uncertainties to be expected in these areas. The flows cannot be extrapolated from known flows nor can they be computed. In some cases they involve new physics, and new testing techniques must be developed to study them as the physics becomes better understood.

2.5.4 New Measurement and Testing Techniques

The demand for higher air vehicle performance is the driving force behind the need for more efficiency and for increased simulation accuracy in wind tunnel testing. This is a trend that appears to be gaining momentum and is continuously placing a strain on wind tunnel measurement

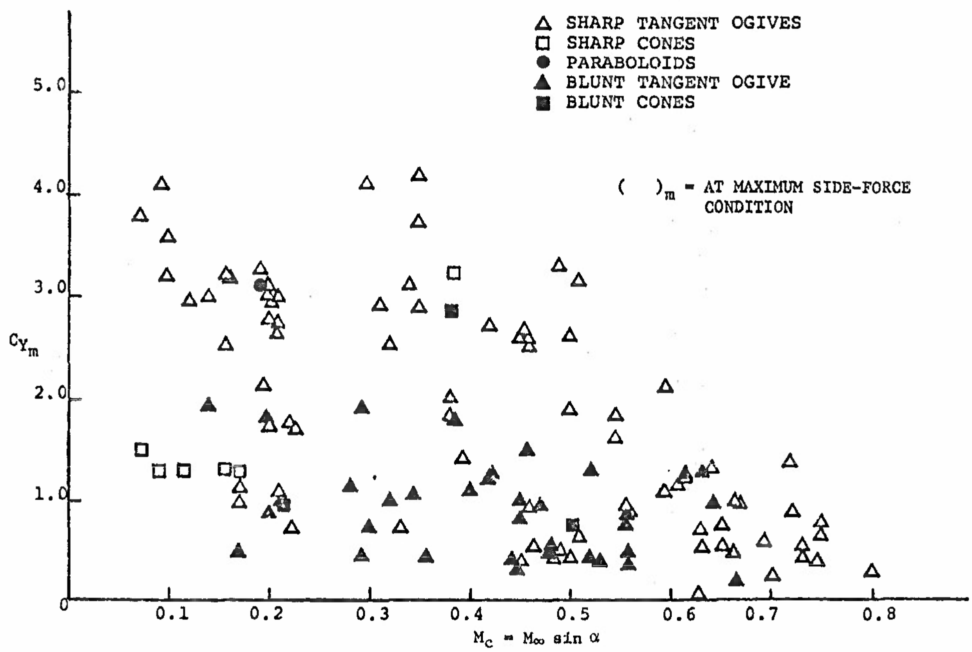


Fig. 2.17 Cy_m as a Function of $M_c = M \sin\alpha m$ for All Points in the Data Base for Which αm is known (Ref. 2.189)

and testing techniques. New concepts for wind tunnel test measurements are often proposed; however, there is usually a great lag between technique development and application in production wind tunnels. Most of these new techniques are highly sophisticated and require great care in their application. In the early stages of their development, these techniques work well with research wind tunnels; nevertheless, some of these techniques show promise for future implementation in production wind tunnel testing.

The literature makes mention of numerous investigations into new types of measurement and testing techniques which reportedly provide higher quality data, particularly data of the flow field away from the model. These techniques also address some of the tunnel simulation accuracy limitations and provide means by which a better understanding of the flow quality can be obtained. Indeed, they appear to be very promising tools which will help in the research needed for understanding such factors as separation, shock wave interaction, transition, and other basic phenomena (see Section 2.6.4).

Many of the new techniques require dedicated computers or specialized computers or specialized computer and numerical analysis methods (e.g., pattern recognition) for efficient application in production tunnels. Only new techniques requiring computers will be discussed here.

Some of the new measurement and testing techniques which show promise include the laser velocimeter (LV), holographic interferometry, Moiré pattern recognition, and infrared scanning. The intelligent wall (which can be considered a testing technique), discussed in Section 2.7 also shows great promise for improving simulation accuracy.

Current flow diagnostic devices such as pitot tubes and hot wires cause flow perturbations which require corrections and do not measure velocity directly (Ref. 2.95). Furthermore, many presently in use cannot measure transient phenomena and have poor spatial resolution.

The new techniques, by way of contrast, are optical and therefore non-intrusive. The earliest was the laser velocimeter (LV). The LV provides direct measurement of velocities involving no correction factors (assuming the particles are moving with the fluid velocity). It has proven to be superior to the conventional techniques used for velocity measurements. The frequency response and continuous measurement capability coupled to a digital computer make the LV technique an excellent device for mapping flow fields, including areas containing shock waves, separation, transition, and reattachment.

Problems still remain with the LV system which make it difficult to use in production tunnels (Refs. 2.166, 2.209, and 2.212). Application of the LV technique requires a dedicated computer of small size for data storage and analysis. The computer size increases if the technique is to be used for turbulence measurements.

Another technique, which is used for analyzing steady and unsteady flow fields, is the holographic interferometer (Ref. 2.167). Holographic techniques are very useful for the examination of two-dimensional flow fields (Ref. 2.167) as well as the aeroelastic and flutter characteristics of tunnel models. The latter use could also be helpful for studying rigid model deflections (Ref. 2.64) and their effect upon measured model performance.

Moirè patterns can also be used to examine model deformation (Ref. 2.3). Both the Moirè and the holographic techniques require the application of pattern recognition methods to automate their analysis before they can be useful measurement tools. This could probably best be accomplished through the use of dedicated computers of appropriate size at the tunnel site although remote access to a central computer could be used if the usage priority were high enough.

The infrared scanning (IR) technique for measuring model surface temperatures has been under development at AEDC for several years. This technique allows complete temperature maps to be made quickly and accurately. Presently the data are placed on analogue tape and analyzed offline, but online analysis is possible, again either with a dedicated computer or by remote access to a central computer. Online analysis of all these techniques is required for production testing.

There appears to be a strong effort in the research and development of optical technologies that may be applied to tunnel testing. The application of these sophisticated techniques can lead to better understanding of flow fields and model effects and by their use significant progress in flow quality can be expected. However, developmental work is required before the techniques can be routinely used in production tunnels.

All of these techniques require online connection to appropriately sized computers and the use of specialized numerical techniques to make them useful in the testing environment.

2.6 CALIBRATION AND BENCHMARK EXPERIMENTS

2.6.1 Historical Background

In an effort to account for disagreement between tests made in different low speed wind tunnels at the same Reynolds number and between wind tunnel tests and free-flight tests, the turbulence sphere was introduced as probably the first of the significant correlation models. Turbulence generated in wind tunnels by the propellor, guide vanes, and vibration of the walls caused some aspects of flow patterns in the tunnel to be similar to those in free flight at a higher Reynolds number (Ref. 2.109). The proper application of the turbulence sphere achieved significant success in establishing effective Reynolds numbers for the tunnels calibrated with it, making possible many important analyses regarding Reynolds number effects. Over the years wind tunnels have become more complex along with the problems they were built to solve. Again, in an effort to account for differences between different tunnels and between tunnels and free flight, other correlation models have been introduced. These are discussed in the following section.

2.6.2 Correlation Studies

For the more complicated, high performance tunnels several types of models have been used in various correlation studies between different tunnels and between tunnels and free flight. These are discussed below:

2.6.2.1 Shock Plate

This device for generating a two-dimensional shock has been a valuable tool in some of the early work in the area of transonic and supersonic test section wall interference. Its main application has been in contributing to the establishment and control of nominal test section conditions for various types of ventilated walls (Refs. 2.108, 2.111, and 2.177).

2.6.2.2 Cone-Cylinder

Testing with this device provided the same type information as did the shock plate but as related to three-dimensional flow (Refs. 2.63 and 2.56).

2.6.2.3 AEDC 10-degree (Included Angle) Transition Cone

One of the more ambitious and comprehensive correlation studies has involved the use of this cone in 23 different wind tunnels in the United States and Western Europe (Refs. 2.195 and 2.47). One significant finding from this series of tests is that acoustics can have an effect on boundary-layer transition, although the details of this effect are as yet undetermined. Results from these tests revealed a large variation in dynamic flow quality among the tunnels investigated, but perhaps the most important fact to emerge was that the mechanics of transition remain largely unknown. What determines the transition Reynolds number is still undefined. This fact alone is very valuable, for it points out a basic problem which, when solved, will quite likely lead to the most significant improvements in aerodynamic simulation in many years.

The details of boundary layer transition are still not fully understood, and their determination would constitute a major breakthrough in fluid mechanics.

2.6.2.4 Complete Airplane Models

This is one area that has gotten completely out of hand. At best, there has been only a weak attempt at coordinating and standardizing tests involving models of this type. Reference 2.57, a 1961 textbook, lists no less than five different correlation models for transonic and supersonic tunnels. Since that time various agencies and private companies have unilaterally introduced several more, and at this writing other correlation models are in the planning stage (Refs. 2.42, 2.93, and 2.191).

One group of the earlier models can be represented by the AGARD B and C models. Coefficients of lift, drag, and pitching moment were measured for the AGARD models in various tunnels at various percentages of blockage with no attempt to hold Reynolds number constant (Ref. 2.57). Increased wall interference with increased model blockage was apparent.

One group of correlation models could be referred to as the transonic transport type. Of this group, the ONERA calibration models have been tested extensively in both the United States and Western Europe (Ref. 2.24).

One observation from these tests is escapable: In some cases there are significant data discrepancies between the tunnels involved even when the model, Mach number, and Reynolds number are apparently fixed. A representative cross-plot showing the discrepancy in moment coefficient is shown in Fig. 2.18. Agreement for the lift and drag coefficients for the ONERA tests was substantially better.

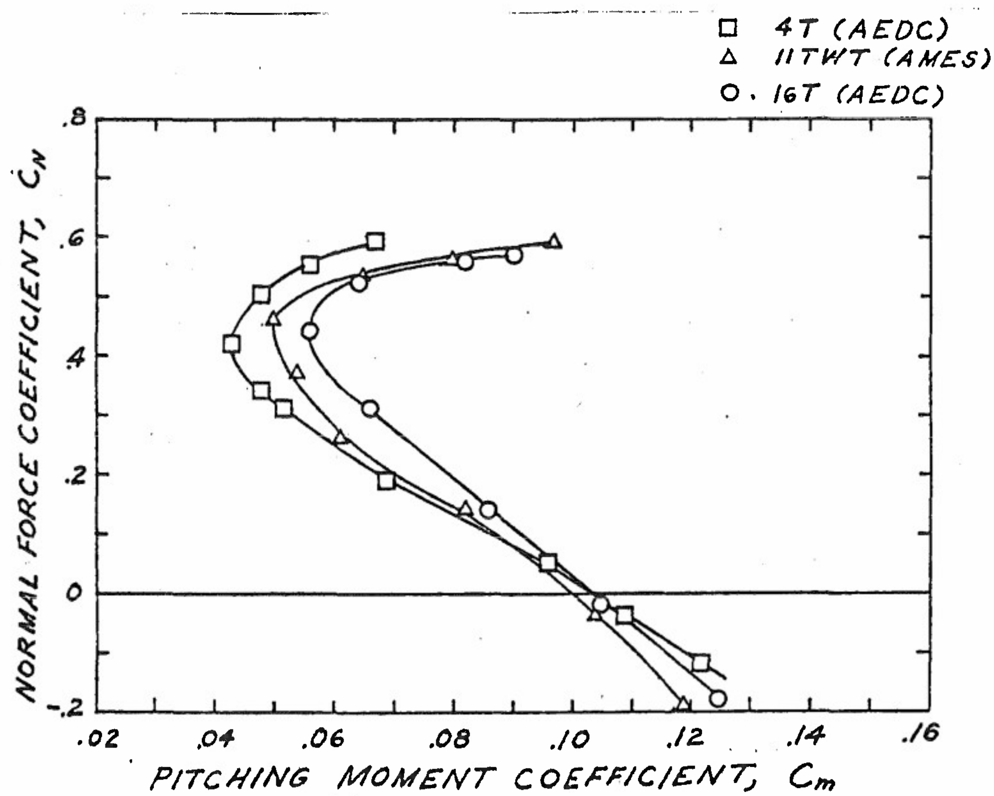


Fig. 2.18 ONERA M^5 Model, M=0.84, Re=1.02 x 10^6, Free Transition (Ref. 2.24)

There are some as yet unexplained variances in data obtained in different wind tunnels at supposedly the same conditions.

A model of the C-5A was used as a correlation model in three different tunnels in the United States (Ref. 2.181). Just as in the case of the ONERA model, lift and drag agreed fairly well, but there were some differences in pitching-moment comparisons.

The apparent discrepancies that have arisen in data comparisons for the complete airplane correlation models must be viewed with the knowledge that these models involve many complex, three-dimensional flow phenomena which interact in some undefined, complicated fashion. When the more basic flow phenomena (such as transition) are understood, perhaps with the aid of benchmark experiments (Section 2.6.4), then it is quite likely that most of the discrepancies will disappear.

With all the different correlation studies that have been made and will be made in the future with a variety of models, it might well be beneficial for the results of some of the tests to be available as a data base for any tunnel that is interfaced with a computer. For example, this could prove helpful in arriving at an effective Reynolds number for a particular tunnel configuration.

2.6.3 Research Wind Tunnels

Research wind tunnels have made a major contribution toward understanding various fluid mechanics phenomena and discovering new facts; however, they will continue to be needed as tools for studying basic problems that are as yet unsolved. Hence, their existence and operation must be maintained and their performance should be improved through the use of new technologies, such as the intelligent wall (discussed in Section 2.7.2) for removing wall interference effects.

Research wind tunnels of high quality must be available for controlled experiments to discover new facts.

It may be advisable to perform some old experiments in these improved research tunnels to check out new measurement techniques such as the laser velocimeter. These tunnels must be dedicated completely to basic research and not subject to impressment into a production schedule on even a part-time basis. The personnel that operates these tunnels must be selected and maintained with an eye to the special skills and temperament that work of this nature requires.

Research wind tunnels must be allowed the freedom to operate without the constraints and objectives of a production-oriented environment. Qualified people to support and operate these tunnels are as necessary as the tunnels themselves.

To make these tunnels operate in the highly controlled manner necessary for good resolution, it probably will be necessary to have them interact very heavily with computers, both in regulating tunnel operating parameters and in data reduction. One important function for these tunnels will be to provide the environment in which a number of benchmark experiments (discussed in the following section) can be run. Another function may lie in providing production tunnels with information that would make better extrapolation to flight conditions possible. This aspect is discussed in Section 2.7.1. Although research tunnels should be primarily used to uncover new facts, they can also be used to verify various numerical codes. This concept is discussed both in the following section and in Section 2.7.4.

2.6.4 Benchmark Experiments

Many basic viscous fluid mechanics phenomena such as transition, shock wave/boundary layer interaction, embedded vortices, and separation are directly influenced by wind tunnel interference effects on a model. They are also associated with the interference of one part of a flight vehicle with another. At the risk of oversimplifying, it may be stated that these phenomena receive significant influence from two sources:

a. Flow-field features (pressure gradient, fluctuations, flow angularity, noise, etc.) essentially far removed from a surface boundary,

b. Viscous effects of the fluid (scaling).

Pertaining to wind tunnels, if "a" is <u>well defined</u>, then "b" will be part of the simulation, and the overall simulation should be a good one. Although many valuable contributions have been made over the years through wind tunnel testing, "a" is still not sufficiently defined for some types of testing needs. On the other hand, for computational fluid mechanics, "a" presents no problem because it can be put in the governing equations and boundary equations. However, "b" becomes a problem if turbulence is involved. The modeling of turbulence, which significantly influences the definition of "b" is simply not adequately done at this time. In fact, quoting from Jones (Ref. 2.77) of NASA Ames, "Little, if anything, new in the understanding of the scaling of aerodynamic data has come about in the past eight years." Realizing the importance of turbulence modeling and the present inadequacy of it, it is optimistic to note that the scientific community is expressing a growing interest in conducting the necessary experiments to make true turbulence modeling a reality. Lee (Ref. 2.98) of Ohio says, "The reaction of the boundary layer to compression in the transonic range often produces an extensive effect upon the flow field near a vehicle and hence upon the aerodynamic forces. The phenomena will remain poorly understood and unpredictable until there is available a body of reliable experimental evidence from which accurate conclusions may be drawn, and against which theoretical predictions may be compared." According to Marvin (Ref. 2.109) of NASA Ames, "Because turbulence modeling is empirical by nature, successful development relies on a substantial data base, not only for verification of postulated models, but for providing guidance in model development."

Experimental information is needed as a basis for a turbulence model or family of models that has physical relevance.

Benchmark experiments to isolate various phenomena for study should be conducted in the research tunnels described in the preceding section. A representative set of benchmark experiments is listed in Ref. 2.109. Basically, the list consists of two-dimensional and three-dimensional attached flows, separation and reattachment flows, trailing edge flows, shock/boundary-layer interaction flows, wake flows, corner flows, and 3-D tip flows. This list, of course, is not inclusive. Whatever the details are for each experiment, the important thing is that only one flow phenomena should be emphasized at a time. Initially, experimental and computational solutions can be compared with analytic solutions to establish credibility and confidence in procedures. *When the geometry of the configuration has increased in complexity to the point that no analytic solution exists, then the experimental and computational solutions should be carried out independently of each other.* When both of these techniques are in agreement, the complexity of the configuration may be increased and the process repeated until the list of benchmarks has been completed.

There is a need for a series of well-posed experiments in the research wind tunnels which are free from free stream and wall interference effects, to isolate and define a number of influential basic phenomena which thus far have avoided sufficient interpretation.

Again, on considering the list of general benchmark experiments mentioned above, if, during the sequence of experimental-computational combinations, a physically relevant turbulence model could be ascertained, then it is possible that all the basic viscous fluid mechanics phenomena mentioned at the beginning of this section could be defined, with the possible exception of transition. Even for transition, it may be that, in the process of determining a turbulence model, the true details of transition may emerge.

2.7 FUTURE INTEGRATED USE OF COMPUTERS AND WIND TUNNELS

2.7.1 Extrapolation to Flight Conditions

2.7.1.1 Overview of Drag Extrapolation

Present wind tunnels are unable to meet the Reynolds number requirements of modern aircraft (see Section 2.3.4). The National Transonic Facility, which is being constructed at NASA-Langley, will provide a testing environment at the necessary Reynolds number, but it will not be able to perform all of the needed high Reynolds number transonic testing. Therefore, the need to extrapolate low Reynolds number tunnel tests to flight conditions will continue to exist.

It is important to be able to extrapolate tunnel tests with the confidence that the result will accurately predict the actual flight situation. This necessitates not only tests in high quality tunnels using high standards of testing techniques but also the use of valid extrapolation procedures. This section will address the latter problem. Uncertain scale effects can have very negative effects on the aircraft design process and the final aircraft. This problem was discussed in detail in Section 2.2.

This section will concentrate upon the extrapolation of the drag coefficient because of the present-day importance of this problem and the large amount of literature about it. The moment coefficient presents a greater problem, but this will not be discussed; only the subsonic and transonic ranges will be covered. The very large problem of the engine installation drag will also be omitted because it is too poorly understood.

2.7.1.2 Reynolds Number Sensitive Flow Phenomena

It is important initially to determine which flow phenomena are sensitive to scale effects (Reynolds number) and which are not because only those sensitive phenomena need to be scaled to flight conditions. The effort toward designing NTF resulted in a study of Reynolds sensitive phenomena, and a list resulting from that inquiry is given in Ref. 2.77. Scale effects have also been studied extensively on supercritical wings (Ref. 2.26). A partial list of phenomena generally accepted as sensitive

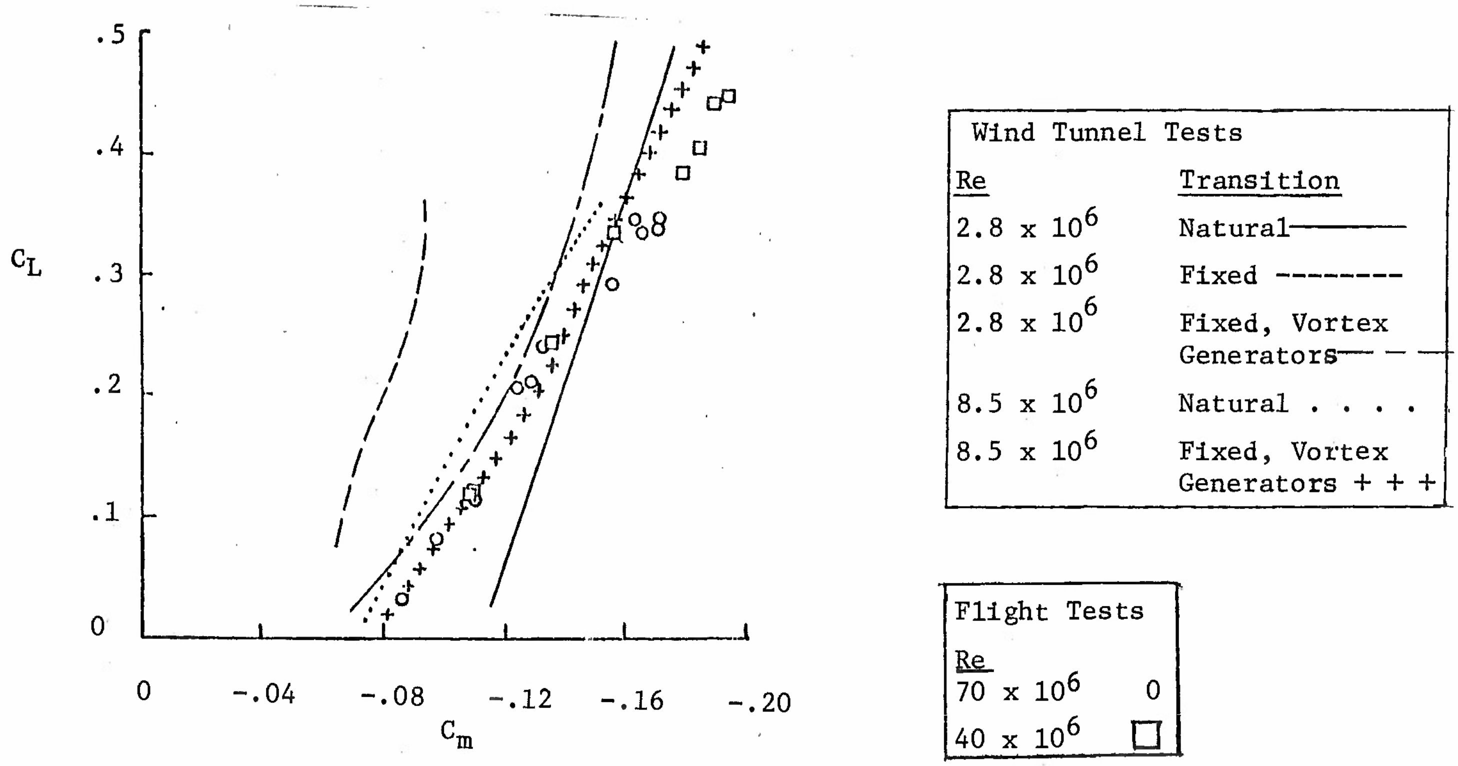


Fig. 2.19 Reynolds Number Effects on C-141 Airfoil Section Properties Instrumentation Location at .637 of Semi-Span, Measured from Body Centerline (Ref. 2.191)

to Reynolds number is as follows: boundary-layer thickness, wall skin friction, boundary-layer transition, flow separation, shock/boundary-layer interaction, and three-dimensional viscous interactions (Refs. 2.11, 2.26, 2.77, 2.98, and 2.191).

There are problems identifying Re sensitive phenomena in a tunnel. For example, most tunnels vary Reynolds number by varying the dynamic pressure, q. High q conditions, however, can cause large deflections of the model (Refs. 2.2 and 2.35) resulting in vastly different geometrical conditions and making it almost impossible to separate the true Reynolds number effect. Wall and tunnel flow quality can also have uncertain influences on the measured phenomena. The true tunnel angle of attack is unknown, because of wall interference effects, and the flight angle of attack is also unknown. Hankey, at AFFDL, has had some correlation success by plotting uncorrected tunnel measurements of lift coefficient versus moment coefficient in an attempt to eliminate the unknown angle of attack. An example is shown in Fig. 2.19. Tunnel flow disturbances can also influence the test results by moving the location of boundary-layer transition thereby influencing the boundary-layer thickness and shock/boundary-layer interactions (Ref. 2.26). Any numerical computations that are used to extrapolate tunnel test results must include corrections, however poorly understood, for wall interference flow quality. The intelligent wall will offer an opportunity to eliminate the large uncertainty due to the wall effect (see Section 2.7.2).

The failure to extrapolate the correct shock location on the C-141 wing from tunnel tests has been the object of much discussion. The original measurements indicated that it would be difficult to predict the flight shock location from the tunnel tests (Ref. 2.11). Later tests performed in the Lockheed-Georgia Co. compressible flow facility (CFF) showed that the high Re tunnel tests matched the flight test shock position (Ref. 2.191). Present theory also indicates movement of the shock with Reynolds number on a supercritical wing (Ref. 2.11). Recent measurements in the Ohio State University two-dimensional transonic wind tunnel place some doubt upon these results. The OSU tunnel has top and bottom plenums which are not pumped but are allowed to come to their own pressures, resulting in essentially interference-free conditions for unseparated two-dimensional transonic flows (Ref. 2.191). The C-141 wing was examined with free boundary-layer transition in that tunnel. The angle of attack was varied until the pressure distribution matched the measured distribution in flight; variation of Reynolds number then showed no essential changes in the shock location or the pressure distribution (Fig. 2.20), casting doubts upon the previous conclusions concerning Reynolds number effects. Even less Reynolds number dependence of the flow over a supercritical wing was observed in this tunnel.

More research needs to be done to determine the influence of tunnel walls on flows about bodies and to obtain more understanding of the effect of Reynolds number changes, when the Reynolds number is large (greater than 5 x 10^6), on flows of aerodynamic interest. Because tunnel and flight Reynolds number do not overlap (and will not until NTF is operational), it is difficult presently to separate the two effects.

2.7.1.3 Present Extrapolation Procedures

Realistic drag predictions use historical data, empirical relationships, wind tunnel data, and theoretical analyses. As pointed out by Bowes (Ref. 2.30), "The manner in which these resources are used to blend together into a prediction is subject to the experience of the design team, the degree to which the configuration resembles previous models, and the amount of proprietary experimental data available to the engineer." The procedures are reasonably accurate if the flow is attached and the pressure distribution does not change very much with Reynolds number.

Discussion will be limited for the moment to the profile drag (which amounts to 60 percent of the drag of a transonic transport (Ref. 21.139)). Present semiempirical extrapolation procedures, such as the Squire-Young momentum defect method (Ref. 2.171) or the flat plate plus shape factor method (Ref. 2.139) require in their greatest generalizations accurate potential flow and boundary-layer computations, using an assumed turbulence model, transition and location, and effective Reynolds number

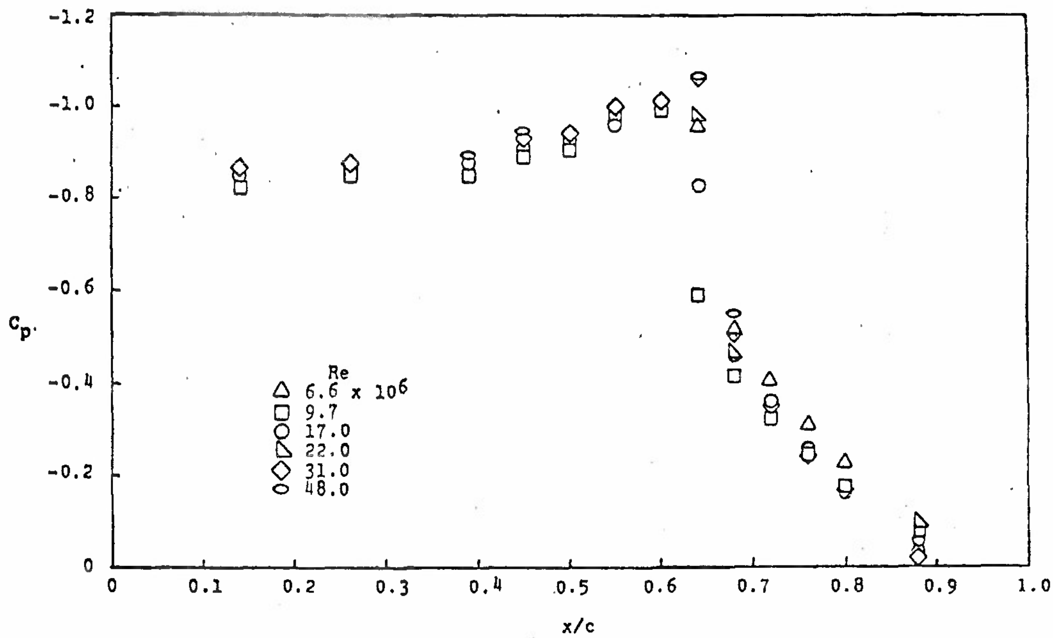


Fig. 2.20 Pressure Distributions on Suction Surface of C-141 Section. M = 0.81, α = 5° (Variation With Reynolds Number)

(Ref. 2.98)

for the tunnel (Refs. 2.42, 2.46, 2.141, 2.194, and 2.195). The effective Reynolds number is required to account in a simple way for the influence of tunnel disturbances on the flow (see Section 2.62). Resulting drag estimates are then corrected for an assumed forward motion of the transition point on the flight vehicle (Refs. 2.2 and 2.141). Note that the actual transition location in flight is unknown (Ref. 2.2).

Problems arise from several sources. For example, the flight vehicle has a roughness that is difficult to model. More importantly, the present semiempirical techniques have problems modeling the interference between the various parts of the vehicle, separated flow regions, compressibility effects (which lead to the drag rise), and the engine integration. Problems also arise with some of the new supercritical wings that are expected to be shock-free at flight Reynolds number but not at the tunnel Reynolds number (Ref. 2.141).

In addition to the above semiempirical techniques, some computational solutions of the viscous flow about two-dimensional aircraft components are proving useful. Three-dimensional techniques cannot be applied as yet. Present computational techniques are useful for critical analysis, but they cannot be used to calculate a drag polar (for example, see Ref. 2.30). At this stage of progress the new analysis techniques have identified drag prediction uncertainties and their sources but have not improved the prediction accuracy.

Drag prediction and extrapolation techniques presently require extensive flight tests for validation. It is a very difficult task to perform an accurate bookkeeping of the sources of drag on a full-size aircraft, not to mention the problem of determining the thrust. For a full discussion see Refs. 2.30, 2.32, 2.125, and 2.139. Figure 2.21 indicates the steps taken by the Lockheed Corporation to analyze the C-130 drag. At the present ime the flight test comparisons are the only means for validating the extrapolation procedures.

It is a common practice to place grit on an aircraft surface near the leading edge to cause early boundary-layer transition and thereby simulate a higher Reynolds number. This method also has the advantage of fixing the transition location for all model orientations, which

C-130 DRAG ACCOUNTABILITY STUDY

- OBJECTIVES
  - IDENTIFY SOURCES OF DRAG
  - GENERATE DRAG DATA BANK
  - DEVELOP DRAG REDUCTION CONCEPTS

- APPROACH
  - USE THEORETICAL METHODS TO DETERMINE PRESSURE AND FRICTION DRAGS OF ISOLATED AND INSTALLED COMPONENTS

  - PERFORM WIND TUNNEL TESTS FOR FILLETING AND AFTER-BODY RE-DESIGN

- THEORETICAL METHODS
  - 2-D TRANSONIC AIRFOIL ANALYSIS METHOD
  - 3-D SUBSONIC PANEL PROGRAM
  - 2-D STRIP BOUNDARY LAYER PROGRAM
  - 3-D BODY BOUNDARY LAYER CODE
  - WEAK INTERACTION SUBSONIC WING PROGRAM

Fig. 2.21 (Ref. 2.141)

makes the extrapolation procedure easier. However, this is a questionable practice. Blackwell (Ref. 2.26) suggests a more rational procedure which requires computations of boundary-layer growth on the model. Also, recall that Lee (Ref. 2.98) obtained good results in his interference-free tunnel with free transition.

The accuracy of the present extrapolation procedures is open to some debate. The present discussion is offered to provide a base from which to compare the future techniques and to identify future opportunities.

It is commonly stated that the wind tunnel is capable of measuring the drag coefficient to within one drag count ($C_D = 0.001$) (Ref. 2.69) but it must be remembered that this is tunnel precision, and not the ultimate simulation accuracy, which can be determined only by comparing extrapolated tunnel measurements and flight test measurements.

First consider the accuracies of the semi-empirical extrapolation procedures. The empirical flat plate skin friction correlations agree with one another to within 1 to 2 drag counts but come from data with a scatter of ± 10 percent (± 3 drag counts) in the Reynolds number range from 3 to 40 x 10^6. Smith and Cebeci (Ref. 2.171) found a 2.9 percent error between measured and calculated profile drag for airfoils using the momentum defect method. This error resulted from the calculation of the trailing-edge momentum thickness, an incorrect assumed transition location, and the empirical wake decay expression. Also, a direct calculation of the wing drag using a potential flow and a turbulent boundary-layer program failed badly. These results would indicate problems with the simplest of drag extrapolation.

Few comparisons between the predicted and flight test measured drag coefficients have been published. One was on the C-5A aircraft where the two figures differed by 1 to 3 percent (2 to 7 drag counts), depending upon the procedure used (Ref. 2.139) (see Fig. 2.22). Bowes (Ref. 2.30) made an extensive examination of the drag prediction problem. He estimated that the minimum profile drag can be estimated to ± 1 percent of total drag, the subcritical lift depending drag to $\pm\frac{1}{2}$ percent, and the compressibility drag to ± 3 percent. Flight test drag measurements were accurate to ± 1 percent for steady-state testing (very expensive)

C-5A

COMPARISON BETWEEN MODEL AND FULL SCALE DRAG

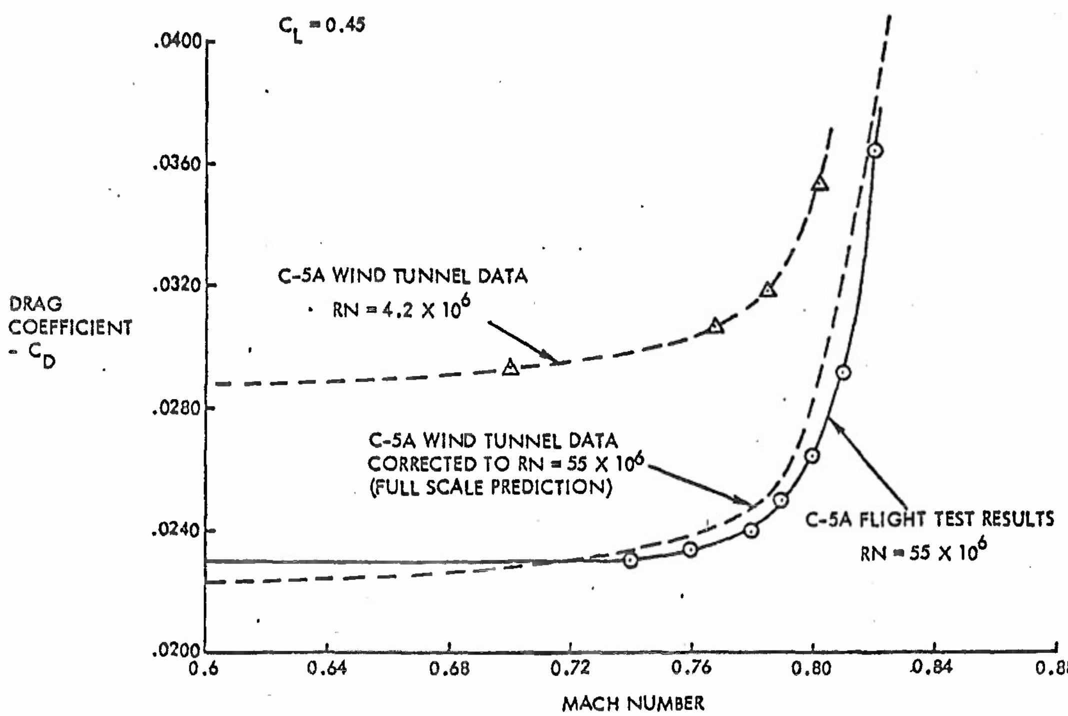


Fig. 2.22 (Ref. 2.141)

and ±4 percent for quasi-steady and dynamic testing. His overall accuracy rating for subsonic transports at cruise conditions is given below.

L/D Level Achieved	Rating
±3 percent	Amazing
±5 percent	Very Good
±7 percent	Average
±10 percent	Below Average

These levels are obviously not acceptable, especially for a high performance military aircraft. *It is anticipated that a combination of simulation improvements in tunnels and greater use of more advanced computational techniques plus the addition of the high Reynolds number tunnel, NTF, will allow improvements to be made in the accuracy of the predicted performance of future aircraft. In addition, less reliance will then have to be made upon experience gained from previous tunnel and flight tests on geometrically similar configurations.*

2.7.1.4 Future Extrapolation Procedures

The next generation of drag extrapolation procedures will take advantage of the advances in computational techniques which are now occurring and the great advances in computer size and speed which have recently taken place. The new computing speed and improved numerical techniques will reduce the computing time and cost to make them attractive for aircraft design. To be useful to the aircraft designer, both the computational techniques and the computing power must be readily available to him. The design techniques will always remain proprietary, and it is therefore necessary that the computing be performed at the company location, by company personnel.

Although the present extrapolating procedures are semiempirical, the future techniques will be based more upon analysis. Computational techniques, validated by experiments, will play an increasingly important role (Ref. 2.32). NTF will play an important role in code validation, assuming that great care is taken to ensure that the simulation accuracy in this tunnel is the best that can be achieved by using intelligent walls, etc. Butler (Ref. 2.32) has suggested a "synthesis" approach to drag estimation which divides the drag sources according to their fluid mechanics origin and allows for the progressive introduction of computational methods as they become available for each source. This analysis technique undoubtedly will be implemented in the future and will hasten the goal of predicting flight drag to within one drag count.

Although the future prospects for computing viscous flows are discussed fully in Section 3.0, a summary of those aspects relating to future drag prediction will be useful here. The ultimate goal would be to calculate the viscous, three-dimensional, turbulent flow about a complete aircraft configuration for the flight Mach number and Reynolds number. That goal will not be attained in the foreseeable future. However, certain aspects of that goal relating to aircraft components will be achieved.

To begin with, the following statements depend upon the availability of a turbulence model with enough sophistication to obtain results with sufficient engineering accuracy. Transition will probably not be understood well enough to be computed a priority, and its position will have to be empirically modeled. Then, assuming a satisfactory turbulence model, three-dimensional viscous flows which are dominated by the external pressure gradient (such as cross flows over fuselages) will be computable, but those flows which are primarily viscous interactions (e.g., wing-body junction with embedded secondary vortices) will not be. Any embedded vortices will have to be added empirically. The shock/boundary-layer interaction and two-dimensional separated regions will result automatically from the computations. This will mean that many individual aircraft components can be analyzed by computations but that the interactions between the individual pieces will still have to be measured in the tunnel. This will greatly assist in determining interactions which are causing problems and in solving these problems.

In the transonic speed range, NTF (with intelligent walls) can be used to validate the computational procedures by examining individual components. Once the codes are validated, then they can be used to extrapolate the data obtained in the lower Reynolds number tunnels, following perhaps the synthesis procedure of Butler (Ref. 2.32), while using empirical interaction and transition information. These codes can also be used to calculate body flows at lower Reynolds number characteristic of existing tunnels, and differences between the computations and the measurements can be used to assess the effect of tunnel interferences.

Future extrapolation procedures will be based upon analysis. Computational techniques, validated by experiments, will play an increasingly important role. *The National Transonic Facility will play an important role in code validation.*

2.7.2 The Intelligent Wall

An excellent possibility for the future integrated use of computers and wind tunnels is the joint use of the computer and the "intelligent wind tunnel" in closed-loop form. Several concepts of this joint use are currently being proposed (Table 2.8 is a list of R & D efforts to design an intelligent wall wind tunnel; these were identified at the time this was written). Investigators report that steady progress has been made since early 1973, and at least one investigator has predicted that a full production intelligent wall wind tunnel will be in operation in the mid 1980's (Ref. 2.93).

The idea of the intelligent wall wind tunnel was first proposed as a "flexible wall" wind tunnel by a group of engineers in England between 1942 and 1944 (Ref. 2.204). Several flexible wall tunnels were built during that period; however, they were not practical, since they were very limited in their test capabilities and moreover were not truly "intelligent," since they were not converging with any numerical solution for the far field (there were no numerical methods available for this purpose in the early 1940's). At that time, the wind tunnel was seen as an adequate simulator of low-speed flight, and aerodynamicists were not confronted with the V/STOL or transonic problems of today.

The flexible wall tunnel concept remained the subject of light discussion and did not receive serious attention until the early 1970's,

INVESTIGATORS	LOCATION	FACILITY (Test Sect.)	Reported	Name of Experiment and Funding Agency
A. Ferri, P. Baronti	Advanced Tech. Lab. Westbury, NY	AFFDL Tunnel Transonic	Jan. 1973	Interference-free Transonic Wind Tunnel (ONR,AFOSR,AEDC)
W. R. Sears, R. J. Vidal J. C. Erickson, Jr., P. A. Catlin	CALSPAN Corp. Buffalo, NY	10" x 12" Transonic	July 1973	Self-correcting Wind Tunnel (ONR,AFOSR,AEDC)
T. M. Weeks	AFFDL Wright-Patt. AFB, OH	15" x 15" Transonic	March 1975	Reduced Interference Slot-Contoured Wind Tunnel (ONR, AFOSR, AFFDL)
M. J. Goodyer, M. Judd S. W. D. Wolf	University of Southampton (U.K.)	6" x 12" Subsonic	Aug. 1975	Self-steamlining Wind Tunnel (NASA-Langley)
J. P. Chevallier	ONERA Chatillon, France	180mm x 180mm Transonic	March 1976	Auto-adaptable Wall Wind Tunnel (ONERA)
R. G. Joppa S. Bernstein	University of Washington, Seattle	8' x 1' Subsonic	April 1976	Minimum-correction Wind Tunnel (NASA-Langley)
J. C. Vayssaire, M. Lansot M. Menard	Aero-Institute Saint-Cyr, France	0.85m x 0.85m Transonic	Oct. 1976	Variable Permeability Wall Wind Tunnel (S.T.Ae')
E. M. Kraft R. L. Parker	AEDC, Arnold AFS, TN	12" x 12" Transonic	July 1977	Adaptive-Wall Wind Tunnel (AEDC)
R. M. Barnwell J. Everhart	NASA-Langley Hampton, VA	6" x 19" Transonic	(current)	Adjustable Wall Wind Tunnel (NASA-Langley)
D. J. Harney A. W. Fiore	AFFDL--Wright-Patt. AFB, OH	9" x 9" Transonic	(current)	Adjustable Wall Wind Tunnel (AFFDL)
J. Lee, J. Gregorik	Ohio State Univ. Columbus, OH	6" x 22" Transonic	(current)	Interference-free Wind Tunnel AFFDL, NASA-Ames, Boeing, Lockheed.

Table 2.8 "Intelligent Wall" Wind Tunnel Experimental Studies

when interest in V/STOL and transonic air vehicles began to place greater demands on the quality of data obtained from wind tunnels. At that time, plans were being drawn up for a National Transonic Facility, and this gave added impetus to the attempt to design an improved test section. Since an intelligent wall wind tunnel design has not yet been completed, the NTF test section will have conventional features (slotted walls); however, it will make some provisions for improvements and for incorporating intelligent wall features as they become feasible (Ref. 2.11).

Aerodynamicists agree that the intelligent wall wind tunnel can improve the quality of test data in a number of ways, among which are:

a. increased flow quality
b. absorption of the shock wave
c. blockage reduction (model and wake)
d. increased model-to-tunnel ratio (higher Reynolds number
e. improved model accuracy (resulting from larger model)

Such improvement on the quality of test data would approximate "interference-free conditions." These conditions are attained using a computational fluid dynamics model to simulate the far field.

In 1972, Professors Ferri and Sears proposed that a wind tunnel that simulates unconfined flow could conceivably be built. At that time, they also proposed the theoretical and experimental basis for the intelligent wall concept. A refined version of their original concept is the basis for current R & D of the intelligent wall wind tunnel. Unconfined flow conditions in the wind tunnel would be achieved through an iterative scheme by active wall control, in such a way that the flow field interior to the tunnel walls would be unaffected by the presence of the walls. Compatability of any two independent variables (at a controlled surface near the tunnel boundary) with the far field or free-air boundary conditions results in an exterior flow that is the same as that which would exist in flight. It then follows that the interior flow must be compatible with that existing in free flight (i.e., the interior flow must be free of wall interference effects).

Tunnel wall adjustments are made on the basis of the difference between the measured and computed parameters (either pressure or flow angularity distributions). The process is repeated over and over, and each time the wall and/or plenum pressure and porosity are adjusted until conditions within the tunnel "converge" with those in the far field. This iteration scheme requires only that a theoretical far field be computed (by digital computer) while the wind tunnel is used as an analog computer to obtain the interior flow field. This is especially significant since the flow field around the model is shock infested, viscous, and separated and would be an extremely difficult problem to solve by digital computer. Instead, the measured pressures or flow angles along the boundary inside the tunnel become the boundary conditions for a boundary value problem. Initial numerical techniques involve calculations of two-dimensional flows over an airfoil using linear potential subsonic theory (Prandtl-Glauert). This method is extended to high subsonic flows with lifting wings where the disturbances in the far field are still very small. At higher Mach numbers, however, the small-disturbance transonic equation replaces the linear theory in order to account for flow disturbances due to shock waves at the tunnel walls. One type of numerical computation involves the use of the Murman and Cole finite-difference technique (Ref. 2.163). A revised version of the Murman and Cole technique is a program which was "improved by a coordinate transformation which maps the infinite domain about the airfoil into a finite domain and hence allows an exact application of the boundary conditions at infinity" (Ref. 2.49). Using a similar Murman-type solution, Lo and Kraft (Ref. 2.100) recently performed a numerical simulation for supercritical flow at $M_\infty = 0.9$ and report that "excellent results were achieved in three iterations and complete convergence to unconfined flow conditions was obtained in five iterations." Some of these two-dimensional techniques can be extended to three dimensional axisymmetric models in circular or axisymmetric tunnels. Nevertheless, three-dimensional computations and experiments have not been conducted as of this writing, although some investigators have made projections and estimates of the measurement and the computational requirements. In the future, extensions to three-dimensional testing at highly supercritical conditions are expected to require the use of the full potential equation. A discussion on the computer size requirements for a hypotehtical three-dimensional case may be found in Section 4.0.

At this point, the details of several intelligent wall concepts can be considered. Figure 2.23 is a sketch of the test section of the CALSPAN two-dimensional one-foot tunnel (self-correcting transonic wind tunnel). The plenum has been segmented, and the top and bottom walls are ventilated (using variable porosity). Twenty sensors along the top and bottom walls are used to measure the streamwise and normal velocity components of the flow. Flow angles could be resolved to 0.03 deg. (Refs. 2.161 and 2.163).

Using a NACA 0012 airfoil with a 6-inch chord, tests were run in the CALSPAN 8-foot tunnel to acquire virtual interference-free data (however, see Section 2.7.1). A test then followed in the 1-foot tunnel (in the conventional mode) where considerable wall interference was noted. Figure 2.24 illustrates how these two sets of data then compare with data acquired after three iterations of the intelligent wall control (adjustment of the plenum pressure and wall porosity). The result shows how the drag coefficient converges to the "interference-free" data from the 8-foot tunnel. Figure 2.25 also shows the convergence of the pitching moment to the interference-free data. Work at this facility is continuing and experiments at higher Mach numbers are being conducted.

Other intelligent wall work which is well documented (Refs. 2.14 and 2.190) involves experiments at the AFFLD-Trisonic Gasdynamics Facility using a 15-inch square slotted-wall test section. Tests were run using a 2.5-inch and a 5.0-inch chord, 6 percent thick biconvex airfoil at Mach number 0.91 and 0.95 at 0, $\pm 2^{\circ}$, and $\pm 4^{\circ}$ angle of attack. Pressures were measured by a movable probe 2 inches from the top wall (measurements were then extrapolated to the wall itself). Flow angularity was measured to within ± 0.03 deg. After calculating the external flow field, the slats were "contoured" (using strips of tape) until interference-free conditions were achieved.

