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Final Report
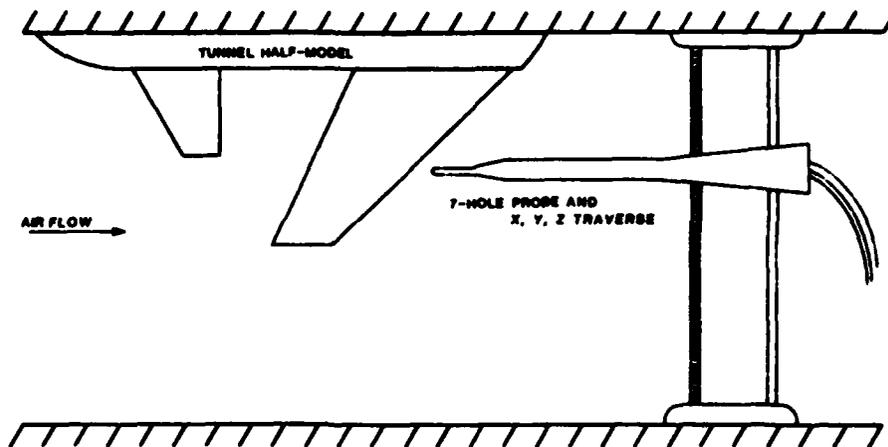
AIR FLOW

TUNNEL HALF-MODEL

7-HOLE PROBE AND
X, Y, Z TRAVERSE

SCHEMATIC OF TYPICAL PROBE/TEST MODEL
INSTALLATION

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Department of Aeronautics
Dean of the Faculty
United States Air Force Academy
Colorado 80840

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COVER:
The cover shows a schematic diagram of a typical experimental test
set-up in the Academy's subsonic wind tunnel. The aircraft model that
is shown has a forward-swept wing with a leading canard. The
seven-hole pressure probe is used to determine the characteristics of
the flow (including cross flow velocities) at various points around
the model and in its wake.

Wind tunnel tests were conducted to determine the effect of the canard
on the forward-swept wing and these tests and their results are
discussed in Capt Kenneth Griffin's article in this Digest. Also
discussed in this Digest is the redesign of the newly developed
seven-hole pressure probe. This redesign effort and the experimental
measurement of the probe's frequency response is contained in the
article written by CIC Scott Schlapkohl and Capt William Buzzell.

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This Digest covers unclassified research in aeronautics performed
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15 February 1982. This report includes technical papers in the
specific areas of aerodynamics, propulsion, experimental
instrumentation, engineering education, and aeronautical history.

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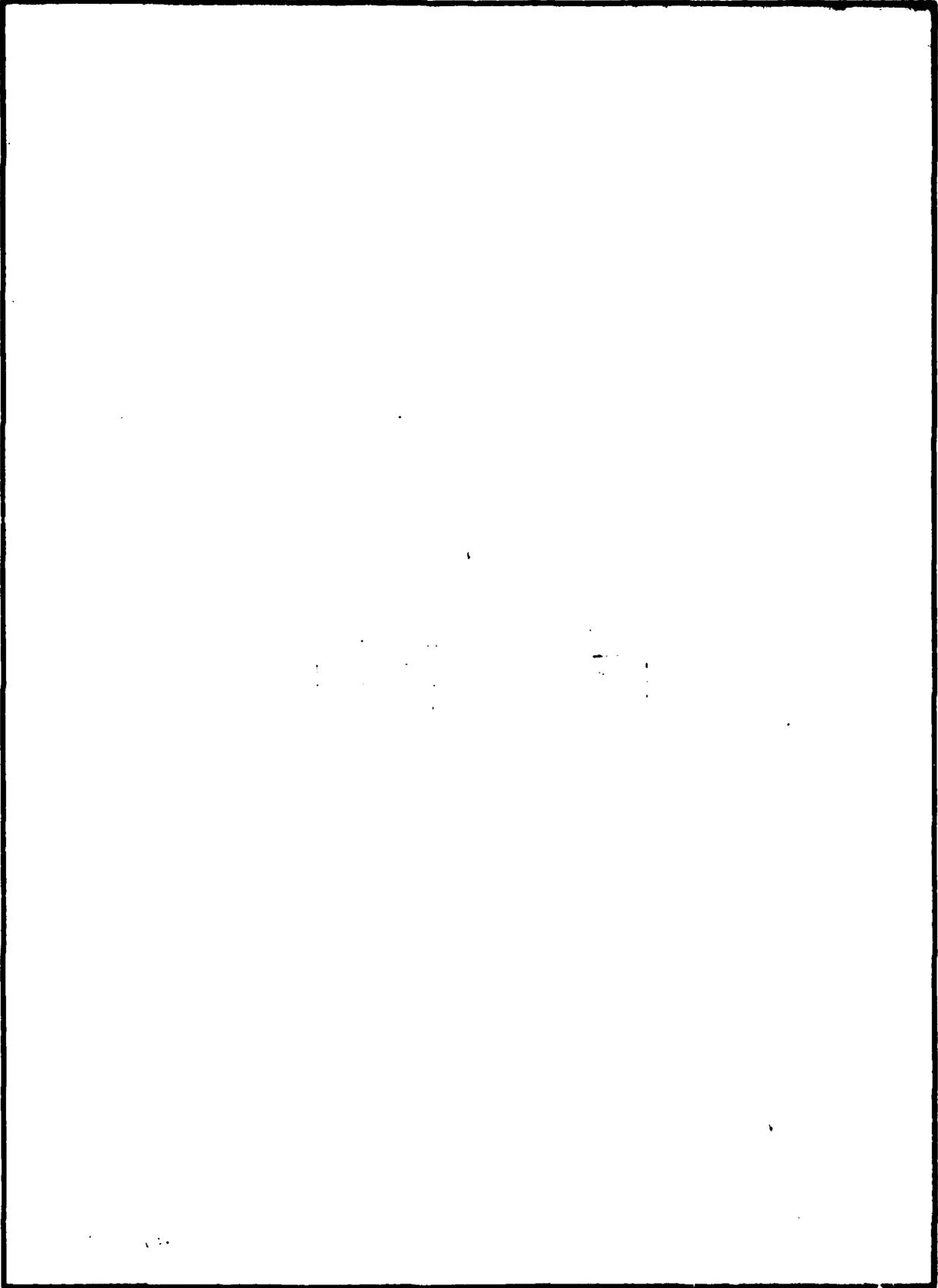
PREFACE

This report is the eighth issue of the <u>Air Force Academy
Aeronautics Digest</u>.* Our policy is to print articles which represent
recent scholarly work by students and faculty of the Department of
Aeronautics, members of other departments of the Academy and the Frank
J. Soiler Research Laboratory, researchers directly or indirectly
involved with USAFA-sponsored projects, and authors in fields of
interest to the USAFA.

In addition to complete papers, the <u>Digest</u> includes, when
appropriate, abstracts of lengthier reports and articles published in
other formats. The editors will consider for publication contributions
in the general field of Aeronautics, including:

> •Aeronautical Engineering
>> Aerodynamics
>> Flight Mechanics
>> Propulsion
>> Structures
>> Instrumentation
> •Fluid Dynamics
> •Thermodynamics and Heat Transfer
> •Biomechanics
> •Engineering Education
> •Aeronautical History

Papers on other topics will be considered on an individual basis.
Contributions should be sent to:

> Editor, <u>Aeronautics Digest</u>
> DFAN
> US Air Force Academy, CO 80840

The <u>Aeronautics Digest</u> is presently edited by Maj A.M. Higgins,
PhD; Maj E.J. Jumper, PhD; Maj Jay DeJongh, 1Lt Karyn Knoll; and Capt
J.M. Kempf, PhD, Department of English, who provided the final
editorial review. Our thanks also to Associate Editors, Martha Arends
and Helen Foster, and Production Artist, Deborah Ross, of Contract
Technical Services, Inc. Starting next issue, Maj Jay DeJongh will be
the Editor-in-Chief of the <u>Digest</u>.

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CONTENTS

SECTION I

Aerodynamics

EXPERIMENTAL DOCUMENTATION OF THE LIFTING SURFACE WAKES
OF A CANARD AND FORWARD-SWEPT WING CONFIGURATION*

Kenneth E. Griffin**

Abstract

This paper summarizes the data collected from a series of
experiments conducted to evaluate the aerodynamic performance of a
canard and forward-swept wing wind tunnel model. In particular we
attempted to determine how the canard affects the airflow over the
forward-swept wing. The data include distributions of total, dynamic,
and static pressures as well as cross velocity magnitudes and
directions both near the model and in its free stream wake. This
experiment was a preliminary test in a program that will lead to the
testing of a more realistic forward-swept wing aircraft design.