Two concurrent efforts in the research and development of the intelligent wall are taking place in Europe, one at St. Cyr, France, and the other at Southampton, England. J. C. Vayssaire and others (Ref. 2.183) report using the 0.85 metre sqaure test section Sigma-4 transonic wind tunnel in an intelligent wall scheme. Excellent results were achieved using a variable permeability wall with movable plates in the plenum chamber and

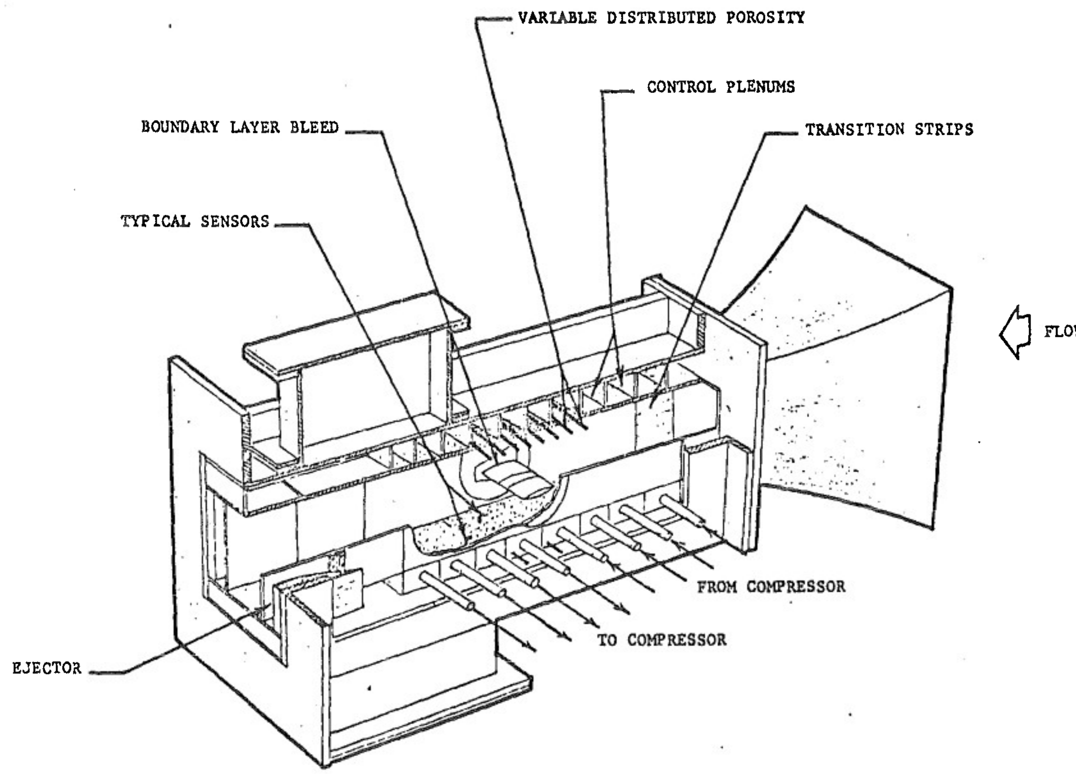


Fig. 2.23 SKETCH OF THE CALSPAN WIND TUNNEL TEST SECTION (Ref. 2.161)

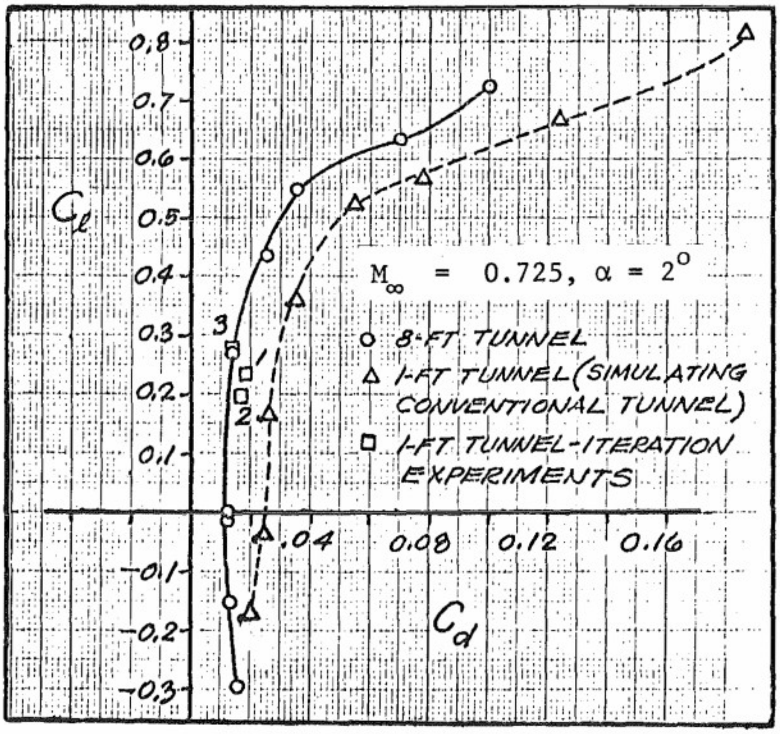


Fig. 2.24 Example of Wall Control Effects on the Drag Coefficient, C_d (Ref. 2.163)

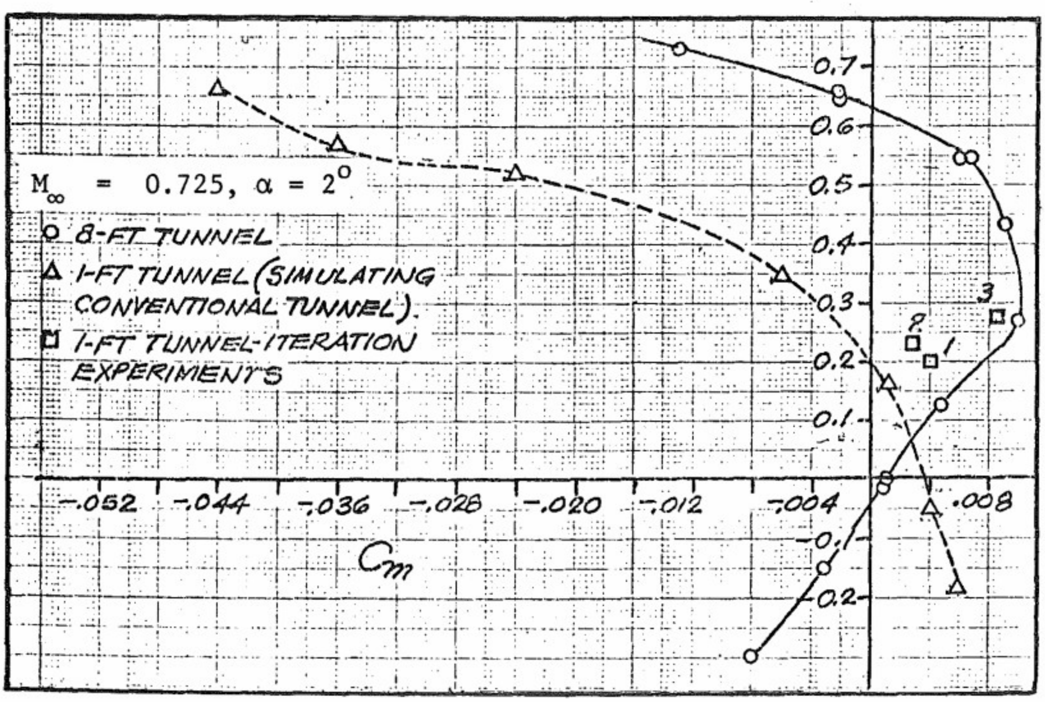


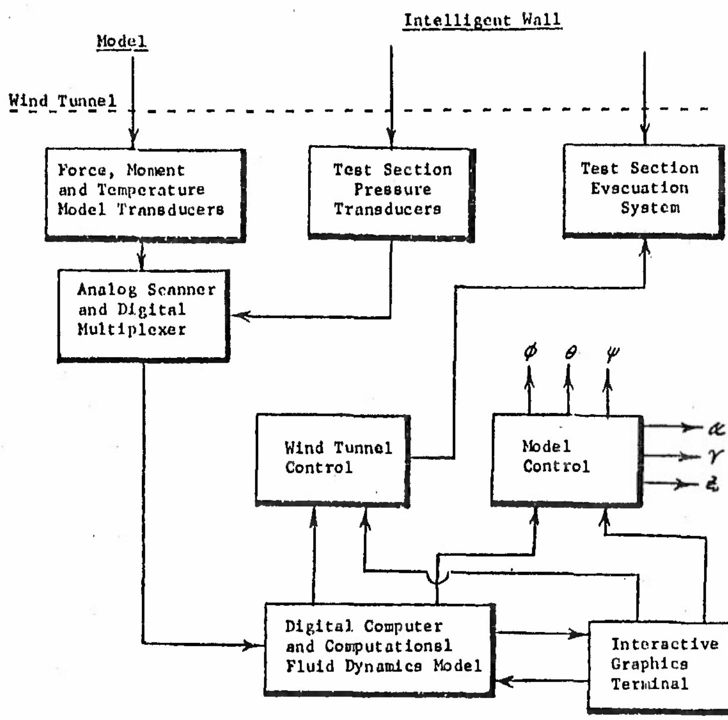
Fig. 2.25 Example of Wall Control Effects on the Pitching Moment Coefficient, C_m (Ref. 2.163)

setting them for calculated permabilities. Drag coefficient data obtained with this scheme agree very well with corrected data obtained from tests with closed walls. All data acquisition and plotting of the test results is done in real time with an on-line computer.

M. Judd and others (Ref. 2.80) report that experiments are currently being carried out in their 6- by 12-inch subsonic tunnel using the intelligent wall scheme. The tunnel is equipped with a series of screw jacks (15 on the top wall and 15 on the bottom wall) which adjust the geometry of the test section to match with the test section to match with the streamlines of the calculated external flow field. Two-dimensional tests have produced excellent results by matching the stream-lined tunnel data with the calculated exterior flow field as well as with the conventional wall tunnel corrected data. Additional work is being done in feasibility studies for automating the mechanical adjustments (screw jacks) on the wall. This procedure would, in effect, close the loop between the wind tunnel and the computer, and according to the Judd report, this would allow "(1) massive reduction in wall setting time, leading to more efficient use of wind tunnel run time, (2) more systematic operation from run to run, and (3) a basic procedure more readily adapted to three-dimensional testing."

In the various experiments, both numerical and physical, the intelligent wall concepts appears to have been conclusively proven for the two-dimensional case. It now seems that proof for the three-dimensional case is close at hand. Computational techniques that deal with highly super-critical conditions are in the development stage; however, mechanical and side wall treatment of the test section continue to be addressable problems. It is evidently clear that the intelligent wall concept has great potential for improving wind tunnel testing; when in closed-loop form (see Fig. 2.26) it will greatly assist in the development cycle of air vehicle design and testing."

A review of the literature reveals that the R & D efforts for the intelligent wall are not receiving the proper stimulus or support. The question can be asked: *why is it that the intelligent wall concept, which has shown promise from the very beginning, has not received the serious attention and support that the ventilated wall tunnel concept received twenty-five years ago?*



Computer Integrated Intelligent Wall Wind Tunnel Concept

Fig. 2.26 (Ref. 2.107)

An organizational effort needs to be made, perhaps in the form of a "formal group" (similar to the AGARD FD Panel working group in Design of Transonic Working Sections) which can coordinate between the funding agencies and the investigators.

Facilities (i.e., pilot tunnels) must be dedicated to R & D of the intelligent wall concept. Experimentalists using these pilot tunnels should communicate and cooperate with those at other facilities, and with those investigators capable of effecting the numerical solutions for the far field. The variety of experimental efforts now under way (see Table 2.8) provides an excellent opportunity to evaluate the variety of possible combinations of walls and plenum chambers and for comparing results in simulation accuracy. Current estimates show that the intelligent wall production wind tunnel will be feasible within the next ten years. The use of a relatively large computer is a vital necessity but is within the state of the art in computers.

Research should continue on "partially adaptive wall" schemes where the walls provide some adjustment but the measurements are corrected for the remaining interference. This approach may be more economical, time wise and costwise, and it offers promise of large, although only partial, simulation improvement.

Another effort that could prove useful at this stage of the R & D would be for the coordinating group to make a sensibility analysis that would indicate: (1) the means by which the measurements of the flow variables near the wall should be made, and the density and accuracy required; (2) the number of numerical mesh points required to calculate the far field with sufficient accuracy; (3) the computational times needed for the calculation of the far field and the subsequent iterations; (4) the mechanical adjustments in the wall boundaries (given limitations on possible adjustments) that can best accomplish the required changes; and finally, (5) the amount of improvement in flow quality, or reduction of wall interference, which can be gained by using various wall schemes (i.e., variable porosity and/or plenum pressure, streamline of walls, etc.) in an intelligent wall wind tunnel.

2.7.3 Test Planning Optimization

An area where the future integrated use of computers and wind tunnels can have great impact on the overall efficiency of wind tunnel testing is test planning optimization. Progress is already being made in this direction, and a healthy trend is developing, especially in those facilities with a moderate degree of automation.

With online computer capability, even within an open-loop mode, it is possible to make online decisions regarding the supervision and/or the modification of testing procedures and objectives. For example, online computers aid in anticipating the steps in the testing procedure in order to avoid errors which might lead to excessive wind tunnel operating time. Some facilities are now using interactive graphics in both open- and closed-loop form for test planning. Interactive graphics will play a major role in test planning optimization in the future. By using a graphics display, data can be plotted and compared to math models, instantaneously allowing selection of critical design data. This information can then become permanent baseline data for future reference.

In this respect, G. M. Bowes (Ref. 2.30) comments that "the computer is very helpful in comparing design, analyzing missions, and providing comparative performance data which suggest optimum trends." J. R. Hagerman (Ref. 2.69) stresses the need for obtaining only the needed data using the computer to "go" from one needed condition to another in an optimized fashion. For the wind tunnel testing of cruise missiles or military transports, this would mean obtaining primarily cruise condition data.

The math models of the future will be much more complex than those currently available (see Section 2.4.4). They will be closer to a complete approximation of the Navier-Stokes equations than present design techniques and as a result will require considerably larger and faster computers to complete solutions in a reasonable length of time (say 10 minutes). If wind tunnel results are to be compared with the computations in anything approaching real time, then such a computer must be available at the tunnel location. This is a necessary requirement if the tunnel is going to be reserved only for the examination of problem areas (i.e., alas which are at variance with the math model results).

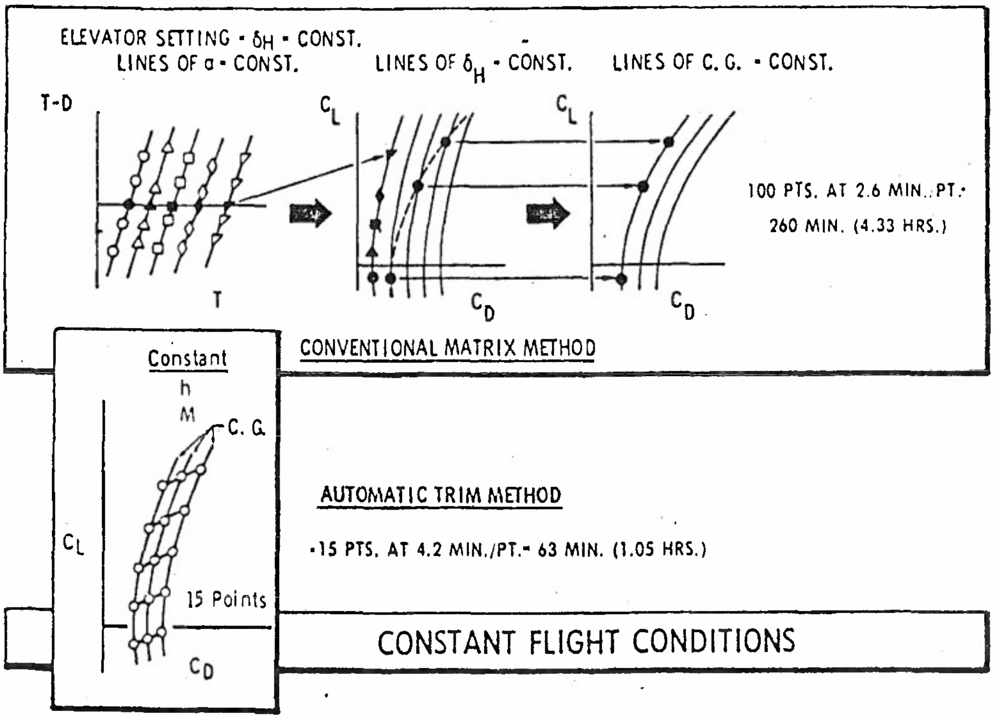
Several methods of test planning optimization have already been mentioned in the section on model controls (i.e., the vehicle trim system and the attitude positioning system (AMAPS)). Some others are under development, such as the Constant Parameter System and the Self-Optimizing Wing. Figure 2.27 illustrates how test planning has been optimized by using automatic trim of the model and the test time thereby reduced from 4.33 hours to 1.05 hours.

Figure 2.28 illustrates how constant-parameter testing can be helpful in test planning optimization. By maintaining a constant lift coefficient and varying the Mach number, one can assess the drag coefficient and the angle of attack in order to best verify the performance of the air vehicle.

Constant-parameter testing allows the model to be tested in a more efficient manner by providing fewer but more critical test points in less time compared to the conventional matrix method. It is expected that automatic control over Mach number will be available in tunnel 4T at AEDC at the end of this year, and this will bring constant-parameter testing closer to production use.

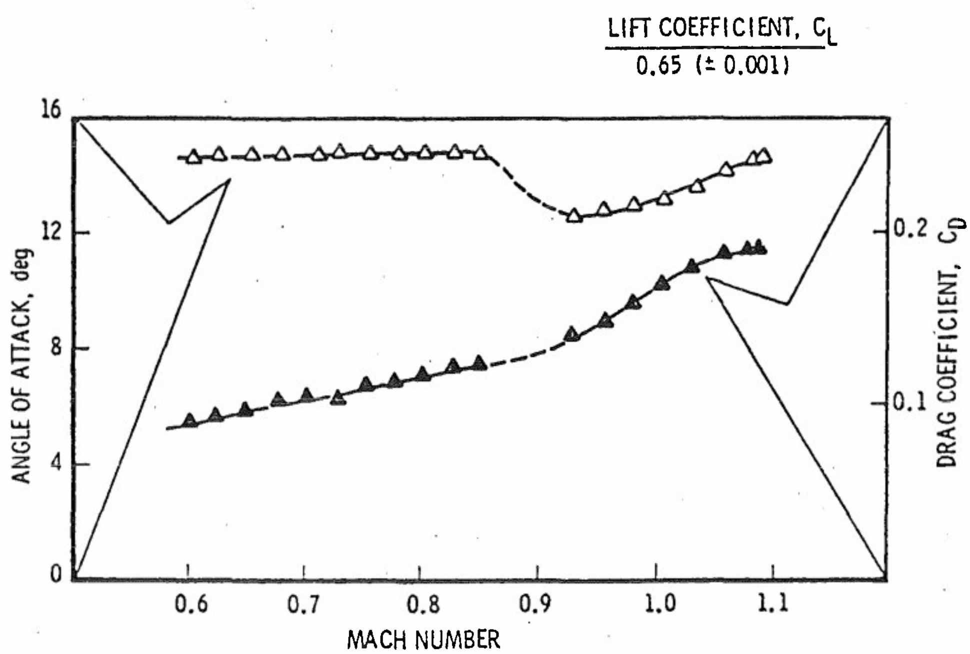
Figure 2.29 illustrates the self-optimizing flexible technology wing, or soft-wing vehicle as currently under development at AEDC; a two-dimensional model of the soft wing is also being tested at General Dynamics. This technique of model control will provide a host of improvements in aerodynamic design. It will assure a major advance in the optimization of air vehicle design and parametric testing. Both of these testing techniques show a very promising trend in computer and wind tunnel integration.

An example of the use of computers for test planning at the research level is given in the report by El-Ramly and Rainbird of Carleton University in Ontario Canada (Ref. 2.48). This report comments on an investigation of the flow behind wings using a computer-controlled system in their 20- by 30-inch low-speed tunnel. This test allowed the investigators to make online plotting and data reduction which made "detailed and accurate flow surveys behind a swept wing at several angles of attack and downstream



Test Optimization Using Automatic Trim Method

Fig. 2.27 (Ref. 2.129)



CONSTANT C_L WITH VARIABLE MACH NUMBER

Test Optimization by Constant Parameter Method

Fig. 2.28 (Ref. 2.129)

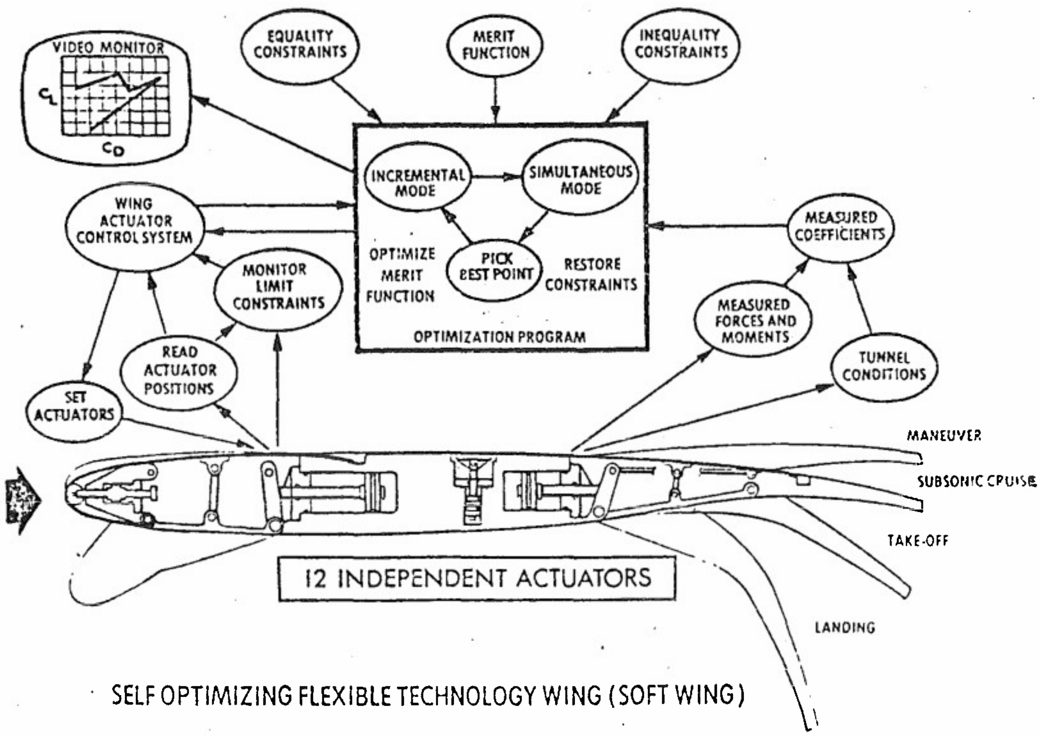


Fig. 2.29 Computer-Controlled Self-Optimizing Flexible Wing Technology Wing (Ref. 2.129)

stations feasible." Online mechanical plotting of circulation distribution, total pressure loss, streamwise vorticity contours, and velocity vectors in the crossflow plane is possible with this closed-loop technique. A simplified form of the flow chart/program used by the investigators is shown in Fig. 2.30.

As the requirements on both the accuracy of the wind tunnel measurements and the accuracy of the simulation become more severe, test planning optimization becomes a real necessity. Future integrated use of computers and wind tunnels will have a significant impact on aerodynamic design approaches, as shown in Fig. 2.31. *Numerical optimized designs will be verified in the tunnel. This will free the tunnel to examine critical areas which will not be computable in the near future. This combination of numerical computations, verified by experiment, plus critical tunnel tests will lead to a much more efficient and improved design process. The future design process will be more the result of analysis than empiricism.*

Future integrated use of computers and wind tunnels appears to be promising. Design by analysis will become more commonplace as tunnels continue to improve with automation

A state-of-the-art computer will be needed at the tunnel testing site, to be used for math model verification during tunnel tests. The computer must be dedicated to this process during testing.

2.7.4 Code Validation

According to Marvin (Ref. 2.109), "development of computational codes for viscous flows is outpacing the ability to appropriately model the turbulence." If indeed this is the situation, then there will be a substantial amount of code validation work in the future after an adequate turbulence model is developed. Although the main purpose for the high quality research tunnels described in Section 2.6.3 is to discover new facts, these tunnels should also be used for verification of the various new codes as they become available. The construction of a computational code essentially consists of the assembly of information bits that, when put together in a composite, will describe a particular flow configuration. The construction of a particular code should be completed before the verification procedure is attempted in a research tunnel. It would be desirable for the research tunnel to be interfaced with a computer, with the code stored for recall on an online basis, so that the actual tunnel boundary conditions could be used as computational boundary conditions. Regions of agreement and disagreement could then be defined quickly and accurately.

The verification procedure should result in a computational code which can be used as an "off-the-shelf" item with well-defined boundaries of application.

Codes for design of particular aircraft configurations are essentially a composite of codes describing more fundamental shapes. These design codes are extremely useful to the aircraft builders (Ref. 2.42) even thought, to keep the design code to a manageable size, certain flow details must be left out. Even so, these design codes must be validated too. However, because of model size and complexity, instrumentation needs, and mission role, the validations will quite likely have to be conducted in production wind tunnels. Here the interfacing of tunnel and computer is extremely important, even more so than for the research tunnels, because of the high cost of operation and scheduling problems. The validation test of a design code in a production wind tunnel should have on-site and online access to a large capacity, high-speed computer. The code to be verified should be stored in the computer and should be able to use the actual tunnel boundary conditions as determined by online measurements. As the flow configuration and boundary conditions are changed, online decisions can be made regarding the validity of the design code in question.

With a computer-integrated wind tunnel, both the validation and application of a computational code will result in a reduction in the number of tunnel entries, a decrease in required run time, and a significant cost savings.

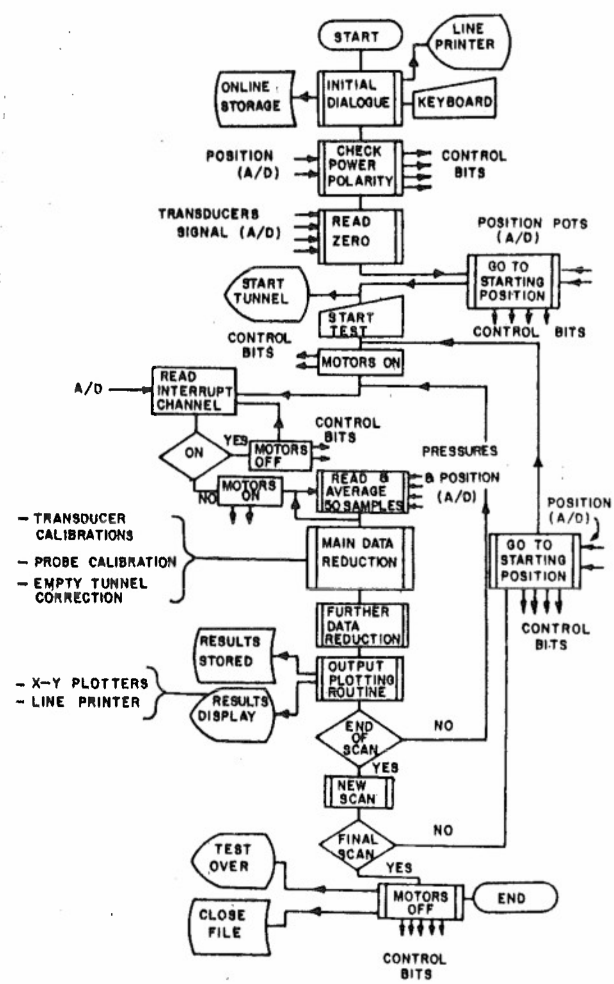


Fig. 2.30 Simplified Flowchart/Program used in a Computer Controlled Measurement (Ref. 2.48)

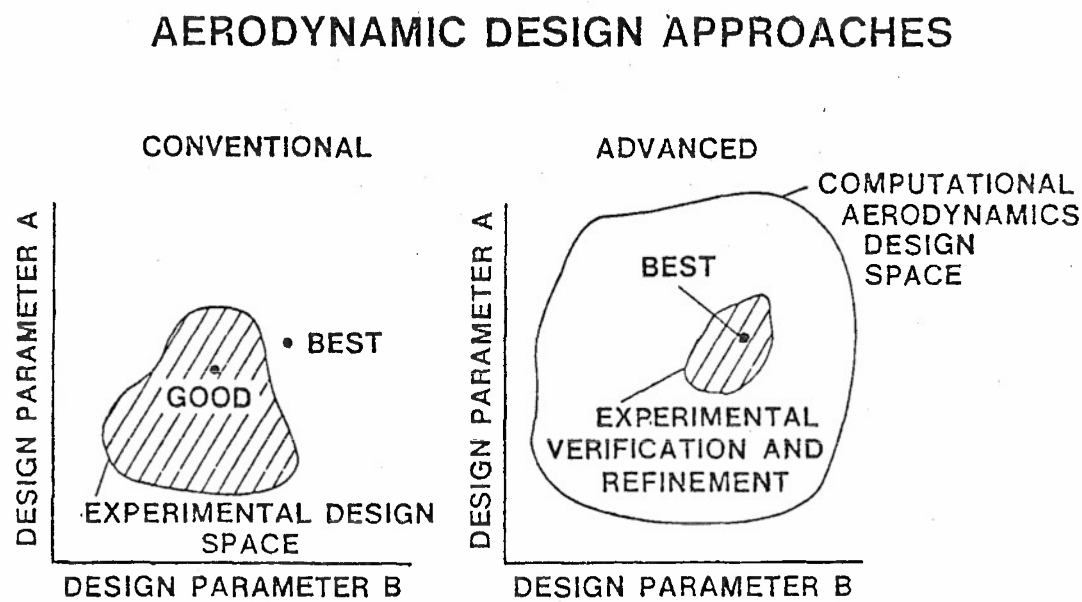


Fig. 2.31 Impact of Computer and Wind Tunnel Integration on the Aerodynamic Design Approaches (Ref. 2.213)

Section 2.0 Wind Tunnel Testing

2.1. A Forecast of Space Technology 1980-2000, NASA SP-387, January 1976.

2.2. A Further Review of Current Research Aimed at the Design and Operation of Large Wind Tunnels, AGARD-AR-83, September 1975.

2.3. Abele, M. and Sanlorenzo, E. "Study of Moire Measuring Techniques for Wind Tunnel Model Deformation." AEDC-TR-75-33, 1975.

2.4. Adams, J. C. "Recent Developments in Supersonic/Hypersonic Analysis Techniques." Presentation for AFOSR Summer Study Program, UTSI, 1977.

2.5. Aerodynamic Analyses Requiring Advanced Computers, Part I and II, NASA-SP-347, March 1975.

2.6. Aerodynamic Drag, AGARD-CPP-124, 1973.

2.7. Airframe Engine Integration, AGARD-LS-53, May 1972.

2.8. Alstatt, M. C. "An Experimental and Analytical Investigation of a Transonic Shock-Wave/Boundary-Layer Interaction." AEDC-TR-77-47, May 1977.

2.9. Antar, B. "Second Order Effects in Unstable Boundary Layers on a Flat Plate." AFOSR Science Report TR-74-0763, 1974.

2.10. Antar, B. and Collins, F. G. "Numerical Calculation of Finite Amplitude Effects in Unstable Laminar Boundary Layers." Phys. Fluids, Vol. 18, p. 289, 1975.

2.11. Baals, D. D., Editor. "High Reynolds Number Research." NASA Workshop held at Langley Research Center, NASA-CP-2009, October 1976.

2.12. Baronti, P. and Elzweig, S. "Preliminary Investigation on the Feasibility of Wall Corrections in Three-Dimensional Transonic Tunnels." ATL TR 212, April 1975.

2.13. Baronti, P. and Ferri, A. "On the Development of Interference Free Transonic Wind Tunnels." ATL TR 223, December 1975.

2.14. Baronti, P., Ferri, A., and Weeks, T. "Analysis of Wall Modification in a Transonic Wind Tunnels." ATL TR 181, February 1973.

2.15. Beckwith, I. E. "Development of a High Reynolds Number Quiet Tunnel for Transition Research." AIAA Journal, Vol. 13, p 300, 1975.

2.16. Belz, R. A., Goethert, W. H., and Bomar, B. W. "Interferometric Measurement of Model Deformation." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 35, March 1976.

2.17. Berndt, S. B. and Sorensen, H. "Flow Properties of Slotted Walls for Transonic Test Sections." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 17, March 1976.

2.18. Bernstein, S. and Joppa, R. G. "The Numerical Computation of the Transonic Flow over Afterbodies Including the Effect of Jet-Plume and Viscous Interactions." AIAA Paper No. 75-62, AIAA 13th Aerospace Sciences Meeting, Pasadena, CA, January 1975.

2.19. Bernstein, S. and Joppa, R. G. "Development of Minimum-Correction Wind Tunnels." Journal of Aircraft, Vol. 13, pp 243-247, April 1976.

2.20. Binion, T. W., Jr. and Anderson, C. F. "An Experimental Investigation of the Acoustic and Wall Interference Properties of Rod and Perforated Wind Tunnel Walls in Two-Dimensional Transonic Flow." AEDC-TR-74-41, September 1974.

2.21. Binion, T. W. and Lo, C. F. "Application of Wall Corrections to Transonic Wind Tunnel Data." AIAA Paper No. 72-10009, AIAA 7th Aerodynamic Testing Conference, Palo Alto, CA, September 1972.

2.22. Binion, T. W. "An Investigation of Three-Dimensional Wall Interference in a Variable Porosity Transonic Wind Tunnel." AEDC-TR-74-76, October 1974.

2.23. Binion, T. W., Jr. "Special Wind Tunnel Test Techniques used at the AEDC." AGARD Conference on Flight/Ground Testing Facilities Correlation,, AGARD-CP-187, Ref. 3, April 1976.

2.24. Binion, T. W. "Test on the ONERA Calibration Models in Three Transonic Wind Tunnels." AEDC-TR-76-133, November 1976.

2.25. Binion, T. W., Jacocks, J. L., and Chevallier, J. P. Meeting Report of the AGARD Fluid Dynamics Panel Working Group on Design of Transonic Working Sections, 1976.

2.26. Blackwell, J. A. "Scale Effects on Advanced Aircraft Wing Designs." Reviews in Viscous Flows. Proceedings of the Lockheed-Georgia Co. Viscous Flow Symposium, June 1976.

2.27. Bogdan, L., Drzewiecki, R. F., and Duryea, G. R. "Wind Tunnel Model Deformation Measuring System." AEDC-TR-74-128, February 1975.

2.28. Boltz, F. W., Kenyon, G. C., and Allen, C. Q. "The Boundary Layer Transition Characteristics of Two Bodies of Revolution, a Flat Plate, and an Unswept Wing in a Low-Turbulence Wind Tunnel." NASA TN D-309, 1960.

2.29. Bomar, B. W., Goethert, W. H., Belz, R. A., and Bentley, H. T. "The Development of a Displacement Interferometer for Model Deflection Measurements." AEDC-TR-76-116, January 1977.

2.30. Bowes, G. M. "Aircraft Lift and Drag Prediction and Measurement." Prediction Methods for Aircraft Aerodynamic Characteristics, AGARD-LS-67, Ref. 4, May 1974.

2.31. Brown, F. N. M. See the Wind Blow. F. N. M. Brown, 1971.

2.32. Butler, S. F. J. "Aircraft Drag Prediction for Project Appraisal and Performance Estimation." AGARD Conference on Aerodyanmic Drag, AGARD-CP-124, Ref. 6, October 1973.

2.33. Chang, P. K. "Drag Reduction of an Airfoil by Injection of Sound Energy." Journal of Aerospace Science, Vol. 28, p 742, 1961.

2.34. Chapman, D. R., Kuehn, D. M., and Larson, H. K. "Investigation of Separated Flows in Supersonic and Subsonic Streams with Emphasis on the Effect of Transition." NACA TN 3869, 1957.

2.35. Chapman, G. T. "Private Communication." July 1977.

2.36. Charnay, G., Comte-Bellot, G., and Mathieu, J. "Development of a Turbulent Boundary Layer on a Flat Plate in an External Turbulent Flow." AGARD Conference on Turbulent Shear Flows, AGARD-CP-93, Ref. 27, January 1972.

2.37. Chevallier, J. P. "Soufflerie Transonique a Parois Auto-Adaptables." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 12, March 1976.

2.38. Chu, C. K., Editor. Computational Fluid Dynamics, AIAA Selected Reprints, 1968.

2.39. Collins, F. G. and Zelenevitz, J. "Influence of Sound Upon Separated Flows over Wings." AIAA Journal, Vol. 13, p. 408, 1975.

2.40. Continuation of the Transonic "Intelligent Walls" Investigation Advanced Technology Laboratories, Inc., ATL Proposal No. 288, April 1974.

2.41. Cox, R. N. and Freestone, M. M. "Design of Ventilated Walls with Special Emphasis on the Aspect of Noise Generation." Paper No. 6, AGARD-R-602, April 1973.

2.42. DaCosta, L. "Computational and Experimental Aerodynamic Data in the Design of Aircraft." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.43. Dix, R. E. "Evaluation of an Internal Balance-Supporting Bracket Simulating Lug Suspension for Captive Stores in Wind Tunnel Tests." AEDC-TR-76-117, 1976.

2.44. Dobs, J. B., Jr. and Hanly, R. D. "Evaluation of Transonic and Supersonic Wind Tunnel Background Noise and Effects of Surface Pressure Fluctuation Measurements." AIAA Paper No. 72-1004, September 1972.

2.45. Dougherty, N. S., Jr., Anderson, C. F., and Parker, R. L., Jr. "An Experimental Investigation of Techniques to Suppress Edgetones from Perforated Wind Tunnel Walls." AEDC-TR-75-88 (AD-A013728), August 1975.

2.46. Dougherty, N. S., Jr. and Steinle, F. W. Jr. "Transition Reynolds Number Comparisons in Several Major Transonic Tunnels." AIAA Paper No. 74-627, July 1974.

2.47. Dougherty, N. S., Jr. "Cone Transition Reynolds Number Data Correlation Study." Flight/Ground Testing Facilities Correlation, AGARD-CP-187, Ref. 3, April 1976.

2.48. El-Ramly, Z. M. and Rainbird, W. J. "Computer-Controlled System for the Investigation of the Flow Behind Wings." Journal of Aircraft, Vol. 14, pp 668-674, 1977.

2.49. Elzweig, S. and Baronti, P. "Wing Profiles at Transonic Speed." ATL-TR-170, April 1972.

2.50. Ferri, A. and Baronti, P. "A Method for Transonic Wind Tunnel Corrections." ATL-TR-171, May 1972.

2.51. Ferri, A., Baronti, P., and Elzweig, S. "Investigation of Wall Interference in Tridimensional Transonic Wind Tunnels Goals and Possibilities." ATL-TR-192, December 1973.

2.52. Ferziger, J. H. "Large Eddy Numerical Simulations of Turbulent Flows." AIAA Paper No. 76-347, July 1976.

2.53. Flight/Ground Testing Facilities Correlation, AGARD-CP-187, June 1975.

2.54. Flight Test Instrumentation, AGARD-LS-50, September 1972.

2.55. Flow Separation, AGARD-CP-168, May 1975.

2.56. Goethert, B. H. "Physical Aspects of Three-Dimensional Wave Reflections in Transonic Wind Tunnels at Mach Number 1.20 (Perforated, Slotted, and Combined Slotted-Perforated Walls.)" AEDC-TR-55-45, March 1956.

2.57. Goethert, B. H. Transonic Wind Tunnel Testing, Pergamon Press, London, England, 1961.

2.58. Goethert, B. H. "Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Wind Tunnel Design and Testing Techniques." AGARD-AR-97, August 1976.

2.59. Goodyer, M. J. and Kilgore, R. A. "The High Reynolds Number Cryogenic Wind Tunnel." AIAA Paper No. 72-995, AIAA 7th Aerodynamic Testing Conference, Palo Alto, CA, September 1972.

2.60. Goodyer, M. J. "The Self-Streamlining Wind Tunnel." NASA TMX-72699, August 1975.

2.61. Goodyer, M. J., et. al. "Analytical Work in Support of the Design and Operation of two Dimensional Self-streamlining Test Section." NASA CR-145019, July 1976.

2.62. Goodyer, M. J. "A Low Speed Self-Streamlining Wind Tunnel." AGARD Conference on Wind Tunnel Design and Testin Techniques, AGARD-CP-174, Ref. 15, March 1976.

2.63. Gray, J. D. and Gardenier, H. E. "Experimental and Theoretical Studies of Three-Dimensional Wave Reflection in Transonic Test Sections." AEDC-TN-55-42, March 1956.

2.64. Griffin, S. A. "Model Systems and Their Implications in the Operation of Pressurized Wind Tunnels." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 36, March 1976.

2.65. Grossman, B. and Melmik, R. E. "The Numerical Computation of the Transonic Flow Over Afterbodies Including the Effect of Jet-Plume and Viscous Interactions." AIAA Paper No. 75-62, January 1975.

2.66. Guarino, J. F. "Instrumentation and data acquisition systems." NASA Workshop held at Langley Research Center, NASA-CP-2009, October 1976.

2.67. Gunn, J. A. and Christopher, J. R., Jr. "Automatic Control of a Transonic Wind Tunnel with a Real-Time Computer System." AGARD Conference on Numerical Methods and Wind Tunnel Testing. AGARD-CP-210, Ref. 8, October 1976.

2.68. Hackett, J. E. and Wildsen, D. J. "Determination of Low Speed Wake Blockage Corrections via Tunnel Wall State Pressure Measurements." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 22, March 1976.

2.69. Hagerman, J. R. Private Communication, August 1977.

2.70. Hawkins, C. J. B. and Partridge, D. W. "An Advanced Computer System for Wind Tunnel Tests." Proceedings, 90th Seminar, Digital Equipment Computer Users Society, 1974.

2.71. "High Reynolds Number Research," NASA Workshop held at Langley Research Center, NASA-CP-2009, October 1976.

2.72 Horstman, C. C. and Rose, W. C. "Hot-Wire Anemometry in Transonic Flow." AIAA Journal, Vol. 15, p. 395, 1977.

2.73. Jackson, F. A. and Heckl, M. A. "Effect of Localized Acoustic Excitation on the Stability of a Laminar Boundary Layer." ARL Report 62-362, 1962.

2.74. Jacocks, J. L. "Determination of Optimum Operating Parameters for the AEDC-PWT 4 ft. Transonic Tunnel with Variable Porosity Test Section Walls." AEDC-TR-69-164, August 1969.

2.75. Jameson, A., Rubbert, P. E., Smith, A. M. O., and Yoshihara, H. "Applied Computational Aerodynamics." AIAA Professional Study Series, Albuquerque, N. M., June 1977.

2.76. Jones, J. L. "Problems of Flow Simulation in Wind Tunnels." AIAA Paper No. 69-660, AIAA Fluid and Plasma Dynamics Conference, San Francisco, CA, June 1969.

2.77. Jones, J. L. "The Transonic Reynolds Number Problem." NASA Workshop held at Langley Research Center, NASA-CP-2009, October 1976.

2.78. Jonkers, H. L. and Mulder, J. A. "New Developments and Accuracy Limits in Aircraft Flight Testing." AIAA Paper No. 76-897, AIAA Aircraft Systems and Technology Meeting, Dallas TX, September 1976.

2.79. Judd, M. "The Magnetic Suspension System as a Wind Tunnel Dynamic Balance." ICIASF 1969 Record, IEEE Transactions on Aerospace and Electronic Systems, p 198, 1969.

2.80. Judd, M., Goodyer, M. J., and Wolf, S. W. D. "Application of the Computer for on-site Definition and Control of Wind Tunnel Shape for Minimum Boundary Interference." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 6, October 1976.

2.81. Kendall, J. M. "Wind Tunnel Experiments Relating to Supersonic and Hypersonic Boundary-Layer Transition." AIAA Journal, Vol. 13, p 290, 1975.

2.82. Kilgore, R. A. et al. "Flight Simulation Characteristics of the Langley High Reynolds Number Cryogenic Transonic Tunnel." AIAA Paper No. 74-80, Washington, D. C., February 1974.

2.83. Kilgore, R. A. "Cryogenic Nitrogen as a Transonic Wind Tunnel Test Gas." AIAA Paper No. 75-143, January 1975.

2.84. Kilgore, R. A., Adcock, J. B., and Ray, E. J. "The Cryogenic Transonic Wind Tunnel for High Reynolds Number Research." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 1, March 1976.

2.85. Kinney, R. B. Symposium on Unsteady Aerodynamics, Univeristy of Arizona, Tucson, 1975.

2.86. Klebanoff, P. S., Tidstrom, K. D., and Sargent, L. M. "The Three-Dimensional Nature of Boundary Instability." Journal of Fluid Mech., Vol. 12, p. 1, 1962.

2.87. Klebanoff, P. S. and Tidstrom, K. D. "Mechanism by which a Two-Dimensional Roughness Element Induces Boundary-Layer Transition." Physics of Fluids, Vol. 15, p 1173, 1972.

2.88. Knapp, C. F. and Roache, P. J. "A Combined Visual and Hot Wire Anemometer Investigation of Boundary Layer Transition." AIAA Journal, Vol. 6, p 29, 1968.

2.89. Kovasznay, L. S. "The Hot Wire Anemometry in Supersonic Flow." Journal of Aerospace Science, Vol. 17, p 565, September 1950.

2.90. Kovasznay, L. S. "Turbulence in Supersonic Flow." Journal of Aeronautical Sciences, Vol. 20, p 657, 1953.

2.91. Kraft, E. M. "An Integral Equation Method for Boundary Interference in Perforated-Wall Wind Tunnel at Transonic Speeds." AEDC-TR-76-43, April 1976.

2.92. Kraft, E. M. and Lo, C. F. "A General Solution for Lift Interference in Rectangular Ventilated Wind Tunnels." AIAA Paper No. 73-209, January 1973.

2.93. Kraft, E. M. "Progress of Adaptive Wall Investigations at AEDC." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.94. Laderman, A. J. "Review of Wind Tunnel Freestream Pressure Fluctuations." AIAA Journal, Vol. 15, p 605, 1977.

2.95. Laser Technology in Aerodynamic Measurements, AGARD-LS-49, June 1971.

2.96. Laufer, J. "Aerodynamic Noise in Supersonic Wind Tunnels." J. Aero. Scie., Vol. 28, p 685, 1961.

2.97. Laufer, J. "Some Statistical Properties of the Pressure Field Radiated by a Turbulent Boundary Layer." Phys. Fluids, Vol. 7, p 1191, 1964.

2.98. Lee, J. D. "Some Effects of Scale and Reynolds Number on the Transonic Shock-Boundary Layer Interaction." Ohio State University, Presented at FRG/USAF Data Exchange Agreement Meeting on Viscous and Interactive Flow Field Effects, Wright-Patterson Air Force Base, OH, April 1976.

2.99. Lennert, A. E., Smith, F. H., and Kalb, H. T. "Application of Dual Scatter Laser, Doppler Velocimeters for Wind Tunnel Measurements." ICIASF 1971 Record, IEEE Transactions on Aerospace and Electronic Systems, p 157, 1971.

2.100. Lo, C. F. and Kraft, E. M. "Convergence of the Adaptive Wall Wind Tunnel." To be published in AIAA Journal, 1977.

2.101. Lomax, H. "Recent Progress in Numerical Techniques for Flow Simulations." AIAA Journal, Vol. 14, pp 512-518, 1976.

2.102. Lovelace, A. M. "Status of Aeronautical Technology." State of the Nation's Air Transportation System, National Academy of Engineering, Washington, DC, 1976.

2.103. MacCormick, R. W. and Baldwin, B. S. "A Numerical Method for Solving the Navier-Stokes Equations with Application to Shock-Boundary Layer Interactions." AIAA Paper No. 75-1 January 1975.

2.104. MacCormack, R. W. "An Efficient Numerical Method for Solving the Time-Dependent Compressible Navier-Stokes Equations at High Reynolds Number." NASA TMX-73, 129, 1976.

2.105. Mack, L. M. "Linear Stability Theory and the Problem of Supersonic Boundary-Layer Transition." AIAA Journal, Vol. 13, p 278, 1975.

2.106. Marcus, H. "Air Force Technical Objective Document, Fiscal Year 1977." AFML-TR-76014, 1976.

2.107. Marschner, B. W., Young, R. L., and others, "Integration of Wind Tunnels and Computers." USAF/ASEE Fellowship in Engineering Systems Design, AEDC & UTSI, June-August 1977.

2.108. Marshall, J. C. "Two-dimensional Wave Cancellation Characteristics of Several Perforated Test Section Wall Liners." AEDC-TM-57-35, June 1957.

2.109. Marvin, J. G. "Experimental Requirements for NASA's Program in Turbulence Modeling." NASA Ames Research Center.

2.110. McDonald, H. and Kreskovsky, J. P. "Effect of Free Stream Turbulence on the Turbulent Boundary Layer." Int. J. Heat Mass Transfer, Vol. 17, p 705, 1974.

2.111. McLafferty, G. H. "Investigation of the Use of Slotted Walls to Cancel Shock Wave Reflections in Supersonic Flow." UAC Report R-15127-3, October 1949.

2.112. McLean, J. D. "Three-Dimensional Turbulent Boundary Layer Calculations for Swept Wings." AIAA Paper No. 77-3, January 1977.

2.113. Melnik, R. E. and Ives, D. C. "On Viscous and Wind Tunnel Wall Effects in Transonic Flows Over Air Foils." AIAA Paper No. 73-660, AIAA 6th Fluid and Plasma Dynamics Conference, Palm Springs, CA July 1973.

2.114. Meier, H. U. "A Combined Temperature and Pressure Probe for Compressible FLow." AIAA Journal, Vol. 7, pp 529-530, 1969.

2.115. Mitchell, J. G. "The Test Facility's Role in the Effective Development of Aerospace Systems." AFSC-TR-71-01, September 1971.

2.116. Mokry, M. and Galway, R. D. "Analysis of Wall Interference Effects on ONERA Calibration Models in the NAE 5 ft. x 5 ft Wind Tunnel." Aeronautical Report LR-594, National Research Council of Canada No. 15953, March 1977.

2.117. Morkovin, M. V. "On Supersonic Wind Tunnels with Low Free-Stream Disturbances." J. Appl. Mech., Vol. 26, pp 3190323, September 1959.

2.118. Morkovin, M. V. "Flow Around Circular Cylinders--A Kaleidoscope of Challenging Fluid Phenomena." Symposium on Fully Separated Flows, A. G. Hansen, Editor. ASME, 1964.

2.119. Morkovin, M. V. "On the Many Faces of Transition." Viscous Drag Reduction Symposium Proceedings, LTV Research Center, 1968 Plenum Press, 1969.

2.120. Morkovin, M. V. "Critical Evaluation of Transition from Laminar to Turbulent Shear Layers with Emphasis on Hypersonically Travelling Bodies." AFFDL-TR-68-149, March 1969.

2.121. Morris, P. J. and Whiffen, M. C. "The Characteristics and Applications of a Two-Axis Laser Velocimeter." Reviews in Viscous Flows, Proceedings of the Lockheed-Georgia Co. Viscous Flow Symposium, June 1976.

2.122. Mort, K. W., Kelly, M. W., and Hickey, D. H. "The Rationale and Design Features for the 40 x 80/80 x 120 Foot Wind Tunnel." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 9, March 1976.

2.123. NASA Outlook for Aeronautics, 1980-2000, NASA Misc. 28, Parts 1, 2, 3, 4, March 1976.

2.124. Newman, P. A. and Allison, D. D. "Comparison of Interference-Free Numerical Results with Sample Experimental Data for the AEDC Wall-Interference Model at Transonic and Subsonic Flow Conditions." NASA TMX-71991, July 1974.

2.125. Norton, D. A. "Airplane Drag Prediction." NY Acad. Sc. Annals, Vol. 154, pp 306-328, 1968.

2.126. Orlik-Ruckemann, K. J. "Survey of Needs and Capabilities for Wind Tunnel Testing of Dynamic Stability of Aircraft at High Angles of Attack." NASA-CR-114583, 1973.

2.127. Owen, F. K., Horstman, C. C., Stainback, P. C., and Wagner, R. D. "Comparison of Wind Tunnel Transition and Freestream Disturbance Measurements." AIAA Journal, Vol. 13, p 266, 1975.

2.128. Page, R. H. and Sernas, V. "Apparent Reverse Transition in an Expansion Fan." AIAA Journal, Vol. 8, p 189, 1970.

2.129. Palko, R. L. "Computer Oriented Testing Capabilities and Techniques development in the propulsion wind tunnel facility (PWT) at the AEDC." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.130. Pankhurst, R. C. and Holder, D. W. Wind Tunnel Technique; An Account of Experimental Methods in Low- and High-Speed Wind Tunnels. Pitman and Sons Ltd., London, England, 1952.

2.131. Parker, A. G. "Use of Slotted Walls to Reduce Wind Tunnel Boundary Corrections in Subsonic Flow." AIAA Journal, Vol. 12, p 1771, 1974.

2.132. Parker, R. L., Jr. and Jacocks, J. L. "Evaluation of Transonic Wind Tunnel Wall Interference Effects for Several Test Section Wall Configurations." AEDC-TR-76-125, August 1976.