I.   Introduction

The effects of wakes on the primary lifting surfaces of aircraft

have been of interest to aero designers and engineers for some time

(Refs. 1 and 2). The typical aerodynamic surfaces that produce these

wakes are canards and strakes. The F-16 aircraft, for example, has a

leading-edge strake, and a canard trimming surface has been proposed

for the Forward-swept Wing Flight Demonstrator, FSWFD. Aerodynamic

surfaces such as a strake or a canard can produce flow fields which

have a significant impact on the flow field around the downstream

primary lifting surface of an aircraft. This phenomenon in turn

affects an aircraft's lift and drag characteristics and, therefore,

its overall flight performance.

In order to more accurately determine the effect of a canard on

the aerodynamic performance of a forward-swept wing aircraft, we set

up a series of tests to measure the flow field around the

forward-swept wing both with and without the canard. The canard on the

FSWFD is placed on the fuselage in front of the forward-swept wing.

Therefore, for our tests we selected a generic form of a forward-swept

wing aircraft which has a canard in front of the wing (lifting)
surface. A schematic diagram of this model is shown in Figure 1.
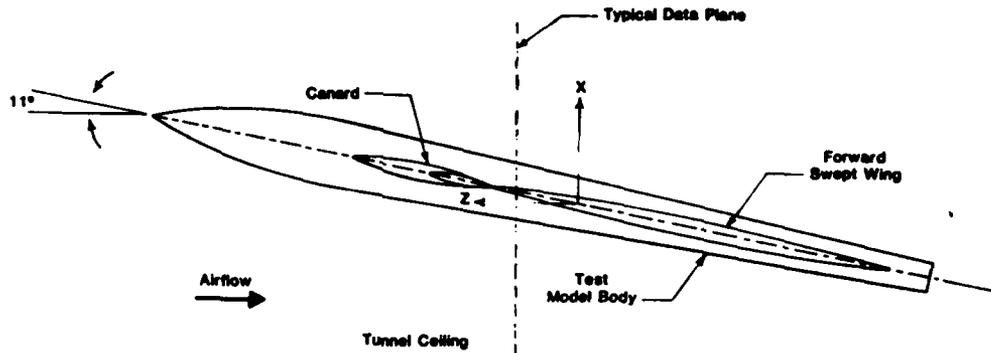
Figure 1:   Wind Tunnel Model of a Generic Forward-Swept
Wing Configuration

The model was placed in the U.S. Air Force Academy's subsonic wind
tunnel and the flow field around the model was measured both with and
without the canard surface. Then, by examining the two sets of data
generated during the tests we were able to determine the effects of
the canard on the airflow around the wing.

To quantify the flow field around the model, we measured the
pressure at numerous points within the airstream as well as the static
and total pressure in the undisturbed flow upstream of the model. We
used a seven-hole pressure probe to measure the pressures within the
airstream and we discuss the operation of this new, unique pressure
measuring device later in this report. The pressure data measured by
the seven-hole probe was then used to calculate values of static and
total pressure at each measurement point. We also calculated crossflow
velocity magnitudes and directions at these grid points. In this study
cross flow refers to the velocity component that is perpendicular to
the free stream velocity vector.

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We were particularly interested in locating and measuring the
strength of the wake behind both the canard and the forward-swept
wing. The wake, of course, is the region in the airflow behind a body
where the airflow has been disturbed because of the body's presence.
This disturbance of the airflow results in a change in the airflow's
direction and speed, and thus the wake can be visualized by plotting
the airflow's velocity at various points in the flow field behind the
body. The airflow's speed is reduced because of friction in the
airflow and friction is created where large velocity gradients are
developed in the fluid boundary layer on a wing, or in the flow field
when strong concentrations of vorticity (rotational flow) are present.
In the region near the core or center line of highly rotational flow,
these crossflow velocity gradients become very large (Ref. 3). This
rotational flow is directly related to lift so that for a wing
generating large lift forces the rotational vortices are intense. The
point is that a reduction in airflow speed due to friction results in
a reduction in the airflow's total pressure and the total pressure
reduction in the airflow can also be used to locate the body's wake.
However, at low angles of attack, where the generation of lift forces
is small, the total pressure drop can be small. Thus a sensitive
measurement of flow field pressures is required to detect the wake in
this case.

As mentioned earlier, we used a seven-hole pressure probe test
apparatus to measure the flow field pressures. This pressure probe was
recently developed at the USAF Academy under the sponsorship of NASA's
Ames Research Center (Ref. 4). This pressure probe is small and has
the ability to measure airstream total pressure and flow velocity,
even though the probe is not aligned directly into the airstream flow.

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This ability is extremely important because airflows over and behind a
wing or canard are very complex and the flow direction is unknown.
Indeed, that is one objective of the test: to find the flow velocity
(direction).

II. Experimental Apparatus

We used three pieces of equipment to conduct these tests: the
seven-hole probe apparatus, the forward-swept wing model with and
without the canard, and the subsonic wind tunnel. Each of these items
is briefly discussed below.

A. Seven-Hole Probe

If we are to locate the wakes in the airflow by detecting a
decrease in airstream total pressure, we must be able to measure total
pressure at various points in the airflow. This is usually
accomplished by aligning a pitot tube so that the flow is directly
into the tube entrance. For the complex flows encountered in these
tests, this would be a difficult and time-consuming task. The
seven-hole probe system eliminates the need to align the probe
directly into the flow. The seven-hole probe is essentially seven
individual probes located around a conical head as shown in Figure 2.
Pressures are measured at each of these ports and the difference in
pressures measured can be used to determine the total pressure in the
flow at the seven-hole probe location as well as the flow direction at
that point. Most importantly, this can be done in a flow field even
when the airflow's direction is not directly into the probe tip, i.e.,
parallel to the pressure probe axis. In fact, accurate measurements
can be made even if the airflow's velocity vector is as much as 80
degrees off the pressure probe's axis (the airflow makes an angle of
80 degrees with the pressure probe free axis). The calibration

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procedure used to translate the seven measured pressures to velocity
and total pressure is described in detail in Ref. 5. Thus, it is this
seven-hole probe, with its high flow angle capability, that allows
rapid measurement of free stream pressures and velocities in and
around wind tunnel models with complex aerodynamic airflows.
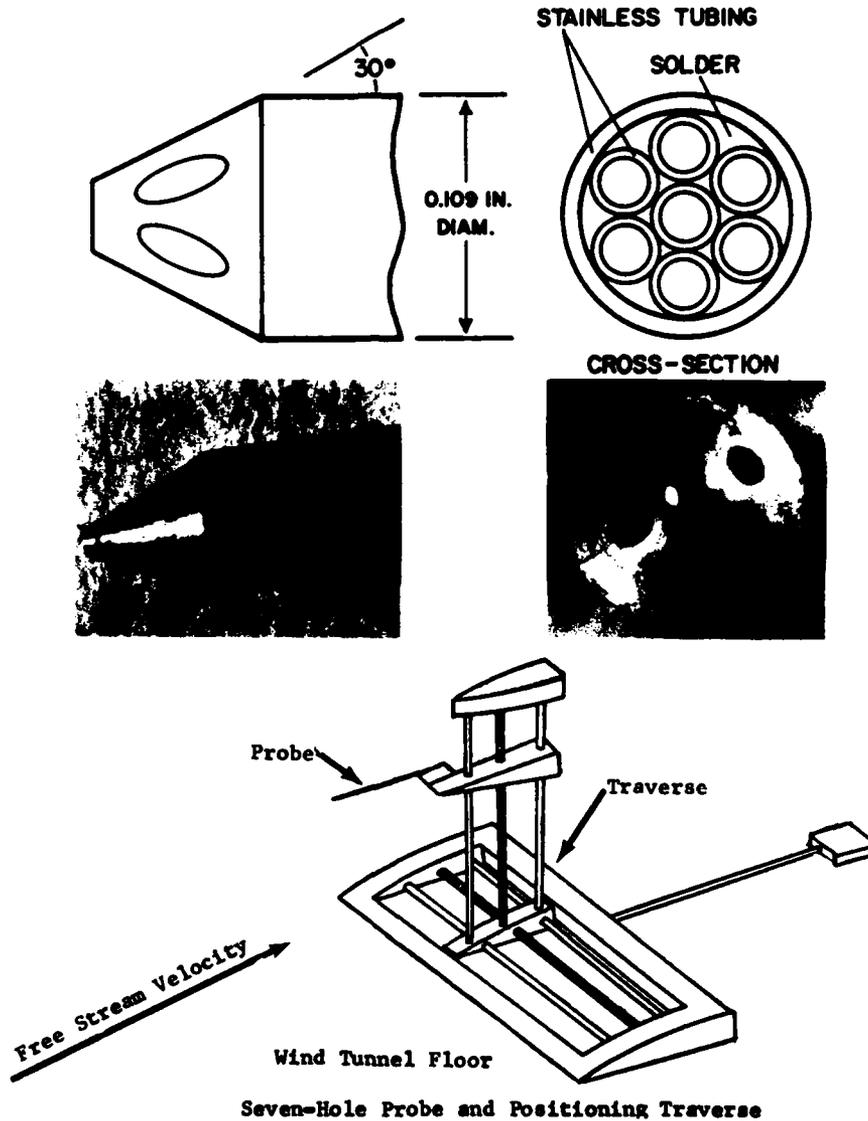
Figure 2:   Seven-Hole Probe and Positioning System