2.133. Pate, S. R. "Measurements and Correlations of Transition Reynolds Numbers on Sharp Slender Cones at High Speeds." AEDC-TR-69-172, December 1969.

2.134. Pate, S. R. "Supersonic Boundary-Layer Transition: Effects of Roughness and Freestream Disturbances." AIAA Journal, Vol. 9, p 797, 1971.

2.135. Pate, S. R. and Brown, M. D. "Acoustic Measurements in Supersonic Transitional Boundary Layers." AEDC-TR-69-182, October 1969.

2.136. Pate, S. R. and Schueler, C. J. "Effects of Radiated Aerodynamic Noise on Model Boundary-Layer Transition in Supersonic and Hypersonic Wind Tunnels." AEDC-TR-67-237, March 1968.

2.137. Pate, S. R. and Schueler, C. J. "Radiated Aerodynamic Noise Effects on Boundary-Layer Transition in Supersonic and Hypersonic Wind Tunnels." AIAA Journal, Vol. 7, p 450, 1969.

2.138. Pate, S. R. "Supersonic-Hypersonic Experimental Aerodynamic Testing Techniques." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.139. Paterson, J. H., MacWilkinson, D. G., and Blackerby, W. T. "A Survey of Drag Prediction Techniques Applicable to Subsonic and Transonic Aircraft Design." AGARD Conference on Aerodynamic Drag, AGARD-CP-124, Ref. 1, October 1973.

2.140. Pearcey, H. H., Harnes, A. B., and Osborne, J. "The Interaction Between Local Effects at the Shock and Rear Separation." Transition Aerodynamics, AGARD-CP-35, September 1968.

2.141. Paterson, J. H. "Evolution of Theoretical Aerodynamic Methods and Wind Tunnel Testing at the Lockheed-Georgia Company." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.142. Pfenninger, W. and Reed, V. D. "Laminar Flow Research and Experiments." Astronautics and Aeronautics, Vol. 4, p 44, July 1966.

2.143. Picklesimer, J. R., Lowe, W. H., and Cumming, D. P. "A Study of Expected Data Precision in the Proposed AEDC HIRT Facility." AEDC-Tr-75-61, August 1975.

2.144. Pindzola, M. and Lo, C. F. "Boundary Interference at Subsonic Speeds in Wind Tunnels with Ventilated Walls." AEDC-TR-69-47, May 1969.

2.145. Pirrello, C. J., Hardin, R. D., Heckart, M. V., and Brown, K. R. "An Inventory of Aeronautical Ground Research Facilities Volume I--Wind Tunnels." NASA-CR-1874, 1971.

2.146. Pope, A. and Harper, J. J. Low-Speed Wind Tunnel Testing. John Wiley and Sons, Inc., New York, 1966.

2.147. Potter, J. L. The Unit Reynolds Number Effect on Boundary Layer Transition. Ph.D. dissertation, M.E. Dept. Vanderbilt University, Nashville, TN, 1974.

2.148. Potter, J. L. and Whitfield, J. D. "Effects of Unit Reynolds Number, Nose Bluntness, and Roughness on Boundary Layer Transition." AEDC-TR-60-5, March 1960.

2.149. Prediction Methods for Aircraft Aerodynamic Characteristics, AGARD-LS-67, May 1974.

2.150. Real Time Computer Based Systems, AGARD-CP-149, May 1974.

2.151. Reed, T. D., Pope, T. C., and Cooksey, I. M. "Wind Tunnel Calibration Procedures Manual." To be published under NASA Contract No. NAS2-8606 by Vought Corporation, Dallas Texas, 1977.

2.152. Reshotko, E. "Boundary Layer Stability and Transition." Annual Review of Fluid Mechanics, Vol. 8, pp 311-349, 1976.

2.153. Ring, L. E. and Milillo, J. R. "Transonic Testing--A Review." AIAA Paper No. 70-580, May 1970.

2.154. Roepke, R. G. "Future Facilities." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.155. Rogler, H. L. and Reshotko, E. "Disturbances in a Boundary Layer Introduced by a Low Intensity Array of Vortices." SIAM Journal of Applied Math,,Vol. 28, p 431, 1975.

2.156. Rooney, E. C. "Development of Techniques to Measure In-Flight Drag of a U.S. Navy Fighter Airplane and Correlation of Flight Measured Drag with Wind Tunnel DATA." AGARD Conference on Aerodynamic Drag, AGARD-CP-124, Ref. 24, October 1973.

2.157. Sandborn, V. A. "Boundary Layer Separation and Reattachment." NASA SP 304, Part I, pp 279-294, 1970.

2.158. Sandborn, V. A. "A Review of Turbulence Measurements in Compressible Flow." NASA TM X-62337, 1974.

2.159. Schueler, C. J., Ward, L. K., and Hodapp, A. E., Jr. "Techniques for Measurement of Dynamic Stability Derivatives in Ground Test Facilities." AGARDograph 121, October 1967.

2.160. Schulz, Gerhard. "Improved Displacement Corrections for Bulky Models and with Ground Simulation in Subsonic Wind Tunnels." AGARD Conference on Wind Tunnel Design and Testing Techniques AGARD-CP-174, Ref. 24, March 1976.

2.161. Sears, W. R. "Self-Correcting Wind Tunnels." Aeronautical Journal, Vol. 78, pp 80-89, February/March 1975.

2.162. Sears, W. R. "Self-Correcting Wind Tunnels--Concept and Demonstration." CALSPAN Report No. RK-5270-A-4, October 1975.

2.163. Sears, W. R. "Some Experiences with the Exploitation of Measurements of the Perturbation Field in a Wind Tunnel to Improve Simulation." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 5, October 1976.

2.164. Sears, W. R. et. al. "Interference-Free Wind Tunnel Flows by Adaptive Wall Technology." ICAS Paper No. 76-02, 10th Annual Congress of the International Council of the Aeronautical Sciences, Ottawa, Canda, October 1976.

2.165. Siddon, T. D. "Investigation of Pressure Probe Response in Unsteady Flow." Basic Aerodynamic Noise Research, NASA SP-207, pp 455-466, 1969.

2.166. Simpson, R. L. "Interpreting Laser and Hot-Film Anemometer Signals in a Separating Boundary Layer." AIAA Journal, Vol. 14, pp 124-126, 1976.

2.167. Simpson, R. L. "Experimental Techniques for Separated Flow." Reviews in Viscous Flows, Proceedings of the Lockheed Georgia Company, Viscous Flow Symposium, June 1976.

2.168. Simpson, R. L., Strickland, J. H. and Barr, P. W. "Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation." J. Fluid Mech., Vol. 79, p 553, 1977.

2.169. Sivello, C. "Calculation of the Boundary-Layer Growth in a Ludweig Tube." AEDC-TR-75-118, December 1975.

2.170. Sloof, J. W. and Piers, W. J. "The Effects of Finite Test Section Length on Wall Interference in 2-D Ventilated Wind Tunnels." AGARD Conference on Wind Tunnel Design and Testing Techniques, "AGARD-CP-174, Ref. 14, March 1976.

2.171. Smith, A. M. O. and Cebeci, T. "Remarks on Methods for Predicting Viscous Drag." AGARD Conference on Aerodynamic Drag, AGARD-CP-124, Ref. 7, October 1973.

2.172. Spangler, J. G. and Wells, C. S. "Effects of Free Stream Disturbances on Boundary Layer Transition." AIAA Journal, Vol. 6, p 543, 1968.

2.173. Starr, R. F. "Experiments to Assess the Influence of Changes in the Tunnel Wall Boundary Layer on Transonic Wall Crossflow Characteristics." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 18, March 1976.

2.174. Sternberg, J. "The Transition from a Turbulent to a Laminar Boundary Layer." Ballistic Research Laboratories Rept. 906, Aberdeen Proving Grounds, Maryland, 1954.

2.175. Stuart, J. T. "Hydrodynamic Stability." Chapter IX in Laminar Boundary Layers, L. Rosenhead, ed., Oxford University Press, 1963.

2.176. Tani, I. "Boundary Layer Transition." Annual Review of Fluid Mech., Vol. 1, pp 169-196, 1969.

2.177. Taylor, H. D. and Manoni, L. R. "Shock Wave Cancellation Characteristics of Two-dimensional Transonic Test Sections." AEDC, July 1956.

2.178. Test Facilities Handbook. Arnold Engineering Development Center, Arnold AFS, TN, May 1974 (10th Edition).

2.179. Tijdeman, H. and Schippers, P. "Results of Pressure Measurements on an Airfoil with Oscillating Flap in Two-Dimensional High Subsonic and Transonic Flow (Zero Incidence and Zero Mean Flap Position)." National Aerospace Laboratory, the Netherlands, NLF Report TR-73078U, 1973.

2.180. Titchener, I. M. and Pecover, B. E. "An Integrated Facility for the Simulation of Some Non-linear Flight Dynamics Problems." ICIASF 1971 Record, IEEE Transactions on Aerospace and Electronic Systems, p 105, 1971.

2.181. Treon, S. L. et al. "Further Correlation of Data from Investigations of a High-Subsonic-Speed Transport Aircraft Model in Three Major Transonic Wind Tunnels." AIAA Paper No. 71-291, AIAA 6th Aerodynamic Testing Conference, Albuquerque, New Mexico, March 1971.

2.182. Uselton, J. C., et. al. "An Examination of the Small Amplitude Dynamic Stability Test Technique." AEDC-TR-74-131, April 1975.

2.183. Varner, M. O. "Noise Generation in Transonic Wind Tunnels." AEDC-TR-74-126, April 1975.

2.184. Vayssaire, J. C., Langot, M., and Menard, M. "Adaptation de la Methode de Joppa a Une Soufflerie a Permeabilite Variable." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 7, October 1976.

2.185. Vidal, R. J. "On Scaling Transonic Wind Tunnel Data." Naval Research Reviews, p. 1, February 1974.

2.186. Wagner, R. D., Maddalon, D. V., and Weinstein, L. M. "Influence of Measured Freestream Disturbances on Hypersonic Boundary-Layer Transition." AIAA Journal, Vol. 8, pp 1664, 1970.

2.187. Wang, K. C. "Separation of Three-Dimensional Flow." Reviews in Viscous Flows, Proceedings of the Lockheed-Georgia Company Viscous Flow Symposium, June 1976.

2.188. Wardlaw, A. B., Jr. and Morrison, A. M. "Induced Side Forces on Bodies of Revolution at High Angle of Attack." NSWC/WOL/TR-75-176, 1975.

2.189. Wardlaw, A. B., Jr. and Morrison, A. M. "Induced Side Forces at High Angles of Attack." J. Spacecraft and Rockets, Vol. 13, pp 589-593, 1976.

2.190. Weeks, T. M. "Reudction of Transonic Slotted Wall Interference by Means of Slat Contouring." AFFDL-TR-75-139, March 1975.

2.191. Weeks, T. M. "Reynolds Number, Separation, and Intelligent Wall Work at AFFDL." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.192. Wells, C. S., Jr. "Effects of Free Stream Turbulence on Boundary Layer Transition." AIAA Journal, Vol. 5, p 172, 1967.

2.193. Whitfield, J. D. "G T & S: Key to Efficient Development of Aerospace Systems." Astronautics and Aeronautics, pp 54-55, June 1974.

2.194. Whitfield, J. D. and Dougherty, N. S., Jr. "A Survey of Transition Research at AEDC." AEDC-TR-77-52, July 1977.

2.195. Whitfield, J. D. and Dougherty, N. S., Jr. "A Survey of Transition Research at AEDC." AGARD Conference on Transonic Turbulent Transition, AGARD-CP-224, Ref. 25, May 1974.

2.196. Williams, C. D. and Parkinson, G. V. "A Low-Correction Wall Configuration for Airfoil Testing." AGARD Conference on Wind Tunnel Design and Testing Techniques, AGARD-CP-174, Ref. 21, March 1976.

2.197. Willmarth, W. W. "Space-Time Correlations and Spectra of Wall Pressure in a Turbulent Boundary Layer." NASA Memo 3-17-59W, March 1959.

2.198. Willmarth, W. W. "Unsteady Force and Pressure Measurements." Annual Reviews of Fluid Mechanics, Vol. 3, p 147-170, 1971.

2.199. Willmarth, W. W. "Pressure Fluctuations Beneath Turbulent Boundary Layers." Annual Reviews of Fluid Mechanics, Vol. 7, p 13, 1975.

2.200. Wills, J. A. B. "Spurious Pressure Fluctuations in Wind Tunnels." Journal of the Acoustical Soc. of Am., Vol. 43, p 1049, 1968.

2.201. Wilson, F. M., Jr. and Maddox, B. W. "Some Recent Innovations in Wind Tunnel Testing Techniques." SAE Paper No. 690677, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, CA, October 1969.

2.202. _Wind Tunnel Design and Testing Techniques_, AGARD-CP-174, October 1975.

2.203. Wulf, R. "Investigations on a Plate with Uniform Boundary Layer Suction for Ground Effects in the 3m x 3m Low Speed Wind Tunnel of DFVLR-AVA." _AGARD Conference on Wind Tunnel Design and Testing Techniques_, AGARD-CP-174, Ref. 24, March 1976.

2.204. Wu, J. M. and Moulden, T. H. "A Survey of Transonic Aerodynamics." AIAA Paper No. 76-326, AIAA 9th Fluid and Plasma Dynamics Conference, San Diego, CA, July 1976.

2.205. Xerikos, J. "Computational/Experimental Aerodynamic Testing." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.206. Ximenez, S. D. "A Study of Viscous Effects in Separated Compressible Flow." Ph.D. Dissertation, University of Alabama, 1968.

2.207. Yoshihara, H. and Magnus, R. "Wind Tunnel Wall Interference in Recent High Reynolds Number Transonic Tests on 2-D Super-Critical Airfoils." GDCA-ERR-73-011, December 1973.

2.208. Zapata, R. N. "Magnetic Suspension Techniques for Large-Scale Aerodynamic Testing." _AGARD Conference on Wind Tunnel Design and Testing Techniques_, AGARD-CP-174, Ref. 39, March 1976.

2.209. Farmer, M. and Hornkohl, J. "Laser Anemometry." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

2.210. Hammond, D. G., and Wilkerson, C., Jr. "An Evaluation of Single and Multiple Sting Support Methods to Obtain Unmodified Interference-Free Wind Tunnel Data." AIAA Paper No. 71-267, 1971.

2.211. Loving, D. L. "Wind Tunnel-Flight Correlation of Shock-Induced Separated Flows." NASA TN D-3580, 1966.

2.212. Wang, C. P. "Laser Anemometry." _American Scientist_, Vol. 65, May-June 1977.

2.213. Peterson, V. L. "Status of Advanced Techniques in Computational Aerodynamics and the Next Major Step." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

3.0 COMPUTATIONAL FLUID DYNAMICS

3.1 Introduction

3.1.1 Historical Perspective of Computational Fluid Dynamics

Computational fluid dynamics may be considered to have begun in 1910 when Richardson solved the discretized form of the Laplace equation; in the following years many efficient methods for solving Laplace-Poisson type equations were developed. However, difficult problems were encountered in the early attempts (in the late 1920's) to solve systems of Poisson equations, and it appears that further work on this problem was not attempted until the 1940's. Also, in 1928, Courant, Friedrich, and Lewy published their treatment of the discretized wave equation; in this paper they developed the important notion of the "zone of dependence" and stated the "CFL" convergence criterion. However, it was not until many years later that the relevance of their work to computations in fluid dynamics was recognized.

During the late 1940's the electronic computer was developed. Von Neumann used this machine in the study of the weather and other fluid flow problems and, subsequently, developed a small perturbation stability criterion and the artificial viscosity method. With the insights gained from these early calculations von Neumann recognized the need for a deeper understanding of the behavior of discretized approximations, and he encouraged work in this area. By the mid-1950's much had been learned; this analysis work culminated in the proof of the Lax Equivalence Theorem for well-posed linear systems of partial differential equations.

Fluid mechanics problems are nonlinear; such problems must be reduced to well-posed linear formulations before computation can be attempted with confidence. In the late 1950's and early 1960's, "matched asymptotic expansions" were the favored applied analysis tools in the United States; computational solutions were considered less "elegant." The Eighth AIAA Sciences meeting in early 1970 signaled a turn of events, however. It was demonstrated that, with proper cautions and careful executions, reliable solutions of even the Navier-Stokes equations could be obtained. The NASA-Ames Laboratory organized a sizable computational fluid dynamics group and, with access to state-of-the-art computing facilities, began large-scale efforts in conducting computational experiments. With the continuing development of larger and faster computers, the current enthusiasm for computational fluid dynamics is certain to reveal further potential capabilities.

3.1.2 Overview of Current and Future Trends

It is usually difficult to perform a sophisticated analysis of any real-world problem, even if there is no demand for full rigor in the treatment given the problem. Thus, heuristic methods are often tolerated and analytic tools are frequently applied to situations in which their applicability may be uncertain. In fact, engineers can proudly point to instances in which they developed important new methods through an intuitive "feel" for a problem long before mathematicians supplied a rigorous foundation for their analysis. It is important, however, that the users of approximate or empirical tools in science remain conscious of the somewhat uncertain nature of these tools and interpret all results obtained in this light.

Computational fluid dynamics represents a powerful new engineering tool; like all other tools, it has its capabilities and its limitations. Computational methods have been extensively used in the determination of potential flow fields, heat transfer and friction in boundary-layer analysis, and, where appropriate, in displacement corrections. Loads predictions have been greatly facilitated, and dynamic structural analysis has been made possible by the speed of computational methods and their capability for coping with relatively complicated geometries. Experienced design engineers have incorporated computational methods into the process of designing, testing, producing, and retesting flight vehicles to great advantage while avoiding pitfalls. The various crucial inputs to potential flow calculations (such as points of transition, separation and shock wave generation, and interaction) have necessarily been supplied by the design team members; therefore, the experience of the design engineers with previously designed systems and analysis of any available wind tunnel data is of utmost importance. Continued progress in computational fluid dynamics methods and the fundamental understanding of them and the availability of larger and faster computers should permit the designers to treat more realistic three-dimensional geometries and various interaction phenomena which remain as important problem areas. The detailed resolution of turbulent phenomena will defy any solution in the foreseeable future; thus the development of turbulence models sufficiently accurate for design purposes remains as another crucial pacing item.

The future of computational fluid dymamics is bright; it is time that more serious consideration was given to the general application of the computational method to practical design problems. With sound precautionary measures in the formulation of the problem and a posteriori study of the results, reliable answers can be obtained for many significant problems; if these computed results are combined with wind tunnel testing and past experience, the uncertainties which designers now face can be reduced.

3.2 CURRENT STATUS OF COMPUTATIONAL TECHNIQUES

3.2.1 Mathematical Analysis

The scientific approach taken toward the numerical solution of a given problem of computational fluid dynamics is very dependent upon the mathematical character of that problem. In particular, the category (elliptic, parabolic, hyperbolic, or mixed) of a partial differential equation system is of primary concern in formulating difference equations, selecting mesh sizes, etc. There follows a brief summary of the current status of computational success with the various problem types.

Elliptic There is a large body of well-established literature for elliptic partial differential equations, and although the existence of some very difficult problems of this type is well known (e.g., the Cauchy problem for Laplace's equation is ill posed), the general situation with regard to the status as it relates to the problems of fluid dynamics is that the elliptic problems can usually be successfully handled in a rather routine manner with a variety of computational methods (Ref. 3.127), even when there are variable coefficients or some small nonlinearities present; both finite-difference and finite-element methods have proven to be effective. For large elliptic problems, iterative methods such as the Gauss-Seidel, alternating-direction implicit, successive over-relaxation, line, or block algorithm have all been used effectively to take advantage of the special structure of the systems of linear equations which arises in the numerical solution of these problems.

Parabolic Although the diffusion problems in two dimensions which most commonly arise in boundary-layer or heat-transfer investigations require somewhat more careful consideration than elliptic problems for their computational solution, the same general statements may be made for them (so long as the diffusivity is constant). The possible anomalies occurring in the direct solution of difference equations for the diffusion equation, for example, are well understood, and implicit methods such as the Crank-Nicholson scheme allow larger time steps than would be permitted by the convergence criteria for the explicit methods (Ref. 3.127).

Parabolic problems exhibit very desirable behavior with regard to the propagation of "disturbances" in the data (the same is true for the previously mentioned elliptic problems); the influence of discontinuities in the initial data of a parabolic problem is damped out with increasing time (Ref. 3.254).

Hyperbolic For simple wave equations the knowledge of the characteristic directions and the domain of dependence which were pioneered in the work of Courant, Friedrich, and Lewy in 1928 (Ref. 3.60) permits reliable solutions to be obtained by either the method of characteristics or by appropriate difference formulations of the problem (Ref. 3.223); the method of characteristics has been found to be the most accurate method for solving shock-free hyperbolic problems and serves as the standard of comparison for all other methods. The far more complicated nonlinear wave equation can be handled confidently if it is known that the solution remains smooth (Ref. 3.263). On the other hand, when a known one-dimensional shock wave propagates into a uniform fluid, the shock-fitting procedures which utilize the Rankine-Hugonoit conditions have proved effective (Ref. 3.223). Alternately, the quadratic "artificial viscosity" terms invented by von Neumann and Richtmyer, (Ref. 3.288), make it possible to approximate with good accuracy the shock wave speed and the magnitudes of the increments in pressure, density, etc., across the shock wave without involving the complication of the "internal boundary conditions" given by the Rankine-Hugonoit equations. Furthermore, this artificial viscosity method extends more easily to multidimensionals. The Lax-Wendroff method of dealing with shocked flows (Ref. 3.166) also gives good results in predicting a shock's propagation into a one-dimensional flow field without any necessity for shock matching.

The developments since 1970 with regard to the mathematical analysis of the problems of computational aerodynamics are encouraging, not so much with respect to specific accomplishments as with regard to the fact that a significant increase in the amount of interest in these matters has become evident (especially in the last few years). A number of mathematicians have attempted to address the enormously difficult problems associated with the existence, uniqueness, and degree of smoothness of solutions of the various boundary value and initial boundary value problems of aerodynamics as well as the criteria for convergence, rate of convergence, stability, and accuracy of specific computational methods. It must be admitted that the number of practical results directly applicable to these questions has remained small, but this is not surprising, if one takes into account the difficulty of the basic problems being considered. Furthermore, some detailed studies of "model" equations (such as the Burgers' equation) which include all the essential aspects of the actual problem of interest have been conducted, and there seems to be hope that some practical guidelines may be gleaned from such investigations (Refs. 3.42 and 3.239). *Study of "model" equations may be a fruitful approach to a better understanding of the numerical solution of fluid dynamics problems, and further, such research should be encouraged.*

On the other hand, the approach taken with regard to the study of the relevant boundary value and initial boundary value problems, per se, seems to have been concentrated mostly on "indirect" investigations; "solutions" in the sense of distributions, Rayleigh-Ritz principle, etc. seem to have received more attention than solutions obtained by "direct" discretization of the differential equations, (see, for example, Refs. 3.185, 3.249, and 3.250). The finite-element method (Ref. 3.264) (a Galerkin procedure which was extensively developed by the structural engineers and, later, given a rigorous foundation by mathematicians) has begun to appear often in papers (for example, Refs. 3.5, 3.82, 3.83, 3.138, and 3.163) posing the analysis of discrete approximations to solutions of partial differential equation systems, a somewhat curious development since it is known that finite-element and finite-difference methods are, in some sense, equivalent approaches. *Both types of information, detailed analysis of model equations and less specific analysis of "weak" solutions of the boundary value problems, per se, contribute significantly to the understanding of numerical fluid dynamics problems, and it is recommended that both types of work be encouraged.*

The question of the comparative efficiency of the various specific numerical procedures applicable in attacking a given problem has begun to receive some attention (see Refs. 3.151 and 3.156 and related literature). In light of the present premium on computer speed and storage when solving problems of computational fluid dynamics, it is important that the comparative efficiency of methods for various problem types be determined in as relevant a fashion as possible and that the overall efficiency of the various methods be enhanced as much as possible. *Combined computational and analytical studies will be needed to provide the critical insights in these matters of algorithm efficiency, and it is recommended that such work be supported.*

3.2.2 Inviscid Flows

The computation of steady, two-dimensional flows is now seemingly routine, and the number of techniques available for this purpose have continually increased (Ref. 3.271). Of particular interest is the ability to compute the inviscid flow over arbitrary airfoil sections (e.g., as described in Refs. 3.8 and 3.34); even multiple-element airfoils and cascades do not present great difficulty (Ref. 3.94). The real power of computational fluid dynamics is demonstrated by the inverse, or design methods, which optimize the airfoil geometry to yield a desired performance level (Ref. 3.35). The computation of transonic two-dimensional flows cannot be accomplished with the accuracy attributed to the linear subsonic or supersonic solutions, but usable results are being obtained. Computational fluid mechanics is playing a central role in the development of new supercritical wing sections. Rough predictions of shock pressure rise and shock position are now possible, but designers want a much higher precision, sufficient, for example, to detect changes of a few percent in drag or lift.

Extensions of these computational techniques to three-dimensional flows have demonstrated significant advances. The most advanced and most implemented methods for subsonic potential flows are the so-called panel methods (Ref. 3.114) but other techniques offer promise for special design or analysis problems. Particularly noteworthy are the newly-developed higher-order surface panel methods (Ref. 3.79). These methods are capable of calculating subsonic potential flow about an arbitrary configuration in a highly accurate, stable and reliable manner.

For transonic three-dimensional flows the fundamental steps from the simple yawed wing (Ref. 3.137) to a swept wing and wing-body combination have been reasonably well mastered (Refs. 3.4 and 3.210), and work is proceeding on the extensions required for the more realistic configurations. Some basic problems remain to be solved, particularly in the realms of application of boundary conditions with involved three-dimensional geometries and resolution of complex interior shocks, but progress in these areas is promising. Far-field boundary conditions in three dimensions are not easily applied, but advances in analytic modeling (Ref. 3.284) and in iterative techniques between interior and exterior flow regions (Ref. 3.73) seem to perform satisfactorily.

Techniques for the computation of three-dimensional supersonic flows yield impressive results. The numerous solutions for the shuttle-orbiter flow field, including finite-rate chemistry effects, are examples of capabilities of computational methods which surpass the ground test simulation capability (Ref. 3.182). For smooth flows or flows with isolated shocks, the method of characteristics is still the most accurate, but the more recent shock-capturing techniques can be used for far more complicated flows. Shock fitting or patching methods offer promise for improving the accuracy of these computations. In practice, no one method is utilized to solve a given flow field. For example, one may use a time-dependent, blunt-body solution to provide starting data for a method-of-characteristics region followed by a downstream finite-difference marching technique (Ref. 3.183). Procedures which do not use a combination of techniques for the solution of fluid dynamics problems are rare (Ref. 3.1).

The computation of unsteady flows has also recently evidenced rapid advancement. According to McCroskey (Ref. 3.188), numerical analyses have generally outpaced detailed experiments in problems that are generally inviscid, whether in the regime of flutter and unsteady airloads predictions, or in transonic aerodynamics.

3.2.3 Boundary-Layer-Type Flows

Prandtl's boundary-layer concept continues to be a useful approximation and permits extension of the inviscid approach to more realistically model the real flow solution. Solution techniques for two-and quasi-three-dimensional flow problems are well developed (Ref. 3.38). Inclusion of specific turbulence models allow the use of these techniques at high Reynolds numbers to obtain results of usable accuracy. Iterative methods that couple the inviscid-viscous boundary-layer methods are capable of treating weak interactions and have been incorporated within many design procedures (Refs. 3.129 and 3.202).

Remarkable progress is evident in the computation of fully three-dimensional boundary layers (e.g., Ref. 3.84). However, fundamental difficulties occur in the specification of transverse boundary conditions near regions where the boundary-layer assumptions are invalid.

There are some basic problems in boundary-layer theory which are at an unsatisfactory stage of development. These include prediction of transition and separation. There are transition criteria based on stability analyses and test data, but these criteria have had only mixed success. No satisfactory analytical methods are available for calculating separating flows or for prediction of separating and reattaching flows. Empirical separation predictive techniques have been developed, however, that have led to a better design methodology. Improvements in aircraft performance in terms of lift-to-drag ratio and maximum lift are impressive (Refs. 3.162 and 3.190).

3.2.4 Navier-Stokes Flows

Computation of flow processes with strong interaction between the nominally inviscid portion and the viscous-dominated regions require solution of the Navier-Stokes equations. These equations are nonlinear and descriptive of large-gradient flows. The major computational difficulty is that the grid or mesh refinement necessary to resolve the flow gradients is dependent on Reynolds number in such a way that only laminar flows can be computed with any semblance of accuracy. Calculation of realistic turbulent flows requires ensemble (time) averaging of the Navier-Stokes equations, which introduces the requirement of turbulence modeling (see Section 3.4.5). In spite of these problems and the limited storage capacity of present computers, many impressive solutions have been obtained. (See Peyret and Vivand, Ref. 3.216, for a recent survey of the useful techniques and a summary of solutions obtained.)

For two-dimensional, incompressible flow the Navier-Stokes equations can be written in terms of stream and vorticity functions. The solution is then found by solving the vorticity and stream function equations separately and iterating between them until convergence is obtained. Techniques for these solutions are discussed by Roache (Ref. 3.225), with additional later methods summarized by Lugt (Ref. 3.176). According to Lomax (Ref. 3.173), the numerical calculation of unsteady, laminar, incompressible flows with separation can be accomplished with accuracy equivalent to experiment. However, Lugt (Ref. 3.176) points out that the solutions are restricted to moderate Reynolds number for two-dimensional flow with severe restrictions in three dimensions. These limitations are attributable to the necessity of maintaining the cell Reynolds number ($\Delta u \Delta x/\nu$) on the order of two for reasonable accuracy (Ref. 3.45).

There are fundamental differences between compressible and incompressible flows: the number of dependent variables and equations increases for compressible flows; furthermore, for supersonic flows the admissibility of shock waves adds complications. An appreciation of the difficulty of obtaining numerical solutions for the compressible Navier-Stokes equations may be realized by the fact that the first publication on the subject evidently did not appear until 1965 (Ref. 3.24).

The development and use of advanced computers has permitted solutions of aerodynamic interest for such laminar conditions as blunt-body flow, base or step flows, flow in the neighborhood of a leading edge of a flat plate, expansion or compression corner flows, shock wave/boundary-layer interaction, and, in a few cases, complete three-dimensional flow fields. Lack of spatial resolution (computer storage) and occasional improper formulation limit the accuracy of these solutions. It would be useful if more investigators placed absolute error bounds on their solution.

With the introduction of turbulence modeling and use of the Reynolds-averaged Navier-Stokes equations, numerical calculation of more realistic flows is possible. For example, Shang and Hankey (Ref. 3.247) used MacCormack's algorithm to compute turbulent supersonic flow over a compression corner with a relaxation eddy viscosity turbulence model. Hung and MacCormack (Ref. 3.123) have extended this work to examine the applicability of the model to high Mach number flows with heat transfer. Deiwert (Ref. 3.70) used the relaxation model to compute transonic flow over a thick airfoil which led to a most outstanding example of an unsteady, turbulent, strongly interacting flow (Ref. 3.169) wherein an oscillating shock/boundary-layer separation was computed which compared favorably with experiment. According to Peterson of NASA-Ames, the real uniqueness of this comparison is that the computation preceded the wind tunnel experiments.

Some preliminary work is evident in three-dimensional flows (see Refs. 3.229, 3.248, and 3.287), but severe limitations in computer memory capacity and the uncertainty associated with turbulence modeling limit the applicability of this work. *Advanced computers, improved algorithms, and better turbulent models are all necessary before the accurate and efficient computation of three-dimensional turbulent flows can become possible.*

3.3 IMPACT ON DESIGN AND LOADS PREDICTION

Aerodynamic problems are becoming more and more complex as demands for aircraft performance and efficiency increase. Therefore, development of accurate computational methods that can be utilized by the aerodynamic engineer to produce the most efficient vehicle is very important. In the last few years many such methods have been developed for designing and analyzing airfoils, wings, and wing-body combinations. Better understanding of flow physics and clever use of large computers have resulted in greater design freedom and confidence and more reliable methods of prediction of aerodynamic loads. The impact of computational methods on aerodynamic design and prediction of loads is discussed below, first for the two-dimensional case and then for the three-dimensional configurations. This discussion is followed by an assessment of the difficulties and the limitations of the computational codes that are presently available.

3.3.1 Design and Optimization of Airfoils

There are two types of numerical processes available for the design and analysis of airfoils. In one technique, called the direct method, the flow about a prescribed airfoil is analyzed, and then, based upon this result, the airfoil shape is modified in an attempt to satisfy the design conditions. The other design formulation is the inverse method, in which the airfoil surface pressures or velocities are specified, and the airfoil shape is subsequently determined. The codes associated with both types of methods usually have an analysis phase which can be used for calculation of loads once the desired shape of the airfoil has been obtained. A well-designed direct flow-field method always yields a solution, because for every geometry there is a corresponding pressure distribution. The inverse problem, on the other hand, exhibits a certain lack of uniqueness. Also, an arbitrarily selected pressure distribution may give rise to physically unrealistic shapes, or shapes that are not acceptable because of structural considerations. In other words, in the inverse method the designer has traded off the direct control over the geometry for better control over the aerodynamics.

The direct approach requires extensive experience on the part of the user, since he must prescribe the initial geometry. The inverse method, on the other hand, requires the specification of a desirable pressure distribution, which is a characteristic that is evidently well understood by the designer. However, much research has been conducted (and indeed, is still in progress) to find pressure distributions which the boundary layer can tolerate and which yield airfoil geometries that have acceptable off-design characteristics and meet the various practical constraints.

There have been many recent attempts to computerize airfoil design procedure. Some representative ones using direct approach are design and optimization methods for subcritical and supercritical airfoils by Barger and Brooks (Ref. 3.8) and the TSFOIL code (Ref. 3.203) for two-dimensional transonic calculations. The latter code is capable of simulating wind tunnel wall effects. Viscous effects have been accounted for in subsonic flow by Morgan (Ref. 3.202). Garabedian (Ref. 3.95) has described the development of a code at the Courant Institute that calculates transonic flow at high Reynolds numbers. For the inverse approach, mention may be made of a method for the design of multi-element, high-lift systems by Beatty and Narramore (Ref. 3.13) and the code developed by Carlson (Ref. 3.35). The latest version of Carlson's code has the capability of taking viscous effects into account.

Most inviscid approaches are quite efficient with respect to computer time, requiring only a few seconds of CPU time per solution on a CDC 7600. However, the process slows down considerably when viscous effects are included.

An important advantage of the computational method is that it allows the use of numerical optimization techniques for automated airfoil design. Vanderplatts, Hicks, and Murman (Ref. 3.283) have investigated one such method which uses direct optimization for two-dimensional flow. They have developed a numerical optimization design code by linking an optimization program based on the method of feasible directions with an aerodynamic analysis program that uses a relaxation method to solve the partial differential equations governing inviscid, small disturbance flow. The numerical optimization minimizes some specified parameter such as the drag coefficient for a set of design parameters describing the airfoil geometry, satisfying a number of specified constraints. These constraints may be aerodynamic (e.g., on lift and moment), geometric (e.g., on airfoil thickness or volume), or related to the pressure distribution (e.g., on pressure coefficient and pressure gradient). A weak point of the method is probably the polynomial contour representation, since it somewhat limits the class of obtainable solutions.

A second procedure being developed at the National Aerospace Laboratory in the Netherlands and described briefly in the article by Sloof (Ref. 3.251) is the so-called constrained inverse method. In this method a target pressure distribution and the geometrical constraints are formulated, and the problem is optimized in the least-square sense. This method is still being refined, and the details are not available at the moment.

Sophisticated computerized design methods are finding increasing acceptance in the aircraft industry. This can be illustrated by taking the example of the Lockheed Aircraft Company (similar programs are in effect with other companies). A total of one computer hour was used in the C-141 wing design. No theoretical computations were made for wing section design; only wing loading was computed using the Falkner planar lifting surface method. More time was spent on theoretical compution on the C-5A, but the wind tunnel still played a major part in finalizing the design. However, the design philosophy is changing. Lockheed is committed to the use of new and advanced computational methods in order to achieve an optimum design for their Advance Technology Aircraft (ATA) now under development. In ATA design, state-of-the-art computational methods are being used including the inverse method of Carlson (Ref. 3.35) and Hicks and Vanderplatt's optimizing technique (Ref. 3.284) mentioned earlier.

3.3.2 Three-Dimensional Configurations

One of the challenging problems is the analysis of the flow past wing-body combinations in three dimensions. Accurate computational techniques for predicting the magnitude and distribution of aerodynamic loads are needed because these loads control the performance flying quality and structural integrity of an aircraft. The importance of having reliable load predictions in an early stage of design is obvious. It is in the area of three-dimensional analysis that the availability of fast and large computers has made the most recent impact.

The most common techniques for solving inviscid linear subsonic and supersonic flow problems are panel methods. These methods have been developed a great deal since the first papers on this subject were published about fifteen years ago. Today complete aeroplane configurations, including the tailplane, nacelles, external stores, and so on, can be calculated with high accuracy. References 3.153 and 3.172 present recent reviews of panel methods.

Recently, improved higher-order panel methods have been developed that employ curved panels and are in principle applicable to arbitrary configurations (see Ref. 3.79 for one such method developed at Boeing). Both analysis (Neumann) and design (Dirichlet) boundary conditions are treated. The method seems to be insensitive to the arrangement of the panels, which is a tremendous advantage from the user's point of view.

For subsonic flow, the compressibility effects are taken into account by the use of Goethert's rule or by corrections based on semi-empirical considerations. For supersonic flow, two of the more popular methods are those of Middleton (Ref. 3.195) and Woodward (Ref. 3.299). The Middleton method has been used in the development of an integrated set of computer programs for wing design, drag-due-to-lift analysis, and calculation of far-field and near-field wave drags and skin friction. The programs operate independently from a common geometry description. The complete set of programs takes about twenty minutes of CPU time on a CDC 6600.

Another code that should be mentioned is SUSSA ACTS (Ref. 3.184), which uses finite-element methods to analyze potential compressible flow (both steady and unsteady) around complex configurations. Another noteworthy method is one by Moretti (Ref. 3.200) for solving the Euler equations for supersonic flow about complex configurations using a shock-fitting, finite-difference scheme of second-order accuracy. In the present state of implementation, however, the scheme is somewhat restricted in the configurations it can handle.

In the area of transonic flow, Bailey and Ballhaus (Ref. 3.4) have used a relaxation procedure with small-disturbance equations for flows about wings and wing-fuselage combinations. The solution process requires about 5 to 15 minutes of run time on a CDC 7600. Another method, put into use recently by the Douglas Aircraft Company, is that of Caughey and Jameson (Ref. 3.137). This method has been used recently in nacelle calculations and calculations of flow past a swept wing.

Coupling of the inviscid codes with three-dimensional boundary-layer codes to account for viscous effects is in the early stages of development. Representative of the most recent attempts in this regard are those by McLean (Ref. 3.190) and Hedman (Ref. 3.111). The nonlinear effects of leading-edge vortex separation have been taken into account using suction analogy by Weber, et al. (Ref. 3.291).

As indicated earlier, aerodynamic loads determine the structural integrity of an aircraft. Since aerodynamic loading and aeroelastic structural analysis are so intimately related, the two problems ideally should be solved simultaneously. Development of the FLEXSTAB code (Ref. 3.78) is a step in this direction. FLEXSTAB is a system of digital computer programs developed by Boeing under NASA sponsorship to evaluate the static and dynamic stability, inertial and aerodynamic loading, and resulting elastic deformations of aircraft configurations. Many practical problems in aeroelasticity are time dependent, and there is a need for development of unsteady aerodynamic methods. References 3.20 and 3.226 represent recent reviews of this subject. A solution of an unsteady problem requires large computer run times; a benchmark solution of time-dependent Euler equations can require as much as 7 hours on a CDC 7600, even for two dimensional flow.

The computer codes developed for analysis and design need verification and validation. Panel methods are generally recognized to be accurate but there is a need for comparison between the various methods. Such a program of comparison is now under way in a cooperative effort by Boeing and some European establishments (Ref. 3.153). An assessment of the inviscid supersonic flow codes of Middleton, Woodward, and Moretti was recently made by Landrum and Townsend (Ref. 3.162). Interestingly, it was found that only the finite-difference code of Moretti predicted load estimates at high angles of attack to any degree of satisfaction.

3.3.3 Assessment of Difficulties and Limitations

Although some of the computational methods described above are capable of providing excellent results, there are certain problem areas and limitations, some of which were mentioned earlier. The present-day computer-aided design systems, even if they contain only a panel method together with just the geometry model, are extremely complicated and require a large amount of maintenance. Accurate results are possible, however, if these systems are implemented in a careful manner.

Viscous effects are difficult to treat, especially in three dimensions. The treatment of turbulent boundary layers is of course affected by the limitations of turbulence modeling. These limitations are discussed elsewhere and will not be dwelled upon here. Also, at critical structural and control design conditions involving large angles of attack, the attached flow theories are found to be inadequate. Attempts to include corrections to improve the situation have thus far proved to be unsatisfactory.

Finally, it may be mentioned that in three dimensions the methods for the design problem (inverse methods) do not seem to be as advanced as methods for direct problems. The direct simulation methods do not add new features to those already available in wind tunnels. In the trial and error process the computer offers the same capabilities as the wind tunnel but possesses greater speed, flexibility, and economy. It seems that the time has come for the development of the inverse method in three dimensions.

3.3.4 Conclusions

In view of the above discussion and review of literature, the following conclusions are drawn:

1. The new computational methods offer a means of reducing aircraft development time and costs.

2. Potential theory is capable of providing good results for unseparated subsonic flows.

3. The transonic flow problem is receiving the emphasis it warrants, and progress is being made and can be expected to favorably impact the design process.

4. The development of three-dimensional potential flow codes and design codes using the inverse method need more attention.

5. There is a continuing need for verification, validation, and comparison of various codes; this will require easier access to large-scale computers by researchers.

6. The inclusion of real fluid effects in design codes is at an early stage of development. Progress is being made but is limited by the present status of the theories for turbulent and interactive phenomena.

7. The availability of faster and larger computers will significantly facilitate the handling of complex three-dimensional and/or unsteady problems.

8. Because of the difficulties cited above, and for the determination of complete configuration aerodynamics, wind tunnel testing is still needed. For the foreseeable future computers and wind tunnels will be complementary.

3.4 FUNDAMENTAL PROBLEM AREAS

The current status of computational methods for fluid mechanics problems as described in Section 3.2 indicates the tremendous strides made in the field since the initial work of Richardson in 1910. Since the development of the modern electronic computer, many impressive calculations have been conducted for problems of research interest, and, at the practical level, computational solutions have begun to have a significant impact on the design process for flight vehicles and, clearly, will have much more of an impact in the future as the computational discipline gains maturity and general credibility. There are, however, significant problem areas which have thus far resisted any general resolution; some of the important special problems areas are discussed in Appendix I. *In order for advanced problems to be competently attempted computationally, it is important that researchers devote serious attention to the problem areas described in Appendix I and in the following subsections.*

3.4.1 Self-Consistency

Within the last few years the importance of attempting to make careful verifications (as far as possible) of the initial results obtained from a fluid dynamics calculation has gained higher recognition, and such checks are now much more widely applied as a matter of routine. The term "conservative difference formulation" has largely come to be understood to apply to one which, in a given problem, has given consistent (to some order of accuracy) values for the mass and momentum fluxes as determined by the computation of surface integrals over various arbitrary closed contours. *Even today, however, checks for this "macroscopic conservancy" are not always performed in numerical fluids studies, and a number of important calculations have been and are being done with "nonconservative" techniques.* The possible rebuttal, to the effect that "nonconservative techniques sometimes give better answers," merely serves to indicate that in some instances the methods presently available are not sufficiently capable of discerning the basic physical phenomena at work and, hence, that much more work needs to be done. It is unacceptable (other than as a short-term measure) to base the quantification of physical effects on methods which deny the known physical origins of these effects.

Another approach (Ref. 3.43) to checking the "self-consistency" of initial calculated results consists of checking on a cell-wise basis (or possibly on the basis of clusters of small numbers of cells) that the fluxes of the dependent variables cancel (within the order of local accuracy of the difference scheme being employed) along the boundary shared between each two (or other small number) of the cells which are adjacent. *The "microscopic conservancy" check should be encouraged since "macroscopic" checking depends upon integral defects to discern nonconservancy, and the procedure of integration is notoriously capable of smoothing out erratic pointwise results.*

3.4.2 Accuracy

In the final analysis one obtains an "answer," and the question then is whether it is sufficiently accurate. Unfortunately, the results of reasonably well-formulated numerical procedures for fluid dynamics problems usually give qualitatively appealing answers and thus encourage possible misplaced confidence in the quantitative results obtained. There has been only relatively little attention devoted (see Refs. 3.42, 3.49, and 3.120) and very slow progress obtained in the error analysis of the more difficult problems of computational fluid dynamics, and results which are both mathematically rigorous and practically applicable are almost nil. These are crucial matters, however, and the quest for the maturation and, ultimately, the complete credibility of the field of computational fluid dynamics demands a more thorough resolution of these most difficult problems. For most of the serious applications intended for the computational discipline, it is essential that one know a reasonable error estimate. *Engineering design of flight systems, utilization of wind tunnel data, etc., cannot fully benefit from the favorable impact promised by the potential of computational fluid dynamics until realistic error bounds as well as approximate answers can be provided.*

3.4.3 Turbulence Modeling

The Navier-Stokes equations will be used as the basis of the discussion of turbulent flow problems. However, there are approaches to turbulence problems which do not use these equations as the starting point (for example, the kinetic and stochastic models or models using quasilinearization with ideal random functions). The vast majority of work in fluid mechanics is based on the applicability of the Navier-Stokes equations in time-dependent form. Therefore, the computational solution of an ensemble of the fully time-dependent Navier-Stokes equations may be considered as the ultimate solution of the turbulence problem.

The computed solution must, however, be sufficiently accurate to permit the evaluation of practically important correlations to within engineering accuracy. Now the spectral analysis of turbulence reveals the dominance of production and dissipation at low and high wave numbers, respectively (i.e., the large-size and small-size eddies). The energy transfer in the wave number space is accomplished by the characteristic nonlinear energy cascading process. Thus, the computed solution must be accurate down to the smallest size eddies where dissipation remains important, and these eddy sizes decrease with increasing Reynolds number.

The size of the important dissipative eddies and the resolution required to calculate these eddies with reasonable accuracy have been considered by various authors (Refs. 3.43, 3.80, and 3.212). On the basis of these authors' findings, and our present knowledge about computer systems, it appears that the computational solution of the time-dependent Navier-Stokes equations in three space dimensions is beyond the capacity of present and anticipated computers. The solution of the same problem in two space dimensions can be accomplished and it has been suggested that such investigations in lower dimensions might provide some insight and help the development of phenomenological models of turbulence. This approach is disputable on purely physical grounds and recent analytical evidence also tend to discredit such an approach (Refs. 3.15, 3.57, 3.90, and 3.92). Consequently, little alternative remains other than direct phenomenological representation of turbulent stresses.

A great many turbulence models have been used or proposed. Since many reviews have appeared recently on the subject (Refs. 3.164, 3.219, and 3.222 for example), the discussion below is brief.

In many models, the laminar viscosity coefficient is replaced by some eddy or turbulent viscosity with dependence on geometry and/or local flow conditions as circumstances warrant. Arbitrary constraints can be introduced to reproduce experimental data but neither the constraint values nor the functional format are universal. The eddy viscosity models are convenient for correlating experimental data without much predictive value. Such was fully demonstrated for turbulent boundary layers and jets in the 1968 Stanford and 1972 Langley conference proceedings.

By taking the velocity moment of the time-dependent Navier-Stokes equations and averaging, one can obtain differential equations of the second-order velocity correlations. The scalar equation for the turbulent kinetic energy is the most widely used. Much empiricism is involved in defining this energy equation properly for solution, and some relationship between the kinetic energy and eddy viscosity must be postulated. Alternatively, a selected group of the velocity correlation equations may be adopted as the transport equations of turbulence. The properties of similtude, invariance, local isotropy, and the like are often selectively applied by individual investigators. To date, these differential methods have not yielded significantly better results than algebraic closure. Complexity of the equation system multiplies with the apparent sophistication of turbulence models. Their computational solutions are difficult, and often physically nonrealizable results are obtained (Ref. 2.67 and 3.244). Computational difficulties with a vast system of equations often confuse and cloud the fundamental weakneses of differential closure models. High-speed computation can aid in the development of some form of turbulence model, but it cannot do so if the proposed models become so complex that the computational solution is difficult and of uncertain accuracy and detailed experimental verification of the model is not possible.

It seems reasonable to expect that the large-scale eddies could be adequately computed with the fully time-dependent Navier-Stokes equations using modeling of the small-scale eddies. The resulting system of equations would be generally more complicated than the Reynolds-averaged Navier-Stokes equations, thus more difficult to solve, and must be computed with temporal accuracy as a time-dependent problem. In this sense the subscale modeling trades the greater computational complexity for somewhat better insight into the physics of turbulence.

The development of better turbulent models depends on the verification of the computed solution with pertinent experimental data, not only of the mean flow properties but the turbulent fluctuating quantities as well. In this regard, close cooperation between the model builders, those doing the computations, and those performing the experiments would greatly facilitate the process. The turbulence model preferably should be reasonably simple, to ease the computational problem, and should contain as much physics as practicable. Both the computational solutions and the experimental data should be given well defined, and preferably comparable error bounds to permit meaningful validation. With the availability of much faster and larger computational facilities, better control of computational errors, and better understanding of turbulence phenomena, there is greater promise now than ever before that the crucial problem of turbulence modeling will be effectively resolved.

In summary, the following conclusions and recommendations are offered:

1. Development of new turbulence models that emphasize physical content (turbulent structures and general behavior) rather than mathematical complexity should be encouraged.

2. Development of better turbulence models will require close cooperation between those doing computations and those doing experiments.

3. Comparisons between computational and experimental results should go beyond the mean flow properties and emphasize the flow details.

4. Reliability of the computational solutions of the system of partial differential equations with turbulence models must be emphasized to avoid confusing the merits and faults of numerical methods with the inadequacies of the turbulence model.

5. Error bounds of comparable magnitudes should be established for both computational solutions and experimental data.

3.5 INTERACTION AMONG EXPERIMENTAL AND COMPUTATIONAL TECHNIQUES

3.5.1 Benchmark Experiments

The advancement of computational fluid dynamics at this stage is intimately dependent on the availability of experimental data.

Two classes of information are required:

1. *Fundamental data to support development of turbulence modeling*
2. *Definitive experiments to serve as standards for establishing the credibility of computational tools*

As discussed by Marvin (Ref. 3.187) and Johnston (Ref. 3.219), there is a basic lack of experimental data to provide the necessary detailed measurements of turbulence properties in compressible flows. The problem is less acute for two-dimensional than for three-dimensional mean flows, but the fluctuating component is always three dimensional. Fundamental experiments are required in both two- and three-dimensional situations that emphasize simple geometries which are amenable to modeling by computational techniques. Detailed measurements of the significant parameters within the turbulent flow field are required as well as the mean surface shear stress.