The probe is approximately 0.1 inch in diameter, so its presence does not provide a significant disturbance in the airflow it is measuring. An automated data collection, reduction, and storage system is used with the probe, and consists of a computer-controlled, three axis probe positioning system and a real-time minicomputer data reduction and storage system.

B. Subsonic Wind Tunnel

These tests were performed in the 2 foot x 3 foot subsonic wind tunnel at the USAF Academy. This continuous flow wind tunnel facility has a testing cross section of nominally 2 foot x 3 foot with a length of 70 inches. The wind tunnel has an operating range of Mach numbers from 0.04 to 0.35. Local atmospheric conditions prescribe wind tunnel total temperature and pressure values. These ambient conditions generally provide airspeeds from 50 feet per second to 400 feet per second, providing Reynolds numbers in the range of $.2 \times 10^6$ to 1.6×10^6 per foot, and dynamic pressures in the range of 1.8 pounds per square foot to 130 pounds per square foot. The wind tunnel test section airspeed was maintained at 100 feet per second for all data points.

C. Wind Tunnel Model

The model used in these tests was a simplified, rigid, generic representation of a forward-swept wing vehicle mounted in the wind tunnel ceiling. It is shown in Figure 1. It is a half span or reflection plane model with the general dimensions shown in Figure 3. The airfoils for both the wing and the canard are bi-convex, sharp leading edge airfoils with thickness-to-chord (t/c) ratios of 0.05 for

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the wing and 0.04 for the canard. Both the wing and the canard have no
twist, and provision was made for several canard positions and
relative angle locations. The fuselage is a simple fairing for the
wind tunnel mounting with no inlet or cockpit representations, and the
lifting surface/body junctions are not filleted or faired in. The
model is at 11 degrees angle-of-attack with the airstream, and the
canard on the model is positioned coplanar with the wing at 0 degrees
angle-of-attack with the body center line.
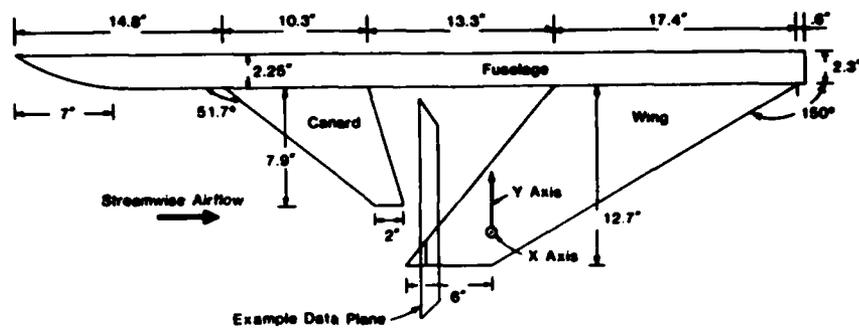
Figure 3:   Wind Tunnel Model Test Geometry and Coordinate
            System

III. Data Organization

A grid-plane approach was used in these tests to map the various
flow fields. By grid-plane approach we mean that a plane was defined
at some location in the flow field perpendicular to the free-stream
flow and data were recorded at equally spaced points within this
plane. These points form a grid, hence the term "grid-plane." The
probe is moved from point to point within the plane and from plane to
plane by the three-dimensional (x, y, z) traverse previously shown in
Figure 2. A typical test set-up is illustrated in Figure 4.
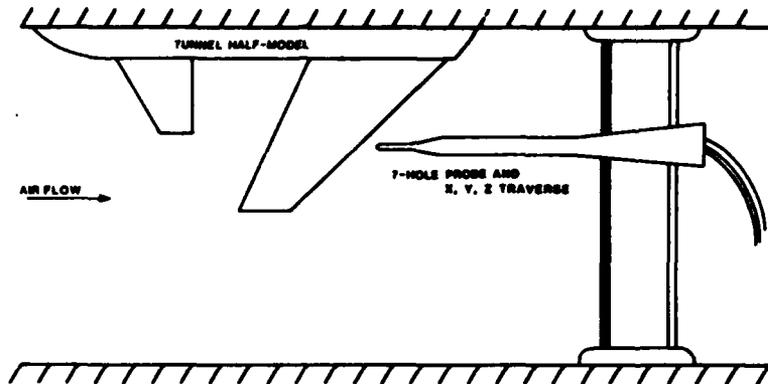
**SCHEMATIC OF TYPICAL PROBE/TEST MODEL
INSTALLATION**

Figure 4: Schematic Diagram of Typical Probe/Test Model
Installation

The coordinate system used to identify the data points relative
to the model has its origin at a point 3 inches inboard of the wing
tip trailing edge, as shown in Figure 3. Notice that the y-axis is in
the spanwise direction and is positive inwards (toward the model
body). The z-axis is along the freestream flow axis direction or, in
other words, is parallel to the wind tunnel center line. The
coordinates of the trailing edge wing tip location then, as defined in
this study, would be (x, y, z) in inches as (0, -3, 0).

We will present the data in planes that have common streamwise,
z, coordinates. In other words, we present values of pressure and
crossflow velocity at various points within a fixed x-y plane, i.e., z
is constant. Figure 3 shows an example data plane at z= 4. Each data
plane (x-y plane) we present will be in progressively more downstream
(negative z direction) planes and for each streamwise location, first
the wing/body data is given and then the wing/body/canard data at that
streamwise location follows.

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We present the pressure data in coefficient form. This pressure coefficient is created by subtracting the freestream total pressure from the total pressure seen locally at the probe tip and dividing this difference by the freestream dynamic pressure ($P_0 - P_\infty$). This pressure coefficient, ΔC_{P_0}, is defined numerically below.

$$\Delta C_{P_0} = \left[\frac{P_{0_L} - P_0}{(P_0 - P_\infty)} \right] \qquad (1)$$

This representation of the pressure allows us to readily determine if there is a deficit of total pressure, since the pressure coefficient becomes increasingly negative with a decrease in P_{0_L}. If there is no change in total pressure, then the pressure coefficient, ΔC_{P_0}, is zero. Thus the pressure coefficient tends to zero at points far away from the model (the data approaches the freestream conditions). The values of ΔC_{P_0} are presented in this paper in contour form. That is, the data points for a given grid-plane (z is constant) are surveyed to determine if the value of ΔC_{P_0} matches a chosen value for a particular contour line. When matching values are obtained throughout the data plane, a contour line of constant ΔC_{P_0} is plotted. Several values of ΔC_{P_0} contours are used to illustrate the locations of flow characteristics in a data plane. Parallel lines of ΔC_{P_0} can indicate the presence of a lifting surface wake, for example, or concentric closed paths that may be near circular can indicate the presence of a vortex core. These pressure contours illustrate the regions of pressure loss that can be identified as the wakes to be monitored. These contours, however, must be used in concert with the cross velocity information to properly identify wake characteristics.

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For example, pressure contours do not directly indicate airflow
direction or speed.

The cross velocity plots were made using the same sets of data
points just described in the pressure contour plots. At each data
point for a particular constant z axis location, an arrow was plotted
to indicate the direction of the component of the local velocity
vector in that plane. The relative velocity magnitude is shown by the
arrow length. This provided the direction and strength for the
downwash wakes and the rotation sense and strength for areas of
concentrated vorticity.

IV. Results

A. Data Plane Visualization

To aid the reader's visualization of the information presented
at each streamwise (z axis) station, we have arranged sample data
plots in the same spatial relationship that their data points have to
the model. We selected streamwise station 4 (z = +4 inches), shown in
Figure 3, placed the data plots in their proper location relative to
the wind tunnel model, and photographed the result. These photographs
are included as Figures 5, 6, and 7. The data plots used in Figures 5,
6, and 7 are presented in detail in Figures 8 and 9.