The availability of experimental data on more complex turbulent flows would allow assessment of the accuracy of turbulence models in realistic situations. Specifically, the effect of corner and tip vortices on the evolution of turbulence and three-dimensional, shock/boundary-layer interactions with and without separation should be given high priority. Development of turbulence models that are sufficient for these problems should prove adequate for the general design problem.

The second class of required experiments relates to the problem of acceptance of computational tools by the design community. Validation of the accuracy of computational methods cannot be demonstrated by comparison with the same experiments utilized to formulate turbulence models. Indeed, it is desired that laminar benchmark experiments be available for the verification of computational methods independent of the empiricism associated with the turbulence modeling. Suggested laminar experiments are flows over two- and three-dimensional obstacles with local separation and reattachment and repetition of Hakkinen's shock/boundary-layer experiments for example. In every instance, measurements of the flow-field properties as well as surface measurements are required to document the quality of the experimental setup and to provide realistic boundary conditions for the computations.

End-to-end validation of computational methods can be provided by comparison with detailed experimental data on simple yet representative aircraft models at transonic conditions. Measurements should include pressure distributions over the model surface as well as integrated model loads. Again, far-field measurements are required. One of the working groups within the AGARD Fluid Dynamics Panel is addressing this problem, and their conclusions and recommendations will be of great interest.

The development and acceptance of computational fluid dynamics requires additional experimental data covering fundamental problem areas such as turbulent and separated flows. Considerably more detailed measurements of crucial examples are required for the next advance in computational techniques.

3.5.2 Optimal Utilization of Data

Experimental results contain information on the complete physical flow process which can be extracted by computational analyses based on the governing equations (Ref. 3.22). Unknown details of the flow can then be obtained, though they are not directly measured or even measurable (Ref. 3.131). The concept of measuring some variables and using them in equations to determine other variables is not new, but widespread implementation of the procedure is not evident.

For example, the measurements of mean velocity profiles in turbulent flows are sufficient to evaluate the Reynolds stresses from the time-averaged Navier-Stokes equations. Considerable accuracy and point-to-point smoothness in measurements are required to allow meaningful numerical differentiation of the data to yield results without excessive error. Independent measurements of the Reynolds stresses would establish confidnece in the procedure and permit improved resolution of large-gradient flows.

As another example, in the case of trailing vortex experiments, the wind tunnel turbulence causes vortex meander and restricts measurements to mean values only. Computations based on these measurements can extract considerably more information on the vortex interaction and decay process (Ref. 3.171). Another possible, but currently impractical, application relates to the stability testing process in wind tunnels. Static stability derivatives are conventionally obtained utilizing steady-state force and moment balances, whereas dynamic stability derivatives are measured with specialized free- or forced-oscillation rigs. In reality, the wind tunnel turbulence and support vibrations are forcing model movement during the steady-state test so that, in principle, both the dynamic and the static stability derivatives could be determined simultaneously with conventional balances. The fundamental limitations to implementation of this process are the necessity for detailed, time-dependent tunnel calibrations, extensive balance calibrations, and the availability of great computational power.

The concept of fitting or matching experimental data to the governing equations also allows the determination of possible errors in the experimental technique. The classic example is the illustration of three-dimensional contamination in supposedly two-dimensional boundary layers. Improved data quality can result from a more detailed analysis of the flow and of the interrelationships between measured quantities.

More emphasis should be placed on the use of computations to verify the wind tunnel data quality and to extract all the significant information from a given set of data.

3.5.3 Computer/Wind Tunnel Integration

In assessing the relative roles of computer and wind tunnel simulation facilities, it is important to recognize that their inherent limitations are complementary. The complementary aspects of numerical methods and wind tunnel testing are summarized in Table 3.1 (taken from Sloof, Ref. 3.251) which lists their main possibilities and limitations.

Wind Tunnel Testing	Numerical Methods
1. Complete physics (full equations of motion)	1. Parts of physics (approximate equations of motion)
2. Wrong geometrical environment (walls, stings, etc.)	2. Correct geometrical environment possible
3. Model changes time consuming and expensive	3. Model geometry easily changed
4. Easy change of flow conditions	4. Change in flow conditions may require a different model
5. Flow about a given body only	5. Type of boundary conditions may be changed
6. Limited accessibility	6. High accessibility

Table 3.1 Complementary Aspects of Wind Tunnel Testing and Numerical Methods

Other limitations of wind tunnels include the model size that can be handled and the flow quality that can be produced. The computer, on the other hand, is limited by its speed and storage capacity.

One of the obvious ways in which computer/wind tunnel integration can be and is being implemented is in planning and interpreting wind tunnel tests. This phase of the integration was elaborated upon in Section 2.4. Another desirable way in which computerized techniques can be used potentially is in extrapolation of wind tunnel data to flight conditions. Considerable improvement in the predictive abilities of the computational methods, particularly with respect to interactive phenomena and transition and turbulence modeling, will have to be achieved before such extrapolations can be carried out with confidence. The extrapolation methods that are presently used are highly empirical. It should be possible to put them on a firmer basis with the current state-of-the-art computational fluid mechanics.

There is another area in which the complementary aspects of wind tunnel testing and numerical methods need to be further exploited. A wind tunnel is, in a sense, an analog computer for solving the full, unsteady Navier-Stokes equations; however, it does not simulate the correct geometrical environment. The numerical methods in their present state, on the other hand, are able to solve only approximate equations. Nevertheless, it is relatively easy to numerically simulate a given set of boundary conditions. Computerized analytical techniques can therefore be used to simulate wind tunnel wall boundary conditions and to adjust wind tunnel wall conditions to simulate free-flight conditions. Some work in this area has already beendone, especially for transonic flow problems. The TSFOIL code (Ref. 3.203) for analyzing and designing two-dimensional transonic airfoils has the capability of providing boundary conditions for solid, perforated, or slotted walls. An attempt in this direction for three-dimensional transonic flow has recently been made by Schmidt, et al. (Ref. 3.242).

A role of the wind tunnel that is likely to be increasingly emphasized is in the substantiation of computational schemes as well as in the verification, sometimes the refinement, of the results of calculations. Before they can be used with confidence, the codes must be thoroughly validated. One way of doing this is by means of careful wind tunnel experiments. Validation is especially needed at high Reynolds numbers for a given numerical scheme to be used with confidence in simulation of or extrapolation to actual flight conditions. One of the major functions of the proposed National Transonic Facility is expected to be the validation of computational codes at high Reynolds numbers.

The wind tunnel and computation methods can also work together to help provide an understanding of the physics of the phenomena. Often the designer is more interested in the physics of the phenomenon than in the quantitative results. In the case of buffeting, for example, from the designer's point of view the important thing is not whether one can predict the buffet intensity that is going to occur, but whether one can get rid of the buffeting. More work needs to be done in using wind tunnels and computational methods in a complementary fashion to isolate the relative effects of various factors that are likely to influence a given complicated physical phenomenon.

3.6 FUTURE PROSPECTS FOR COMPUTATIONAL FLUID DYNAMICS

3.6.1 Computer Requirements

There is an immediate general need for the availability of faster and larger computers to permit computational fluid dynamics to contribute more significantly to real design problems. There is also a specific need for much faster and larger computers for the solution of Navier-Stokes equations (and the like) to provide more information about interaction problems in fluid mechanics and thus to help the designers to make better estimates. The latter requirements are much more demanding but offer a much more significant payoff.

Currently available large computers with an average speed of about 1 MFLOP (million floating point operations per second) are quite adequate for the solution of inviscid flows and boundary-layer flow fields in two space dimensions with reasonably complicated geometry. The faster and larger machines among those presently available can even handle some simple three-dimensional flow problems; with one or two orders of magnitude increase in overall computing speed there should be improvements in this area.

The computational solution of the Navier-Stokes equation for some of the typical viscous interaction problems has been successfully carried out with sufficient reliability to complement wind tunnel data (as was mentioned in Section 3.1.2 and described in subsequent sections). Most of the currently available computers are marginally adequate for treating simple problems of this type in two space dimensions, but there is promise that significant improvements in the accuracy of the results obtained thus far can be improved.

The integration of the Navier-Stokes equations in two space dimensions generally requires a total of about 10^3 floating point operations per mesh point for four variables. Currently available machines can accommodate about 10^3 to 10^4 mesh points; thus, for such a computational field, a single sweep (assuming 1 MFLOP capability) will require from 1 to 10 seconds. The solution of a problem should typically be achieved in 10^3 (or less) iterations (or time steps) so that on the order of an hour of CPU time would be required. However, treatment of viscous interaction problems in three space dimensions appears beyond the reach of present computers; much larger and faster machines will be needed. In three space dimensions, 10^5 to 10^6 mesh points will be needed in the field of computation for adequate resolution; assuming no further complications arise in this treatment of increased space dimension, a machine capable of about 10^2 MFLOP will be required if the solution is to be obtained in a matter of hours. Furthermore, when complicated turbulence models are involved in the calculation, additional dependent variables and equations will be involved so that a capacity of 10^3 MFLOP would be demanded of the "future computer."

The past record of computer development has been so impressive that one has come to expect an order of magnitude speed improvement every 5 to 10 years; such circumstances have tended to foster excessive optimism on the part of the users in relying on computer speed and capacity improvement for the solution of problems which cause difficulty on the machines available at a given time. However, it is clear that continued such improvements in hardware are not to be expected in the future; thus improvements in the computational methods are essential. For the present, computer scientists must rely on the use of parallelism (concurrent operations and multiplicity of hardware) to increase the "effective" speed of computation since there will be limited increases in "physical" speed. The management of parallel operations demands such highly sophisticated software that only "single instruction-multiple processor" (SIMP) machines will be constructed for the present and near future. Such SIMP machines require either that all the parallel processors do the same operation under the same instruction (Illiac IV) or that the same operation be repeated over a long sequence of operands in a pipeline fashion (Star). The speed advantage of the SIMP machine can be realized only with "vector mode" operations. When a program does not call for concurrent or repeated operations, the SIMP machines will operate in scalar mode and thus incur speed reduction due to idle processors or pipe-filling time; therefore, the overall speed achieved in the solution of a given problem will depend heavily on the relative number of scalar operations or operations that can be only minimally vectorized.

In this respect the solution of large fluid mechanics problems with SIMP machines creates many difficulties. The 5 to 10 million words, representing the dependent variables at the approximately 10^6 mesh points in the field of computation, should be updated during every sweep in the order of a second; this time includes the time required to search and identify the addressed words in the memory, fetch them, transmit them to the control processor(s) for updating, and, finally, store the new values at appropriate memory locations. This can be done if all these words are stored in the fast, random access memory, directly accessible to the CPU. Such fast memory is expensive; thus, the size of the largest such memory currently being offered is only 10^6 words (CRAY I). A majority of the data are stored at somewhat remote and inaccessible mass storage locations in some slower access units; to keep the parallel processors busy at full speed data must be transferred in the appropriate order to the fast-access memory locations. This task of data management significantly complicates the software and calls for parallel paths of sufficient widths and fast input-output devices and memory units. A slight lag in the rate of data supply to the CPU will quickly result in the exhaustion of the needed data in the fast-access memory and the halt of the machine (the "Page Fault"). When the fast, direct-access memory is too "small" page faults can occur so frequently that the machine is doing little besides transferring data back and forth among various memory locations. A simple solution to this problem consists of providing large enough fast-access memories, expensive as they may be; fast memory capabilities are expected to increase rapidly in future computers.

A more functional difficulty of using SIMP machines for solving problems in computational fluid dynamics is the relative content of scalar and vectorizable operations. Computational fluid dynamics problems are generally initial boundary-value problems with boundary point values to be updated along with the interior point values. The operations at all the interior points are readily amenable to vectorization (for certain stencils, the vectorization is obvious, but for other stencils, much skill may be needed). The operations at boundary points are not vectorizable; they can vary considerably and frequently do vary along the various parts of the computational boundary. Thus, all those operations must be conducted in scalar mode (or rather short vector mode). The sequential operation of updating alternately the interior and the boundary points is natural and causes no problem in most of the currently available sequential machines. If such sequential programs are used on computers with parallel processors of the various kinds (Illiac, Star, Cray, ASC, etc.) more time will be required because the parallel machines will run in scalar mode exclusively and will have to pay the penalty of the overhead of carrying the complicated software for parallel operations.

It is therefore necessary to convert the existing sequential programs in order to take advantage of vector processing capabilities. The computer manufacturers have learned much from the experiences of Illiac IV and Star and are trying to provide some software capability of vectorizing current Fortran programs for use in their parallel processors. However, they have so far failed to deal with the fundamental nature of the logic of the existing programs which involve alternating operations--one highly vectorizable, the other not. The penalty to be paid for a small fraction of scalar operations is extremely high; orders of magnitude increase of the parallel speed may not even double the overall speed if roughly equal times are spent on vector and scalar operations. *It is important that the future computers to be designed for computational fluid dynamics enhance the total effective speed rather than only the speed under parallel operations.* This is especially important to agencies and institutions which wish to continue the use of their vast library of sequential programs.

3.6.2 Fast Algorithms

A helpful solution to the computer manufacturer's difficulty just referred to is for the computational aerodynamicists to rewrite their programs to maximize the vector content of the operations, or even better, to devise new ways (algorithmic logic) of solving their problems with an absolute minimum of scalar operations. Besides the question of the economics of converting the existing library of CFD programs, the computational fluid dynamicists are poorly equipped to do the task, even if they are willing.

Software to control a sophisticated computer and to derive the maximum speed from the parallel machine is extremely complex and depends largely on the specific architecture and various component capabilities of the computer. The computer manufacturers now consider the development cost of software to support a machine to be as great or greater than that of the hardware itself. Most computational fluid dynamicists cannot even begin to think about programming at the machine level. Computational fluid dynamicists have demonstrated their ability to write Fortran programs which in most instances can be improved by a factor of two or more by a professional programmer. Even the scientists and programmers at the Los Alamos Scientific Laboratory, with their personnel resources and high level of expertise, need many years of practice to utilize their many large computers efficiently. Those able to write efficient computational fluid dynamics programs for the new parallel machines will be few indeed. Moreover, computational fluid dynamicists have their own problems and should not be required to become proficient in a new programming language. It is therefore highly desirable for the manufacturer of a parallel machine to supply the users with a conversion code from Fortran, or at least a minimum extension for vectorizing.

The conversion routine to take advantage of whatever parallelism exists in a basically serial code is clearly a complex proposition. Research in the direction of developing new ways (not just algorithms or stencils) for solving the partial differential equation system can be highly rewarding if the new ways are particularly adaptable to vectorized computation. Different types of algorithms may be favored by different parallel machine architectures. Thus, implicit finite difference algorithms and Galerkin-type finite-element or spectral algorithms are favored by parallel processors such as Illiac IV. Explicit finite-difference algorithms are favored by the pipeline processors like Star. The Texas Instrument ASC machine with two or four pipes may favor some other types of special algorithms. More research effort in this area is required and should include problems associated with the boundary conditions, which are of a "scalar" nature.

A distinctive approach to the solution of three-dimensional flow problems is the method of splitting operators. A 3-D operator such as the Navier-Stokes is replaced (or approximated in some weak sense) by a succession of one-dimensional operators. This method is useful for time-dependent problems with suitable boundary conditions which are computed at sufficiently small time steps. The application of this method to steady-state flow problems requires modifications that leave much to be desired. With better understanding and methods of implementation, the splitting method may greatly reduce the need of ever larger computers and should be supported by research funding.

3.6.3 Fundamental Studies and A Posteriori Error Bounds

For the class of viscous interaction problems that requires the solution of the Navier-Stokes equations at large Reynolds number, the field of computation generally contains regions with mixed hyperbolic and elliptic (or parabolic) behavior. The imposition of boundary conditions to formulate the discretized problem properly is uncertain especially since some of the regions in question are always extraneous (i.e., superfluous from the view of the partial differential equations). The simpler discretization algorithms often do not permit the computations to remain stable in both the hyperbolic and the parabolic regions. Stability of computation is often achieved by (1) introducing artificial viscous terms in the differential equations, (2) incorporating smoothing routines or setting upper bounds of variations or various other computational artifices, and (3) altering the boundary conditions.

When periodic boundary conditions are imposed, both the stability and convergence for some discretized form of the Navier-Stokes equations based on some simple algorithms can be mathematically proven. If the lift and drag forces acting on a body embedded in the flow field with periodic boundary conditions are found to be distinctly nonzero, then the discretization formulation is not self-consistent. This inconsistency is of fundamental importance and is due to the accumulation of local discretization errors generally neglected by order of magnitude arguments. Although there is no sure way to avoid all discretization errors, it is possible to avoid the accumulation of those physical qualities which must be conserved in the physical space (i.e., mass, momentum, and energy). There may be errors in the fluxes of these quantities across a given physical boundary, but when the two neighboring volumes are added together, those errors must cancel identically so that the conservation laws applied to the combined volume will receive no contributions from the interior (even in the forms of doublets, quadrupoles, or vortices). From the potential theory of thin airfoils and circular cylinders, such doublets and vortices distributed over a line or surface can be used to represent physical bodies like venetian blinds or grids. The residual "higher order" errors in the fluxes of these conserved quantities cannot be tolerated within the field of computation just as those blinds and grids cannot be tolerated in wind tunnel test sections. There are many different ways to achieve such "conservation difference" algorithms, but they are not always achieved by writing the differential equations in the so-called conservation or divergence form, $\frac{\partial}{\partial t} U + \frac{\partial}{\partial x} F(U,X) =)$, even if "U" represents the mass, momentum, and energy. The conservation of the discretized equations must be checked in physical space coordinates.

Such conservation laws in arbitrary discretized volumes, not the differential equations, are the laws established by experiments as the foundation of physics. The uncertainties on the boundary of the physical experiments correspond to the uncertainties of specifying the boundary conditions in our computation. The discretization errors on the boundary, just like measurement errors in physical experiments, are not avoidable, even if the discretization errors do not accumulate in the strict conservation form. It is necessary to study the effects of these uncertain boundary conditions on the computed solution--just as wind tunnel data should be studied to isolate the various effects of the tunnel operating conditions. Physical phenomena are insensitive to measurement errors on the boundary; thus our computed results and wind tunnel results should be likewise insensitive to small variations of boundary conditions. Mathematically, this is what is meant by the term "well posed." When it is not known how to render a well-posed problem mathematically, it is clearly desirable to assure the insensitivity of the solution relative to perturbations of various boundary data, including the various spurious factors that may have been introduced into the difference formulation, deliberately or unknowingly. When the solution is sensitive to the adjustment of such boundary parameters, the solution should be very carefully studied and most probably should be rejected. It is not satisfactory to adjust the computational details to reproduce a desired result. Indeed, the variability of the results on any such computational details should be considered as part of the inherent error of the computed results. Credibility of a computed result will come only when reasonable bounds can be set on all the errors.

The errors in a computational solution of a consistent set of discretized equations (e.g., free from artificial viscosity) for a given physical problem consist primarily of three major sources:

1. Round-off error, (Er), is an accumulation of the error caused by finite precision arithmetic with local round-off error (εr) and may be estimated according to random accumulation (i.e., $Er = \varepsilon_r N^{\frac{1}{2}}$, where N is the total number of floating point operations of the computation). For a given computer and a limited value of Er (say less than 1 percent) the total number of operations (or machine CPU time) may thus be limited by this error bound.

2. Discretization error (Ed) is an accumulated error in the interior of the field of computation due to the local discretization error (εd) according to the numerical formulation of the physical problem.

3. Boundary error (Eb) is an accumulated error in the interior of the field of computation due to the uncertainties of the well posed boundary formulation of the computation that departs from the physical boundary formulation.

A rigorous estimate of error Ed may be obtained with the energy method, but the bounds are generally too broad to be of practical significance. Stability of a computation essentially means the boundedness of the error at all Δx, $\Delta t \to 0$, and as such will vanish as both Δx and $\Delta t \to 0$. The practical question is how small the Δx and Δt should be in order that the error may be reasonably small (i.e., within the engineering requirements). An analysis (Ref. 3.42) of a class of discretized forms of Burger's equation as a one-dimensional model of the Navier-Stokes equation based on second-order conservative difference algorithms leads to an upper bound estimate of this error $Ed \leq 0.03\ (Re)^2$ where Re is the mesh Reynolds number based on the velocity change per mesh, the mesh size, Δx, and the total viscosity (physical and numerical). Later computational studies of physical flow fields with Navier-Stokes equations have shown that this estimate is a very good upper bound for $Re \lesssim 2$ but that it rapidly became a tremendous overestimate of the error as $Re \gtrsim 4$. This is so for a strictly conserved discretized formulation. Otherwise, limited experience with the Navier-Stokes equation shows that the above estimate becomes an overestimate only when Re is appreciably larger than 10. In the practical applications of such an estimate, it is important to compute at such a low mesh Reynolds number, which can be marginally met for two-dimensional flow problems with currently available computers. Much is needed to analyze the accumulated discretization error to provide some meaningful but simple upper bounds of this Ed at least for Re as large as 10 to 20. This is the case because, with three-dimensional problems in view, even orders of magnitude improvement of the computer power cannot possibly yield anything much better than $Re \sim 10$ to 20. Analysis for the understanding of discretized approximation at "coarse" mesh is of primary importance in substantial improvement of the predictive reliability of computational fluid dynamics.

Better understanding of the errors caused by boundary conditions through analysis of the discretized formulation may be much harder to estimate. Fortunately, a reasonable experimental technique can help us in estimating the errors. One can assess the extent of the errors at the boundaries by performing sensitivity studies and summing the influence from the individual errors.

If any of the individual errors is too large fractionally, compared with the data perturbation, the discretization formulation is poorly posed and should be rejected. Thus Eb is essentially a measure of the well-posedness of the discretization formulation. The typical perturbation of the data should include at least:

1. Mesh refinement
2. Field enlargement and/or alteration
3. Different initial data
4. Different implementation of sensitive boundary conditions
5. Impulsive-type disturbances of unit magnitude at key locations on the boundary and throughout the interior to estimate the influence functions of different types of boundary errors

The a posteriori study described above has been carried out for at least two widely different cases of rather complex fluid mechanics problems. The computed results have been compared with experimental data and other computational results. It was fully demonstrated that computational solutions of the full Navier-Stokes equations to have prediction value equal to experimental data. It was also demonstrated how wrong the computed solutions can be if one does not carefully complete the a posteriori study. It is true that the a posteriori study is in part heuristic and much dependent on perturbation arguments. Its technique and foundation need to be improved and more soundly established. Much analysis needs to be encouraged in this direction. The error bounds of computational solutions established from the a posteriori study, even in its present form, may be accepted as valid support of the credibility of the computational results. The current situation is that, for computations with sufficiently refined mesh sizes of Re $\sim$ 10, the dominant contribution to the overall error E is the boundary error Eb, even for well-posed formulations.

The heuristic nature and the inadequate analytic foundation of the present error estimate can be remedied by more case studies of benchmark problems by careful comparison of computed results with carefully executed experimental data, both with reasonable error bounds.

Computers, computational aerodynamics, and wind tunnel testing can be integrated in direct ways. The computer controlled wind tunnel can serve as a large analog computer to provide and to help identify the correct boundary conditions in the computational solution of the same problem. If the wind tunnel data should be different from the computed results by more than can be explained by the discretization error, Ed, of the computation and the measurement errors of the test, the flow quality of the wind tunnel must be improved. When this is done, conditions of the flow field will be altered along with the test data. The computation of the flow field can be performed (on line, if possible) in an iterative fashion with adjustments of the tunnel flow to improve the overall simulation. The wind tunnel as an analog device helps to eliminate the largest uncertainties in the computational solution, i.e., the formulation of the flow conditions on the computation boundary. Both tools are able in a highly complementary way to establish the credibility of test and computed results. From such results, extrapolation to flight conditions can be much more confidently accomplished. The potential benefit in terms of time and cost in the flight test stage of the development of a large aeronautical system is much larger than the effort to be spent in increasing our confidence of extrapolation. The cost of even the largest computer needed is much less than the wind tunnels under consideration. Investigation into the feasibility of such an integrated wind tunnel/computer facility seems to warrant serious consideration.

In view of the above discussion, the following suggestions are offered:

I. *In the computational solution of fluid dynamics problems:*

1. *The discretized formulation should satisfy the integrated conservation laws for arbitrary combinations of discretized volumes throughout the field of computation to the desired order of accuracy (not merely the local truncation errors).*

2. An error analysis should accompany each computational solution with the sensitivity and influence of the arbitrary parameters inherent in the discretized formulation documented, both in the interior and on the boundary. An absolute error bound of key results should be made, with breakdown of the sources of errors if at all possible, and at least the most important ones identified.
3. Analysis of the discretized formulations and their solutions of meaningful models of Navier-Stokes equations should be encouraged to establish simple and narrow upper bounds of the various error sources. The most important one is the accumulated discretization error for coarse mesh computations when the mesh Reynolds number is large.
4. Analysis of the discretized formulations of the Navier-Stokes equations with and without turbulent modeling transport equations under nontrivial boundary conditions should be encouraged, especially in connection with the techniques of rendering a poorly posed problem "well posed" for computational purposes.
5. Development of algorithms and logic for the solution of initial boundary value problems of Navier-Stokes equations particularly suited to take advantage of parallel computers should be encouraged.

II. On the Integration of Computational Fluid Dyanmics with Wind Tunnel Testing:

1. Carefully executed computational results with error bounds should be checked with similarly reliable wind tunnel data, preferably including some important local flow variables rather than only global properties for a selected set of benchmark problems.
2. Quality and reliability of the wind tunnel test data should be improved, possibly with the help of computer control, in research wind tunnels particularly suitable for carrying out the specific benchmark tests.

3. The feasibility of an online integrated wind tunnel-computer facility should be studied as an analog-digital device that can very significantly increase the reliability of the extrapolation process in the development of large aeronautical systems.

III. On the Super Computers

1. Super computers for solving complex fluid dynamics problems should possess balanced speeds for scalar and vector processing rather than having orders of magnitude difference in the two modes of operation.

APPENDIX I MATHEMATICAL PROBLEM AREAS

The most immediate matter of practical concern encountered when an attempt to computationally generate an approximate solution for a given fluid flow problem is initiated is that of achieving stability of the numerical calculation. The work of von Neumann (Ref. 3.207) and others provides the required insights in certain special cases, but, for the most part, these results are not directly applicable to problems of significant difficulty since they are usually derived for linear systems of equations. Unfortunately, the nonlinear terms of the Navier-Stokes equations are often not negligible in the problems of fluid dynamics, and (far worse, as a practical problem) the computational problems are often ill-posed, with the result that unstable calculations will often result during the initial attempts to generate a computer solution for a given problem (well-posedness of the differential problem need not result in a well-posed difference problem); the numerical algorithm being employed in such a case must then be altered in some fashion or another in order to render the calculation stable. In the attempt to do this there are two possibilities:

a) Alter the method of discretizing the differential equations

b) Alter the implementation of the boundary conditions.

The usual approach to the resolution of the computational instability lies in performing slight alterations of the boundary condition implementation. Due to the fact that these calculations tend to be highly sensitive to the boundary conditions (Ref. 3.198) it is usually possible to obtain a stable computation by (rather small) alterations of the boundary treatment. It is possible, however, that the resulting "perturbed" calculation will not be consistent with the problem originally posed. The details of these matters are very incompletely understood; a much deeper understanding of the mechanisms involved is essential for progress in this context to accelerate, and it is recommended that such work be encouraged.

There seems to have been a rather general neglect of ill-posed problems among mathematicians in the past; it may be that this was due to a general feeling that these problems were inherently completely intractable. However, increased consideration has more recently been given to the details of ill-posedness perhaps because of the general growth of computational fluid dynamic knowledge and success and the subsequent realization that the ill-posedness of these problems is probably not due to a lack of understanding of the basic physics of the processes involved but, instead, is a consequence of the physical phenomena per se. At the practical level, the most crucial matter is to more fully understand the consequences of ill-posedness (or conditional ill-posedness, etc.) in actual computations--that is, in the solution of the discretization of the differential problem. Most of the work done in the study of ill-posed problems to date seems to have been devoted to the differential problems; the consideration of the numerical analysis aspects is, understandably, a more recent concern. Some results concerning the latter problems have begun appearing; however, it is recommended that the continuation and extension of such investigations be supported. In particular, one would hope that such work might eventually make it possible to more fully distinguish between numerical instability of a fluid dynamics calculation and physical instability of the flow itself.

Energy methods are potentially extremely powerful in that they consider the stability of the <u>entire</u> computational problem (i.e., the interior and the boundary considerations are simultaneously addressed). This is especially important since, as mentioned before, the boundary conditions often have an overriding effect on the stability of the algorithm. Unfortunately, energy methods involve very complicated implementation, even for extremely simple problems; for problems of any complexity it is often impossible to successfully determine the problems stability via this approach (Ref. 3.223). Furthermore, the energy methods yield criteria sufficient merely for stability; these criteria are likely to be very conservative (and far from necessary). The information obtained from energy methods also yields very little understanding of how much liberty may be taken with the boundary conditions (Ref. 3.45).

For the present, the extrapolation of the linear stability theory to nonlinear problems via the analysis of the local linearizations remains the most practical general approach to determining stability criteria. The fundamental difficulty here is that such an analysis, apart from being nonrigorous, does not account for the boundary condition treatment at all, and, of course, these considerations are often the more critical ones (Ref. 3.45). Much remains to be learned concerning the prediction of the effect of the boundary condition specification on stability; practical guidelines (not necessarily rigorous ones) are badly needed to complement the existing analysis which is presently possible using the local linearization approach at points in the interior of the domain. It is recommended that such research be encouraged and supported.

Convergence The Lax Equivalence Theorem gives an elegant and rather practical criterion for convergence of a finite-difference discretization of a partial differential equation system, but it is applicable only to linear systems. For the (usually) nonlinear problems of advanced fluid dynamics there is a lack of any generally effective criterion for the convergence of numerical methods; of course, one can always apply the criterion derived for linear problems in hopes that such an extrapolation may be somewhat valid, but this is not a completely satisfactory solution. Furthermore, a convergent process can well be so slowly convergent as to be of nothing more than purely theoretical interest; thus information concerning the rate of convergence of a numerical procedure for a fluid flow problem is also crucial (but usually not available with the present state of the art).

Energy methods do allow a rigorous analysis of convergence (a successful stability calculation with an energy method yields easy corollaries concerning convergence, uniqueness, etc. (Ref. 3.45)), but, as mentioned above, the details of energy method calculations are so difficult that complicated problems can rarely be analyzed by these techniques.

Parabolic Equations Since there does not appear to be any generally effective method for convergence analysis, it is necessary to concentrate on developing methods for limited classes of problems; such work should be encouraged. The situation described in Section 3.2 for diffusion equations with constant diffusivity is less optimistic when convective terms become involved; the presence of this first-order term may change in some obscure manner the considerations which were appropriate for the constant diffusivity case. Furthermore, the methods used for a single (scalar) parabolic equation do not generalize to allow treatment of systems of simultaneous parabolic equations, and, in such problems, there are often difficulties in preventing the accumulation of errors due to truncation and boundary data inaccuracy (Ref. 3.45).

Hyperbolic Problems Where solutions are involved which are discontinuous because of the presence of shock waves, there is often difficulty either with the practical aspects of the methods for dealing with the shock or with the quality of the solution obtained, especially for non-uniform flow fields or complex shock shapes. Shock fitting, even for a known shock propagating into a uniform flow field, becomes very difficult to manage in multidimensional flow problems (Ref. 3.223). As mentioned previously, the artificial viscosity methods are more adaptable to the higher dimensional situations, but in order to suppress the occurrence of unreasonable oscillations in the solutions obtained, it is usually necessary to use values of artificial viscosity which are huge in comparison to realistic values for the viscosity of the fluid itself (Ref. 3.45). This may cause a rather large spread in the width of the computed shock transition region and greatly affect the details of the computed flow field. The result of the calculation of a shock's propagation in a one-dimensional problem by the Lax-Wendroff method is apt to display considerable oscillation at the shock location (Ref. 3.223); multidimensional solutions of such problems using this method are often difficult to achieve because of uncertainty of the stability aspects of the calculation. Artificial viscosity terms are frequently added to the equations in an attempt to prevent the occurence of nonlinear instability phenomena; the basic causes at work in such situations are very incompletely understood.

The most fundamental problem concerning the solution of hyperbolic equations, however, is the lack of any generally effective method for predicting the location and shape of shocks which develop during the flow (and thus are not known shocks, as were those discussed above) (Ref. 3.45). Several approaches to the prediction of shocks are presently in use, but these typically involve heavy interaction between the calculation as it proceeds and a very practiced human observer whose experience and judgement in "tweaking" certain aspects of the computer program are all-important; the overall flavor of the predictions of shocks that result is that of art, rather than science. Much remains to be done before shocked flows can be routinely predicted with confidence and detailed accuracy. *These are extremely important problems, and it is essential that basic research (in addition to computational experiments) in this area be supported.*

3.1. Adams, J. C., Jr. "Numerical Calculation of the Three-Dimensional Hypersonic Viscous Shock Layer on a Sharp Cone at Incidence." Proceedings of the 25th Meeting Heat Transfer and Fluid Mechanics Institute, Davis, California, June 1976.

3.2. Adamson, T. C. and Feo, A. "Interaction Between a Shock Wave and a Turbulent Boundary Layer in Transonic Flow." SIAM J. Appl. Math., Vol. 29, pp 121-145, 1975.

3.3 Atias, M., Wolfshtein, M. and Israeli, M. "Efficiency of Navier-Stokes Solvers." AIAA Journal, Vol. 15, pp 263-266, February 1977.

3.4 Bailey, F. R. and Ballhaus, W. F. "Comparisons of Computed and Experimental Pressures for Transonic Flows about Isolated Wings and Wing-Fuselage Configurations." NASA SP 347, pp 1213-1231, 1975.

3.5 Baker, G. A. and Dougalis, V. A. "The Effect of Quadrature Errors on Finite Element Approximations for Second Order Hyperbolic Equations." SIAM J. Numer. Anal., Vol 13, pp 577-598, 1976.

3.6. Ballhaus, W. F. and Goorjian, P. M. "Implicit Finite-Difference Computations of Unsteady Transonic Flows About Airfoils, Including the Treatment of Irregular Shock-wave Motions." AIAA Paper 77-205, January 1977.

3.7. Ballhaus, W. F., Jameson, A. and Albert, J. "Implicit Approximate-Factorization Schemes for the Efficient Solution of Steady Transonic Flow Problems." NASA TMX 73202, 1977.

3.8. Barger, R. L. and Brooks, C. W. "Computerized Procedures for Airfoil Design." NASA SP 347, pp 703-712, 1975.

3.9. Barnwell, Richard W. "A Time-Dependent Method for Calculating Supersonic Angle of Attack Flow About Axisymmetric Blunt Bodies with Sharp Shoulders and Smooth Nonaxisymmetric Blunt Bodies." NASA TN D-6283, 1971.

3.10. Barnwell, Richard W. "Approximate Method for Calculating Transonic Flow About Lifting Wing-body Configurations." NASA TR R-452, 1976.

3.11. Bauer, F. and Garabedian, P. "Computer Simulation of Shock Wave Boundary Layer Interaction." Commun. Pure & Appl. Math., Vol. 26, pp 659-665, 1973.

3.12. Beam, R. and Warming, R. "An Implicit Finite Difference Algorithm for Hyperbolic Systems in Conservation Law Form." J. Comp. Phys., Vol. 22, pp 87-110, 1976.

3.13. Beatty, T. D. and Narramore, J. C. "Inverse Method for the Design of Multielement High-Lift Systems." J. Aircraft, Vol. 13, pp 393-398, June 1976.

3.14. Becker, R. "Stollwelle und Detonation." Z. Physik, Vol. 8, p 321, 1922.

3.15. Bell, T. L. and Nelkin, M. "Nonlinear Cascade Models for Fully Developed Turbulence." Phys. Fluids, Vol. 20, pp 345-350, 1977.

3.16. Belotserkovskii, O. "Numerical Methods of Some Transonic Aerodynamics Problems." J. Comp. Phys., Vol. 5, pp 587-611, 1970.

3.17. Belotserkovskii, O. M. "Direct Numerical Simulation of Complex Gas Dynamic Flows." 11th International Symposium on Space Technology and Science, Tokyo, Japan, 1975.

3.18. Bennekers, B., Roos, R. and Zwaan, R. J. "Calculation of Aerodynamic Loads on Oscillating Wing/Store Combinations in Subsonic Flow." AGARD Conference on Wing-with-Stores Flutter, AGARD CP-162, October 1974.

3.19. Benton, E. and Platzman, G. "Tables of Solutions of the One-Dimensional Burger's Equations." Quart. Appl. Math., Vol. 30, pp 195-212, 1972.

3.20. Bland, S. R. "Recent Advances and Concepts in Unsteady Aerodynamic Theory." NASA SP 347, pp 1305-1326, 1975.

3.21. Bore, C. L. "Examples of Load Prediction Difficulties." AGARD CP 204, 1976.

3.22. Bracco, Frediano V. "On the Optimal Utilization of Experimental Data." AIAA Journal, Vol. 13, pp 1421-1422, November, 1975.

3.23. Bradshaw, P. "An Improved Van Driest Skin Friction Formula for Compressible Turbulent Boundary Layers." AIAA Journal, Vol. 15, pp 212-214, February 1977.

3.24. Brailovskaya, I. Y. "A Difference Scheme for Numerical Solution of the Two-Dimensional, Nonstationary Navier-Stokes Equations for a Compressible Gas." Soviet Physics-Boklady, Vol. 10, No. 2., pp 107-110, August 1965.

3.25. Briley, W. R. and McDonald, H. "Numerical Prediction of Incompressible Separation Bubbles." J. Fluid Mech., Vol. 69, pp 631-656, June 1975.

3.26. Brillant, H. M. "Shock Wave Boundary Layer Interactions in Laminar Transonic Flow." AIAA Journal Vol. 12, pp 323-329, March 1974.

3.27. Brune, G. W. "New Approaches to Inviscid Flow/Boundary Layer Matching." AIAA Journal, Vol. 13, pp 936-938, July 1975.

3.28. Burggraf, O. R., Stewartson, K., and Belcher, R. "Boundary Layer Induced by a Potential Vortex." Phys. Fluids, Vol. 14, pp 1821-1833, 1971.

3.29. Buzbee, B., Golub, G., and Neilson, C. "on Direct Methods for Solving Poisson's Equation." SIAM J. Numer. Anal., Vol. 7, pp 627-656, 1970.

3.30. Caldwell, C. S. "Rates of Convergence of Approximate Solutions of Parabolic Initial-Boundary Value Problems." SIAM J. Numer. Anal., Vol. 6, pp 1121-1135, 1974.

3.31. Cannon, J. R. and Knightly, G. H. "Some Continuous Dependence Theorems for Viscous Fluid Motions." SIAM J. Appl. Math., Vol. 18, pp 627-640, 1970.

3.32. Cannon, J. R. and Knightly, G. H. "A Note on the Cauchy Problem for the Navier-Stokes Equations." SIAM J. Appl. Math., Vol. 18, pp 641-644, 1970.

3.33. Cannon, J. R. and DuChateau, P. "Approximating the Solution to the Cauchy Problem for LaPlace's Equation." SIAM J. Numer. Anal., Vol. 14, pp 473-483, June 1977.

3.34. Carlson, L. A. "Transonic Airfoil Analysis and Design Using Cartesian Coordinates." J. Aircraft, Vol. 13, pp 349-356, May 1976.

3.35. Carlson, L. A. "Inverse Transonic Airfoil Design Including Viscous Interaction." NASA CP 2001, pp 1387-1398, 1976.

3.36. Carter, James E. "Numerical Solutions of the Navier-Stokes Equations for the Supersonic Laminar Flow over a Two-Dimensional Compression Corner." NASA TR-R-385, 1972.

3.37. Carter, James E. "STAYLAM: A Fortran Program for the Suction Transition Analysis of a Yawed Wing Laminar Boundary Layer." NASA TMX 74013, 1977.

3.38. Cebecci, T., Kaups, K., and Moser, A. "Calculation of Three-Dimensional Boundary Layers." AIAA Journal, Vol. 14, pp 1090-1094, August 1976.

3.39. Cebecci, C., Kaups, K., and Ramsey, J. A. "A General Method for Calculating Three-Dimensional Compressible Laminar and Turbulent Boundary Layers on Arbitrary Wings." NASA CR-2777, 1977.

3.40. Chambers, T. L. and Wilcox, D. C. "Critical Examination of Two-Equation Turbulence Closure Models for Boundary Layers." AIAA Journal, Vol. 15, pp 821-828, June 1977.

3.41. Cheng, H. K. and Hafez, M. M. "Transonic Equivalence Rule: A Nonlinear Problem Involving Lift." J. Fluid Mech., Vol. 72, pp 161-188, November 1975.

3.42. Cheng, S. I. "Accuracy of Difference Formulation of Navier-Stokes Equations." Phys. Fluids, Supplement II, pp II34-II41, December 1969.

3.43. Cheng, S. I. "Numerical Integration of Navier-Stokes Equations." AIAA Journal, Vol. 8, pp 2115-2122, December 1970.

3.44. Cheng, Sin-I and Chen, J. H. "Slip, Friction, and Heat Transfer Laws in a Merged Regime." Phys. Fluids, Vol. 17, pp 1677-1687, 1974.

3.45. Cheng, S. I. "A Critical Review of Numerical Solution of Navier-Stokes Equations." Progress in Numerical Fluid Dynamics, Springer-Verlag, New York, 1975.

3.46. Cheng, R. T. "Numerical Solution of the Navier Stokes Equations by the Finite Element Method." Phys. Fluids, Vol. 15, pp 2098-2105, 1972.

3.47. Cheung, T. Y. "Approximate Solutions and Error Bounds for Quasilinear Elliptic Boundary Value Problems." J. Comp. System Sci., Vol. 7, pp 306-322, 1973.

3.48. Cheung, T. Y. "Quasilinear Parabolic Boundary Value Problems." SIAM J. Numer. Anal., Vol. 10, pp 1061-1079, 1973.

3.49. Cheung, T. Y. "Approximate Solutions and Error Bounds for Quasi-linear Hyperbolic Initial Boundary Value Problems." SIAM J. Numer. Anal., Vol. 12, pp 37-45, 1975.

3.50. Cheung ,T. Y. "Three Nonlinear Initial Value Problems of the Hyperbolic Type." SIAM J. Numer. Anal., Vol. 14, pp 484-491, 1977.

3.51. Chin, R. "Dispersion and Gibbs Phenomenon Associated with Difference Approximations to Initial Boundary Value Problems for Hyperbolic Equations." J. Comp. Phys., Vol. 18, pp 233-247, 1975.

3.52. Chorin, A. J. "On the Convergence of Discrete Approximations to the Navier-Stokes Equations." Math. Comp., Vol. 23, pp 341-353, April 1969.

3.53. Chorin, A. J. "Numerical Study of Slightly Viscous Flow." J. Fluid Mech., Vol. 57, pp 785-796, March 1973.

3.54. Chorin, A. J. "Gaussian Fields and Random Flow." J. Fluid Mech., Vol. 63, pp 21-32, March 1974.

3.55. Chushkin, P. "Supersonic Flow About Conical Bodies." J. Comp. Phys., Vol. 5, pp 572-586, 1970.

3.56. Clark, R. A., Ferziger, J. H., and Reynolds, W. C. "Evaluation of Subgrid-Scale Turbulence Models Using a Fully Simulated Turbulent Flow." NASA-CR-152642, 1977.

3.57. Clever, W. C. and Meecham, W. C. "Time-Dependent Wiener-Hermite Base for Turbulence." Phys. Fluids, Vol. 15, pp 244-255, 1972.

3.58. Cloutman, L. D., Hirt, C. W., and Romero, N. C. "SOLA-ICE: A Numerical Solution Algorithm for Transient Compressible Fluid Flows." Los Alamos Scientific Lab LA-6236, 1976.

3.59. Cole, J. D. "Modern Developments in Transonic Flow." SIAM J. Appl. Math., Vol. 29, pp 763-787, 1975.

3.60. Courant, R., Friedricks, K. D., and Lewy, H. "Uber die partiellen Differenzengleichungen der mathematischen Physik." Math. Ann., Vol. 100, pp 32-74, 1928.

3.61. Crawford, M. E., Kays, W. M., and Moffat, R. J. "Heat Transfer to a Full-Coverage Film-Cooled Surface with 30 Deg. Slant-Hole Injection." NASA CR-2786, 1976.

3.62. Crown, J. C. "A New Approach to the Calculation of Transonic Flows." SIAM J. Appl. Math., Vol. 20, pp 677-697, 1971.

3.63. Culham, W. and Varga, R. "Numerical Methods for Time-Dependent, Nonlinear Boundary Value Problems." Soc. Petroleum Eng. J., Vol. 11, pp 374-388, 1971.

3.64. Daly, B. J. and Harlow, F. H. "Transport Equations in Turbulence." Phys. Fluids, Vol. 13, pp 2634-2649, November 1970.

3.65. Davies, T. and Walker, G. "On Solutions of the Compressible Laminar Boundary Layer Equations and Their Behavior near Separation." J. Fluid Mech., Vol. 80, pp 279-292, April 1977.

3.66. Davis, G. and Mallinson, G. D. "An Evaluation of Upwind and Central Difference Approximations by a Study of Recirculating Flow." Computers and Fluids, Vol. 4, pp 29-43, 1976.

3.67. Deardorff, J. W. "A Numerical Study of Three-Dimensional Turbulent Channel Flow at Large Reynolds Numbers." J. Fluid Mech., Vol. 41, p 453-480, April 1970.

3.68. Deardorff, J. "On the Magnitude of the Subgrid Scale Eddy Coefficient." J. Comp. Phys., Vol. 7, pp 120-133, 1971.

3.69. Deiwert, G. S. "Simulation of Turbulent Transonic Separated Flow Over an Airfoil." NASA SP-347, 1975.

3.70. Deiwert, G. S. "Recent Computation of Viscous Effects in Transonic Flow." Proceedings, International Conference on Numerical Methods in Fluid Dynamics, pp 159-164, Springer-Verlag, 1976.

3.71. Dendy, J. E., Jr. "Alternating Direction Methods for Nonlinear Time-Dependent Problems." SIAM J. Numer. Anal., Vol. 14, pp 313-326, 1977.

3.72. Deshpande, S. M. "The Connection Between Elliptic Navier-Stokes Equations and Harmonic Functionals." Quart. Appl. Math., Vol. 31, pp 43-52, 1973.

3.73. Dickson, L. J., Chen, A. W., and Rubbert, P. E. "A New Approach to Far-Field Boundary Conditions in Transonic Computations." 5th International Conference on Numerical Methods in Fluid Dynamics, the Netherlands, 1976.

3.74. Dodge, P. R. and Lieber, L. S. "A Numerical Method for the Solution of the Navier-Stokes Equations with Separated Flow." AIAA Paper 77-170, January 1977.

3.75. Donaldson, C. "Calculation of Turbulent Shear Flows for Atmospheric and Vortex Motions." AIAA Journal, Vol. 10, pp 4-12, January 1972.

3.76. Douglas, J. A Survey of Numerical Methods for Partial Differential Equations, Academic Press, New York, 1961.

3.77. Douglas, J. and Gunn, J. "A General Formulation of Alternating Direction Methods." Numer. Math., Vol. 6, 1964.

3.78. Dusto, A. R. et. al. "A Method for Predicting the Stability Characteristics of an Elastic Airplane." NASA CR 114712, 1974.

3.79. Ehlers, F. E., Johnson, F. T., and Rubbert, P. E. "Advanced Panel-Type Influence Coefficient Methods Applied to Subsonic and Supersonic Flows." NASA SP-347, pp 939-984, 1975.

3.80. Emmons, H. W. "Critique of Numerical Modeling of Fluid Mechanics Phenomena." Annual Review of Fluid Mechanics, Vol. 2, pp 15-36, 1970.

3.81. Falk, R. S. "An Analysis of the Penalty Method and Extrapolation for the Stationary Stokes Equations." Advances in Computer Methods for Partial Differential Equations, R. Vichnevetsky, ed., L'Association Internationale pour le Calcul Analogique, pp 66-69, 1975.

3.82. Falk, R. S. "A Finite Element Method for the Stationary Equations Using Trial Functions which do not have to satisfy div(v) = 0." Math. Comp., Vol. 30, pp 698-702, October 1976.

3.83. Falk, R. S. and King, J. T. "A Penalty and Extrapolation Method for the Stationary Stokes Equations." SIAM J. Numer. Anal. Vol. 13, pp 814-829, 1976.

3.84. Fannelop, T. K. "Three-Dimensional Turbulent Boundary Layer in External Flows--A Report on Euromech 60." J. Fluid Mech., Vol. 71, pp 815-826, October 1975.

4.85. Farmer, O. A. and Ramshaw, J. D. "A Method for Rapid Attainment of the Steady State in Two Dimensional Time-Marching Supersonic Flow Calculations." J. Comp. Phys., Vol. 24, pp 23-28, 1977.

3.86. Fix, G. and Gunzburger, M. "Dynamic Boundary Conditions for Viscous Flow Problems." Computers & Math. Appl., Vol. 3, pp 53-63, January 1977.

3.87. Fletcher, C. A. J. and Holt, M. "Supersonic Viscous Flow over Cones at Large Angles of Attack." J. Fluid Mech., Vol. 74, pp 561-591, April 1976.

3.88. Fomin, V. M., Vorozhtsov, E. V., and Yanenko, N. N. "Differential Analysers of Shock Waves: Theory." Computers and Fluids, Vol. 4, pp 171-183, 1976.

3.89. Fornberg, B. "On a Fourier Method for the Integration of Hyperbolic Equations." SIAM J. Numer. Anal., Vol. 12, pp 509-528, 1975.

3.90. Frenkiel, F. N. and Klebanoff, P. S. "Higher-Order Correlations in a Turbulent Field." Phys. Fluids, Vol. 10, pp 507-520, March 1967.

3.91. Frenkiel, F. N. and Klebanoff, P. S. "Correlation Measurement in a Turbulent Flow using High-Speed Computing Methods." Phys. Fluids, Vol. 10, pp 1737-1747, August 1967.

3.92. Frisch, V., Lesieur, M. and Sulem, P. L. "Crossover Dimensions for Fully Developed Turbulence." Phys. Rev. Lett., Vol. 37, pp 895-897, October 1976.

3.93. Garabedian, P. and Korn, D. "Analysis of Transonic Airfoils." Commun. Pure & Appl. Math., Vol. 24, pp 841-851, 1971.

3.94. Garabedian, P. and Korn, D. "A Systematic Method for Computer Design of Supercritical Airfoils in Cascade." Commun. Pure & Appl. Math., Vol. 29, pp 369-382, 1976.

3.95. Garabedian, P. R. "Transonic Flow Theory of Airfoil and Wings." NASA CP 2001, pp 1349-1358, 1976.

3.96. Gawain, T. "A Unified Heuristic Model of Fluid Turbulence." J. Comp. Phys., Vol. 5, pp 383-405, 1970.

3.97. Ghia, K. N. and Davis, R. T. "Corner Layer Flow: Optimization of Numerical Method of Solutions." Computers and Fluids, Vol. 2, pp 17-34, January 1974.

3.98. Ghia, V. and Davis, R. T. "Navier-Stokes Solutions for Flow past a Class of 2-D Semi-infinite Bodies." AIAA Journal, Vol. 12, pp 1659-1665, December 1974.

3.99. Gottlieb, D. and Gustafson, B. "On the Navier-Stokes Equations with Constant Total Temperature." Studies Appl. Math., Vol. LV, pp 167-185, 1976.

3.100. Grabowski, W. J. and Berger, S. A. "Solutions of the Navier Stokes Equations for Vortex Breakdown." J. Fluid Mech., Vol. 75, pp 525-544, June 1976.

3.101. Grad, H. "Singular Limits of Solutions of Boltzmann's Equation." Rarefied Gas Dynamics, pp 37-53, Academic Press, New York, 1974.

3.102. Gupta, R. N. and Rodkiewicz, C. M. "Unsteady Boundary-Layer Induced Pressures at Hypersonic Speed." Phys. Fluids, Vol. 14, pp 1332-1339, 1971.

3.103. Hadamand, J. Lectures on Canchy's Problem in Linear Partial Differential Equations. Yale University Press, 1923.

3.104. Hafez, M. M. and Cheng, H. K. "Convergence Acceleration of Relaxation Solutions for Transonic Flow Computations." AIAA Journal, Vol. 15, pp 329-336, March 1977.

3.105. Hafez, M. M. and Cheng, H. K. "Shock-Fitting Applied to Relaxation Solutions of Transonic Small-Disturbance Equations." AIAA Journal, Vol. 15, pp 786-793, June 1977.

3.106. Hall, M. G. "Methods and Problems in the Calculation of Transonic Flows." Proceedings, International Conference on Numerical Methods in Fluid Dynamics, pp 65-74, Springer-Verlag, 1976.

3.107. Hamielec, A. E., Hoffman, T. W., and Ross, L. L. "Numerical Solution of the Navier-Stokes Equations for Flow Past Spheres: Part I." J. American Inst. Chem. Engr., Vol. 13, pp 212-219, March 1967.

3.108. Hanjalic, K. and Launder, B. E. "Contribution Towards a Reynolds-Stress Closure for Low-Reynolds-Number Turbulence." J. Fluid Mech., Vol. 74, pp 593-610, 1976.

3.109. Hankey, W. L., Jr. and Holden, M. S. "Two-Dimensional Shock Wave-Boundary Layer Interactions in High Speed Flows." AGARD ograph No. 203, June 1975.

3.110. Harten, A., Hyman, J. M., and Lax, P. D. "On Finite Difference Approximations and Entropy Conditions for Shocks." Commun. Pure & Appl. Math., Vol. 29, pp 297-322, 1976.

3.111. Hedman, S. G. "Pressure Distributions for a Swept Wing Body Configuration Obtained from Coupling Transonic Potential Flow Calculations and Boundary Layer Calculations." AGARD CP 204, 1976.

3.112. Hellend, K. N., VanAlta, C. W. and Stegen, G. R. "Spectral Energy Transfer in High Reynolds Number Turbulence." J. Fluid Mech., Vol. 79, pp 337-360, February 1977.

3.113. Helliwell, W. S. and Lubard, S. C. "An Implicit Method for the Three Dimensional Viscous Flow with Application to Cones at Angle of Attack." Computers and Fluids, Vol. 3, pp 83-101, 1975.

3.114. Hess, J. L. and Smith, A. M. O. "Calculation of Nonlifting Potential Flow About Arbitrary Three-Dimensional Bodies." J. Ship. Res., Vol. 8, pp 22-42, 1964.

3.115. Hewitt, B. L., et. al. "Computational Methods and Problems in Aeronautical Fluid Dynamics." Academic Press, London, 1976.

3.116. Hirsch, R. and Rudy, D. "The Role of Diagonal Dominance and Cell Reynolds Number in Implicit Difference Methods for Fluid Mechanics Problems." J. Comp. Phys., Vol. 16, pp 304-310, 1974.

3.117. Hirt, C., Amsden, A., and Cook, J. "An Arbitrary Langrangian-Eulerian Computing Method for All Flow Speeds." J. Comp. Phys., Vol. 14, pp 227-253, 1974.

3.118. Hirt, C. W., Nichols, B. D., and Romero, N. C. "SOLA--A Numerical Solution Algorithm for Transient Fluid Flows." Los Alamos Scientific Lab, Rep. LA-5852, April 1975.

3.119. Hodge, B. K. "Prediction of Hypersonic Laminar Boundary-Layer/Shock-Wave Interactions." AIAA Journal, Vol. 15, pp 903-904, July 1977.

3.120. Hoffman, J. "Accuracy Studies of the Numerical Method of Characteristics for Axisymmectric, Steady Supersonic Flows." J. Comp. Phys., Vol. 11, pp 210-239, 1973.

3.121. Holst, T. L. "Numerical Solution of Axisymmetric Boattail Flow Fields with Plume Simulators." AIAA Paper 77-224, January 1977.

3.122. Horstman, C. C., et. al. "Reynolds Number Effects on Shock-Wave Turbulent Boundary Layer Interactions--A Comparison of Numerical and Experimental Results." AIAA Paper 77-42, January 1977.

3.123. Hung, C. M. and MacCormack, R. W. "Numerical Solutions of Supersonic and Hypersonic Laminar Compression Corner Flows." AIAA Journal, Vol. 14, pp 475-481, April 1976.

3.124. Hung, C. M. and MacCormack, R. W. "Numerical Simulation of Supersonic and Hypersonic Turbulent Compression Corner Flows." AIAA Journal, Vol. 15, pp 410-416, March 1977.

3.125. Hung, T. K. and Brown, T. "An Implicit Finite Difference Method for Solving the Navier Stokes Equations Using Orthogonal Curvilinear Coordinates." J. Comp. Phys., Vol. 23, pp 343-363, 1977.

3.126. Inger, G. R. "Similitude Properties of High-Speed Laminar and Turbulent Boundary-Layer Incipient Separation." AIAA Journal, Vol. 15, pp 619-623, May 1977.

3.127. Issacson, Eugene and Keller, Herbert. Analysis of Numerical Methods. John Wiley & Sons, New York, 1966.

3.128. Israeli, M. "A Fast Implicit Numerical Method for Time-Dependent Viscous Flows." Studies Appl. Math., Vol. XLIX, pp 327-350, 1970.

3.129. Issa, R. I. and Lockwood, E. C. "A Hybrid Marching integration procedure for the prediction of two-dimensional supersonic boundary layers." ASME Trans Ser. I-J of Fluids Engr., Vol. 99, pp 205-212, March 1977.

3.130. Issa, R. I. and Lockwood, F. C. "On the Prediction of 2-D Supersonic Viscous Interaction Near Walls." AIAA Journal, Vol. 15, pp 182-188, February 1977.

3.131. Jacocks, J. L. "Aerodynamic Characteristics of Perforated Walls for Transonic Wind Tunnels." AEDC-TR-77-61, June 1977.

3.132. Jaffe, N. A., Okamura, T. T., and Smith, A. M. O. "Determination of Spatial Amplification Factors and Their Application to Predicting Transition." AIAA Journal, Vol. 8, pp 301-308, 1970.

3.133. Jaikrishnan, K. R., Szeri, A. Z., and Rohrer, W. M. "A Study of Transonic Flows around Spheres." J. Fluid Mech., Vol. 80, pp 17-31, April 1977.

3.134. Jain, A. C. "Numerical Solutions of Navier-Stokes Equations for the Structure of a Trailing Vortex." NASA TM-X-73,361, 1977.

3.135. Jameson, A. "Iterative Solution of Transonic Flows over Airfoils and Wings Including Flows at Mach 1." Commun. Pure & Appl. Math., Vol. 27, pp 283-309, 1974.

3.136. Jameson, A. "Numerical Computation of Transonic Flows with Shock Waves." International Union of Theoretical and Applied Mechanics, Springer Verlag, New York, 1975.

3.137. Jameson, A., et. al. "A Brief Description of the Jameson-Caughey NYU Transonic Swept-Wing Computer Programs--FLO22." NASA TM-X-73996, 1976.

3.138. Jamet, P. and Raviart, P. A. "Numerical Solution of the Stationary Navier-Stokes Equations by Finite Element Methods." Computing Methods in Applied Sciences and Engineering, Part I, Glowinski, R. and Lions, J. L., ed., Lecture Notes in Computer Science, Vol. 10, pp 193-223, Springer-Verlag, New York, 1974.

3.139. Jenson, V. G. "Viscous Flow Round a Sphere at Low Reynolds Number." Proc. Roy. Soc. London, A 249, 1959.

3.140. Joga, T. and Oguchi, H. "Numerical Analysis on Source Expansion Flow into Vacuum." Phys. Fluids, Vol. 15, pp 766-771, 1972.

4.141. John, F. "Formation of Singularities in One Dimensional Nonlinear Wave Propagation." Commun. Pure & Appl. Math., Vol. 27, pp 377-405, 1974.

4.142. John, F. "Delayed Singularity Formation in Solutions of Nonlinear Wave Equations in Higher Dimensions." Commun. Pure & Appl. Math., Vol. 29, pp 649-682, 1976.

3.143. Johnson, F. T. and Rubbert, P. E. "Advanced Panel-Type Influence Coefficient Methods Applied to Subsonic Speeds." AIAA Paper 75-50, January 1975.

3.144. Kalman, T. P., Rodden, W. P., and Giesing, J. P. "Application of the Doublet Lattice Method to Nonplanar Configurations in Subsonic Flow." J. Aircraft, Vol. 8, pp 406-413, 1971.

3.145. Kaups, K. and Cebeci, T. "Prediction of Turbulent Boundary Layers on Cones at Incidence." AIAA Journal, Vol. 15, pp 727-730, May 1977.

3.146. Keller, J. D. and South, J. C., Jr. "RAXBOD: A Fortran Program for Inviscid Transonic Flow over Axisymmetric Bodies." NASA TM-X-72831, 1976.

3.147. Kimble, K. R. "A Finite Element Solution of Unsteady Flow Problems for Three-Dimensional Wings and Bodies." AIAA Paper 76-328, July 1976.

3.148. King, J. T. "New Error Bounds for the Penalty Method and Extrapolation." Numer. Math., Vol. 23, pp 153-166, 1974.

3.149. Klemp, J. B. and Acruos, A. "A Moving-Wall Boundary Layer with Reverse Flow." J. Fluid Mech., Vol. 76, pp 363-382, July 1976.

3.150. Klineberg, J. M. and Steger, J. L. "On Laminar Boundary-Layer Separation." AIAA Paper No. 74-94, January 1974.

3.151. Knops, R. J., ed. Symposium on Non-Well-Posed Problems and Logarithmic Convexity, Springer-Verlag, New York, 1973.

3.152. Kolmogorov, A. N. Compt. Rend. Acad. Sci., VRSS, Vol. 32, p. 16, 1941.

3.153. Korner, H. "The Calculation of Flow Fields by Panel Methods--A Report on Eurmech 75." J. Fluid Mech., Vol. 74, pp 181-189, January 1977.

3.154. Krause, Egon. "Application of Numerical Techniques in Fluid Mechanics." Aeronaut. J. Vol. 78, pp 337-354, August 1974.

3.155. Krause, E., Hirschel, E. H., and Kordulla, W. "Fourth Order 'Mehrstellen'--Integration for Three Dimensional Turbulent Boundary Layers." Computers and Fluids, Vol. 4, pp 79-92, 1976.

3.156. Kreiss, H. and Oliger, J. "Comparison of Accurate Methods for the Integration of Hyperbolic Equations." Tellus, Vol. 24, pp 199-215, 1972.

3.157. Kuhn, G. D. and Nielsen, J. N. "Prediction of Turbulent Separated Boundary Layers." AIAA Paper No. 73-663, July 1973.

3.158. Kupka, I. and Osher, S. "On the Wave Equation in a Multi-Dimensional Corner." Commun. Pure & Appl. Math., Vol. 24, pp 381-393, 1971.

3.159. Lagerstrom, P. "Solutions of the Navier-Stokes Equations at Large Reynolds Number." SIAM J. Appl. Math., Vol. 28, pp 202-214, 1975.

3.160. Lamar, J. E. "Some Recent Applications of the Suction Analogy to Vortex-Lift Estimates." NASA SP 347, pp 985-1012, 1975.

3.161. Lan, C. E. "Some Applications of the Quasi Vortex-Lattice Method in Steady and Unsteady Aerodynamics." NASA SP-405, Paper No. 21, 1976.

3.162. Landrum, E. J. and Townsend, J. C. "Assessment of Existing Analytic Methods for Prediction of High Angle of Attack Loads on Delta Wings at Supersonic Speeds." AGARD CP 204, 1976.

3.163. Laskaris, T. E. "Finite Element Analysis of Compressible and Incompressible Viscous Flow and Heat Transfer Problems." Phys. Fluids, Vol. 18, pp 1639-1648, 1975.

3.164. Launder, B. E. and Spalding, D. B. "The Numerical Computation of Turbulent Flows." Computer Meth. Appl. Mech. and Engr., Vol. 3, pp 269-289, 1974.

3.165. Laurentiev, M. M. "On the Cauchy Problem for the LaPlace Equation." Izvert. Akad. Nauk. SSSR., Vol. 20, pp 819-842, 1956.

3.166. Lax, P. and Wendroff, B. "Systems of Conservation Laws." Comm. Pure & Appl. Math., Vol. 13, pp 217-237, 1960.

3.167. Lax, P. and Wendroff, B. "On the Stability of Difference Schemes." Commun. Pure & Appl. Math., Vol. 15, p 363, 1962.

3.168. Lax, P. and Wendroff, B. "Difference Schemes with High Order of Accuracy." Comm. Pure & Appl. Math., Vol. 17, p 381, 1964.

3.169. Levy, L. L., Jr. "An Experimental and Computational Investigation of the Steady and Unsteady Transonic Flow Field About an Airfoil in a Solid-Wall Test Channel." AIAA Paper 77-678, 1977.

3.170. Li, C. P. "A Mixed Explicit-Implicit Method for the Compressible Navier-Stokes Equations." Proceedings, International Conference on Numerical Methods in Fluid Dynamics, pp 285-292, Springer-Verlag, 1976.

3.171. Lilley, David G. "An Inverse Computational Code for Turbulent Swirling Boundary Layer Flow." Computers and Fluids, Vol. 4, pp 45-58, 1976.

3.172. Loeve, W.. "The Calculation of Aerodynamic Characteristics of Wing-Body Combinations at Subsonic Flight Speeds." Proceedings, International Conference on Numerical Methods in Fluid Dynamics, pp 75-83, Springer Verlag, 1976.

3.173. Lomax, H. "Recent Progress in Numerical Techniques for Flow Simulation." AIAA Journal, Vol. 14, pp 512-518, April 1976.

3.174. Lomax, H. "Turbulence and Numerical Wind Tunnels." Computer Science and Scientific Computing; Proceedings of the Third Conference, pp 127-153, Academic Press, 1976.

3.175. Lugt, H. J. and Ohring, S. "Laminar Flow Behavior Under Slip-Boundary Conditions." Phys. Fluids, Vol. 18, pp 1-8, 1975.

3.176. Lugt, H. J. "Recent Advances in the Numerical Treatment of the Navier-Stokes Equations." Computational Fluid Dynamics, AGARD-LS-86, Ref. 2, April 1977.

3.177. Lumley, J. L. and Takevchi, K. "Application of Central-Limit Theorems to Turbulence and Higher-Order Spectra." J. Fluid Mech., Vol. 74, pp 433-468, 1976.

3.178. Lundgren, T. S. and Wang, F. C. "Eddy Viscosity Models for Free Turbulent Flows." Phys. Fluids, Vol. 16, pp 174-178, 1973.

3.179. MacCormack, R. W. "An Efficient Numerical Method for Solving the Time-Dependent Compressible Navier-Stokes Equations at High Reynolds Number." NASA TMX-73129, 1976.

3.180. Manro, M. E., et. al. "Comparisons of Theoretical and Experimental Pressure Distributions on an Arrow-Wing Configuration at Transonic Speeds." AGARD CP 204, 1976.

3.181. Marchuk, G. I. Methods of Numerical Mathematics. Springer-Verlag, New York, 1975.

3.182. Marconi, F., et. al. "Computation of High-Speed Inviscid Flows about Real Configurations." NASA SP 347, pp 1411-1155, 1975.

3.183. Marconi, Frank; Salas, Manuel; and Yaeger, Larry. "Development of a Computer Code for Calculating the Steady Super/ Hypersonic Inviscid Flow Around Real Configurations." NASA CR-2675, 1976.

3.184. Marino, L. and Chen, L. T. "Indicial Compressible Potential Aerodynamics around Complex Aircraft Configurations." NASA SP 347, pp 1067-1110, 1975.

3.185. Marsden, J. "A Formula for the Solution of the Navier-Stokes Equations Based on a Method of Chorin." Bull. American Math. Soc., Vol. 80, pp 154-158, January 1974.

3.186. Martin, E. D. "A Fast Semidirect Method of Computing Transonic Aerodynamic Flows." AIAA Journal, Vol. 14, pp 914-922, July 1976.

3.187. Marrin, J. G. "Turbulence Modeling for Compressible Flows." NASA TM X-73188, 1977.

3.188. McCroskey, W. J. "Some Current Research in Unsteady Fluid Dynamics/ the 1976 Freeman Scholar Lecture." ASME Transactions, Ser. I: Journal of Fluids Engineering, Vol. 99, pp 8-39, March 1977.

3.189. McDonald, H. and Briley, W. "Three Dimensional Supersonic Flow of a Viscous or Inviscid Gas," J. Comp. Phys., Vol. 19, pp 150-178, 1975.

3.190. McLean, J. Douglas. "Three-Dimensional Turbulent Boundary Layer Calculations for Swept Wings." AIAA Paper No. 77-3, January 1977.

3.191. Mellor, G. L. and Herring, H. J. "Simple Eddy Viscosity Relations for Three-Dimensional Turbulent Boundary Layers." AIAA Journal, Vol. 15, pp 886-887, June 1977.

3.192. Mendenhall, M. R., et. al. "Calculation of the Longitudinal Aerodynamic Characteristics of Wing-Flap Configurations with Externally Blown Flaps." NASA CR-2705, 1976.

3.193. Messiter, A. F. "Boundary Layer Flow Near the Trailing Edge of a Flat Plate." SIAM J. Appl. Math., Vol. 18, pp 241-257, 1970.

3.194. Middleton, W. D. and Lundry, J. "Aerodynamic Design and Analysis for Supersonic Aircraft." NASA CR-2520, 1975.

3.195. Middleton, W. D., et. al. "A Computational System for Aerodynamic Design and Analysis of Supersonic Aircraft." NASA CR 2715, 1976.

3.196. Miner, E. W. and Lewis, C. H. "Hypersonic Ionizing Air Viscous Shock-Layer Flows over Non-analytic Blunt Bodies." NASA CR-2550, 1975.

3.197. Moretti, G. and Bleich, G. "Three Dimensional Flow around Blunt Bodies." AIAA Journal, Vol. 5, pp 1557-1562, September 1967.

3.198. Moretti, G. "Importance of Boundary Conditions in the Numerical Treatment of Hyperbolic Equations." Phys. Fluids, Supp II, pp 13-20, 1969.

3.199. Moretti, Gino. "A Pragmatical Analysis of Discretization Procedures for initial-and-boundary-Value Problems in Gas Dynamics and their Influence on Accuracy - or - Look Ma, No Wiggles!" POLY-AE/AM Report No. 74-15, Polytechnic Institute of New York, September 1974.

3.200. Moretti, G. "Computations of Unsteady Flows: A realistic view of the state-of-the-art and of prospectives for the future." Proceedings, Unsteady Aerodynamics Symposium, University of Arizona, Vol. 2, pp 435-451, 1975.

3.201. Montgomery, D. Lectures in Theoretical Physics. Gordon and Breach, New York, 1967.

3.202. Morgan, H. L. "A Computer Program for the Analysis of Multi-element Airfoils in Two-Dimensional Subsonic, Viscous Flow." NASA SP 347, pp 713-748.

3.203. Murman, E. M., et al. "TSFOIL--A Computer Code for Two-Dimensional Transonic Calculations Including Wind-Tunnel Wall Effects and Wave Drag Evaluation." NASA SP 347, pp 769-788, 1975.

3.204. Murphy, J. D. "An Efficient Numerical Method for Solving the Incompressible Navier-Stokes Equations." AIAA Paper 77-171, January 1977.

3.205. Nardo, C. and Cresci, R. "An Alternating Direction Implicit Scheme for Three Dimensional Hypersonic Flows." J. Comp. Phys., Vol. 8, pp 268-284, 1971.

3.206. Ng, K. H. and Spalding, D. B. "Turbulence Model for Boundary Layers near Walls." Phys. Fluids, Vol. 15, pp 20-30, 1972.

3.207. O'Brien, G. G., et. al. "A Study of the Numerical Solution of Partial Differential Equations." J. Math. Phys., Vol. 29, pp 223-251, 1951.

3.208. Ogana, W. "Numerical Solution for Subcritical Flows by a Transonic Integral Eqn Method." AIAA Journal, Vol. 15, pp 444-446, March 1977.

3.209. Oleinik, O. A. "On the Cauchy Problem for Weakly Hyperbolic Equations." Commun. Pure & Appl. Math., Vol. 23, pp 569-586, 1970.

3.210. Onura, M. and Aoki, T. "A numerical method of transonic flow and its application." Mitsubishi Juko-Giho, Vol. 13, pp 1-9, 1976. (in Japanese)

3.211. Orszag, S. A. "Numerical Simulation of Incompressible Flows within Simple Boundaries, I, Galerkin (Spectral) Representations." Studies Appl. Math., Vol. L, pp 293-328, 1971.

3.212. Orszag, S. and Jayne, L. "Local Errors of Difference Approximations to Hyperbolic Equations." J. Comp. Phys., Vol. 14, pp 93-103, 1974.

3.213. Payne, L. E. "Bounds in the Cauchy Problem for the LaPlace Equation," Arch. Rational Mech. Anal., Vol. 5, pp 35-45, 1960.

3.214. Payne, L. E. "Some General Remarks on Improperly Posed Problems for Partial Differential Equations," Lecture Notes in Mathematics, No. 316, Springer-Verlag, New York, 1973.

3.215. Peaceman, D. W. and Rachford, H. H., Jr. "The Numerical Solution of Parabolic and Elliptic Differential Equations." SIAM Journal, Vol. 3, 1955.

3.216. Peyret, R. and Viviand, H. "Computations of Viscous Compressible Flows Based on the Navier-Stokes Equations." AGARD AG-212, 1975.

3.217. Popinski, Z. and Baker, A. J. "An Implicit Finite-Element Algorithm for the Boundary Layer Equations." J. Comp. Phys., Vol. 21, pp 55-84, 1976.

3.218. Pracht, W. E. and Brachbill, J. U. "BAAL: A Code for Calculating Three-Dimensional Fluid Flows at All Speeds with An Eulerian-Langrangian Computing Mesh." Los Alamos Scientific Lab LA-6342, 1976.

3.219. "Reviews in Viscous Flow." Proceedings of the Lockheed-Georgia Company Viscous Flow Symposium, June 1976.

3.220. Reyhner, T. A. "Cartesian Mesh Solution for Axisymmetric Transonic Potential Flow Around Inlets." AIAA Journal, Vol. 15, pp 624-631, May 1977.

3.221. Reyhner, T. A. "Transonic Potential Flow Around Axisymmetric Inlets and Bodies at Angle of Attack." AIAA Paper 77-145, January 1977.

3.222. Reynolds, W. C. "Computation of Turbulent Flows." Annual Review of Fluid Mechanics, Vol. 8, pp 183-208, 1976.

3.223. Richtmyer, R. D. and Morton, K. W. Difference Methods for Initial Value Problems, Interscience Publishers, New York, 1967.

3.224. Rimon, Y. and Cheng, S. I. "Numerical Solution of a Uniform Flow over a Sphere at Intermediate Reynolds Numbers." Phys. Fluids, Vol. 12, pp 949-959, May 1969.

3.225. Roache, P. Computational Fluid Dynamics, Hermosa, 1972.

3.226. Rodden, W. P. "State-of-the-Art in Unsteady Aerodynamics." AGARD R-650, 1976.

3.227. Rogallo, R. S. "An ILLIAC Program for the Numerical Simulation of Homogeneous Incompressible Turbulence." NASA TMX 73203, 1977.

3.228. Rom, J. "Flows with Strong Interaction Between the Viscous and Inviscid Regions." SIAM J. Appl. Math., Vol. 29, pp 309-328, 1975.

3.229. Roscoe, D. F. "The Solution of the Three-Dimensional Navier-Stokes Equations Using a New Finite Difference Approach." International J. Numer. Meth. Engr., Vol. 10, pp 1299-1308, 1976.

3.230. Rosen, G. "Navier-Stokes Initial Value Problem for Boundary-Free Incompressible Fluid Flow." Phys. Fluids, Vol. 12, pp 2891-2903, 1970.

3.231. Rosen, J. B. "Approximate Solutions and Error Bounds for Quasi-linear Elliptic Boundary Value Problems." SIAM J. Numer. Anal., Vol. 7, pp 81-104, 1970.

3.232. Ross, B. B. and Cheng, S. I. "A Numerical Solution of the Planar Supersonic Near Wake with its Error Analysis." Proceedings, Second International Conference on Numerical Methods in Fluid Dynamics, Berkeley, California, September 1970.

3.233. Rubbert, P. E. and Saaris, G. R. "Review and Evaluation of a Three-Dimensional Lifting Potential Flow Analysis Method for Arbitrary Configurations." AIAA Paper 72-188, January 1972.

3.234. Rubesin, Morris W. "A One-Equation Model of Turbulence for use with the Compressible Navier-Stokes Equations." NASA TM X-73128, 1976.

3.235. Rubesin, M. W. "Numerical Turbulence Modeling." Computational Fluid Dynamics, AGARD-LS-86, Ref. 3, April 1977.

3.236. Rubin, S. G. and Graves, R. A., Jr. "Viscous Flow Solutions with a Cubic Spline Approximation." Computers and Fluids, Vol. 3, pp 1-36, 1975.

3.237. Rusanov, V. V. "Advanced Techniques for Computation of Supersonic Flow." AIAA Paper 77-173, January 1977.

3.238. Sachdev, P. "Some Exact Solutions of Burgers-Type Equations." Quart. Appl. Math., Vol. 34, pp 118-122, 1976.

3.239. Saffman, P. G. "Model Equations for Turbulent Shear Flow." Studies Appl. Math., Vol. LIII, pp 17-34, 1974.

3.240. Sakurai, A. "A new finite difference scheme with explicit-implicit property for the calculation of the compressible Navier-Stokes equations." Japan Soc. for Aeronautical and Space Science, Transactions, Vol. 19, pp 126-139, September 1976.

3.241. Sameh, A. H., Chen, S. C., and Kuck, D. J. "Parallel Poisson and Biharmonic Solvers." Computing, Vol. 17, pp 219-230, 1976.

3.242. Schmidt, et. al. "Numerical Simulation of Three-Dimensional Transonic Flow Including Wind Tunnel Wall Effects." AGARD CP 210, 1976.

3.243. Schumann, V. "Subgrid Scale Model for Finite Difference Simulations of Turbulent Flows in Plane Channels and Annuli." J. Comp. Phys., Vol. 18, pp 376-404, 1975.

3.244. Schumann, V. "Realizability of Reynolds-Stress Turbulence Models." Phys. Fluids, Vol. 20, pp 721-725, 1977.

3.245. Scrugs, R. M. et al. "Vortex/Jet/Wing Interaction by Viscous Numerical Analysis." AGARD CP 204, 1976.

3.246. Sears, W. R. and Telionis, D. P. "Boundary Layer Separation in Unsteady Flow." SIAM J. Appl. Math., Vol. 28, pp 215-235, 1975.

3.247. Shang, J. S. and Hankey, W. L., Jr. "Numerical Solutions for Supersonic Turbulent Flow over a Compression Ramp." AIAA Journal, Vol. 13, pp 1368-1374, October 1975.

3.248. Shang, J. S. and Hankey, W. L., Jr. "Numerical Solution of the Compressible Navier-Stokes Equations for a Three-Dimensional Corner." AIAA Paper 77-169, January 1977.

3.249. Shapiro, V. L. "Isolated Singularities for Solutions of the Nonlinear Stationary Navier-Stokes Equations." Trans. American Math. Soc., Vol. 187, pp 335-364, 1974.

3.250. Shapiro, V. L. "Generalized and Classical Solutions of the Nonlinear Stationary Navier-Stokes Equations." Trans. American Math. Soc., Vol. 216, pp 61-79, 1976.

3.251. Slooff, J. W. "Wind Tunnel Tests and Aerodynamic Computations; Thoughts on Their Use in Aerodynamic Design." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 11, June 1976.

3.252. Smith, A. M. O. and Cebeci, T. "Remarks on Methods for Predicting Viscous Drag." AGARD Conference on Aerodynamic Drag, AGARD-CP-124, Ref. 7, October 1973.

3.253. Smith, A. M. O. "High-Lift Aerodynamics." J. Aircraft, Vol. 12, pp 501-530, 1975.

3.254. Smith, G. D. Numerical Solution of Partial Differential Equations. Oxford University Press, New York, 1965.

3.255. Smoller, J. and Conley, C. "Shock Waves as Limits of Progressive Wave Solutions of Higher Order Equations, I." Commun. Pure & Appl. Math., Vol. 24, pp 459-472, 1971.

3.256. Smoller, J. and Conley, C. "Shock Waves as Limits of Progressive Wave Solutions of Higher Order Equations, II." Commun. Pure & Appl. Math., Vol. 25, pp 133-146, 1972.

3.257. Smoller, J. A. and Taylor, M. E. "Wave Front Sets and the Viscosity Method." Bull. American Math. Soc., Vol. 79, pp 431-436, 1973.

3.258. Solomon, J. M., et. al. "Three-Dimensional Supersonic Inviscid Flow Field Calculations on Re-entry Vehicles with Control Surfaces." AIAA Paper 77-84, January 1977.

3.259. Srinivas, K., Gururaja, J., and Prasad, K. "An Assessment of the Quality of Selected Finite Difference Schemes for Time-Dependent Compressible Flows." J. Comp. Phys., Vol. 20, pp 140-159, 1976.

3.260. Steger, J. L. and Kutler, P. "Implicit Finite Difference Procedure for the Computation of Vortex Wakes." AIAA Journal, Vol. 15, pp 581-590, April 1977.

3.261. Stewartson, K. "On the Asymptotic Theory of Separated and Unseparated Fluid Motions." SIAM J. Appl. Math., Vol. 28, pp 501-519, 1975.

3.262. Stollery, J. L. "Supersonic Turbulent Boundary Layers: Some Comparisons Between Experiment and Theory." Aeronaut. Quart., Vol. 27, pp 87-98, May 1976.

3.263. Strang, W. G. "Accurate Partial Difference Methods II: Nonlinear Problems." Numer. Math., Vol. 6, p 37, 1964.

3.264. Strang, Gilbert and Fix, George J. An Analysis of the Finite Element Method, Prentice Hall, Englewood Cliffs, NJ, 1973.

3.265. Summa, J. M. "A Numerical Method for the Exact Calculation of Airloads Associated with Impulsively Started Wings." AIAA Paper 77-2, January 1977.

3.266. Swartz, B. and Wendroff, B. "The Relative Efficiency of Finite Difference and Finite Element Methods, I: Hyperbolic Problems and Splines." SIAM J. Numer. Anal., Vol. 11, pp 979-993, 1974.

3.267. Swartz, B. and Wendroff, B. "The Relation Between the Galerkin and Collocation Methods Using Smooth Splines." SIAM J. Numer. Anal., Vol. 11, pp 994-996, 1974.

3.268. Tam, K. K. "On the Asymptotic Solution of Viscous Incompressible Flow Past a Heated Parabloid of Revolution." SIAM J. Appl. Math., Vol. 20, pp 714-721, 1971.

3.269. Tannehill, J. C., Holst, T. L., Rakiel, J. V., and Keys, J. W. "Comparison of a Two-Dimensional Shock Impingement Computation with Experiment." AIAA Journal, Vol. 14, pp 539-540, April 1976.

3.270. Taylor, P. "The Linear Stability of No-Slip Boundary Conditions in the Numerical Solution of Nonsteady Fluid Flows." J. Comp. Phys., Vol. 6, pp 268-287, 1970.

3.271. Taylor, T. D. "Numerical Methods for Predicting Subsonic, Transonic, and Supersonic Flow." AGARDograph No. 187, January 1974.

3.272. Tellonis, D. P. and Tsahalis, D. Th. "Unsteady Turbulent Boundary Layers and Separation." AIAA Journal, Vol. 14, pp 468-473, April 1976.

3.273. Temam, R. On the Theory and Numerical Analysis of the Navier-Stokes Equations. Lecture Notes No. 9, University of Maryland, 1973.

3.274. Temam, R. Navier-Stokes Equations--Theory and Numerical Analysis. North Holland Publishing Company, Amsterdam, 1977.

3.275. Thiede, P. G. "Prediction Method for Steady Aerodynamic Loading on Airfoils with Separated Transonic Flow." AGARD CP 204, 1976.

3.276. Thompkins, W. T., Jr. and Epstein, A. H. "A Comparison of the Computed and Experimental Three-Dimensional Flow in a Transonic Compressor Rotor." AIAA Paper 76-368, July 1976.

3.277. Thompson, P. Numerical Weather Analysis and Prediction, Macmillan, New York, 1961.

3.278. Thompson, R. C. "Convergence and Error Estimates for the Method of Lines for Certain Nonlinear Elliptic and Elliptic-Parabolic Equations." SIAM J. Numer. Anal., Vol. 13, pp 27-43, 1975.

3.279. Trapp, J. and Ramshaw, J. "A Simple Herusitic Method for Analyzing the Effect of Boundary Conditions on Numerical Stability." J. Comp. Phys., Vol. 20, pp 238-242, 1976.

3.280. Trulio, J. G. and Yeung, H. N. "Iterative Solution of the Equations for Steady Viscous Compressible Flow, Based on Similitude." ARL-TR-74-0138, November 1974.

3.281. Tsahalis, Demos T. "Laminar Boundary Layer Separation from an Upstream-Moving Wall." AIAA Journal, Vol. 15, pp 561-566, April 1977.

3.282. Tsugé, S. and Sagara, K. "Kinetic Theory of Turbulent Compressible Flows and Comparison with Classical Theory." Phys. Fluids, Vol. 19, pp 1478-1485, 1976.

3.283. Vanderplatts, G. N., Hicks, R. N., and Murman, E. M. "Application of Numerical Optimization Techniques to Airfoil Design." NASA SP 347, pp 749-768, 1975.

3.284. VanDyke, M. "Are There Better Ways to Use the Computer?--A Look At Semi-Analytical Schemes." Proc. AIAA 2nd Computational Fluid Dynamics Conference, Hartford, Conn., p 101, 1975.

3.285. Van Dyke, M. "Computer Extension of Perturbation Series in Fluid Mechanics." SIAM J. Appl. Math., Vol. 28, pp 720-734, May 1975.

3.286. VanLeer, B. "Towards the Ultimate Conservative Difference Scheme III, Upstream-Centered Finite Schemes for Ideal Compressible Flow." J. Comp. Phys., Vol. 23, pp 263-275, 1977.

3.287. Viegas, J. R. and Coakley, T. J. "Numerical Investigation of Turbulence Models for Shock Separated Boundary Layer Flow." AIAA Paper 77-44, January 1977.

3.288. von Neumann, J. and Richtmyer, R. D. "A Method for the Numerical Calculation of Hydromatic Shocks." J. Appl. Physics, Vol. 21, pp 232-237, March 1950.

3.289. Wang, K. C. "Numerical Solution of Three-Dimensional Boundary Layer Equations." MML TR 76-14c, Martin Marietta, February 1976.

3.290. Wang, K. C. "Computation of Three-Dimensional Aerodynamic Flow." AFOSR-TR-76-1115, August 1976.

3.291. Weber, J. A., et. al. "A Three-Dimensional Solution of Flows over Wings with Leading Edge Vortex Separation." NASA SP 347, pp 1013-1034, 1975.

3.292. Weinberger, H. F. "On Optimal Numerical Solution of Partial Differential Equations." SIAM J. Numer. Anal., Vol. 9, pp 182-198, 1972.

3.293. Werle, M. J., Dwoyer, D. L. and Hankey, W. L. "Initial Conditions for the Hypersonic Shock/Boundary Layer Interaction Problem." AIAA Journal, Vol. 11, pp 525-530, April 1973.

3.294. Werle, M. J. and Batsa, V. N. "New Method for Supersonic Boundary Layer Separations, AIAA Journal, Vol. 12, pp 1491-1497, November 1974.

3.295. White, J. "A New Form of Artificial Viscosity." J. Comp. Phys., Vol. 11, pp 573-590, 1973.

3.296. Wilcox, D. C. and Chambers, T. L. "Numerical Simulation of Nosetip Transition: Model Refinement and Validation." AFOSR-TR-76-1112, July 1976.

3.297. Wirz, H. J. "Relaxation Methods for Time-Dependent Conservation Equations in Fluid Mechanics." Computational Fluid Dynamics, AGARD-LS-86, Ref. 4, April 1977.

3.298. Woodward, Frank A. "Analysis and Design of Wing-Body Combinations at Subsonic and Supersonic Speeds." J. Aircraft, Vol. 5, pp 528-534, 1968.

3.299. Woodward, F. A. "An Improved Method for the Aerodynamic Analysis of Wing-Body-Tail Configurations in Subsonic and Supersonic Flow." NASA CR-2228, 1973.

3.300. Wu, J. C. "Numerical Boundary Conditions for Viscous Flow Problems." AIAA Journal, Vol. 14, pp 1042-1049, August 1976.

3.301. Yanenko, N. N. The Method of Fractional Steps. (English translation by M. Holt) Springer-Verlag, New York, 1971.

3.302. Yoshihara, H. "Fixes to the 3d Transonic Small Disturbance Theory." CASD-ERR-75-012, General Dynamics/Convair Division, 1975.

3.303. Young, D. M. "Convergence Properties of the Symmetric and Unsymmetric SOR Methods and Related Methods." Math. Comp., Vol. 24, pp 793-808, 1970.

4.0 COMPUTER SYSTEMS AND AERODYNAMICS

4.1 Computer Systems Panel Perspective

The computer systems panel has viewed itself as a service organization, addressing the needs of both the experimentalist and the computational fluid dynamicist. Through the years, the computer needs of these specialists have been evolving even as the ability of the computers to assist them was changing. There seem to be three natural time divisions in computer development: the pre-computer era, before 1950, the early computer era, 1950-1965, and the modern era, 1965 to the present. Figure 4.1 shows the advances made in computational speed over the years.

4.1.1 Historical Overview

In the era before the advent of the electronic digital computer (that is, before the early 1950's), the two branches of aerodynamics were virtually independent. Beginning with the Wright brothers, the wind tunnel was used to help in aircraft design. From that time, both wind tunnels and airplanes grew in size and complexity, given a healthy push by World War II.

Computational fluid dynamics, on the other hand, was much more of a theoretical discipline, having little impact on the production of aircraft. Almost immediately, it was discovered that numerical methods were needed to solve the problems in this field, and larger and larger amounts of arithmetic were needed to approximate a solution. Even with the boundary-layer assumption, the problems were long and tedious.

During the period of the 1950's to the middle 1960's, the early computer era, many significant advances in aerodynamics and related areas were made. In the computer field itself, technology was exploding. The vacuum tube gave way to the transistor and solid state circuitry. This meant great reductions in size and power requirements, allowing the development of faster computers with larger memories.

Integrated circuits were on the horizon and promising even faster speeds and even larger memories. The development of Fortran and other high-level languages made the computer usable to the scientific community.

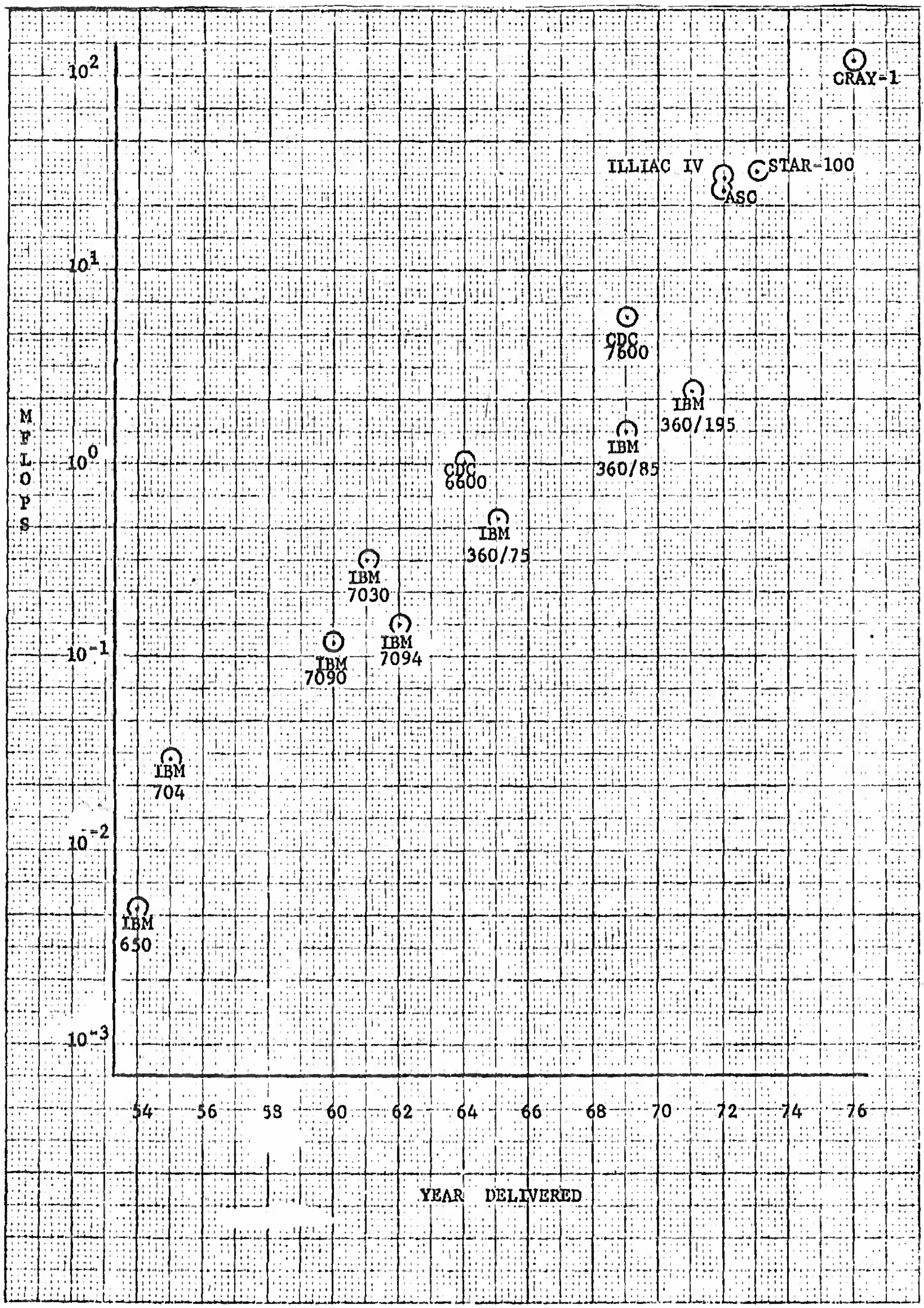


Fig. 4.1 Computer Speed Trends

Now one did not have to study the computer for years to be able to use it. The computer become ubiquitous as academies and industry embraced this tool. The question changed from, "Is a computer available?" to "What computer is available?"

The computational aerodynamicist quickly began to use this powerful tool. A new era seemed to be arriving as he could now solve his problems in days or hours instead of weeks or months, and he could now be a part of the design process. However, this science and this tool were both new, and the inevitable setbacks began. As is frequently the case, in the rush to solve problems a number of critical assumptions were made, not all of which were justified. Moreover, as aircraft speed regimes widen, some previously justifiable assumptions were no longer valid.

As a result of computational difficulties, wind tunnels remained almost totally dominant in the field. Their use and growth continued. As aircraft manufacturers needed better data they pushed the wind tunnels for more accuracy and more data. As the amount of design data from the wind tunnels increased, it was only natural that the computer should be used to collect and store it.

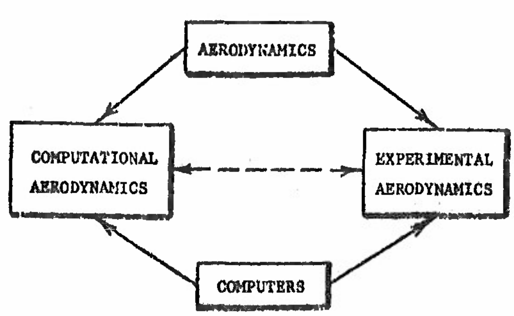
Since the middle 1960's computers have continued to improve. Discrete logic has given way to integrated circuits; however, there is some belief that standard computer technology is pushing against some inherent limitations, such as the speed of light. Most of the recent progress, however, has come not from technological advances, but from architectural innovations. If a job can be divided equally between five different machines, then that configuration should do the job five times faster than one machine. For example, if at one point five multiplications are required, one could give each machine one of the multiplications. This method could be used with ten machines to get ten times the speed; unfortunately, it is rarely that simple. This process of paralleling or vectorizing problems is nontrivial. How does the machine know when five different multiplications can be done at once? Moreover, there are times when the operations must be done serially (that is, one at a time).

Two other problems present themselves. First, a high-level language is needed which can be used efficiently with these machines and also by the FORTRAN user. Much remains to be done in this area. Second is the problem of component failure. As complex as these machines are, a way must be found to reduce the impact of inevitable part failures.

In this period, computational fluid dynamics has made steady progress. Codes have been developed for inviscid flow both in two-dimensions and to a large extent in three-dimensions which seem to be quite functional. The codes are finding their way into the design process and are fairly well accepted. Other than the boundary layer, viscous flow remains a serious problem. Many experts believe that separated and turbulent flow problems cannot be handled on present-day computers, and some now call for a machine to handle the time-averaged Navier-Stokes equations.

Wind tunnels decreased in number during this period as their cost of operation mounted rapidly. In those tunnels remaining, however, computers are being used to increase productivity. They are used both for data gathering and management systems and for control purposes. Some comparison of the data produced with the data expected is being done and used to make test decisions. By and large, however, the use of computers with wind tunnels is just beginning.

The Computer Systems Panel feels that computers, wind tunnels, and computational aerodynamics relate as shown in the diagram. The hope is to use the computer to make the interface indicated by the dotted line a more substantial link.



4.1.2 Investigation of the Problems

This panel started with several broad objectives. The first was to determine the current status of both the experimental and the computational aerodynamic methods, as well as the status of computer systems. The panel would then identify areas for computer-aided improvements and recommend directions for research and development.

The methods used to pursue these objectives were varied. Specialists in the appropriate fields were brought in to give lectures to the entire study group. These included experimentalists, computational aerodynamicists, numerical analysts, and computer scientists. Their backgrounds and affiliations varied; i.e., Arnold Engineering Development Center, other government installations, academia, and private industry. The computer systems area included representatives of major computer companies, including IBM, CDC, CRAY, and others, as well as computer specialists from the University of Illinois at Urbana, the Institute for Advanced Computation at NASA/Ames, and others. The proposal for a computational aerodynamics computer at NASA/Ames was presented by representatives of that facility as well as by the contractors for the preliminary stage. All speakers met with individual panels for more detailed talks and question and answer sessions.

The panel made use of its proximity to the test facilities at Arnold Center, making several trips there for observation.

During all of these activities, a literature search was under way by the panel. This included computerized key work searches conducted through the facilities of both NASA and Georgia Tech, as well as a more traditional search of periodicals and books. This search was expanded to include use of the facilities at the Redstone Scientific Information Center in Huntsville, Alabama.

Similar activities were undertaken by both other panels, each concentrating on their respective areas, and intra-panel discussion proved very helpful. All this information was shared by the four computer panel members, and a constant interchange of ideas among the panel sharpened these concepts. The panel began the study with diverse backgrounds, but there developed a large common area for discussion, ideas, and conclusions.

4.2 COMPUTERS AND EXPERIMENTAL AERODYNAMICS

4.2.1 Collection, Reduction, and Display of Wind Tunnel Data

It is not unrealistic to view the wind tunnel as a generator of aerodynamic data. This viewpoint serves to accentuate the data system concepts associated with the acquisition and processing of wind tunnel data. The paragraphs which follow will discuss the role of computers and associated data handling systems within the wind tunnel environment. Areas will be discussed where improvements can be made and the conclusions and recommendations of the Computer System Panel will be noted.

4.2.1.1 Wind Tunnel Data Systems

An operating wind tunnel is capable of generating large quantities of raw data in a very short period of time. Figure 4.2 illustrates the various sources of data and the types of data associated with a wind tunnel facility and also indicates data management functions which must be accomplished during tunnel operation. The data types and computer functions indicated by the figure will vary depending upon the particular wind tunnel being examined. A highly instrumented tunnel will include all of the features listed; and, as a rule, when more sophistication is built into a facility, the data rates associated with their operation become greater. For example, data systems required to support adaptive wall features or laser velocimeter systems must be quite powerful.

An inefficient data acquisition/processing system generally requires longer-than-necessary tunnel testing. Recent cost trends of computer systems capable of supporting wind tunnel data systems (a cost which is steadily decreasing), and electric energy required for tunnel operation (a cost which is dramatically increasing), have combined to generate a strong economic inducement to increase wind tunnel efficiency through the incorporation of advanced data acquisition/processing systems into wind tunnels (Ref. 4.70).