Recall that the unit normal to the data plane makes an 11 degree
angle with the fuselage centerline, i.e., the wind tunnel model is
mounted at an 11 degree angle-of-attack, as shown in Figure 1. Notice
also that the data plane selected was located on the low pressure side
of the model. All the data was taken at points on this side of the
model. This data plane does not intersect with the canard planform,
but is just slightly downstream of the canard trailing edge. A small
portion of the wing is intersected near the leading-edge wing tip.

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Figure 5: Wind Tunnel Model and Typical Data Plane

Figure 6: Typical Velocity Data
Plane Location
Relative to Model

Figure 7: Typical Pressure Data
Plane Location
Relative to Model

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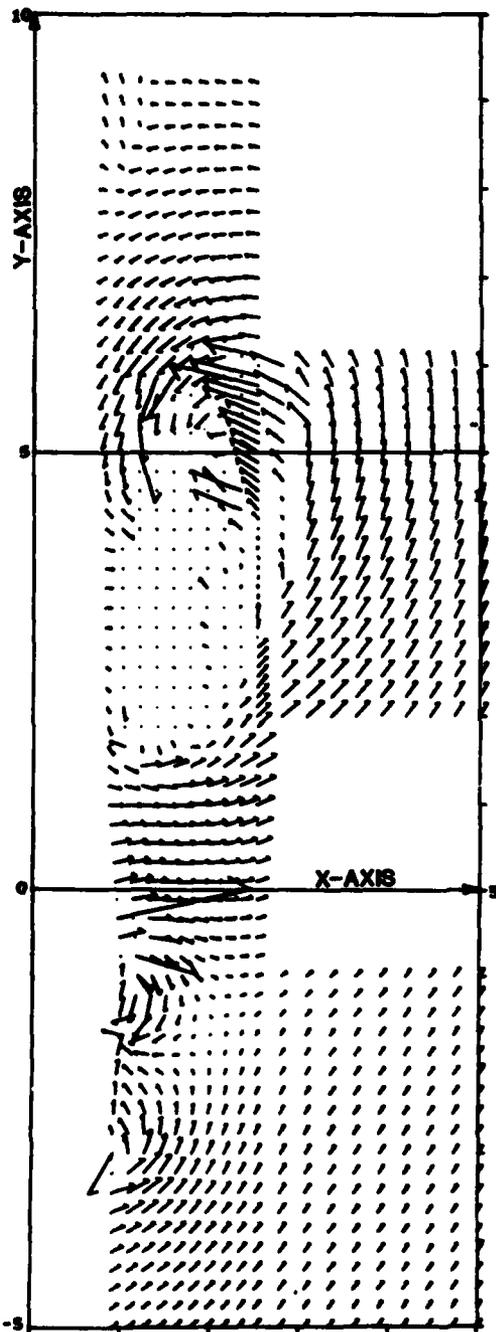
Figure 8: Cross Velocity
Vectors with
Canard
Z = +4 Inches
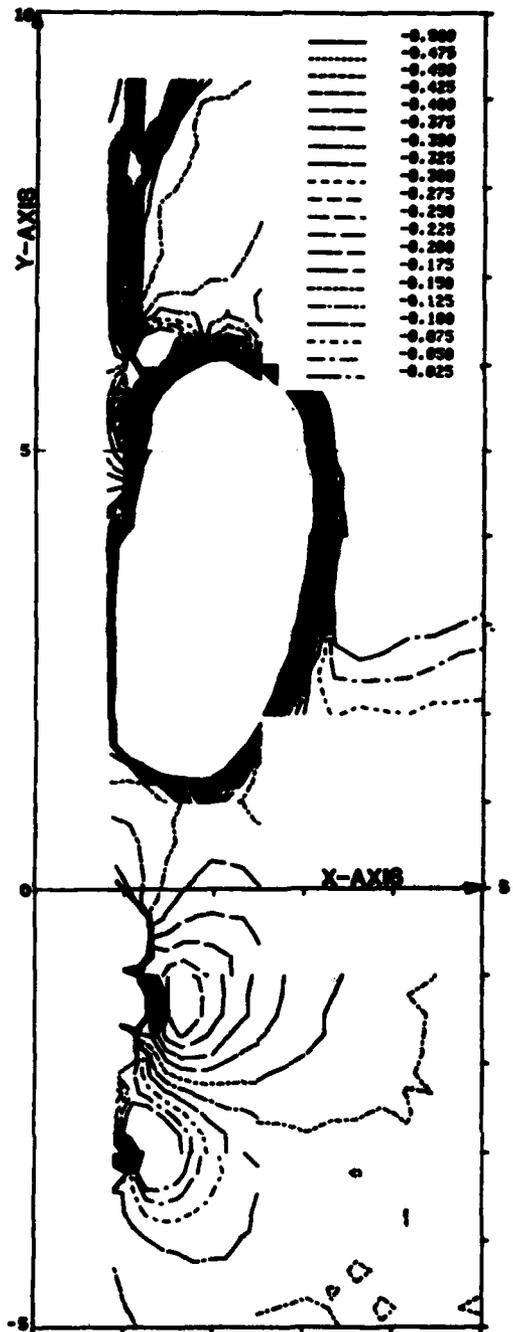
Figure 9: Total Pressure
Coefficient
Contours with
Canard
Z = +4 Inches