The use of computer-based systems in the wind tunnel environment has produced beneficial effects above and beyond the reduction of cost

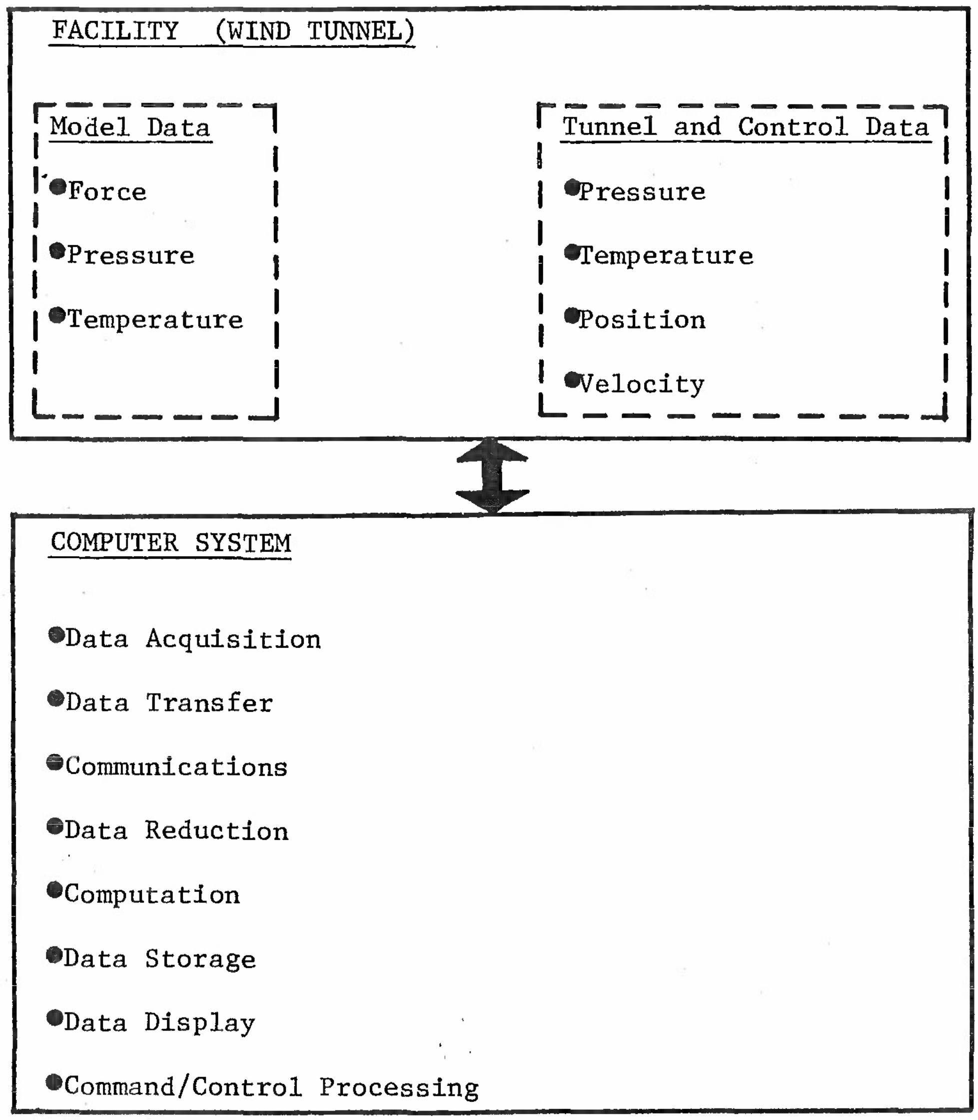


FIG. 4.2 Wind Tunnel and Computer System Functions

per data point. Such a system can enhance the overall operation of the wind tunnel. The on-line display of test data in engineering units quickly informs the operator of test status, and if appropriate controls exist, allows for rapid adjustment of tunnel conditions when required. Calibration procedures are enhanced by the use of computer-aided systems. These systems can also facilitate automatic out-of-tolerance alarms and safety shutdown capability (Ref. 4.117). Graphic display systems can present data in a visual format which is easily understood and produce hard copy output for permanent documentation. The development of more sophisticated graphics systems, including interactive features when appropriate, is an area where significant progress could be achieved in wind tunnel testing facilities.

4.2.1.2 Assessment of Data Systems for Wind Tunnels

A number of automated data systems have been integrated into wind tunnel facilities. Perhaps the most noticeable feature of this group of systems is the variety of schemes used. An economical system utilized at the Unsteady Aerodynamics Laboratory of the National Aeronautical Establishment (Canada) utilizes a programmable calculator to perform offline processing of data. The data are collected by a special purpose acquisition system during the test; they are then processed during the pumping period required by this blowdown tunnel (Ref. 4.72). The other end of the spectrum includes a distributed processing system which is comprised of a network of minicomputers. Each computer is dedicated to the acquisition, preliminary processing, and display of data associated with a particular tunnel subsystem, (e.g., six-component balance, pressure measurement system, etc.). The action of these front-end processors can be directed and coordinated by a supervisory computer. These systems possess the capability of executing fully automatic tests directed entirely by the supervisory computer (Refs. 4.73 and 4.123).

A centralized system, based on a single central computer has been incorporated into the four-foot transonic tunnel at the Arnold Engineering Development Center. This system monitors and displays tunnel status and will also allow for automatic control of tests. It has been estimated that the computer-driven displays in this system have increased the tunnel productivity by 7 to 10 percent (Ref. 4.70). Boeing Aerospace Company has developed a modular, standardized data and control system concept which allows a number of specialized systems to be derived from one fully configured, hypothetical system. This approach promises considerable cost savings through the use of standardization techniques (Ref. 4.117).

A wide variety of techniques are currently being used to accomplish the data management functions in support of wind tunnel facilities. The more sophisticated applications involve on-line data reduction and display using CRT terminals. The desirability of advanced data handling capabilities is well recognized by the experimental community and the impetus to make greater strides toward optimum use of data management techniques will probably be provided by economic pressures.

4.2.1.3 Improved Wind Tunnel Data Systems

An overview of current practice in wind tunnel data systems indicates that computers have had significant beneficial impact in many areas. Furthermore, existing digital systems technology is capable of meeting demands made by highly sophisticated data management systems which support wind tunnel testing. With very few exceptions, data system requirements established for wind tunnel facilities can be met by off-the-shelf equipment which is both proven and reliable. Indeed, many tunnel facilities are making innovations in this area and usually lack only the monetary means to accomplish further advancements. The following paragraphs will discuss the principal areas of data systems technology as they relate to wind tunnel applications. Figure 4.3 shows a general computer system configuration and the discussion will reference the different subsystems indicated.

The use of distributed minicomputers to perform pre-processing functions is already being exploited. A minicomputer which is dedicated in a local manner and which can perform certain mundane processing functions can relieve the central computer of overly complex software and processing

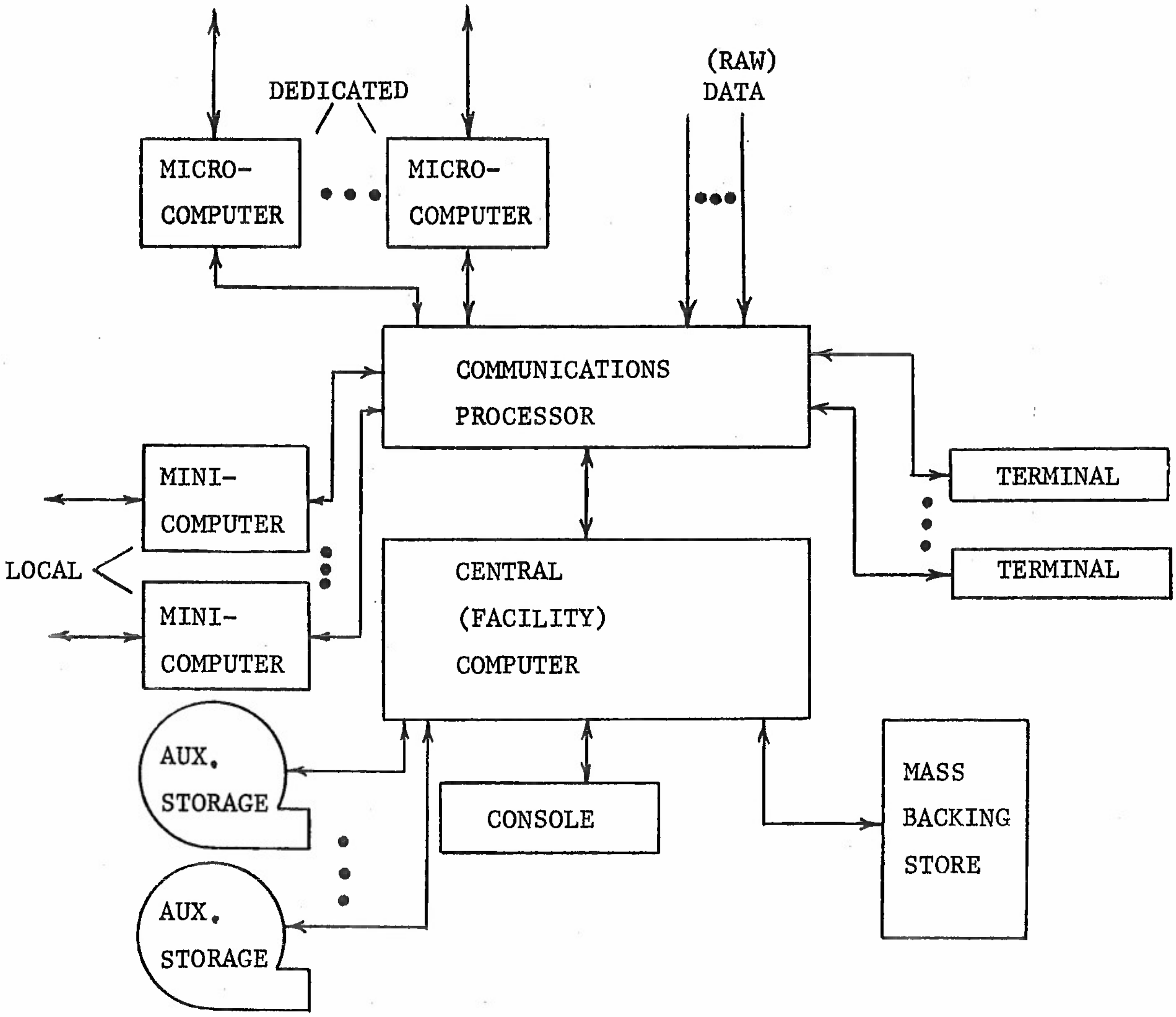


Fig. 4.3 General Computer Support System

requirements. Functions such as data verification, data reduction, data conversion and formatting, generation of control commands, etc., are likely data management tasks which could be handled by a local processor.

Microprocessors should yield another useful level to the distributed processing hierarchy which is rapidly developing in process control areas. Microcomputer systems could be applied in a dedicated fashion in support of individual wind tunnel instruments. Individual microprocessor elements could probably find useful applications within specialized wind tunnel measurement devices. Because of the flexibility inherent in the microprocessing concept, certain instruments which previously could perform only a very narrow range of functions may be applied to a wider range of applications. The possibility of the development of "smart" instruments could prove very cost-effective.

The application of interactive terminals within wind tunnel data systems offers tremendous potential for more productive testing models. The section which follows, 4.2.2, will discuss computer control of wind tunnels, and the interactive terminal is an important component of the control system. In addition, the graphics terminal offers great benefits in on-line, real-time monitoring of test results. Technology breakthroughs in recent years have made "smart" terminals available, as well as introduced floppy disks for local storage, color CRT's, and very sophisticated graphics software and hardware features. These features can be extremely useful in an off-line mode to enhance data analysis techniques. The development of custom graphics software could be very beneficial.

The communications processor shown in Figure 4.3 would relieve the central computer of the many communications tasks which are required in a system having a large number of distributed elements. Depending upon the magnitude of the communications processing task, a minicomputer or medium-scale computer might be used. Because of the tremendous popularity of terminal installations, there are many very efficient processors available from various manufacturers.

The mass storage or backing store indicated in the figure represents a reasonably fast storage medium to be used when large amounts of data must be accessed at a rate which does not seriously degrade processing speed. The present most popular technology is disk storage; however, a breakthrough in charge-coupled devices (CCD's) on magnetic bubble memories could change this situation to provide significant improvements in speed and size for this type of memory.

The auxiliary storage generally used for most current applications is magnetic tape. This technology is not likely to change in the near future, or next five years. The use of magnetic tape for purposes of archival storage is adequate in most cases; however, the volume of data which is sometimes encountered in production wind tunnel facilities taxes even tape storage capabilities.

The central computer acts as the data system nerve center and exercises overall control of processing functions. This computer must be selected carefully so as to meet all data system requirements and remain adaptable to any new requirements which could be placed on it. The processing capability required of this computer will depend on the particular installation, the extent of distributed processing which is used, and the overall data system organization.

The application of computerized data management systems to wind tunnel data acquisition/display/reduction tasks has produced impressive results. Effective systems are being designed and implemented through the use of presently available digital technology. Wind tunnel data systems do not require advancements of the state-of-the-art of digital systems technology.

Some simplified computational models can be executed in a real-time, interactive mode in conjunction with a wind simulation. However, advancements in computer technology and computational models are necessary before testing schemes involving more complex models can be considered.

The natrual evolution of computer systems is producing many new devices and techniques (e.g., color graphics and interactive terminals) which further enhance data processing systems. Considering the demonstrated abilities of relatively inexpensive computer systems to increase the productivity and efficiency of wind tunnels, the investigation and application of advanced digital technology should be strongly encouraged.

4.2.2 Computer Control of Wind Tunnels

4.2.2.1 Wind Tunnel Control Systems

The necessity for replacement of manual controls with automatic controls, whenever possible, within wind tunnel facilities is quite apparent. The advantages gained by automatic control systems in the areas of operational speed, accuracy, efficiency, and elimination of human factors represent significant savings in time and money. It should be noted that efficiency is intended to include the generation of meaningful data, not merely the gross production of more data.

The argument which can be made for the implementation of computer control systems for wind tunnels can be quite convincing in terms of the operational and monetary savings to be gained. However, the costs of implementation must be given careful consideration. These costs can take many forms, and the list given below outlines certain possible disadvantages inherent in automatic control schemes.

1. The basic dollar cost of automatic control systems is quite high, especially when relatively fast reponse times are critical.
2. In the modification of an existing wind tunnel, the cost of the control system implementation can be a significant fraction of the original cost of the entire facility. Such modifications are sometimes extremely difficult to justify, despite the advantages which can be attained.
3. There is a danger in excessive automation in a wind tunnel. That is, the facility becomes so complex that advantages gained by control systems are outweighed by operational and maintenance problems. This danger is especially evident in modifications to existing wind tunnels.
4. Another danger associated with excessive automation is that the users of a production wind tunnel can become frustrated when faced with an overly difficult task in familarizing themselves with the wind tunnel.
5. Control system reliability must be very high. Savings in efficiency attributable to automatic control of tunnel operations can easily be erased when tests must be repeated because of equipment malfunctions.

Looking at the benefits which can be reaped from a more extensive application of computer control to wind tunnel facilities, the following list is somewhat self-evident but worth documenting:

1. Computer-based control features offer significant cost savings. The savings can often far outweigh the cost of implementation, especially in the face of spiralling energy costs.

2. Automated control functions offer greater precision for tunnel operations and also the opportunity for recording pertinent tunnel data for verification purposes.

3. Automatic control of wind tunnel functions can have a number of indirect benefits; for instance, operational improvements can result when manual operation can be eliminated, or certain safety features can be built in to eliminate possibility of certain operator errors.

4. The availability of automated tunnel controls, especially model control, offer the test engineer the opportunity to construct more sophisticated (or more efficient) wind tunnel test sequences.

5. Automated control functions form the foundation for more work in the development of interactive test sequences. This concept could have a profound effect on the efficiency levels which can be reached by wind tunnel test facilities.

The potential advantages in the adoption of automatic control functions within wind tunnel facilities are tremendous. Care must be taken, however, to see that control functions are carefully planned, control hardware is highly reliable, and control systems are carefully documented to assist users. If these three criteria are met, the question regarding tunnel control automation becomes simply a study of cost effectiveness. The automation of tunnel control functions can be evaluated on its merits relative to accuracy, usefulness, and efficiency versus dollar costs.

The most important control parameters for wind tunnels are those which affect tunnel efficiency and accuracy. Efficiency is critical from the standpoint that tunnel expenses (energy, operation, and maintenance) are literally putting many wind tunnels out of business. The accuracy parameter becomes more and more important as the expense of acquiring data points grow.

4.2.2.2 Assessment of Computer Control Systems

A number of very successful automation schemes have been built into production wind tunnels (for example, the Tunnel 4T Real-Time Control and Display System at AEDC described in Ref. 4.70). Other implementations are being planned, such as the control functions to be built into the National Transonic Facility (NTF) at Langley Research Center (Ref. 4.69). The different types of wind tunnel control systems which have been implemented by individual tunnel facilities are shown below.

TUNNEL CONTROLS	MODEL CONTROLS
Hydraulic & Pneumatic System	Programmed Position Control
Wall Angle Control	Adaptive Scanivalve Control
Nozzle Control	Vehicle Trim System
Temperature Control	Propellant Supply System
Flow-Field Probing	Fuel System
Scanivalve Control	Captive Trajectory System
Vacuum System	Captive Aircraft Departure System
Stagnation Pressure Control	Model Support System
Plenum Evacuation System	
Variable Wall Porosity	
Ejector Flaps Control	
Atmospheric Dryer System	

The controls listed above are proven systems used either in a research or a production mode, and the implementation involves the type of system shown in Fig. 4.4. The data acquisition/control computer performs two functions: (1) acquisition and storage of data from various transducers and associated instrumentation, including A/D converters, and (2) broadcast of the appropriate measured and reference data for subtraction by a comparator. The comparators supply error signals to associated D/A converters, and the analog error signals act as inputs to electro-mechanical drive systems.

The basic control system described above is a deceptively simple concept. In practice, a myriad of design questions must be properly

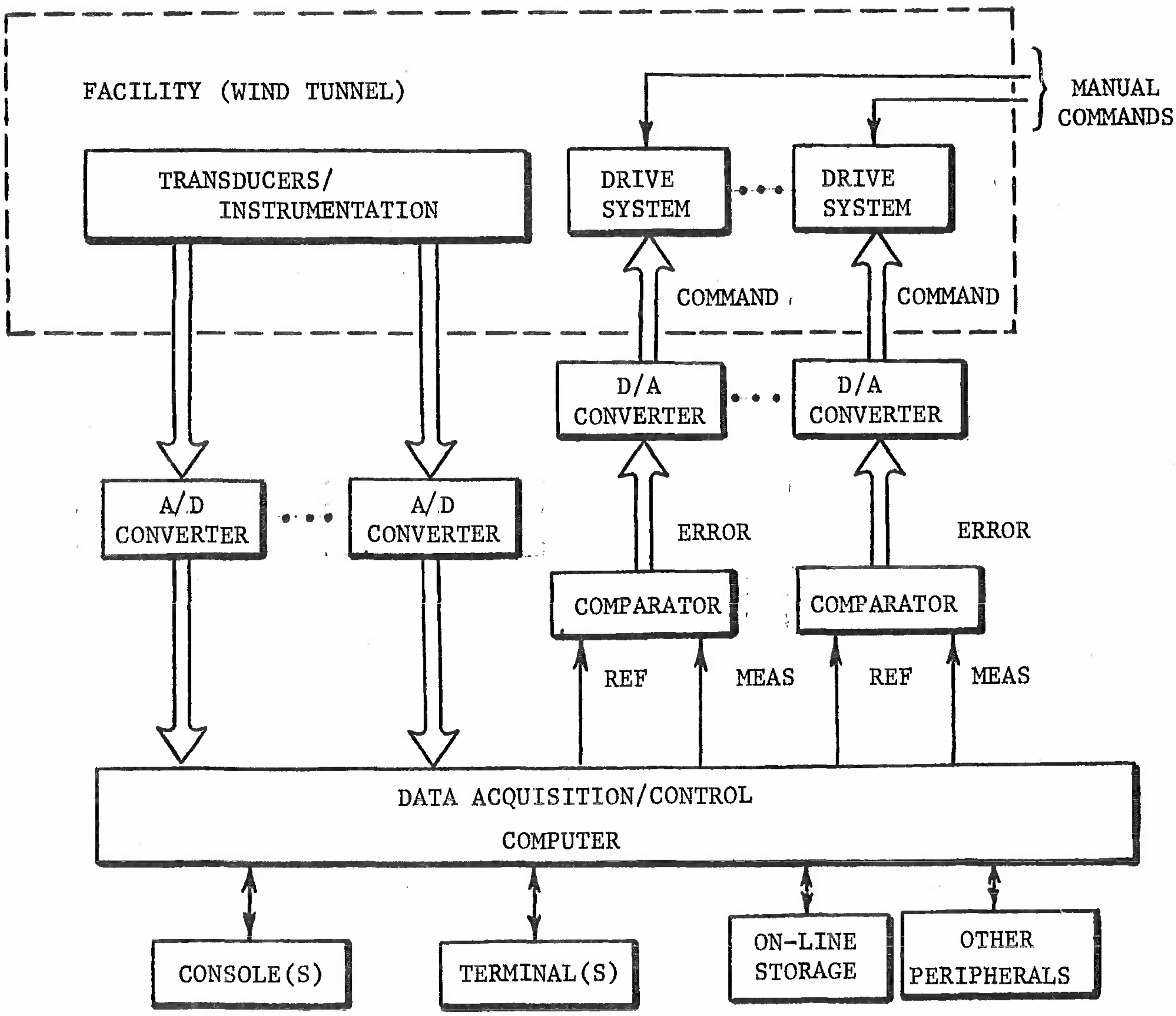


Fig. 4.4 Functional Diagram of Automatic Control System

answered to insure a system with superior performance levels. The following list includes the more important design questions, and these can be answered only in terms of an individual wind tunnel facility:

1. What degree of accuracy is possible for measured parameters? Equivalently, what errors are introduced by the transducer/instrumentation/analog-to-digital converter, prior to input for computer processing?
2. What is the nature of the data acquisition/control computer(s)? It is necessary to know their speed requirements, memory re-requirements, communication requirements, accuracy requirements or word length, processing requirements, and display requirements. It is also necessary to know whether these requirements would best be met by a centralized or a distributed system.
3. How well does the data/control computer address the overall testing requirements for the facility and how flexible is the computer in terms of additional, unforeseen control requirements?
4. What errors are introduced by the comparator, digital-to-analog converter, and drive system hardware?
5. What minimum response times are required from the overall feedback control system?

Continued improvements in wind tunnel flow quality, efficiency, and operational modes which can be realized by the introduction of automatic control systems will not be achieved without difficulties. Principally, any control improvements should first be proven in a research environment. This requires an investment in high quality research wind tunnels, where justifications are most difficult. Presently, there are very few first-rate research wind tunnel installations in the United States, and many of these are dedicated to particular research objectives which do not include studies in control system integration.

If the alternative approach -- "borrowing" of production wind tunnel time for investigation of tunnel control--is investigated, an equally difficult set of problems arises. Production wind tunnels depend upon the timely delivery of design data to users, and any encroachment upon resources for purposes other than purely operational ones is viewed with alarm. This mode of thought tends to stagnate development of existing wind tunnels, and the result is that any improvements through modification of control features can be accomplished only through tremendous perseverence.

Finally, the cost difficulties which must be faced also limit the implementation of tunnel control improvements. Even for proven control techniques, the high cost--mostly dollar costs, but also production time costs--of tunnel modifications tends to limit progress. For example, it is typical for individual compressor units for large production installations to cost in the neighborhood of millions of dollars. This sort of cost can be borne only by major government programs; research activities are not blessed with funding of this magnitude.

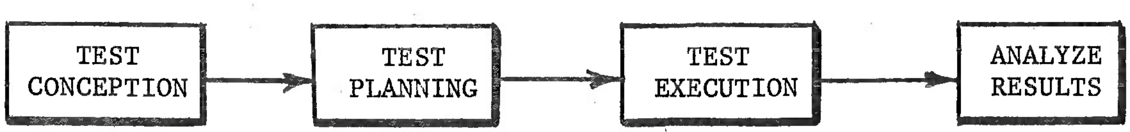
Computer control features were not widely utilized in the earlier wind tunnels because of a lack of sophistication in computer/control engineering at the time these tunnels were planned. Tunnel modifications to incorporate computer-controlled functions are difficult to realize for two reasons:

(i) the expense is high--a significant fraction of the original cost, or sometimes more than the original cost

(ii) some users are wary of certain modifications to wind tunnels because of their reliance on past interpretations of tunnel data.

4.2.2.3 Improved Tunnel Control Systems

Improvements in wind tunnel test methods which can result from more extensive use of computer-controlled tunnel automation features would change some basic test methods. The overall wind tunnel test procedure can be viewed as shown below:



Under present modes of testing, a large proportion of the effort is expended within the last block, analyzing results. The addition of improved tunnel control features would change the above diagram to that which is shown in Fig. 4.5. In this figure, the planning and test execution phases are much more sophisticated, and introduce

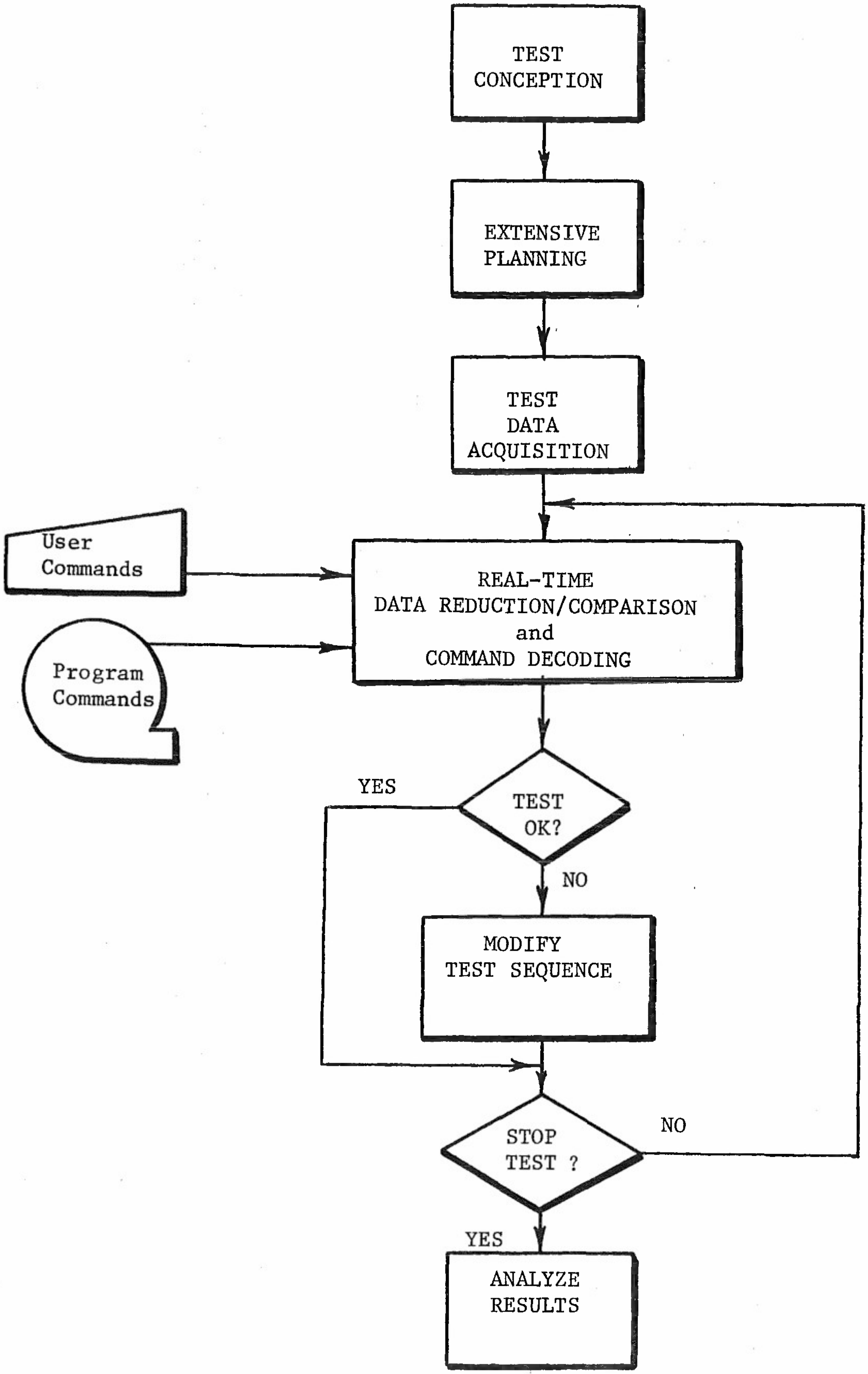


Fig. 4.5 Flow Diagram Showing Interactive Test Sequence

possibilities for more efficient use of the wind tunnel facility. The primary advantage lies in the possibility of making real-time testing decisions based on previous planning, availability of near-real-time tunnel data, and an interactive capability for the test monitor. Tests could be controlled directly by the user or by programmed test sequences which monitor critical tunnel parameters.

Many of the test methods described above have been successfully used as part of the testing done on jet engine designs. The AEDC Engine Test Facility, for example, uses online monitoring of test data to make real-time decisions concerning test sequences. The principal components needed for successful automation in such cases are the availability of suitable tunnel control features and a good understanding of interactive techniques which are possible through state-of-the-art data systems.

Whenever possible, wind tunnel facilities should incoporate closed-loop, interactive features to allow the user to observe critical test parameters in real time and to modify test sequences when appropriate. This mode of operation places more emphasis on test planning and leads to more sophisticated testing techniques.

4.2.2.4 Computer Facilities Required

It is not possible to enumerate particular control schemes to determine the computer requirements for each one; the number of different control problems and the number of different types of wind tunnel installations would prohibit such an attempt. It is possible, however, on the basis of the reading, discussions, and observations of the Computer Systems Panel, to suggest some logical ground rules to be followed in further development of automatic control functions for wind tunnels.

For existing wind tunnels, Fig. 4.6 illustrates the principal processes which must be included in the development cycle for the implementation of any automatic control system function. As this diagram shows, the initial task is the definition of a well-defined control objective and the means to accomplish this objective. It is

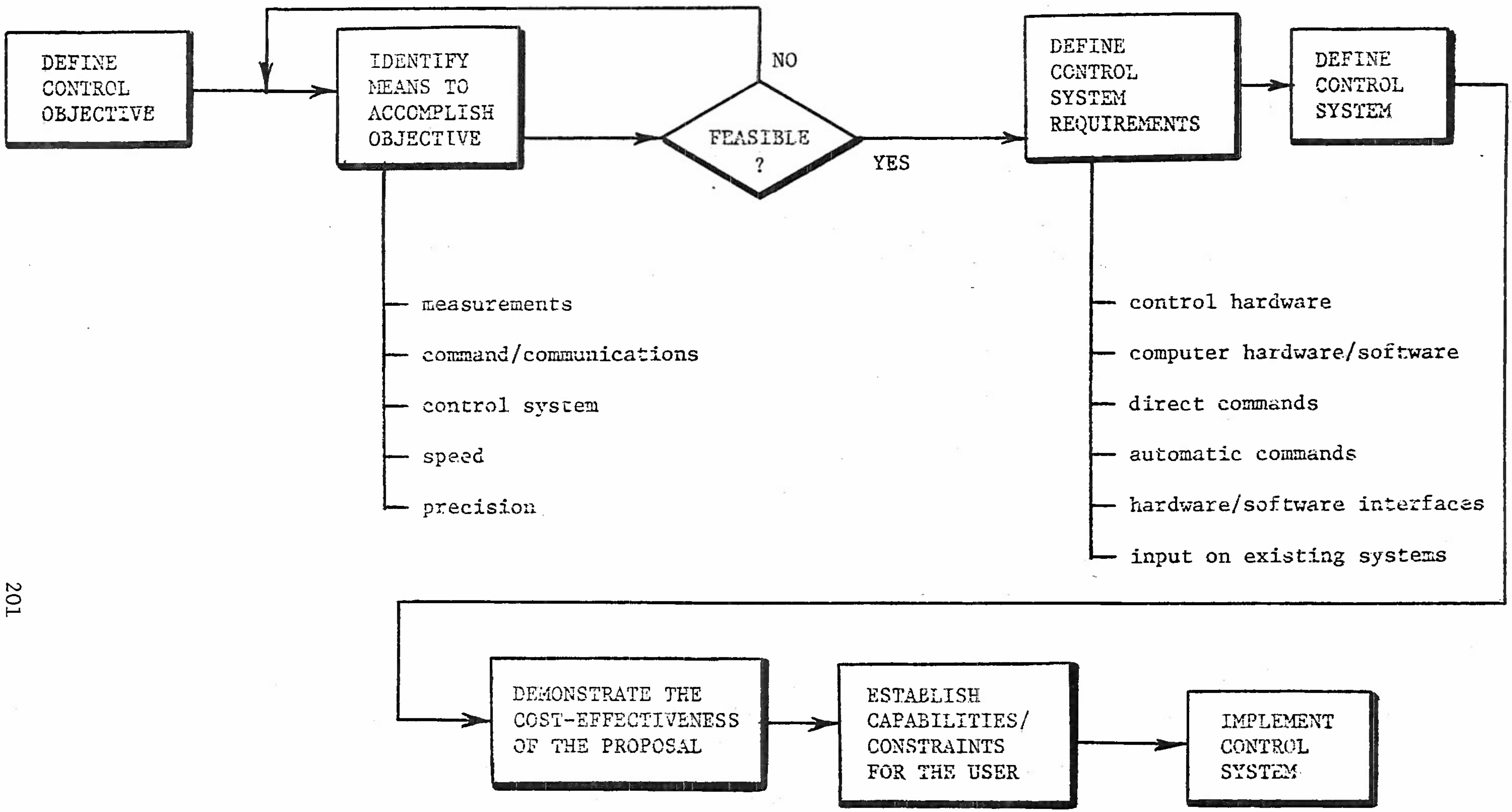


Fig. 4.6 Methodology for Definition and Implementation of Automatic Control Function

in this phase of development that either a research or a production wind tunnel is needed for concept testing; control modifications to wind tunnel facilities cannot be based on purely analytic investigations.

After the feasibility of any particular control approach is firmly established, the control system needed to accomplish this function is defined. Fortunately, the sophistication which has been achieved in computer-based feedback control systems is adequate for the development of presently conceived control functions. The single exception was found by the panel to be the adaptive wall problem and this is addressed in a separate section of the report. The biggest danger in the modification of existing wind tunnels to include automatic control functions is that hastily planned implementations may result in unreliable or needlessly complex systems.

The final three steps in the development process include demonstrating the cost effectiveness of a tunnel control implementation, establishing the capabilities and constraints of the implementation, and finally installing the control feature. A number of successful wind tunnel modification efforts can be cited where the implementation costs have been more than offset by improvements in data quality or tunnel efficiency.

Figure 4.7 illustrates the key processes involved in defining the automatic control functions to be included in the development of new wind tunnel facilities. The diagram shows steps which are basically the same as those described for modifications to existing tunnels. However, two important differences exist. First, the identification of control system functions can be given much more attention since the construction of a new tunnel removes the restrictions imposed by an existing configuration. It is this step which, for a production facility, would greatly benefit from any results obtained by research wind tunnel facilities.

The other significant difference from the previous methodology is the definition phase for computer system resources. When an existing facility does not restrict the choice of a computer support system, it is possible to take maximum advantage of the recent developments in localized, dedicated processing functions, computer networking,

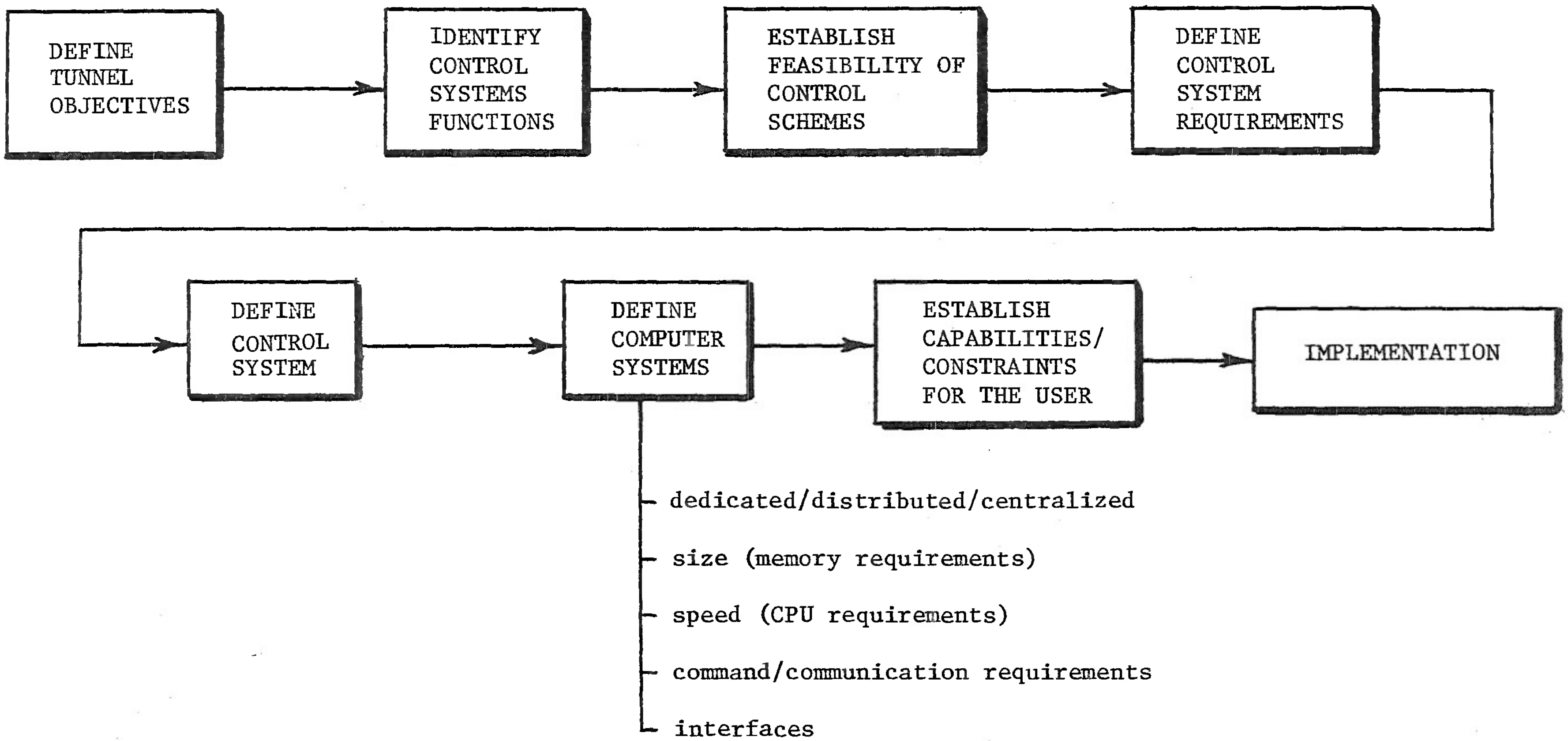


Fig. 4.7 Methodology for Definition of Automatic Control Functions

microprocessors, minicomputers, and communications processors. Tremendous strides have been made in recent years in developing various forms of the digital computer as system components. This serves to relieve the central computer of the necessity of performing such a large number of tasks that its function becomes unmanagably complex. Distributed processing will also allow more flexibility to be retained by the control computer.

Computer control of wind tunnels should be given special consideration during planning stages since later conversions are difficult. A maximum number of automatic control features should be incorporated; however, care should be taken to choose proven control techniques, to avoid disorganized implementations, and to build in flexibility to allow for future enhancements.

The computer/control system technology is available to implement automatic control features which are both highly complex and reliable. Wind tunnel facilities which have incorporated such features have demonstrated the effectiveness of these schemes.

4.2.3 The Adaptive Wall Wind Tunnel

A look toward the future indicates that the Adaptive, or Intelligent, Wall Wind Tunnel holds great promise for the improvements in the experimental acquisition of aerodynamic data. Research dealing with this concept indicates that wall interference effects, particularly in the transonic region, can be significantly reduced (Ref. 4.146). In this way, larger models (yielding larger Reynolds number) can be tested under conditions which more closely resemble free-flight conditions, and a significant improvement in the quality of the simulation can be expected.

Examination of existing wind tunnel facilities shows that wall interference effects can significantly degrade the overall simulation quality of the wind tunnel (Ref. 4.146). Shock wave reflections and tunnel blockage, induced by the model and its support system, are among the most noticeable of these problems. Various compensation techniques have been applied to the problem in an effort to minimize these effects.

The most notable methods include slotted or otherwise porous walls (with fixed or variable porosity) used in conjunction with plenums to which suction has been applied. The application of these methods has significantly reduced wall interference problems; however, it is clear that they have not eliminated them (Ref. 4.146). Tunnels employing these techniques exhibit wall interference effects which are not negligible. The problem is most acute when critical tests (e.g., high angle of attack) are performed. The shortcomings of compensation techniques have furthered the investigation of the Intelligent Wall Wind Tunnel concept, which allows the tunnel walls to adapt to the flow field generated by any reasonable model attitude in such a way as to eliminate interference.

4.2.3.1 The Intelligent Tunnel Concept

A detailed description of the Intelligent Wall Concept, including its theoretical justification, has been presented elsewhere in this report. Therefore, the salient characteristics of this concept will be briefly reviewed in the following function description:

1. The entire flow field will be solved by partitioning the field into two parts. The interior region is within the wind tunnel test section; the exterior, or far-field, region extends from the boundary of the interior region to infinity.
2. The interior region will be solved by the analog simulation performed in the wind tunnel test section.
3. The far-field solution will be arrived at through a numerical simulation performed by a digital computer.
4. The walls will be iteratively adjusted until the two solutions, when matched at their mutual boundary, indicate the presence of interference-free conditions. When this condition is met, data will be taken.

The Intelligent Wall Wind Tunnel is seen to be a hybrid simulation system which effectively merges the simulation capabilities of the wind tunnel and the digital computer (Ref. 4.99). The Wind Tunnel is used to simulate the (complicated, viscous, shock infested) interior region where digital simulation is, as yet, inadequate. The digital computer simulates the (slightly disturbed, invisid) exterior region which would require a wind tunnel of prohibitive size and cost.

The ultimate application of the Intelligent Wall concept will occur in a three-dimensional, production-oriented wind tunnel. At present, research (which includes the physical construction of an intelligent tunnel) is being conducted only in the two-dimensional area, but a three-dimensional scheme seems feasible. The most effective adaptive mechanism has not yet been agreed upon. Promising techniques include variable geometry walls and multiple plenums, with individual control of plenum pressure, used in conjunction with variable porosity walls. Perhaps the best technique will be some combination of these methods. It is clear that the construction of a three-dimensional adaptive wall wind tunnel will require a significant additional investment in tunnel hardware. In addition to the conventional data acquisition and control systems, an elaborate electro-mechanical system must be constructed to control the adjustments required at the wall. Existing systems perform the far-field computation off-line; the results are used to manually adjust the walls for the next iteration. A much more effective procedure involves on-line computation of the far-field solution and computer-control of the wall adjustment hardware (Ref. 4.80). This control scheme must be adapted if the adaptive wall is to become a production testing tool. The availability of a computer system to support this effort is examined in the following section.

4.2.3.2 Computer Facilities Required

The operation of an intelligent wall system is summarized by the flow diagram shown in Fig. 4.8.

It is observed that three operations (sense interior condition; compute exterior conditions; adjust walls) must be iteratively performed before data acquisition for a single test condition can begin. A production environment requires that, within reason, no single operation in this loop excessively dominate the adaptation time for the system. Each operation must be examined and its completion time estimated. The interior region conditions are determined by measuring certain components of the flow field at the boundary of the interior region. A modern data acquisition system can be expected to perform this task

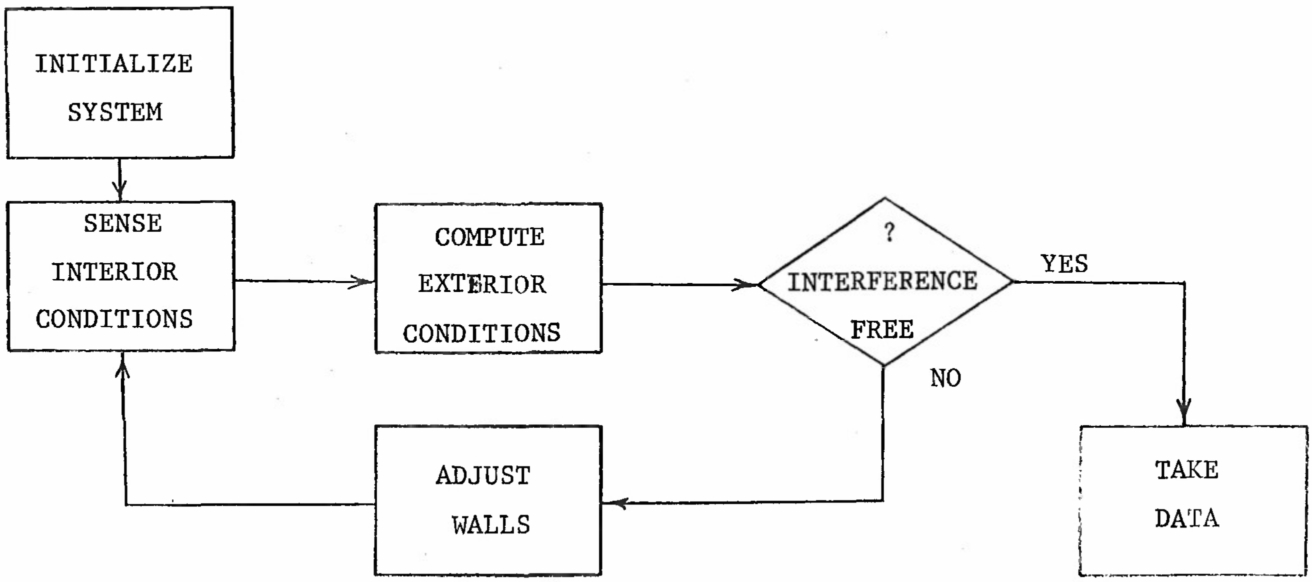


Fig. 4.8 Adaptive Wall Adjustment Procedure

in a matter of a few seconds, at worst. The wall adjustment operation involves the electro-mechanical actuation of jacks, motors, pumps, and/or valves. It seems reasonable to expect that, at best, a few seconds will be required to accomplish this task. An examination of existing intelligent wall tunnels, when extrapolated to reasonable three-dimensional schemes, indicates that the data acquisition and control procedures described above are well within the capabilities of existing minicomputer supported process control systems. The availability of a computer capable of performing the far-field solution in a matter of seconds must be assured if a production-oriented, intelligent wall wind tunnel is to be implemented.

The computational speed required to support an adaptive wall depends on a number of factors; these include 1) solution time, 2) coarseness of the computational mesh, and 3) method used to analyze the exterior region. A conservative estimate of the order of magnitude of this speed will be determined. One approach to the exterior region involves the numerical solution of a finite-difference approximation of the transonic small disturbance equation (Ref. 4.100). This solution would be performed in a cylindrical computational mesh (Fig. 4.9) and is based upon the interior region conditions as reflected at the boundary.

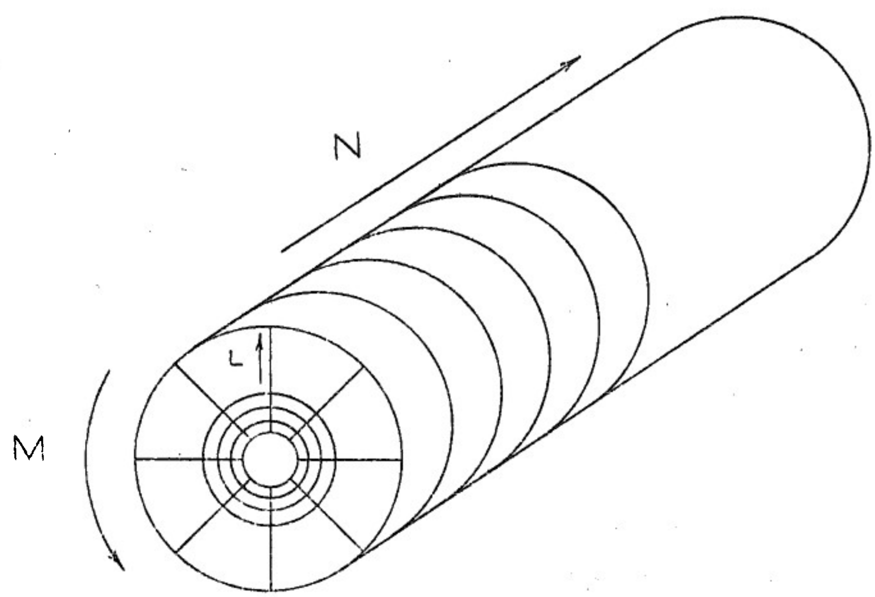


Fig. 4.9 Computational Mesh

The computational space is composed of N circular planes; each plane is composed of M radial rays, and each ray contains L computational mesh points. An examination of the solution to the transonic small disturbance equation indicates that a tridiagonal system of equations, of order L, must be solved for each ray within the computational model. Thus, a single iteration through the computational space involves the solution of (M x N) tridiagonal systems. This set of systems must be solved a number of times until the entire solution has converged. Figure 4.10 is an expansion of the process "computer exterior region" from Fig. 4.8.

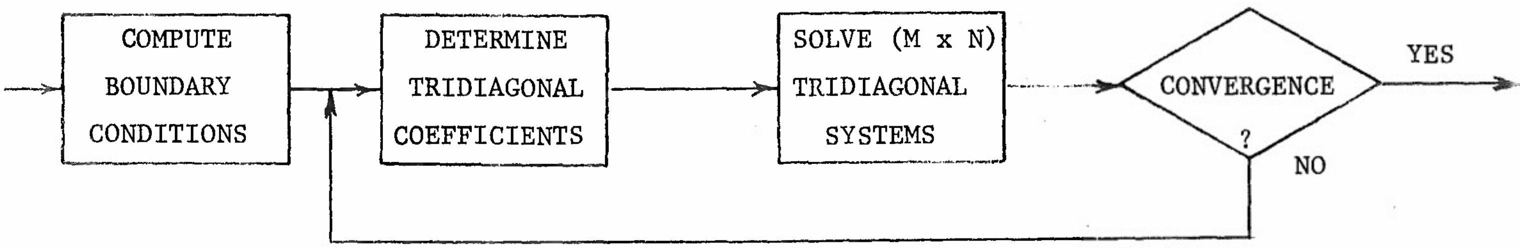


Fig. 4.10 Computation of Exterior Region

The rate of computation, R, can now be approximated as:

$$R = \frac{I \times 0}{T}$$

Where: I = Number of iterations required for convergence

0 = Number of operations per iteration

T = Required solution time

The variable 0 represents the number of operations required to define (compute coefficients) and solve the set of tridiagonal systems generated by the solution procedure. Appendix II indicates that the number of operations required to solve a tridiagonal system of order L is approximately 9L. The number of operations required to compute the tridiagonal coefficients is comparable to the number of operations required for solution. Therefore, for the computational model proposed, 0 can be expressed as:

$0 = M \times N \times 18L$ (Operations required to define and solve (M x N) tridiagonal systems of order L.)

R is then seen to be:

$$R = \frac{I \times M \times N \times 18L}{T}$$

The following values are reasonable estimates of the quantities involved:

I = 100 (Iterations for Convergence)

M = 12

N = 50 } (Definition of Computational Mesh Size)

L = 30

T = 5 (Solution Time (Sec.) Required for Production Environment)

These values indicate that a computer capable of operating at an <u>effective</u> rate of approximately 6.5 million floating point operations per second (MFLOPS) is required to support a production-oriented three-dimensional intelligent wall wind tunnel. This computational rate exceeds the capabilities of existing, readily available computers. It is reasonable to assume that a solution time of 10 minutes could be tolerated in a research environment. A computer capable of operating at an effective rate of 0.05 MFLOPS can fulfill this requirement, and such machines are presently available. A parallel development of adaptive wall technology and computer systems can be anticipated. A moderate rate of advancement of computer systems can be expected to supply appropriate support for the intelligent wall as it develops into a production testing technique.

An examination of the computational model proposed indicates that 18,000 mesh points are involved. This value indicates that the memory requirements of the adaptive wall are insignificant when compared to the computational speed requirement. Memory sizes available within present minicomputer systems are equal to the task.

This examination of the computer support required by the intelligent wall wind tunnel indicates that adequate computer hardware is, and will continue to be available to support the development of this concept. Data acquisition/control system requirements and memory requirements do not demand an advancement of the state of the art.

Although a three-dimensional production tunnel could not be supported at this time, its construction is not imminent. A strong research and development effort can be supported with available computer technology.

Assuming a reasonable research and development period for the Intelligent Wall Wind Tunnel and expected advancements in computer technology, inadequate computational power will not prevent the eventual construction of a production-oriented, three-dimensional intelligent wall wind tunnel.

4.3 COMPUTERS AND COMPUTATIONAL AERODYNAMICS

This section will discuss the applicability of computers, present and future, to the solution of computational aerodynamics problems. Whereas in Section 3.0 the emphasis was on the computational aspects, the emphasis here will be on the computing machinery and software. The reader is referred to Section 3.0 for a more comprehensive discussion of the nature of computational problems.

4.3.1 Nature of the Computational Problem

Three aspects of typical computational aerodynamics problems are of interest with respect to the digital computer: 1) the nature of the equations, 2) the nature of the solution procedure, and 3) the performance characteristics of a suitable computer.

4.3.1.1 Nature of the Equations

The flow of a fluid is typically a quite complicated process and, consequently, quite difficult to model mathematically. This is particularly true of the fluid flows of interest to aerodynamicists, which may involve turbulence, boundary-layer separation, shock wave interactions, and other complications. In the case of turbulence, for example, the size of the eddies present in the flow field is a random, though bounded, variable. To the complexities of fluid must be added deficiencies in expressing the essential properties and characteristics of the real fluid involved.

While the foregoing is not a complete description of the obstacles, it is clear that difficulties arise from a lack of fundamental understanding of the development and solution of definitive fluid flow models. However, the modeling concept has permitted substantial progress. Modeling entails the substitution of a mathematically tractable approximation for an intractable theoretical equation(s). The limitations of the model must, of course, be recognized. As a substitute for theory, the model will have a limited range of applicability, beyond which the calculated results will be of dubious merit. For the present discussion, these constraints are notable because they also apply equally to computer programs generated from the theoretical equations augmented by the model relations.

The time-averaged Navier-Stokes equations are generally regarded as the theoretical relations applicable to a wide range of aerodynamics problems. When augmented by additional equations (i.e., from models), so that the number of unknown variables equals the number of equations, the Navier-Stokes equations may be regarded as soluble. In form, the equation set is a collection of nonlinear partial differential equations. Analytic, closed form solutions are not possible (except for carefully contrived and simplified problems). Instead, the flow field is discretized for two primary reasons: 1) the mathematics is rendered tractable, and 2) the problem is mapped into the domain of the digital computer.

This view of aerodynamics problems is not restricted to the Navier-Stokes type of flow alone. Discretization is applied to other types of flow as well. The form of the discretized equations will vary with the type of flow, but the general characteristics of the problem remain the same (that is, a large number of variables and a large number of equations resulting from the discretization of the flow field). For three-dimensional solutions, five variables per grid point is a minimum. The values of the variables associated with certain elements are fixed, owing to the proximity of the element to a physical boundary.

4.3.1.2 Nature of the Solution Procedure

With the preceeding, somewhat simplified description of computational aerodynamics problems as a perspective, the method of solution must be discussed. Just knowing the equations, the grid pattern for the matrix and the boundary conditions does not enable a programmer to directly write a program. A variety of numberical techniques may be employed to effect the solution. For the purposes of this discussion, the relative merits of one method or another will be avoided in preference to a discussion of the impact of the general properties of the applicable numerical techniques on the computer and the programmer.

First, consider the enormity of a minimal problem. A grid division of 1,000 in each of three coordinate directions is not inconceivable (and may possibly still be too coarse for some situations). At five variables per grip location, the number of variables would be 5 x 10^9. If each variable had to be treated independently, this would certainly be an overwhelming problem. However, the nature of the numerical methods is to perform the same type of operation at each grid location. Vector and matrix operators are convenient in describing the mathematics of the numerical methods.

Second, the vector mathematics apparently applies only to the interior points of the grid. The operations performed at the flow-field boundary are generally scalar in nature. That is, it is not readily apparent that calculations performed at the boundaries will be vectorizable. The number of anticipated boundary elements is on the order of 10^7 based on the 1,000 unit metric.

Third, the solution of discretized problems employing numerical procedures is inherently repetitive in nature. As a consequence, the large number of vector and scalar operations must be performed repeatedly upon each iteration. Though it could be significantly higher, depending upon the convergence properties of the numerical method, 10^2 appears to be the order of magnitude for the number of iterations. The large number of iterations has two implications on computer solutions to computational aerodynamics problems: 1) The execution times will be high for computers of conventional, scalar architectures; 2) The large number of iterations will tend to introduce significant round-off errors for machines of short word length.

4.3.1.3 Performance Characteristics of a Suitable Computer

With the preceding thoughts on the nature of computational aerodynamics problems and solutions in mind, one can now approach the task of identifying the essential characteristics of a suitable computer. In a subsequent section, the state of computing machinery will be examined to ascertain suitabilities for applications in computational aerodynamics.

Before proceeding, it is necessary to identify the operating environment of the computing system. It is assumed that the programs will be written in high level scientific languages. The programs will be based on present numerical techniques and will be executed in a stand-alone mode. The computer will not simultaneously execute more than one program. The final consideration involving the computer operating environment is the acceptable execution time. A 10-minute execution time to solve the entire flow field has been suggested on numerous instances throughout this study. It seems likely that the 10-minute execution time originated from the familiarity of programmers with computing systems and problems yielding short execution times. This arbitrarily selected execution time stems from what has been deemed convenient for a production computational aerodynamics computer. While the 10-minute figure will be used here, less impatient users can easily calculate the computing speed on their preferred time basis. It is ~~expected~~ expected that many users, particularly those in research environments, may be quite satisfied with execution times of 10 to 12 hours.

In order to achieve a 10-minute execution time, the rate of processing floating point operations must be at least of magnitude 10^3 megaflops (million floating point operations per second). This can be accomplished by designing the computer to perform a multitude of operations at one time. The vector nature of the interior flow-field computations suggests a parallel processing machine. Each of several processors would perform the same operation simultaneously on an equal number of consecutive grid points. The greater the number of processors the greater the effective processing rate of the machine. A typical present-day computer can perform a floating point computation in 200 nanoseconds, suggesting on the order of 200 processors to achieve the desired 10^3 megaflop processing rate. However, this ignores the operating system overhead, the scalar processing penalty, the memory management operations, and the input/output operations. These and other contingencies may require either that the number of parallel processors to be increased (up to perhaps 600) or that the processors be designed to execute faster.

Arguments for increasing the speed of the individual parallel processing units apply equally to the scalar processing capability, which must also be fast. While the number of scalar operations is less than the number of array operations, it must be recalled that these operations can only be executed sequentially. Pipelining the processor increases its speed by a factor of three or more. In the pipeline concept, the processor is subdivided into a sequence of subprocessors , called segments. Each segment has a specific task to perform, and each works simultaneously with the others. An analogy can be drawn between an assembly line and the pipelined computer concept. For a three-segment piepline, the operations are apparently performed in almost one third the time of a conventional processor. Some sacrifice in time occurs as the pipe is initially filled and as the pipe is emptied at the conclusion of a string of scalar computations. Thus, the greatest benefit from pipeline processors will be realized if the computations are batched. That is, all of the scalar computations are performed in one batch, as are the vector computations. Note that for a pipeline, the sequential computations must be carefully organized, or the computation may actually be slower.

For the computer to sustain the suggested 10^3 megaflop rate, a certain sophistication in the memory will also be required. To support the parallel and scalar processors, a large and very fast direct access main memory is essential. Since this memory will be expensive, it would not be reasonable to expect to store all of the variables. The direct access main memory will be supplemented by a backing store sufficient to store all of the variable values. When necessary, a page of the backing store will be copied into the main memory, replacing the former contents, which had previously been copied back into the backing store. The backing store would be less expensive per bit than the main memory since the requirement for speed is less stringent. Some care must be exercised to ensure that the paging (i.e., transferral of data between the backing store and main memory) is efficient and minimal. This appears to be most strongly influenced by the nature of the numerical technique and the format of variables within the backing store.

To the parameters of speed and memory size must be added the equally important concept of accuracy. The length of each computing word determines the accuracy with which floating point numbers may be stored. This accuracy introduces round-off errors during computations involving the multiply, divide, or other similar operators. Because of the large number of operations performed on each variable in the solution of a computational aerodynamics problem, the word length for floating point numbers should be as large as possible. Increasing the word length for a memory of specified size increases the cost of the memory since the number of components increases. For example, a 1K 64-bit memory will cost approximately the same as a 2K 32-bit memory. To some researchers, a word length of at least 64 bits appears necessary for computational aerodynamics.

Fundamentally, there is little distinction between 1) a serial computer executing a program instruction set in sequence, or 2) a parallel computer executing a parallelized version of the same program. The number of operations performed remains, practically speaking, the same. If a strictly serial computer were assigned to a computational aerodynamics problem of moderate complexity, an execution time of one week (or at least several days) seems likely. It also seems likely that during a week of full-time computation at least one hardware item will fail. The failure may be hard or soft, but one should presume that the failure influences a computed result. It would be futile to continue processing with the error, and equally futile to restart the entire calculation. Instead, the machine should incorporate 1) error detection and correction codes (e.g., Hamming codes) and 2) restart capability, resuming a computation from the point of interruption. These features will minimize the frequency of errors as well as the impact of an error on execution time. As an example, consider the serial machine trudging through a five-day execution of a computational aerodynamics problem. If a hard failure should occur on the fourth day and if no error detection/correction and restart capability has been provided, then the four days of execution will have been wasted. Note that it is the number of operations performed per job that determines the probability of successful job completion without error (or, to say it another way, as the number of processors is increased, so is the probability of at least one processor failing).

The parallel, pipelined computer architecture is quite complicated by comparison to the serial computers with which most programmers are familiar. The experience of programming for a parallel computer will seem most unnatural to the programmer initially, and may be expected to result in inefficient parallel programs (Ref. 4.88). Consequently, the support software designed for the parallel computer should assist the programmer in parallelizing the traditionally sequential instructions he composes. When parallelizing software is provided, 1) at least partially parallelized versions of sequential programs are produced for execution, and 2) the programmer can review the parallelized program to locate statements which may be hindering the parallelization. To facilitate the use of parallel computers, the language supported should be an extension of a familiar high level scientific language, such as FORTRAN. The FORTRAN language can easily be augmented with a repertoire of vector instructions using a keyword identifier, not unlike the MAT statements in the BASIC language.

4.3.2 Available/Planned Computer Systems

Having considered the nature of the computational aerodynamics problem and its dictates for computer requirements, it is appropriate now to survey the capabilities of contemporary computing equipment designs. This section will be subdivided according to 1) currently available computer systems, 2) computer systems currently under development, and 3) technological advances.

4.3.2.1 Currently Available Computer Systems

Many computer systems are available today with a variety of speeds and capabilities. It is the subset of available computers which possess very large memory capabilities and very fast execution times that is of interest to computational aerodynamics. The speed of a computer is determined principally by the processor design and implementation. Two distinct processor classifications have emerged. A serial processor performs unitary operations in a sequential mode. That is, individual instructions are executed one at a time. Parallel processors perform a number of operations simultaneously by performing the same operation on a group of memory locations. This parallel mode of operation gives parallel architectures a significant speed advantage over scalar types for problems principally involving vector mathematics.

A third type of processor design, which is applicable to both parallel and serial machines, is the pipelined processor. In this concept, each processor is segmented, with each segment performing a portion of the total operation to be performed. A three-segment pipeline processor will produce computational results approximately three times faster than a conventional processor of comparable technological sophistication. When applied to an array machine, each individual parallel processor would be segmented into a pipeline.

The foregoing general classification of computers by processor type will form the basis for discussing the computer systems which are currently available. An attempt has been made to name and describe the salient features of all computing systems which are currently available and appear applicable to the solution of computational aerodynamics problems. Pipelined processors will not be discussed separately from the scalar and parallel architectures, since pipelining is a technique applicable to both for increasing the processing speed and is usually transparent to the programmer. For certain problems, the programmer must be aware of the pipeline architecture to avoid penalties in processing speed.

The serial machines are variations on the traditional von Neuman architectures. Notable large memory machines in this classification are the Amdahl 470, IBM 360-91, IBM 370-195, Burroughs 7800, and the CDC 7600. Each of these employs pipelining features to enhance the serial processing rate. In terms of size, all of these machines depend upon different types of backing stores (i.e., virtual memory, disc, etc.) to augment the main memory for computational aerodynamics problems. Care will be necessary when preparing programs for these machines to preclude severe penalties in speed due to excessive data transmission with the backing store. To promote efficient memory utilization and to promote conservation of machine time, computational aerodynamics problems must be executed in a stand-alone mode. The execution times for meaningful aerodynamics problems could be on the order of a week. Such execution times are more than an inconvenience to a user anxiously awaiting results, for the long execution time also makes necessary the periodic preparation of backup tapes (or disc files, if preferred) to enable restarting the program in the event of an interruption.

The inconveniences of speed and size for serial machines are counterbalanced by the operating system and applications software which has been developed for these machines. This software includes efficient operating systems and user oriented high level languages amenable to scientific computations. To be sure, these languages are primarily serial in design, while the computational aerodynamics problems are principally of the vector type. However, a knowledgeable programmer can be expected to write reasonably efficient code to serialize vector operations. Because of the long history of serial computers as scientific computational tools, capable programmers abound. Near-optimal translations of aerodynamics algorithms into high level computer code can be achieved. The applicability of serial machines to computational aerodynamics rests on the strengths of the available software and familiar high level languages.

Historically speaking, the parallel computers are a recent innovation. These machines are computationally fast and well suited to vector problems but lack the software support provided for the serial machines. Computers employing parallel processors include the CDC STAR-100 and 100A, Cray-1, ILLIAC-IV, and TI-ASC. Each of these machines has certain special capabilities for array arithmetic. Rather than engaging in a detailed description of each machine, however, attention will be focused on more general considerations.

Under ideal conditions, vector machines achieve processing rates of from 50 to approximately 200 megaflops (Ref. 4.124). Although serious data flow problems are encountered in keeping processors busy, the optimal processing rate depends upon the length of the vector operands and the absence of scalar operations. The Cray-1 and ILLIAC-IV are structured for multiples of 64. That is, these machines are most efficient with vector operands of 64 components. For the STAR and ASC, the longer the vector the greater the processing speed. Ortega and Voigt (Ref. 4.124) point out that vector lengths of 10,000 or more are required for STAR and ASC to attain the highest processing rate. These vector length requirements, which assure high processing rates, should have minimal impact on computational aerodynamics applications. The flow field is partitioned into a three-dimensional array of finite elements. For computational purposes, arrays are linearized for storage in the machine. Reference vectors prepared from the lower and upper limits of the array bounds speed access to a specified array element. Each access may be treated as the beginning of a vector of whatever length suits the machine and the problem.

So far, only the speed of processing vector operands has been discussed. Computational aerodynamics problems may also require scalar arithmetic operations involving the grid points at the boundaries of the control volume. With the exception of the Cray-1, the penalty for performing scalar operations with a vector machine are severe (Ref. 2.124). For example, Ortega and Voigt, (Ref. 4.124) cite a scalar operation time of 1 microsecond for the STAR. Approximately 10 percent of the execution time would be consumed performing scalar calculations, which comprise 0.2 percent of the total number of calculations for an aerodynamics problem as described in Section 4.3.1. Thus, for the STAR, an execution time on the order of 16 hours can be expected, based on the problem outlined in Section 4.3.1, with an average of five diadic operations required in the computation of each array variable. By contrast, the ASC scalar speed is twice that of the STAR (Ref. 4.124). A scalar cycle time of 12.5 nanoseconds (Ref. 4.124) for the Cray-1 with a maximum vector processing rate of 160 megaflops (Ref. 4.26, 4.124) leads to the expectation of an execution time on the order of 4 hours as compared to the previous 16-hour estimate for the STAR. This is something of an overstatement of the speed of the Cray-1 since the Cray speed is based on executing assembly language programs, whereas the STAR (and the ASC) execution rates are based on vector FORTRAN programs (Ref. 4.26).

To be sure, the execution times cited in the preceeding paragraph are optimistic since the assumption of complete adaptability of the numerical technique to the computer architecture is inherent. In practice, such fortuitous circumstances may seldom exist. The penalty for communication between the main memory (or computational registers, etc.) and the backing store has not been included in the speed calculations. This penalty in execution time could be devastating. Stone (Ref. 4.156) cautions that the data (i.e., the vectorized array variables) must be organized efficiently. This is no mean task, since vector computers are recent innovations and few in number. Programming expertise for vector machines is quite embryonic, and not necessarily dependent upon scalar expertise. Stone (Ref. 4.156) alludes to this philosophical dichotomy in discussing the evolution of parallel algorithms from serial algorithms. Furthermore, manufacturers of the vector machines have marketed the hardware before making the operating and programming software available.

At present a variety of scalar and vector computers are available for computational aerodynamics. The large scalar machines are suitable if large execution times and stand-alone operation can be tolerated. Software support and programmers capable of efficient scalar codes are the primary advantages of scalar machines.

The array machines have speed advantages over scalar machines but lack the software support. Software for array machines, programmers capable of writing efficient parallel programs, and algorithms tailored to the unique capabilities of array processors will elevate the vector machines to a useful computational aerodynamics tool.

4.3.2.2 Computer Systems Currently Under Development

The principal advanced computing systems with applicability to computational aerodynamics include the CDC Star 100C, Burroughs BSP, PEPE, STARAN, and PHOENIX. With the exception of the PHOENIX, these advanced computer systems are general purpose vector machines. A discussion of the PHOENIX concept is deferred to the close of this section.

The STAR 100C, BSP, PEPE, and STARAN may be regarded as general purpose vector machines suitable for computational aerodynamics problems, although not specifically developed for this application; these vector machines have at least reached the conceptual design stage. The PEPE and STARAN (byte oriented) exist as working prototypes. A working prototype of the BSP is anticipated within a year. Although the operating characteristics (i.e., speed, memory size, and number of processors, etc.) of these machines differs somewhat from existing vector machines, an appreciable extension of vector processing capabilities is not anticipated.

The Burroughs BSP falls in the 30- to 50-megaflops range, with a scalar mode speed of 2 megaflops (Ref. 4.159). These characteristics are similar to the CDC STAR 100 and the TI-ASC. Similarly, the STAR 100C, as an evolution of the STAR 100, will not possess vastly different operating characteristics. The primary thrust with the STAR 100C is an improvement in the scalar mode processing rate and decreased pipe set up time. The performance of the PEPE derives from 288 processing elements, each with a 1-megaflop rate. The scalar mode for PEPE is essentially 1 megaflop (Refs. 4.114, 4.164). However, the PEPE word length is 32 bits, requiring computations in double precision and concomitantly reducing the processing rates by half. The Goodyear STARAN also employs a 32-bit word for floating point operations which can be reconfigured for 64 bits but with the penalty of halving the speed. The associative array employed in STARAN is unique, containing 256 words of 256 bits each which may be accessed in either bit or word direction (Refs. 4.64, 4.65, 4.66, and 4.124). Up to 32 such arrays are possible. Since a floating point operation requires 40 microseconds, an array processing rate of 6.4 megaflops is possible with one array. The maximum array rate of 200 megaflops is possible with 32 arrays.

An indictment of the software support will almost certainly be as applicable to these machines as to the current vector computers. It is as important to develop software to permit the user to manipulate the machine intelligently as it is to develop the machine itself. What is needed is a vector computing system rather than a vector computer.

The PHOENIX, an evolutionary offspring of ILLIAC-IV, is currently under study by NASA (Refs. 4.151, 4.152). At present, the PHOENIX is the only advanced computer system being designed with computational aerodynamics clearly in mind. It is clear that current advanced parallel processors are incapable of the 1-gigaflop processing rate suggested for computational aerodynamics computers. Perhaps by specifically tailoring the machine to suit the algorithm, and by taking advantage of recent technological advancements, the PHOENIX can achieve the desired processing rate. However, it seems desirable to continue development and application of other computer architectures to computational aerodynamics.

A variety of advanced vector computer systems is emerging. Like the current vector machines, the software support is lacking. In deference to the novelty of parallel programming, it is suggested that the application of as many of the new architectures as possible to computational aerodynamics problems be attempted. The accurate prediction of the architecture which will be most convenient to this class of problems seems remote at this time. However, by benchmarking the new architectures with computational aerodynamics programs, insights into machine design, operating system design and applications software design will be gained.

4.3.2.3 Crucial Technological Advances

The comparison of available and evolving computer systems to the requirements anticipated for meaningful aerodynamics computations as outlined in Section 4.3.1 leads to the identification of several areas requiring technological advances. Simply stated, computers need to be faster, larger, more reliable, and more easily programmed for vector problems. The area requiring principal attention is the latter, namely the development of software. This discussion of technological advances has been limited to technologies anticipated within 5 years. Devices and methods (i. e., cryogenics, VLSI) presently in the laboratory have been excluded.

The processing speed of a vector computer is influenced by a variety of design parameters. The extent of the desired speed increase is an order of magnitude faster than the maximum speed of the Cray-1. Since computational aerodynamics problems involve scalar as well as vector operands, both types of operations must be enhanced. The rate of scalar operations is determined primarily by component design. Although the speed of light and circuit resolution are often cited as limitations on scalar speed, it appears reasonable to expect a 2- to 3-nanosecond cycle time or faster (Refs. 4.16 and 4.156). This is a significant decrease from the scalar execution time for the Cray-1, but a greater than tenfold increase in the array processing speed is required to yield an overall order-of-magnitude increase in speed. Some technological refinements may increase the vector speed (e.g., LSI); however, the suggestions of Stone (Ref. 4.156) appear to be the most promising. Notable is the increase in the degree of parallelism. This is the most direct approach but could be costly unless the unit price per processor can be significantly reduced. The application of multiprocessing also seems to hold promise but questions of synchronization and queueing have yet to be resolved (Refs. 4.135 and 4.136). Increasing the degree of parallelism is the most certain method of achieving an order-of-magnitude increase in speed.

Note that as the speed of the processor increases, the rate of data access and data transmission must also increase. Broad-band communication between the main memory and the backing store is indicated. The 2.56×10^{10} bit bandwidth of the STAR 100A correlates to 4×10^{8} words of 64 bits each, which exceeds the minimal 8M word main memory forecast for computational aerodynamics (Ref. 4.34). The speed and size of the memory itself can be enhanced by adopting CCD, or bubble technology when the reliability and the cost of these devices become acceptable. Their use appears necessary for the 128M word fast-backing store.

While the architecture of the machine is not generally thought of as technological in nature, architecture is nevertheless a crucial factor determining processing speed. One fault of the general purpose machines is the many layers of software controlling the operation of of the computer (Ref. 4.88). It is inefficient to superimpose software onto an architecture to force the machine to perform special operations. However, efficiency in performing computations is lost if the machine architecture does not (appear) to match the problem structure (Ref. 4.136). Consequently, careful tailoring of the computer to computational aerodynamics problems must be considered, particularly the mix of scalar and vector operations.

Reliability is a nebulous parameter to describe. However, a computer suitable for computational aerodynamics applications should 1) make few errors, 2) detect the errors, and 3) require a minimum of "down" time to effect repairs. The first two requirements can be handled with error-detection/correction codes, such as Hamming codes. Some sacrifice is entailed in storage capacity, accuracy, and speed as several bits from each word are commandeered to contain the parity data. This strategy has already been deployed on some vector-processing machines (i.e., Cray-1, STAR, etc.). The discussion of the time required for repair is beyond the scope of this report; however, it is pointed out that this parameter is highly dependent upon the component design and mainframe design. The reality of maintainability should be acknowledged by the designers and fabricators of the machine early in the design process.

The final technological advance identified as necessary to the development of a computational aerodynamics computer system is suitable parallel software (Refs. 4.88 and 4.89). Two classes of software are required. First, a high level programming language suited both to the vector nature of the problem and to the serial nature of the programmer must be developed. A high level language permits the programmer to express the problem with ease and clarity (Ref. 4.10). CDC, Goodyear, Burroughs, Los Alamos Laboratory, NCAR, and others are working on vector languages (Ref. 4.26 and 4.135). The favored approach is the extension of an existing and familiar high level language (such as FORTRAN) to include a repertoire of vector instructions. Fitting a FORTRAN compiler to accept a set of keyword identifiers for vector operations and perform the translation to their machine code equivalents is expected to be an easily performed task.

The second software item may not be as easily provided as an extended compiler. Optimizing software is required to parallelize programs (Refs. 4.89, 4.135, and 3.136). Existing aerodynamic programs are scalar, and the programs to be written in the near future will likely reflect the novelty of parallel programming. What appears necessary is a parallelizing precomplier which transforms serial or partially parallel programs into their highly parallelized forms. The output should be in the high level language so that the precompiler serves tutorially as well as in the role of production tool.

Certain advances in hardware and software are required to address a series of meaningful computational aerodynamics problems. The technology to construct such a computer appears to be more advanced than the parallel software.

4.3.3 Alternatives in Computing Facilities

It is clear that a completely satisfactory computer for the solution of computational aerodynamics problems has not yet been designed. In this section, the avenues to developing a computational aerodynamics computing facility will be discussed.

4.3.3.1 General Strategy

The general strategy outlined here will be recognized as a rather cautious approach but also as an optimistic approach. The computational aerodynamics computer is of a highly specialized design, expected to have little applicability beyond the aerodynamic field. The computational aerodynamics computer will not be mass produced. Perhaps as many as four or as few as one will be constructed, so that the development costs cannot be recovered in distributed fashion over a large production run. The computational aerodynamic computer will be executing programs based on algorithms, numerical techniques, models, and theoretical relations which have not yet been rigorously tested in the computing environment. The computational programs currently available appeal only to certain segments of the aerodynamic community. Differences in the approaches (i.e., the models, the theory and the numerical techniques embodied in the program) could profoundly affect the design of the aerodynamics computer. The computational aerodynamic computer requires certain technological advances. Traditionally, computers are marketed with five-year-old technology. It is necessary to freeze the design early in the development phase and the technology must be reasonably proven at that point in time. Dependence on exotic or unproven technologies is an open invitation to disaster. Finally, the computational aerodynamics computer system will be expensive to design and construct. A cost of $100M is not inconceivable. The strategy to be outlined, though conservative, can be expected to deliver a computational aerodynamic computing facility within ten years and with reasonably expectation of utility.

The essential features of this recommendation are depicted in Figure 4.11. In the figure, three parallel paths of improvements are identified. The primary path leads to the advanced computational aerodynamic computer and is recognized to be an evolutionary path. It is proposed that existing computational algorithms employing existing software be utilized to perform computational aerodynamics problems using a contemporary, fast serial computer. The machine should be operated in a dedicated environment with large execution times expected. As confidence in the computational procedures accumulates, the path leads to the use of a (then) contemporary parallel computer. It should be emphasized that a minimum of hardware development be included through the parallel computation step. These steps are for the primary purpose of initiating and supporting the other two evolutionary paths.

Experimentation with machine architecture other than those currently available can be accomplished by emulating the new architecture on a suitable current machine. The emulation will execute slowly but affords the user the cheapest access to (apparently) special purpose architectures (Ref. 4.136). This experimentation should include not only various physical machine structures, but also various problem formulations. Lomax (Ref. 4.102) suggests that problem reorganization, while destroying the apparent orderliness, may produce a very efficient computer program. For successful development of

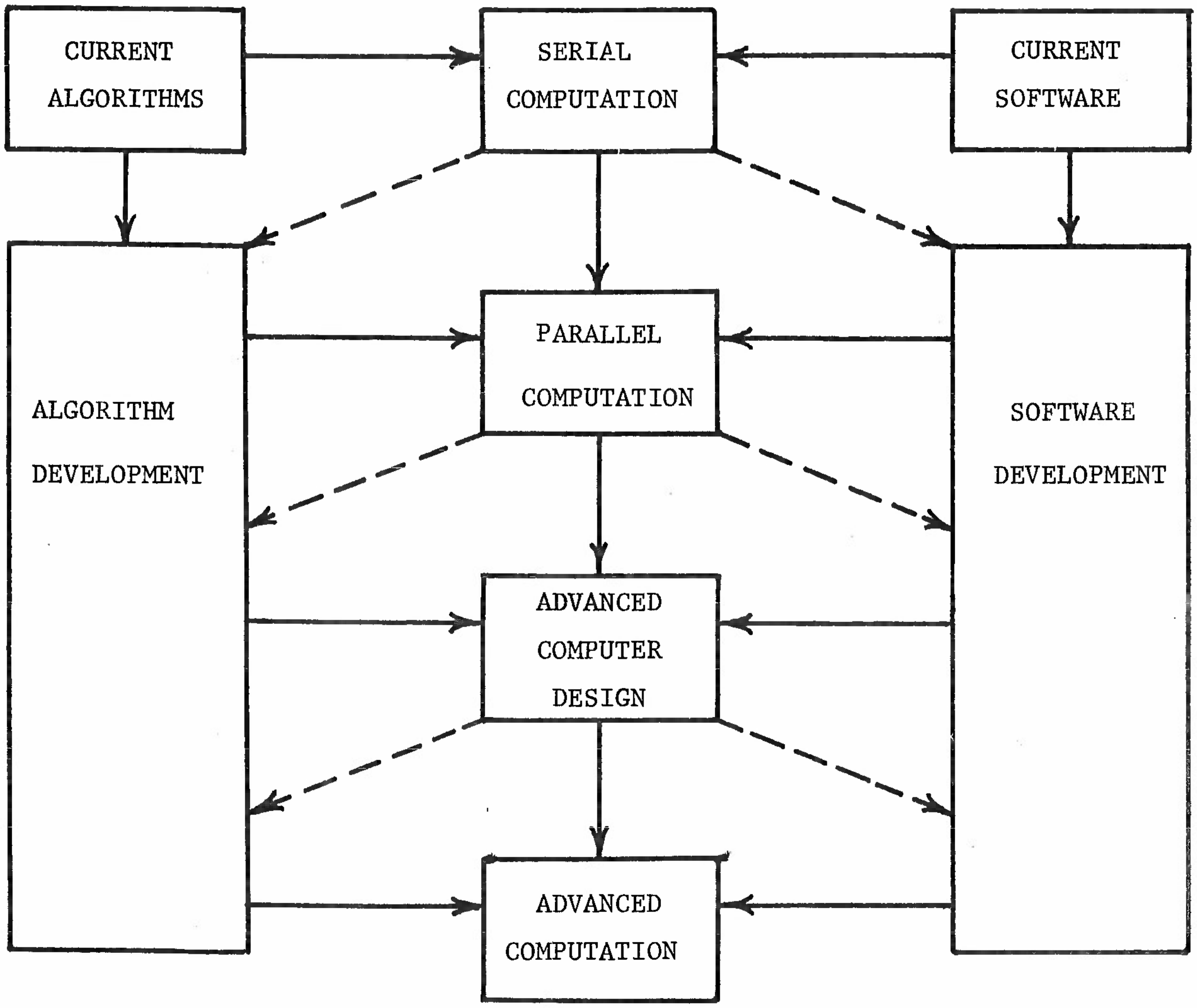


Fig. 4.11 Development Strategy for Computational Aerodynamics Facility

special purpose computers, the mutual interaction of machine and problem is inescapable.

The serial computation may be expected to reveal problems and deficiencies in the current computational aerodynamic procedures. Simultaneous with the improvement of the algorithms, development should begin on the parallel processing software essential to the execution of computational aerodynamic algorithms on parallel computers. As is apparent from Fig. 4.11, this procedure of upgrading the computational algorithms and the parallel software is viewed as a highly interactive and coordinated effort. Particular care must be exercised to ensure that a broad (if not inclusive) segment of the computational aerodynamics population is included in the serial and parallel performance studies.

Hopefully, a concensus as to the performance characteristics for the computational aerodynamic computer can be realized . From this concensus a comprehensive set of design (i.e., performance) specifications can be prepared. There are several quite different ways to progress from the design specifications to the advanced computational aerodynamic computer system. Basically, the question to be answered is who will perform the work. It is evident that the financing will be by the government in any case. It should also be realized that the serial and parallel performance studies would not only be funded by the government, but quite possibly would be conducted under government supervision as well. Three important factors necessitate close government supervision: 1) the large expense of the project, 2) the diversity of the interested groups, and 3) the potential benefit to the national interest.

The question of who will perform the work is best approached by considering the nature of the governmental supervision. The government may 1) purchase a suitable computer developed by a private concern, 2) engage a private concern to design and build the advanced computer, or 3) engage several private concerns to design the advanced computer, with one of the designs to be selected for construction. Each of these philosophies will be discussed in subsequent paragraphs. Direct design and construction of the advanced computer by a government agency has not been considered probable or advantageous.

4.3.3.2 Private Development

Of the three approaches, this is the least probable. Traditionally, computers have been developed by private concerns. However, the market expectations have been far larger than those anticipated for a highly specialized computer for computational aerodynamics. From one to four of the machines may be constructed, and the development costs portend to be quite large. Few computer manufacturers could afford such a risk for a special purpose machine. It is likely that new breakthroughs in general purpose computers will be announced during the next decade by various computer manufacturers. The probability of such a machine adapting to computational aerodynamics problems is a matter for conjecture, but recall that the operating requirements for computational aerodynamics are quite demanding (e.g., computational speed, memory capacity, memory access speed, etc.). Note also that for various reasons "new" computers are evolutions of "old" computers, and upward compatability becomes the key design goal.

4.3.3.3 Government Development

This procurement philosophy places a single computer manufacturer under the direct supervision of a government agency. Government and business interact closely throughout the design and construction of the computational aerodynamics computer. In fact, government employees will probably make or approve all of the key design decisions. These design decisions are crucial to the success of the facility, since decisions contrary to the needs of computational aerodynamicists would be disastrous. If this option is selected, and it is a good selection for many reasons, it is strongly recommended that a panel of nationally recognized experts representing the many diverse viewpoints in computational aerodynamics be appointed to periodically review the progress of the design.

4.3.3.4 Subsidized Competitive Development

The procurement philosophy outlined here is something of a hybrid of the preceding two developmental approaches. From a request for proposal (RFP) published by a government agency, private companies prepare proposals outlining the details and costs of the computer design. Several companies would be selected to prepare detailed designs from their proposed conceptual design. Thus, several companies would be independently working on the technological advances deemed essential to the computational aerodynamics computer. At the conclusion of the period alloted for the detailed design, the companies having achieved this milestone would be invited to submit proposals for the construction of prototype computers. Only the most promising design/construction proposal would be funded. It is speculated that perhaps two competing designs would be fabricated. As each machine became operational, it would be benchmarked using the computational aerodynamic programs which evolved during the parallel processing phase of the development program. The superior machine would be selected for further development (if necessary) and the selected company would begin fabrication of additional computers. This approach, entirely funded by the government, would be more expensive than either of the other two procurement philosophies. It is expected to produce a superior computer in the same fashion that this selection procedure is employed in the selection of advanced fighter aircraft (e.g., the fly-off comparison of the YF-15 and YF-16 using the F-5 to simulate Russian tactics).

4.3.3.5 The Operating Environment

One of the three aforementioned procurement strategies will produce a computational aerodynamics computer. Government ownership and operation will be necessary because of the expense. However, the operation of the computer is as critical as the instrument itself. The national computing facility concept will be viable to computational aerodynamicists only if it is available to all who require this service. It is not expected to be a free service, but it is expected that charges would be based only on the operating expenses. The actual operation may be handled directly by a government agency, or by a contractor under the supervision of a government agency. These modes of operation are not dissimilar to those employed at the various government-owned wind tunnel facilities. However, the facility should not be operated and dominated by any of the users or the operating agency. A service concept is desired.

Like the wind tunnels, the computing facility must be dynamic. The computing facility must continually improve procedures and equipment. Improvements to numerical methods, modeling techniques, and theory should be widely distributed. Continued development of parallel processing software will certainly be required.

4.3.3.6 Impact on Aerodynamics

It is clear that neither the experimental aerodynamicists nor the computational aerodynamicists are capable of designing air vehicles from their own devices exclusively. In point of fact, neither is likely to reach the point of describing true aerodynamic behavior independently of the other.

The recommended procedure envisions these two disciplines together, since both are attempting to produce the same result--accurate design data. Although somewhat idealistic at present since advances in both the experimental and computational disciplines are clearly necessary, the following air vehicle test procedure is suggested. 1) Perform model tests in the wind tunnel. 2) Perform computations, using the advanced computational aerodynamics computer, on the flow field surrounding the model with wind tunnel boundary conditions. 3) Compare the experimental and computational results, making such adjustments as are necessary and justified. 4) Generate the design data using the computer with in-flight boundary conditions applied to the full scale air vehicle. 5) Compare the design data with flight test data after construction of the vehicle.

While this program of producing design data is reasonably self-explanatory, several comments are appropriate. First, by performing computations based on the model in the wind tunnel, the experimental facility is relieved of the burden of exactly duplicating in-flight conditions. For example, the quest for a Reynolds number/Mach number match would be eliminated. To be sure, improvements in flow quality shock capture, etc. will still be advantageous. Second, capricious alteration of numerical modeling parameters to produce a match with experimental data must be avoided. Step (3) of the above procedure entails a critical examination of both experimental and computational procedures whenever disagreement in the data is present. This is the critical step. Third, the flight test data should be used to verify and improve both the experimental and the computational methods. Finally, the central theme of this study has not been "computers versus wind tunnels," but rather "computers and wind tunnels." This algorithm for air vehicle design is one example of a cooperative enterprise involving both the computer and the wind tunnel.

The future of computational aerodynamics is indeed bright. Computer technology and architectural advances portend the construction of a machine suitable to meaningful aerodynamics computations within five years. However, this is really only a beginning since the frontiers of more complex aerodynamics problems, of greater computational accuracy, and of reduced execution times will yet lie ahead. These frontiers are varied, as are the aerodynamicists exploring them. The crucial factor is open communication and cooperation. The potential lines of communication within the aerodynamics area are shown in Fig. 4.12.

To foster the communication and cooperation essential to progress in computational and experimental aerodynamics, an annual conference sponsored by the aerodynamics societies in cooperation with interested government agencies be conducted on the theme "computers and wind tunnels." The thrust of this technical meeting should be the mutual interaction of computation, experiment, and computers as a unified topic.

The development of a computational aerodynamic computer system should be orderly and systematic. Current scientific computers should be used to verify and improve computational procedures and should be used to simulate the performance of proposed advanced computer architecture prior to the implementation of a computer design.

Computing systems should be made available to the entire aerodynamics community. Current scientific computers should be made

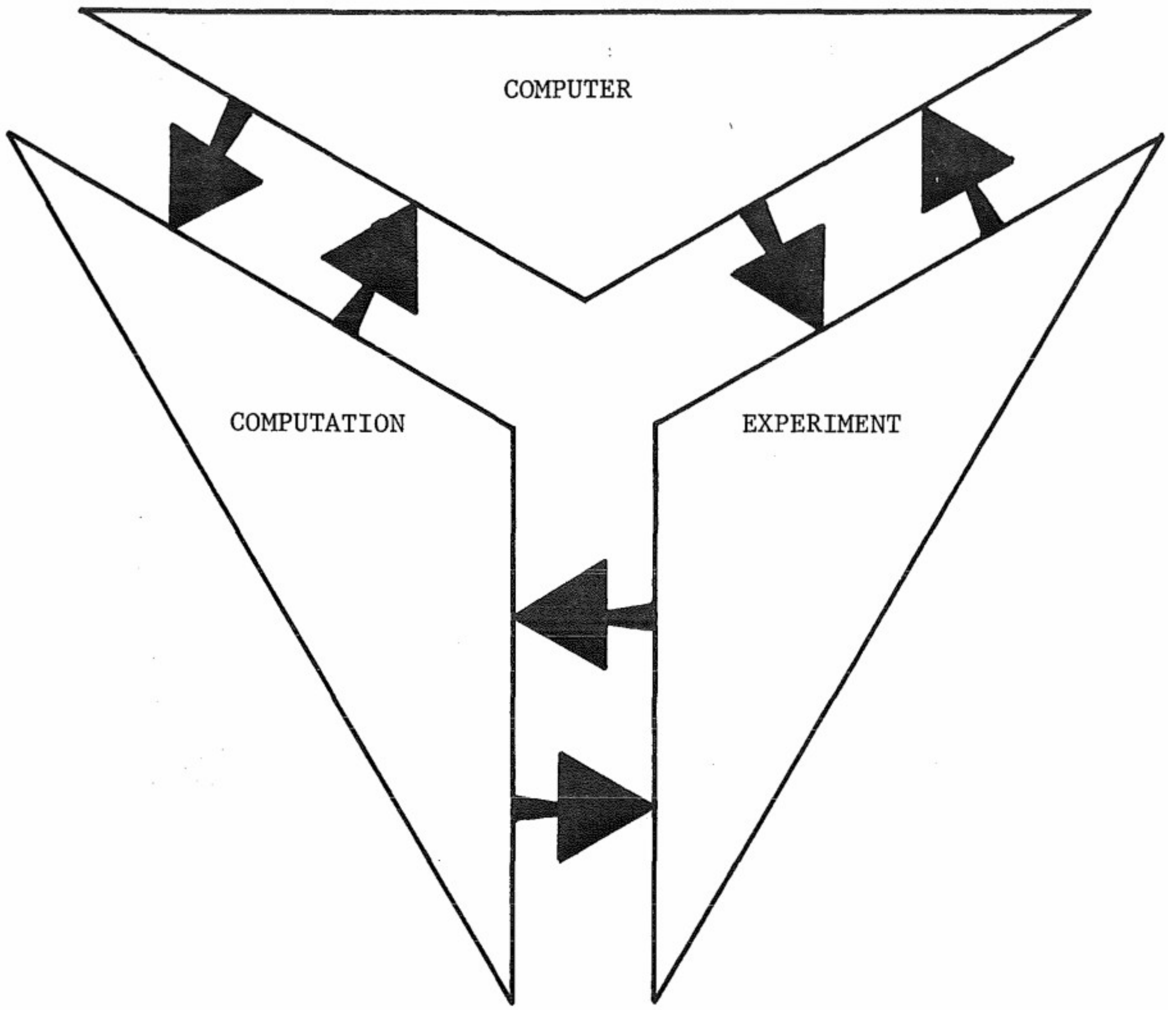


Fig. 4.12 Information Transfer Diagram for Computational Aerodynamics

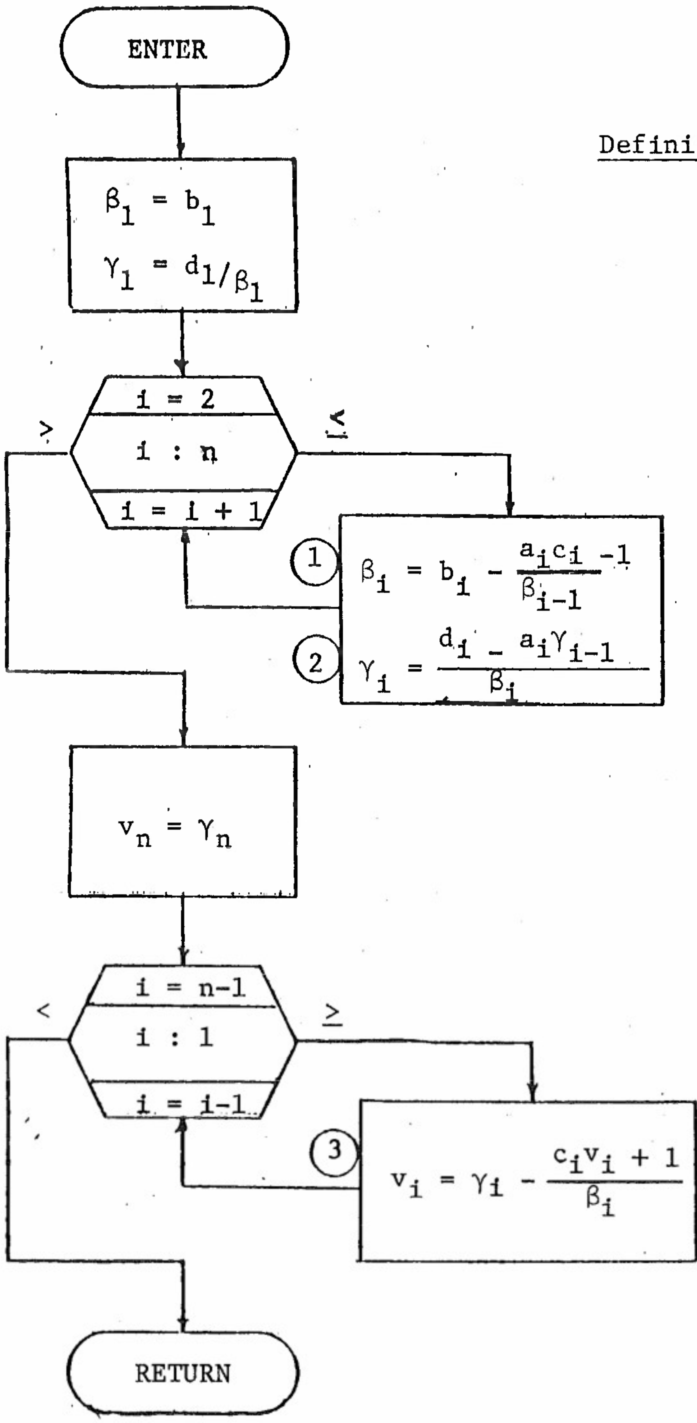
available as soon as possible for the verification and simulation studies mentioned above. The advanced computers should also be widely accessible to foster further developments in computational aerodynamics.

Government operation and ownership of the advanced computational aerodynamics computing facilities seems inevitable from a financial point of view. It is strongly recommended that these facilities remain free of domination by government agencies to preclude the exclusion of any sectors of the computational aerodynamics field.

The development of software suitable both to the machine and to the programmer is as crucial as the machine design itself. A vector high level language and a vectorizing precompiler should be developed to suit the advanced computer and the problem.

An annual workshop on the topic of computers and wind tunnels should be conducted by interested government agencies, such as AFOSR, in cooperation with the aerodynamics societies. The thrust of this technical meeting should be the mutual interactions of computation, experiment, and computers as a single topic.

Appendix VI Operations Required for Solution of Tridiagonal System by Recursion Algorithm (Ref. 4.30).



Definitions: a_i, b_i, c_i, d_i Tridiagonal Coefficients

β_i, γ_i Intermediate Recursion Coefficient

n Order of System

Analysis:

Process \ Operations Required	Sub.	Mul.	Div.
(1)	n - 1	n - 1	n - 1
(2)	n - 1	n - 1	n - 1
(3)	n - 1	n - 1	n - 1

For n >> 1, Total Number of operations Required is approximately 9n.

Note: Only operations within loops are counted to simplify analysis.

Section 4.0 Computer Systems and Aerodynamics

4.1. Adkins, G. and Pooch, U. W. "Computer Simulation: A Tutorial." Computer, pp 12-17, April 1977.

4.2. Antar, B. and Collins, F. G. "Numerical Calculation of Finite Amplitude Effects in Unstable Laminar Boundary Layers." Phys. Fluids, Vol. 18, p 289, 1975.

4.3. Argyris, J. H., Dunne, P. C., and Bichat, B. "A Plate Analogy for Plane Incompressible Viscous Flow." Invited Paper presented At International Conference on Computational Methods in Non-linear Mechanics, Texas Institute for Computational Mechanics, Austin, 1974.

4.4. Arlowe, H. D. "Dynamic Data Acquisition." Instrumentation in Aerospace Industry, Vol. 18, pp 297-306, 1972.

4.5. Astakhov, A. D. "Efficiency Bounds for Multiprocessor Computer Systems." Automation and Remote Control, Vol. 36, No. 6, pp 997-1001, November 20, 1975.

4.6. Auerbach Publishers, Inc. "CRAY-1 System Report." Auerbach Computer Technology Reports, 1977.

4.7. Baan, A. Computers in Quantitative Gas Chromatography--An Assessment of Processing Technique Accuracy. Doctoral Dissertation, Eindhoven, Technische Hogeschool, 1975.

4.8. Barsby, J. E. "Separated Flow Past a Slender Delta Wing at Incidence." Aero. Q., pp 120-128, 1968.

4.9. Barns, G. H., Brown, R. M., Kato, M., Kuck, D. J., Slotnick, D. L., and Stockes, R. A. "The ILLIAC IV Computer." IEEE Transactions on Computers, Vol. C-17, pp 746-757, August 1968.

4.10. Basili, V. R. "Language as a Tool for Scientific Programming." Computer Science and Scientific Computing; Proceedsings of the Third Conference, p 1-23, Academic Press, New York, 1976.

4.11. Batcher, K. E. "The FLIP Network in STARAN." Goodyear Aerospace Corporation Working paper.

4.12. Batcher, K. E. "The Multidimential Access Memory in STARAN." IEEE Transactions on Computers, Vol. C-26, pp 174-177, 1977.

4.13. Berg, R., et al. "PEPE--An Overview of Architecture, Operations, and Implementation." Proceedings, National Electronics Conference, IEEE, New York, pp 312-317, 1972.

4.14. Bernitt, D. J. "Instrumentation Applications of Minicomputers in Aircraft Technology." Proceedings, 8th International Aerospace Instrumentation Symposium, Cranfield, Beds., England, March 24-27, 1975.

4.15. Bernstein, S. and Joppa, R. G. "The Numerical Computation of the Transonic Flow over Afterbodies Including the Effect of Jet-Plume and Viscous Interactions." AIAA Paper No. 75-62, AIAA 13th Aerospace Sciences Meeting, Pasadena, CA, 1975

4.16. Bloch, E. and Galage, D. J. "Component Progress: Its Effect on High Speed Computer Architecture and Machine Organization." Talk presented at University of Illinois Symposium for Parallel Computation, April 1977.

4.17. Boutier, A. "Data Processing in Laser Anemometry." Conference Generale Sur L: Anememetrie Laser, Saint-Louis, Haut-Rhin, France, May 1976.

4.18. Brailovskaya, I. "A Difference Scheme for Numerical Solution of the Two-Dimensional Non-stationary Navier-Stokes Equations for a Compressible Gas." Soviet Physics, Doklady, Vol. 10, pp 107-110, 1965.

4.19. Brent, R. "The Parallel Equation of Arithmetic Expressions in Logarithmic Time." Complexity of Sequential and Parallel Numerical Algorithms, J. F. Traub, Ed., Academic Press, 1973.

4.20. Browne, J. C. "Data Definition Structures, and Management in Scientific Computing." Computer Science and Scientific Computing; Proceedings of the Third Conference, pp 25-56, Academic Press, New York, 1976.

4.21. Brubaker, W. and Franks, J. "Parallel Processing--An Approach to Large Scale Numerical Problem Solution in Real-Time." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.22. Bulman, D. M. "Stack Computers." Computer, pp 14-16, May 1977.

4.23. Bulman, D. M. "Stack Computers: An Introduction." Computer, pp 18-28, May 1977.

4.24. Buzbee, B. L. "A Fast Poisson Solver Amenable to Parallel Computation." IEEE Trans. Computers, Vol. C-22, pp 793-796, 1973.

4.25. Buzbee, B. L., Golub, G. H., and Nielson, C. W. "On Direct Methods for Solving Poisson's Equation." SIAM Journal of Numerical Analysis, Vol. 7, pp 627-656, 1970.

4.26. Calahan, D. A., Joy, W. N., and Orbits, D. A. "Preliminary Report on Results of Matrix Benchmarks on Vector Processors." Systems Engineering Laboratory Report, No. 94, University of Michigan, Ann Arbor Michigan.

4.27. Cambra, J. M. "The Revolution in Data Gathering Systems." ICIASF '75 Record, Ottawa Canada, pp 1-25, 1975.

4.28. Cambra, J. M. and Tolari, G. P. "Real Time Computer Data System for the 40 x 80 ft Wind Tunnel Facility at Ames Research Center." Instrumentation in Aerospace Industry, Vol. 20, pp 345-370, 1974.

4.29. Cambra, J. M. and Trover, W. F. "The Revolution in Data Gathering Systems--Mini and Microcomputers in NASA Wind Tunnels." 1975--ICIASF, Ottawa, Canada, September 22-24, 1975.

4.30. Carnahan, B., Luther, H. A., and Wilkes, J. O. Applied Numerical Methods. John Wiley & Sons, Inc., New York, 1969.

4.31. Chapman, D. R., Mark, H., and Pirtle, M. W. "Computers vs. Wind Tunnels for Aerodynamic Flow Simulations." Astronautics & Aeronautics, pp 22-35, April 1975.

4.32. Computational Fluid Dynamics Branch, CFD--A Fortran Based Language for ILLIAC IV, internal paper, NASA Ames Research Center, 1973.

4.33. Cray Research, Inc. "Cray-1 Computer System: An Introduction to Vector Processing." Pub. No. 2240002A, 1977.

4.34. Control Data Corporation, Control Data STAR-100 Computer, Features Manual, 1975.

4.35. Cooley, J. W. and Tukey, J. W. "An Algorithm for Machine Calculation of Complex Fourier Series." Math. Comp., Vol. 19, pp 297-301, 1965.

4.36. Cornell, J. A. "PEPE in Fluid Dynamics Applications." SDC Internal Working Paper, September 22, 1976.

4.37. Cray Research, Inc. "Cray-1 Computer System Reference Manual." Pub. No. 2240004, 1976.

4.38. Cray Research, Inc. "Cray-1 Computer System, Preliminary CRAY-1 FORTRAN (CFT) Reference Manual." Pub. No. 2240009, 1977.

4.39. Cray Research, Inc. "The Cray-1 Computer System." Pub. No. 224008A, 1976.

4.40. Croll, R. H. and Peterson, C. W. "A Laser Velocimeter DAta Acquisition, Processing, and Control System." 1975 ICIASF, Ottawa, Canada, September 22-24, 1975.

4.41. daCosta, A. L. "Application of Aerodynamic Computational Methods to the Design and Analysis of Aircraft." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.42. Dayman, B., Jr. and Fiore, A. W. "Aerodynamic Testing and Simulation: Saving Lives, Time, and Money." Astronautics and Aeronautics, pp 56-61, June 1974.

4.43. Dean, G. W. and White, S. W. "Data Acquisition and Processing in the NGTE Altitude Test Facility." ASME Paper 75-GT-124, 1975.

4.44. El-Ramly, Z. M. and Rainbird, W. T. "Computer-Controlled System for the Investigation of the Flow Behind Wings." Journal of Aircraft, Vol. 14, pp 668-674, 1977.

4.45. Elrod, T. H. "The CDC 7600 and SCOPE 76." Datamation, pp 80-85, April 1970.

4.46. Enslow, P. H., Jr. "Multiprocessor Organization--A Survey." ACM Computing Surveys, Vol. 9, pp 103-129, March 1977.

4.47. Falk, H. "Computers: All Pervasive." IEEE Spectrum, pp 38-43, January 1977.

4.48. Falk, H. "Reaching for a Gigaflop." IEEE Spectrum, Vol. 13, pp 65-69, October 1976.

4.49. Feng, T. "An Overview of Parallel Processors and Processing." ACM Computing Surveys, Vol. 9, pp 1-2, March 1977.

4.50. Ferri, A., Elzweig, S., and Baronti, P., "Numerical Solution of Transonic Flows about Quasi-Cylindrical Configurations." AIAA Journal, Vol. 12, pp 1447-1448, 1974.

4.51. Ferziger, J. H. "Large Eddy Numerical Simulation of Turbulent Flows." AIAA Paper No. 76-347, July 1976.

4.52. Finger, H. J. and Cambra, J. M. "A Computer-Controlled, One-Board Data Acquisition System for Wind Tunnel Testing." ITC Los Angeles, CA, pp 337-346, 1974.

4.53. Flynn, M. "Some Computer Organizations and Their Effectiveness." IEEE Transactions of Computing, Vol. C-21, pp 948-960, 1972.

4.54. Fox, L. "Introductory Numerical Analysis." Proceedings, 1974 Institute of Mathematics and its Applications Conference on Computational Methods and Problems in Aeronautical Fluid Dynamics, University of Manchester, England, pp 15-52, 1976.

4.55. Freuler, R. J. "State-of-the-Art Data Acquisition and Reduction Techniques for Transonic Airfoil Testing." ICIASF '75 Record, Ottawa, Canada, pp 67-75, 1975.

4.56. Fuijleschot, P.H. "EGOIST--The NLR Approach to Wind Tunnel Data Systems." 1975 ICIASF, Ottawa, Canada, September 22-24, 1975.

4.57. Fulton, R. E. and Voigt, S. J. "Computer-Aided Design and Computer Science Technology." Computer Science and Scientific Computing; Proceedings of the Fluid Conference, pp 57-82, Academic Press, New York, 1976.

4.58. Fung, H. S. and Yau, S. S. "Associative Processor Architecture-- A Survey." A. C. M. Computing Surveys, Vol. 9, pp 3-28, March 1977.

4.59. Gamelin, P. A. "STARAN as a Space Computation Center (SCC) Processing Alternative." MITRE Corporation Report No. MTR 2836, June 1974.

4.60. Garabedian, P. R. and Korn, D. G. "Analysis of Transonic Airfoils." Communication of Pure and Applied Mathematics, Vol. 24, pp 841-862, 1971.

4.61. Gelbach, H. R., Willsie, H. D., and Luick, R. E. "A Near Real Time Data Acquisition/Reduction Facility for the Boeing Wind Tunnels." Instrumentation in Aerospace Industry, Vol. 18, pp 199-204, 1972.

4.62. George, J. A. "An Efficient Band-Oriented Scheme for Solving n by n Grid Problems." Proceedings of the Fall Joint Computer Conferences, pp 1317-1320, 1972.

4.63. Gilmore, P. "Numerical Solution of Partial Differential Equations by Associative Processing." Proceeding; 1971 FJCC, AFIPS Press, Montvale, New Jersey, pp 411-418, 1971.

4.64. Goodyear Aerospace, The STARAN E System Overview, Working Paper No. AP-123226, September 29, 1976.

4.65. Goodyear Aerospace, STARAN--A New Class of Computer, System Description, 1977.

4.66. Goodyear Aerospace, STARAN Reference Manual, GER-15636A, September 1973.

4.67. Greenspan, D. "Numerical Studies of Viscous Incompressible Flow for Arbitrary Reynolds Number." University of Wisconsin, Computer Science Technical Report 11, 1968.

4.68. Grossman, B. and Melnik, R. E. "The Numerical Computation of the Transonic Flow over Afterbodies Including the Effect of Jet-Plume and Viscous Interactions." AIAA Paper No. 75-62, January 1975.

4.69. Guarino, J. F. "Instrumentation and Data Acquisition Systems." NASA Workshop held at Langley Research Center, NASA-CP-2009, October 1976.

4.70. Gunn, J. A. and Christopher, J. P., Jr. "Automatic Control of a Transonic Wind Tunnel with a Real-Time Computer System." AGARD Conference on Numerical Methods and Wind Tunnel Testing AGARD-CP-210, Ref. 8, October 1976.

4.71. Hakkinen, R. J. "Experiment vs. Computation in Fluid Dynamics--Computation or Corroboration?" Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.72. Hanff, E. S. "An Economical High Speed Data Acquisition and Processing System for Wind Tunnel Experiments." ICIASF '73 Record, pp 252-256, 1973.

4.73. Hawkins, C. J. B. and Partridge, D. W. "An Advanced Computer System for Wind Tunnel Test." Proceedings; 90th Seminar Digital Equipment Computer Users Society, 1974.

4.74. Hendrickson, R., Puglisi, C., and Russell, R. "Cray I Vector Processor and Future Development." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.75. Henle, R. A., et al. "The Application of Transistor Technology to Computers." IEEE Transactions on Computers, Vol. C-25, pp 1289-1303, 1976.

4.76. High, M. D. "Experimental Data and Acquisition Systems--Present and Future Requirements." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.77. Hitch, H. P. Y. "Practical Requirements in Industry." Proceedings, 1974 Institute of Mathematics and its Applications Conference on Computational Methods and Problems in Aeronautical Fluid Dynamics, University of Manchester, England, 1976.

5.78. Institute for Advanced Computation, A Prospectus for High Speed Computing, Phoenix Project memorandum number 006, February 25, 1977.

4.79. Jameson, A., Rubbert, P. E., Smith, A. M. D., and Yoshihara, H. "Applied Computational Aerodynamics." AIAA Professional Study Series, Albuqueraue, N. M., June 1977.

4.80. Judd, M., Goodyer, M. J., and Wolf, S. W. D. "Applications of the Computer for on-site Definition and Control of Wind Tunnel Shape for Minimum Boundary interference." AGARD Conference on Numerical Methods and Wind Tunnel Testing Ref. 6, October 1976.

4.81. Jurgen, R. K. "Independent R & D: Three Viewpoints." IEEE Spectrum, pp 50-53, November 1976.

4.82. Kalb, H. T. and Cline, V. A. "New Techniques in the Processing and Handling of Laser Velocimeter Burst Data." Review of Scientific Instruments, Vol. 47, pp 708-711, June 1976.

4.83. Keller, T. W. Cray-1 Evaluation Final Report, Los Alamos Scientific Laboratory Informal Report LA-6456-MS, December 1976.

4.84. Kelley, M. W., Dickinson, S. O., and Maynard, E. E. "Applications of the Real-Time Data Analysis System in the Ames 40 x 80 ft Wind Tunnel." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 3, October 1976.

4.85. Knight, J., Poole, W., and Voight, R. "System Balance Analysis for Vector Computers." Proceedings 1975 ACM National Conference, pp 163-168, 1975.

4.86. Kock, W. E. "Optical Computing, an Example of Change." Proceedings of the IEEE, Vol. 65, pp 6-9, January 1977.

4.87. Kuck, D. J. "ILLIAC IV Software and Applications Programming." IEEE Transactions on Computers, Vol. C-17, pp 758-770, August 1968.

4.88. Kuck, D. J. "Supercomputers for Ordinary Users." Proceedings I, 1972 AFIPS Conference, Vol. 41, 1972.

4.89. Kuck, D. J. "A Survey of Parallel Machine Organization and Programming." ACM Computing Surveys, Vol. 9, pp 29-60, March 1977.

4.90. Kuck, D. J., Chen, S-C., and Muraoka, Y. "On the number of Operations Simultaneously Executable in FORTRAN-like Programs and their Resulting Speedup." IEEE Transactions on Computers, Vol. C-21, pp 1293-1310, December 1972.

4.91. Lambiotte, J. and Voigt, R. "The Solution of Tridiagonal Linear Systems on the CDC STAR-100 Computer." ACM Transactions Math. Software, Vol. 1, pp 308-329, 1975.

4.92. Lawrie, D. "Thoughts Regarding a Gigaflop Computer." Private Communication.

4.93. Lawrie, D. H., Layman, T., Baer, D., and Randal, J. M. "Glypnir-- A Programming Language for ILLIAC IV." Communication of the ACM, Vol. 18, pp 157-164, March 1975.

4.94. Lawrie, D. H. "Memory Systems for Parallel Array Processors" Proceeding Eleventh Annual Allerton Conference of Circuit and System Theory Allerton House, Monticello, IL, pp 568-576, 1973.

4.95. Lax, P. D. and Wendroff, B. "Systems of Conservation Laws." Communications of Pure & Applied Math., Vol 13, pp 217-237, 1960.

4.96. LeCann, R. P. "The Benefits of Real Time Computer Analysis of Experimental Aircraft Test Data." Proceedings, 8th International Aerospace Instrumentation Symposium , Cranfield, Beds., England, March 24-27, 1975.

4.97. Leithe, C. E. "Some Aspects of Computing with Array Processing." Atmospheric Technology, pp 21-25, September 1973.

4.98. Li, H. F. "A Structured Study of Parallel Pipeline Systems, Ph.D. Thesis, California University, Berkeley.

4.99. Lo, C. F. and Kraft, E. M. "Convergence of the Adaptive Wall Wind Tunnel." to be published in AIAA Journal, 1977.

4.100. Lomax, H. "Turbulence and Numerical Wind Tunnels." Computer Science and Scientific Computing; Proceedings of The Third Conference, pp 127-153, Academic Press, New York, 1976.

4.101. Lomax, H. "Recent Progress in Numerical Techniques for Flow Simulation." AIAA Journal, Vol. 14, pp 512-518, 1976.

4.102. Lomax, H. "Recent Progress in Numerical Techniques for Flow Simulation." Proceedings II, 1972 AFIPS Conference, Vol. 41, 1972.

4.103. MacCormick, R. W. "An Efficient Numerical Method for Solving the Time-Dependent Compressible Navier-Stokes Equations at High Reynolds Number." NASA TMX-73, 129, 1976.

4.104. MacCormick, R. W. and Baldwin, B. S. "A Numerical Method for Solving the Navier-Stokes Equations with Application to Shock-Boundary Layer Interaction." AIAA Paper 75-1, January 1975.

4.105. MacCormick, R. W. and Stevens, K. G. "Fluid Dynamics Application of the ILLIAC IV Computer." Proceedings, 1974 Institute of Mathematics and its Applications Conference on Computational Methods and Problems in Aeronautical Fluid Dynamics, Univ. of Manchester, England, pp 448-465, 1976.

4.106. Mack, L. M. "Linear Stability Theory and the Problem of Supersonic Boundary-Layer, Transition." AIAA Journal, Vol. 13, p 278, 1975.

4.107. Madnick, S. E. "Trends in Computers and Computing--The Information Utility." Science, Vol. 195, pp 1191-1199, March 18, 1977.

4.108. Marcal, P. V. "General Purpose Program for Finite Element Analysis--Some Computational Considerations," Computer Science and Scientific Computing; Proceeding of the Fluid Conference, pp 155-162, Academic Press, New York, 1976.

4.109. Martin, H. G. "A Discourse on a New Super Computer, PEPE." System Development Corp. Working Paper.

4.110. Marvel, O. E. "PIRATE--Pipeline Infra-red Array Track Electronics Dynamic Ordered File Processing Architecture." Proceedings, IEEE Region 3 Conference, Orlando, FL, 1974.

4.111. Marvin, J. G. "Experiments Planned Specifically for Developing Turbulence Models in Computations of Flow Field around Aerodynamic Shapes." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 14, October 1976.

4.112. McHugh, D. "New Computer Architecturial Concepts for Super Computers." Presentations for AFOSR Summer Study Design Program, UTSI, 1977.

4.113. McIntyre, D. E. "An Introduction to the ILLIAC IV Computer." Datamation, pp 60-67, April 1970.

4.114. McKay, J. M. and Martin, H. G. "Paraller-Element Processing Ensemble (PEPE)." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.115. McLean, J. B. "Three-Dimensional Turbulent Boundary Layer Calculations for Swept Wings." AIAA Paper No. 77-3, January 1977.

4.116. McLean, J. D. "Three-Dimensional Turbulent Boundary Layer Calculations for Sweep Wings." AIAA Paper No. 77-3, AIAA 15th Annual Aerospace Science Meeting, Los Angeles, CA, January 1977.

4.117. Michellich, M. O. "A Modular Design for Standardization of Digital Test Data and Control Systems." Instrumentation in Aerospace Industry, Vol. 20, pp 377-384, 1974.

4.118. Milhram, G. A. "Simulation: Statistical Foundations and Methodology." Academic Press, Inc., New York, 1972.

4.119. Miller, W. "Software for Roundoff Analysis." ACM Trans. on Math., Software, Vol. 1, pp 108-128, 1975.

4.120. Miranker, W. "A Survey of Parallelism in Numerical Analysis." SIAM Reviews, Vol. 13, pp 524-547, 1971.

4.121. Murine, G. E. "The Role of the Microprocessor in Real-Time Preprocessing of Multispectral Scanner Data." Proceedings, Seminar on Advances in Image Transmission Techniques, San Diego, CA, August 1976.

4.122. Murphy, J. O. and Wade, R. M. "The IBM 360/195." Datamation, pp 72-79, April 1970.

4.123. North, R. J., Partridge, D. W., and Brown, E. C. "A Multicomputer Instrumentation System for a New Pressurized Low Speed Wind Tunnel." ICIASF '73 Record, pp 262-271, 1973.

4.124. Ortega, J. M. and Voigt, R. G. "Solution of Partial Differential Equations on Vector Computers." ICASE Report NO. 77-7, 1977 Army Numerical Analysis and Computer Conference, March 1977.

4.125. Palco, R. L. "Computer Oriented Testing Capabilities and Techniques Development in the Propulsion Wind Tunnel Facility (PWT) at the AEDC." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.126. Pate, S. R. "Supersonic-Hypersonic Experimental Aerodynamics Testing Techniques." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.127. Paul. G., Jr. "Scientific Computer and Vector Processing--An Outlook" Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.128. Paul, G., Jr. and Wilson, M. W. "The Vector Language: An Experimental Language for Vector/Matrix Array Processing." IBM Working Document, Palo Alto, CA.

4.129. Pease, M. "An Adaptation of the Fast Fourier Transform for Parallel Processing." Journal of the ACM, Vol. 15, pp 252-264, 1968.

4.130. Peterson, V. L. "Status of Advanced Techniques in Computational Aerodynamics and the Next Major Step." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.131. Phillips, R. L. "Software Tools for Computer Graphics." Computer Science & Scientific Computing; Proceedings of the Third Conference, pp 205-226, Academic Press, New York, 1976.

4.132. Pindzola, M. "Propulsion Testing." Astronautics & Aeronautics, pp 63-66, July/August 1974.

4.133. Poole, W. and Voight, R. "Numerical Algorithms for Parallel and Vector Computers: An Annotated Bibliography." Computing Reviews, Vol. 15, pp 379-388, 1974.

4.134. Prichard, G. D. "A Central Controller/Display System with Real Time Processing for Remote Data Acquisition Units." ITC Los Angeles, CA, 1974.

4.135. Ramamoorthy, C. V. and Li, H. F. "Pipeline Architecture." ACM Computing Surveys, Vol. 9, pp 61-102, March 1977.

4.136. Reddi, S. S. and Teustel, E. D. "A Conceptual Framework for Computer Architecture." ACM Computing Surveys, Vol. 8, pp 277-300, June 1976.

4.137. Reynolds, P. A. "Flight Simulating." Astronautics & Aeronautics, pp 58-63, July/August 1974.

4.138. Roache, P. J. Computation Fluid Dynamics, N. M., 1972.

4.139. Rogler, H. L. and Reshotko, E. "Disturbances in a Boundary Layer Introduced by a Low Intensity Array of Vortices." SIAM Journal of Applied Mathematics, Vol. 28, p 431, 1975.

4.140. Rudolph, J. A. "A Production Implementation of an Associative Array Processor--STARAN." Proceedings I, 1972 AFIPS Conference, Vol. 41, 1972.

4.141. Rumbaugh, J. "A Data Flow Multiprocessor." IEEE Transactions on Computers, Vol. C-26, pp 138-146, February 1977.

4.142. Sammet, J. Programming Language: History and Fundamentals. Prentice-Hall, Englewood Cliffs, N. J., 1969.

4.143. Sandborn, V. A. "Limitations of Measurement and Analysis in Non-equilibrium Turbulent Boundary Layers, Including Separation." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.144. Schaefer, D. H. and Strong, S. P. III. "TSE Computers--Ultra-light Speed Optical Processing for Two Dimensional Binary Image." Proceedings of the IEEE, Vol. 15, pp 129-138, January 1977.

4.145. Scharf, L. L. and Moose, P. W. "Information Measures and Performance Bounds for Array Processors." IEEE Transactions on Information Theory, Vol. IT-22, pp 11-21, January 1976.

4.146. Sears, W. R. "Some Experiences with the Extrapolation of Measurements of the Perlubation Field in a Wind Tunnel to Improve Simulation." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 5, October 1976.

4.147. Sheffield, R. W. and Orbock, D. "Space Simulation." Astronautics & Aeronautics, pp 67-69, July/August 1974.

4.148. Slooff, J. W. "Wind Tunnel Tests and Aerodynamic Computations: Thoughts on Their Use in Aerodynamic Design." AGARD Conference on Numerical Methods and Wind Tunnel Testing, AGARD-CP-210, Ref. 11, October 1976.

4.149. Somerville, A. J. "Computer Controls of the General Dynamics High Speed Wind Tunnel." Instrumentation in Aerospace Industry, Vol. 18, pp 183-187, 1972.

4.150. Spalding, D. B. "Numerical Computation of Steady Boundary Layers--A Survey." Proceedings, 1974 Institute of Mathematics and its Applications Conference on Computational Methods and Problems in Aeronautical Fluid Dynamics, University of Manchester, England, pp 466-491, 1976.

4.151. Stevenson, D. "Bibliography of Phoenix Project Memoranda." Private Communication.

4.152. Stevenson, D. "Probable Trends in High Performance Computing in the 1980-1990 Era." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.153. Stillman, N. J. "A Feasibility Study of the Applicability of a Hardware Associative Memory to Computer Graphics." Ph.D. Dissertation, Syracuse, University, Syracuse, New York, 1972.

4.154. Stillman, N. J. and Berra, P. B. "A Comparison of Hardware and Soft-ware Associative Memories in the Context of Computer Graphics." Communication of the ACM, Vol 20, pp 331-339, 1977.

4.155. Stone, H. "An Efficient Parallel Algorithm for the Solution of a Tridiagonal Linear System of Equations." Journal of the ACM, Vol. 20, pp 27-38, 1973.

4.156. Stone, H. "Computer Architecture in the 1980's" Proceedings of the Third ICASE Conference on Scientific Compiling: Computer Science and Scientific Computing, Academic Press, New York, pp 255-281, 1976.

4.157. Stone, H. "Parallel Processing with the Perfect Shuffle." IEEE Trans. Computers, Vol. C-20, pp 153-161, 1971.

4.158. Stone, H. "Problems of Parallel Computation." Complexity of Sequential and Parallel Numerical Algorithms, Academic Press, New York, pp 1-16, 1972.

4.159. Stout, G. and Johnson, W. "Burroughs Corporations--Large Computer Systems." Presentation for AFOSR Summer Study Design Program, UTSI, 1977.

4.160. Strang, G. and Fix, G. F. An Analysis of the Finite Element Method, Prentice-Hall, Englewood Cliffs, NJ, 1973.

4.161. Stroke, G. W. "Optical Computing." IEEE Spectrum, Vol. 9, pp 24-41, December 1972.

4.162. Strong, J. P. III "TSE Computers--A Means for Massively Parallel Computations." Proceedings, Seminar on Optical Information Processing--Real-Time Devices and Novel Techniques, San Diego, CA, August 24-25, 1976.

4.163. System Development Corporation. PEPE Development Program. March 4, 1975.

4.164. System Development Corporation. PEPE Hardware Reference Manual, February 1, 1977.

4.165. Taylor, C. and Hood, P. "A Numerical Solution of the Navier-Stokes Equations Using the Finite Element Technique," Computers and Fluids, Vol. 1, pp 73-100, 1973.

4.166. Thurber, K. J. and Wald, L. D. "Associative and Parallel Processors." Computing Survey, Vol. 7, pp 215-255, 1975.

4.167. Titchener, I. M. and Pecover, B. E. "An Integrated Facility for the Simulation of some Non-Linear Flight Dynamics Problems." ICIASF 1971 Record, IEEE Transactions on Aerospace and Electronic Systems, p 105, 1971.

4.168. Wachowski, T. J. "Services of the Institute for Advanced Computing (IAC)." Private communication,

4.169. Wakefield, R. M. and Pearson, B. D., Jr. "A Description of a General Use Automated Data Reduction System." ICIASF 1973 Record, pp 257-260, 1973.

4.170. Wambold, J. C. and Park, W. H. "A Data Processing Method Using a Better Physical Description of Random Signals." Instrumentation in the Aerospace Industry, Vol. 20, pp 371-376, 1974.

4.171. Watson, W. J. "The TI-ASC--A Highly Modular and Flexible Super Computer Architecture." Proceedings I, 1972 AFIPS Conference, Vol. 41, 1972.

4.172. Way, J. L. "Applications in Fluid Mechanics Research of a Portable Data Acquisition and Processing System." 1975 ICIASF, Ottawa, Canada, September 22-24, 1975.

4.173. Welch, H. O. "GFDL Benchmark." SDC Internal Working Paper, November 5, 1976.

4.174. White, F. M. "Viscous Fluid Flow, McGraw Hill, New York, 1974

4.175. Whitfield, J. D. "Ground Testing and Simulation: Key to Efficient Development of Aerospace Systems." Astronautics & Aeronautics, pp 54-55, June 1974.

4.176. Whitfield, J. D. and Potter, J. L. "Simulating High-Speed Aerodynamics." Space/Aeronautics, pp 83-91, March 1967.

4.177. Wulf, W. A. "Minicomputer Complexes--Progress and Prospects." Proceedings, Third Conference on Computer Science and Scientific Computing, Williamsburg, VA, April 1-2, 1976.

4.178. Wulf, W. A. and Bell, C. G. "C. MMP--A Multi-Mini Processor." Proceedings II, 1972 AFIPS Conference, Vol. 41, 1972.

4.179. Xerikos, J. "Applications of Contemporary Computational Techniques to Aerospace Vehicle Design." Presentation for AFOSR Summer Study Design Program, 1977.

4.180. Yasaki, E. K. "Super-Super Computer." Datamation, pp 150-152, March 1977.

4.181. Graham, W. F. "The Parallel and the Pipeline Computer." Datamation, pp 68-71. April 1970.

Outline of AFOSR-ASEE-UTSI-AEDC Summer Faculty Program
June 13 - August 19, 1977

WEEK 1

Monday, June 13

AM 1. 9:00--Welcome of Participants and Observers--Dean Charles Weaver, UTSI

2. Introduction of AEDC, ARO, and UTSI Personnel:
Dr. Leith Potter, ARO, Inc.
Mr. Ross Roepke, USAF/AEDC

3. Outline of Program Objectives--Panel Assignments: Dr. Bernard Marschner, UTSI

4. Introductory Lecture on Theoretical Background on Fluid Mechanics and Aerodynamics: Dr. James Wu, UTSI

PM 1. 1:30--Introduction to Concepts of Boundary Layer, Turbulence, and Separation: Dr. Trevor Moulden, UTSI

2. 3:30--"Aerodynamic Problems in the Development of Air Vehicles across the Speed Regimes" Dr. J. L. Potter, ARO, Inc.

Tuesday, June 14

AM 1. 9:00--"Status of the Art in the Acquisition of Aerodynamic Data by Experimental Methods" Dr. Michael High and Dr. Sam Pate of ARO, Inc.

2. 10:30--Introductory Lecture on Numerical Methods and Background in Solutions of Partial Differential Equations: Dr. Ken Kimble, UTSI

PM 1. Working Panel Meetings

2. 4:30--Reception for participants at Officer's Open Mess

Wednesday, June 15

AM 1. 9:00--"Current Methods, Problems, and Progress on Finite Differences and Finite Elements for the Numerical Solution of Partial Differential Equations" Dr. Ken Kimble, UTSI

2. "Overview of Computer Architecture Concepts" Dr. Bernard Marschner, UTSI

PM 1. Working Panel Meetings

Thursday, June 16

AM 1. 9:00--"Computational Aerodynamics Dr. John Adams, ARO, Inc.

2. Working Panel Meetings

PM 1. Working Panel Meetings

Friday, June 17

AM 1. 9:00--"New Approaches to Experimental Aerodynamics Facilities"
Dr. Wendell Norman, ARO, Inc.

2. Working Panel Meeting

PM 1. Working Panel Report Presentations
a. progress
b. recommendations for study procedure

WEEK 2

Monday, June 20

AM 1. Presentation of a review of a technical report by a
Summer Study Participant

2. Working Panel Meeting

PM 1. Working Panel Meeting

Tuesday, June 21

1. Tour of AEDC

2. Present Facility Briefing

3. Facility Planning Briefing: Mr. R. O. Dietz, USAF/AEDC

Wednesday, June 22

AM 1. 9:00--Presentation of a review of a technical report by a
Aummer Study Participant

2. Working Panel Meeting

PM 1. Working Panel Meeting

Thursday, June 23

AM 1. 9:00--"Computational Experimental Aerodynamic Testing"
Dr. James Xerikos, McDonnell-Douglas

PM 1. Working Panel Meetings

Friday, June 24

AM 1. "Limitations in Measure and Analysis in Non-Equilibrium Flows Including Separation" Dr. Virgil Sandborn, CSU

PM 1. Working Panel Meeting

2. 3:00--Panel Progress Presentations and Discussions

WEEK 3

Monday, June 27

AM 1. 9:00--"Computational and Experimental Aerodynamic Data in the Design of Aircraft" Dr. Larry daCosta, Boeing

PM 1. Working Panel Sessions

Tuesday, June 28

AM 1. 9:00--"Status of Advanced Techniques in Computational Aerodynamics and the Next Major Step" Dr. Victor Peterson, NASA-Ames

PM 1. 1:30--"Future Computer Capabilities" Dr. F. R. Bailey, NASA-Ames

Wednesday, June 29

AM 1. Working Panel Sessions

PM 1. Working Panel Sessions

Thursday, June 30

AM 1. Working Panel Meeting

PM 1. Working Panel Meeting

Friday, July 1

AM 1. Working Panel Meetings

PM 1. Working Panel Meetings

2. Presentation of Working Panel Reports

WEEK 4

Tuesday, July 5

AM 1. Working Panel Meeting

PM 1. Working Panel Meeting

Wednesday, July 6

AM 1. 9:00--Control Data Corporation: Mr. Dick McHugh

PM 1. Working Panel Meeting

Thursday, July 7

AM 1. Institute for Advanced Computation: Mr. Thomas Wachowski

PM 1. Working Panel Meeting

Friday, July 8

AM 1. 9:00--"Experiences in Experimental and Computational Aerodynamics"
Dr. Raimo Hakkinen, McDonnell-Douglas

PM 1. Working Panel Meeting

2. 3:00--Presentation of Working Panel Reports

WEEK 5

Monday, July 11

AM 1. Cray Research, Inc.: Dr. Richard Hendrickson, Dr. Charles Puglisi, and Dr. Richard Russell

PM 1. Working Panel Meetings

Tuesday, July 12

AM 1. Goodyear Aerospace Corporation: Mr. Wayne Brubaker

PM 1. Working Panel Meetings

Wednesday, July 13

AM 1. Review of panel presentations for Steering Committee

PM 1. Working Panel Meetings

Thursday, July 14

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meeting

Friday, July 15

AM 1. Lockheed-Georgia Company: Mr. Jack Patterson

PM 1. Working Panel Meeting and review of progress report presentation

Sunday, July 17

7:30 p.m.: Presentation of Progress Report to Steering Committee
- a. Technical Director
- b. Working Panel Chairmen

WEEK 6

Monday, July 18

AM 1. Meetings with Steering Committee

PM 1. Meetings with Steering Committee

Tuesday, July 19

AM 1. "Techniques and Effectiveness of Programming Strategies for High Speed Computers" Dr. D. H. Lawrie, University of Illinois, Urbana, Champaign

PM 1. Working Panel Meeting

Wednesday, July 20

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Group Meeting

2. Review of Steering Committee Recommendations

Thursday, July 21

AM 1. Schedule review meeting reassignment of membership in working panels

PM 1. Working Panel Meeting

Friday, July 22

AM 1. 9:00--Presentation of a review of a technical report by a Summer Study Participant

2. Working Panel Meeting

PM 1. Presentation of new working panel schedules and study plans

WEEK 7

Monday, July 25

AM 1. 9:00--Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meeting

Tuesday, July 26

AM 1. BMDATC-P: Mr. Joe McKay
Systems Development Corporation: Mr. Hiram Martin

PM 1. Working Panel Meeting

Wednesday, July 27

AM 1. Wright Patterson Air Force Base: Dr. Thomas Weeks

2. Working Panel Meeting

PM 1. Working Panel Meeting

Thursday, July 28

AM 1. Burroughs, Inc.: Mr. Gordon Stout and Mr. W. Johnwon

PM 1. Working Panel Meeting

Friday, July 29

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Presentation of Draft Outline of Report by Working Panel

WEEK 8

Monday, August 1

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meetings

Tuesday, August 2

AM 1. Presentation of local resource speakers selected by a working panel

PM 1. Working Panel Meeting

Wednesday, August 3

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meeting

Thursday, August 4

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meetings

<u>Friday, August 5</u> (First Draft of Final Report Due)

AM 1. Working Panel Meetings

PM 1. Working Panel Meetings

<u>WEEK 9</u>

<u>Monday, August 8</u>

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Review of First Draft Reports Due

<u>Tuesday, August 9</u>

AM 1. Presentation of local resource speaker selected by a working panel

PM 1. Working Panel Meeting

<u>Wednesday, August 10</u>

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Working Panel Meetings

<u>Thursday, August 11</u>

AM 1. IBM of New York: Dr. George Paul

PM 1. Panel Reviews of Draft Report

<u>Friday, August 12</u>

AM 1. Presentation of a review of a technical report by a Summer Study Participant

PM 1. Submittal of reviews of Second Draft of Report

WEEK 10

Monday, August 15

AM 1. Panel Meeting

PM 1. Panel Meeting

Tuesday, August 16

AM 1. Panel Meeting

PM 1. Panel Meeting

Wednesday, August 17

AM 1. Review of Final Reports by Panel

PM 1. Review of Final Reports by Panel

2. Practice of Presentation for Steering Committee

Thursday, August 18

AM 1. Formal Presentation to Steering Committee

PM 1. Critique of Report by Steering Committee

Friday, August 19

AM & PM Corrections of Report by Panel

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AFOSR SUMMER STUDY DESIGN LECTURE

"Scientific Computing, Vector Processing, and Outlook"

by

Dr. George Paul

Dr. George Paul, Industry Administrator for Scientific Computing with IBM in New York, will present a lecture to the AFOSR Summer Study Participants on Thursday, August 11, 1977 at 9:00 a.m. Dr. Paul obtained his B. S. in Mathematics from Rice University as well as his Ph.D. in Electrical Engineering from Rice. An outline of his lecture is as follows:

1. Scientific Performance
2. Performance Measurements
3. Future Trends
4. Design Principles
5. Vector Architecture
6. High Level Language Support
7. Restructuring
8. Compact Technology Trends

LECTURE DATE: Thursday, August 11, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

by

Mr. G. Stout
Mr. W. Johnson

A lecture presented by Mr. G. Stout and Mr. W. Johnson of Burroughs Corporation is scheduled for Thursday, July 28, 1977 at 9:00 a.m. in the Short Course Room at UTSI. The two gentlemen will give an overview of possible solutions to the high-speed computation problem. A review of BSP (Burroughs Scientific Processor) will also be given. The Burroughs Corporation is a contractor to NASA-Ames for the initial study on the Computational Fluid Dynamics machine. Anyone who is interested is invited to attend the lecture.

LECTURE DATE: Thursday, July 28, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

by

Dr. Thomas Weeks

Dr. Thomas Weeks of Wright-Patterson Air Force Base in Ohio will present a lecture at UTSI on Wednesday, July 27, 1977 at 9:00 a.m. Dr. Weeks will discuss the following topics: transonic wind tunnel adaptive wall, Reynolds number sensitive phenomena, and procedures for extrapolating wind tunnel tests to flight Reynolds numbers, as well as the Flight Dynamics Laboratory experience with some of the aerodynamic computational codes. Anyone who is interested is invited to attend the lecture.

LECTURE DATE: July 27, 1977 (Wednesday), 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Parallel-Element Processing Ensemble (PEPE)"

by

Mr. J. M. McKay
Mr. H. G. Martin

The associative parallel array concept will be developed and the current architecture will be presented. The unique features of the architecture and the impact of these features on applications and application's software will be emphasized. The parallel Fortran (PFOR) language that has been developed along with complete support software system will be presented. Emphasis in the software area will be on the software tools and programming--methods that will allow the potential user to utilize the inherent computing power of the machine. Various classes of applications benchmarks will be discussed and performance data taken from the current hardware given.

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Mr. J. M. McKay is the PEPE Project Manager at BMD-ATC in Huntsville, Alabama. Mr. H. G. Martin is in the Data Processing Division of System Development Corporation.

LECTURE DATE: Tuesday, July 26, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Techniques and Effectiveness of Programming Strategies for High Speed Computers"

by

Dr. D. H. Lawrie

Dr. D. H. Lawrie will present a lecture surveying various techniques used to take advantage of high speed (parallel and pipeline) computers. Program loop distribution (vectorizing) and algorithms for the solution of recurrence relations will be discussed, as well as some results of our efforts to restructure programs automatically. These techniques will be related to specific architectural features in order to give an overall assessment of effectiveness.

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Dr. Duncan H. Lawrie is an Assistant Professor in the Department of Computer Science at the University of Illinois, Urbana-Champaign.

LECTURE DATE: Tuesday, July 19, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Parallel Processing--An Approach to Large Scale Numerical Problem Solution in Real Time"

by

Mr. M. W. Brubaker
Mr. J. T. Franks

Mr. M. W. Brubaker and Mr. J. T. Franks of the Goodyear Aerospace Corporation will present a lecture to AFOSR Summer Study Participants on Tuesday, July 12, 1977. The lecture will involve a brief introduction to Goodyear Aerospace Corporation and its history, as well as the STARAN Parallel Processor. The background, concept, and features of the STARAN will be discussed. Also on the agenda are discussions on advanced development programs concerning the STARAN, such as the Byte-Oriented STARAN and the parallel pipelined STARAN. Anyone interested in this lecture is invited to attend.

LECTURE DATE: Tuesday, July 12, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"CRAY I Vector Processor and
Future Developments"

by

Dr. Richard Hendrickson
Dr. Charles Puglisi
Dr. Richard Russell

Cray Research, Inc. was founded in 1972 by Seymour Cray, principal architect of the CDC 7600 and other computers. CRI's CRAY I Vector Processor has been accepted as a powerful tool by the Weather Forecast and Research and Nuclear Research Committees. It is clear that CRAY I architecture, especially its capabilities for "chaining" has great potential for wind tunnel applications and aerodynamics research. Anyone interested may attend the lecture.

LECTURE DATE: Monday, July 11, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Experiment vs. Computation in Fluid Dynamics--
Competition or Corroboration?"

by

Dr. R. J. Hakkinen

The interaction between computation and experiment in fluid dynamics will be illustrated by examples involving transonic flow, viscous-inviscid interactions and turbulent entrainment phenomena. The unresolved conflicts between computational and experimental results in some cases, and the dependence of numerical schemes on empirical information in others, point out the continued need for close cooperation between numerical analysis and experimentalists. Since the issues of concern are often of a rather fundamental nature, they also offer good opportunities for research projects applicable to the validation of new computational techniques.

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Dr. Raimo J. Hakkinen, a native of Helsinki, Finland, graduated with honors from the Technical University of Finland with a degree in Aeronautical Engineering. He then went on to obtain both his Master's Degree and his Ph.D. in Aeronautics from the California Institute of Technology. He is currently with McDonnell-Douglas Corporation. As Chief Scientist-Flight Sciences at the McDonnell-Douglas Research Laboratories since 1970, Dr. Hakkinen directs research in transonic, high-lift and internal fluid dynamics, aerodynamic noise and arc heater technology. In addition, Dr. Hakkinen is serving McDonnell-Douglas Corporate Engineering as Aerothermodynamics technology coordinator. Dr. Hakkinen has also been associated with such universities as Massachusetts Institute of Technology, UCLA, and California Institute of Technology. He is active in several professional societies, such as the AIAA. Dr. Hakkinen is the author of numerous publications.

LECTURE DATE: Friday, July 8, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Probable Trends in High Performance
Computing in the 1980-1990 Era"

by

Mr. David Stevenson

Frequently occurring patterns of computation in large scale scientific computing include vector operations, case statements, and event driven simulation. The way these patterns are coded on today's high performance computer architectures (such as a multiple functional unit processor, an array processor, and a pipelined arithmetic unit) reveals the limitations of the various approaches to high speed computing and suggests possible evolutions in these architectures. Current ideas and discernable trends in hardware component technology, software engineering and systems design indicate which of the possible developments are likely to be the most profitable. Several examples, depending upon the interests of the study group, will be treated in depth to illustrate the possible impact of these trends on large scale computing systems of the 1980's and beyond.

* * * * * * *

David Stevenson is Manager of the Advanced Studies Department of the Institute for Advanced Computation, NASA/Ames. He did graduate work in mathematics at the University of Oregon and in computer science at Carnegie-Mellon University before joining the Institute in 1975. The Institute maintains the ILLIAC IV computer, a large, sophisticated array processor.

LECTURE DATE: Thursday, July 7, 1977 at 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"New Computer Architectural Concepts for
Super Computers"

by

Mr. Dick McHugh

Mr. Dick McHugh of Control Date Corporation in Boulder, Colorado, will present a lecture to the AFOSR Summer Program Participants and all interested persons on Wednesday, July 6, 1977. The lecture will deal with the design philosophy of the new STAR 100C Computer.

LECTURE DATE: Wednesday, July 6, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Short Course Room

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AFOSR SUMMER DESIGN STUDY LECTURE

"Application of Aerodynamic Computational Methods to the Design and Analysis of Aircraft"

by

Mr. A. L. daCosta

The present state of the art in aerodynamic design requires extensive configuration iterations through repeated wind tunnel t esting that is costly, time consuming, and relies heavily on in-house experiences and expertise. Significant advances have been achieved recently in aerodynamic computational methods which allow calculation of flows around three dimensional configurations and provide valuable guides to those seeking understanding of specific problems or those pursuing innovative design concepts.

A great amount of effort and emphasis has been placed on the validation of these methods and to establish limits of their applicability. This paper addresses to the application and validity of aerodynamics methods in the subsonic, transonic, and supersonic speed regimes for solving flows about complex three dimensional configurations, including boundary layer effects.

* * * * * * *

Mr. A. L. (Larry) daCosta received his BS in Aeronautical Engineering from Purdue University in 1954, followed by his MS degree also from Purdue in 1956. Mr. daCosta is the manager of the Configuration Concepts Group in the Aerodynamics Research Unit of the Boeing Commercial Airplane Company. He was responsible for the development of the advanced military STOL transport (YC-14) high-speed configuration.

Mr. daCosta joined the Boeing Company in 1958. His early responsibilities at Boeing included development of transonic and supersonic configuration concepts and two-dimensional transonic airfoils.

LECTURE DATE: Monday, June 27, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Auditorium

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AFOSR SUMMER DESIGN STUDY LECTURE

"Limitations of Measurements and Analysis in Non-Equilibrium Turbulent Boundary Layers, Including Separation"

by

Mr. V. A. Sandborn

While great strides have been made in the modeling and calculation of turbulent shear flows, areas such as severe pressure gradient boundary layer flows are at best poorly predicted. Prediction of these highly non-equilibrium flows will depend on more realistic models of the turbulence and the mean flow than are currently considered. A review of the physical aspects of non-equilibrium turbulent boundary layers will be presented. Details of flow in the region of boundary layer separation will be included. Both subsonic, incompressible and compressible, as well as supersonic flows will be covered. For compressible flow, it has become evident that freestream mass flow gradients, as well as the pressure or velocity gradient is important in describing the boundary layer development.

* * * * * * *

Professor Virgil A. Sandborn, Professor of Civil Engineering at Colorado State University, holds a B. S. degree from the University of Kansas, a Masters degree from the University of Michigan in Aeronautical Engineering. His experience includes eleven and one-half years at the Lewis Research Center of the National Advisory Committee for Aeronautics which later became part of NASA. Prof. Sandborn joined the CSU staff on August 1, 1963, in the Fluid Mechanics Program of the Civil Engineering Department. Prof. Sandborn has authored or co-authored more than eighty technical reports.

LECTURE DATE: June 24, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Auditorium

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AFOSR SUMMER DESIGN STUDY LECTURE

"Application of Contemporary Computational Techniques to Aerospace Vehicle Design"

by

Dr. James Xerikos

The computational methods currently used in the design of aerospace vehicles will be assessed in terms of their application to specific aspects of vehicle sizing. The relative success in treating slender supersonic and hypersonic configurations as opposed to transonic and supersonic wing-body-tail configurations will be discussed. Representative computational methods will be characterized, pointing out the seemingly subtle differences in analyses that can strongly affect the utility of finite difference codes. In addition the relationship between "rapid design" aerodynamic computer programs and the so-called exact methods will be indicated by example.

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Dr. Jamex Xerikos serves as Branch Chief of Aerodynamics at McDonnell-Douglas Astronautics Company in Huntington Beach, California. During his academic training at the University of Illinois, Dr. Xerikos served as Research Assistant, Teaching Assistant, and Instructor in the Department of Aeronautical Engineering. Joining McDonnell-Douglas in 1959, Dr. Xerikos joined the Douglas Missiles and Space Systems Division as a research specialist in fluid mechanics. His subsequent positions included Chief, Fluid Mechanics Section Aeromechanics Research Branch; and Chief, Fluid Physics Branch, Physical Sciences Department. Dr. Xerikos has directed Government sponsored investigations treating a wide range of fluid mechanic and aerodynamic topics.

LECTURE DATE: Thursday, June 23, 1977, 9:00 a.m.

LECTURE PLACE: UTSI Auditorium

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH-SPONSORED
ASEE-UTSI-SUMMER DESIGN STUDY PROGRAM
TO BE CONDUCTED AT THE
UNIVERSITY OF TENNESSEE SPACE INSTITUTE
JUNE 13-AUGUST 19, 1977

I. Objectives

A. To provide a design study experience on a realistic and pertinent engineering subject for the faculty participants

B. To ascertain the current status of experimental aerodynamic facilities and test methods and the current status of aerodynamic computational methodologies and computer systems

C. To prepare an estimate of future developments in experimental and computational aerodynamics consistent with projected design needs with special emphasis on the impact of the next generation of experimental and computational facilities

D. Explore means of obtaining and improving aerodynamic data by developing concepts for integrated use of computers and wind tunnels

E. To prepare for faculty participants to make future contributions in the area of experimental and computational aerodynamics

II. Methodology

A. A review of current literature in the following three areas will be made:

1. Experimental facilities and methodology for wind tunnel testing of advanced military air vehicles

2. State of the art in computational fluid mechanics and aerodynamics

3. Design trends of computer architecture and computer implementation techniques as they pertain to computational aerodynamics and wind tunnel testing

B. Material will be presented by contributors in the three fields under consideration to aid in the understanding of computational and experimental aerodynamics.

C. A brief written assessment of the current status of the three areas will be prepared.

D. A written estimate of future trends, capabilities, and limitations for the interaction between computational aerodynamics, experimental aerodynamics and advanced computer design and implementation

E. Study participants will present reviews of current technical reports in the three areas.

SUMMER DESIGN STUDY PANEL MEMBERS

Panel 1: Experimental Methods in Acquisition of Aerodynamic Data	Source of Highest Degree	Organization	Area of Interest
*Collins, Frank G.	University of California-Berkeley	Aerospace Engineering UTSI Tullahoma, TN 37388	Aerospace Engineering
Garcia, Sal R.	Texas A &.M University	Maritime Systems Engrg. Moody College Galveston, TX 77553	Engineering Systems
Jones, Michael	North Carolina State Univ.	School of Engineering UT-Chattanooga Chattanooga, TN 37401	Mechanical Engineering
Tirres, Carlos	Air Force Institute of Technology	Engineering Division Motlow State Community College Tullahoma, TN 37388	Aerospace Engineering

Panel 2: Computational Methods in Acquisition of Aerodynamic Data	Source of Highest Degree	Organization	Areas of Interest
*Cheng, Sin-I	Princeton University	Princeton University Department of Aero-space Engineering	Aerospace Engineering
Chambless, Donald A.	Tulane University	Auburn University at Montgomery Mathematics Department Mongtomery, AL 36117	Mathematics
Jacocks, James L.	University of Tennessee Space Institute	Senior Engineer PWT/ARO, Inc. Arnold AFS, TN 37389	Aerospace Engineering
Sahai, Vireshwar	Virginia Polytechnic Institute	Tenn. Tech. University Engineering Science Dept. Cookeville, TN 38501	Engineering Mechanics

Panel 3: Computer Developments for Support of Acquisition of Aerodynamic Data	Source of Highest Degree	Organization	Areas of Interest
*Hornfeck, William A.	Auburn University	Electrical Engineering Program Gannon College Erie, PA 16501	Electrical Engineering
Broome, Lesunda Eugene	University of Houston	Mathematics Dept. Moody College Galveston, TX 77553	Mathematics
Cunningham, James R.	University of Florida	School of Engineering UT-Chattanooga Chattanooga, TN 37401	Chemical Engineering
Dick, Gregory M.	Stanford University	University of Pittsburgh, Johnstown Division of Engineering Technology Johnstown, PA 15904	Electrical Engineering
Technical Director			
Marschner, Bernard W.	California Institute of Technology	Department of Computer Science Colorado State University Fort Collins, CO 80523	Computer Systems/ Computer Analysis
Project Administrator			
Young, Robert L.	Northwestern University	Associate Dean The University of Tennessee Space Institute Tullahoma, TN 37388	Mechanical Engineering

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M. A. (English) Middle Tennessee State University

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