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USAFA-TR-82-3

This geometry is shown in Figure 3. Notice also in Figure 3 that data
planes intersect the model along lines that correspond to spanwise
lines in the lifting surfaces and bulkhead-like curves in the
fuselage.

    B. Data Plane Analysis

        Now that we have explained how the data points are related
geometrically to the wind tunnel model, we can discuss the pressure
coefficient and cross-velocity data shown in Figure 8 and 9 and relate
this data to the model.

        As we previously discussed, Figure 6 is a plot of cross-velocity
data mounted on a plate with the data points at their correct location
relative to the wind tunnel model. These cross-velocity vectors are
components of the local total velocity in the data plane. The vector
magnitudes and directions indicate the strength and sense of the flow
field at these points around the model.

        From Figure 6 we can see that the canard and forward-swept wing
surfaces are creating downwash and rotational flows are
characteristics of lifting surfaces. These cross-velocities can be
seen in better detail in Figure 8. The downwash from the canard
trailing edge is shown by the velocity vectors oriented generally in
the negative x direction in the y=6 to y=7 regions. The influence of
the strong concentration of tip vorticity from the canard causes the
downwash vectors to curl towards this concentration.

        When moving outboard in this plane (negative y direction), the
influence of the wing is detected at the y=-1 inch location. This
location corresponds to the intersection of the wing forward-swept
leading edge and the data plane. The leading edge separation vorticity
that is formed due to the sharp leading edge is causing this vorticity

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with the rotational sense of the vortex due to the positive sweep of the leading edge. The leading edge separation vortex core is roughly parallel to the wing leading edge and, thus, the data plane slices this vortex in an oblique way such that the velocity projections provide a clockwise rotational sense to the vortex.

At the tip of the wing (1, -3, 4), the cross velocity vectors show formation of the usual vortex that occurs because of the attempt by the flow to relax the pressure difference at the tip of finite surface producing lift. Note also that the surface velocity vectors on the wing indicate that the spanwise flow on the forward-swept wing is from tip to root from approximately y=-3 inches to y=-1 inches.

In Figure 7 a contour plot of a small range of ΔC_{P_0} is shown in the same way that the cross-velocity plot was just presented. The contour lines represent lines of constant ΔC_{P_0} from -.5 to -.025. This narrow range was chosen to accentuate the canard wake region. Therefore, the large losses in the center of the canard tip system are not shown since they would require much larger values of ΔC_{P_0} loss.

The location of the canard wake can easily be identified by the contour lines between the fuselage and the canard tip region. This can be seen in more detail in Figure 9. The canard wake is located at approximately x=2, y=4 and is shown bounded on either side by strong concentrations of ΔC_{P_0} loss, with a connecting line of lesser strength loss in ΔC_{P_0}.

The wing vortex systems also appear on this plot in Figure 6, next to the geometry that generates them. The leading edge separation and the wing tip vorticity are causing losses in their shear layers of viscosity near their rotational cores.

The subsequent plots should be interpreted in the same way. They were developed from data collected at points on the same side of the

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model lifting surfaces at various z locations. For each data plane the
cross velocity and ΔC_{P_o} contour plots are presented side by side to
help correlate the downwash and total pressure changes in the data
plane.

C. Effects of Canard on Flow Field

We have explained how the pressure data was reduced to cross
velocities and pressure coefficients, ΔC_{P_o} , at each grid point and
how these results are arranged and presented. We now will show the
effect of the canard on the flow field around the forward-swept wing.
To do this, we will present the wind tunnel results, ΔC_{P_o} contours and
cross velocities, for both the wing/body and the wing/body/canard
configurations. These plots are organized in planes of points that
have the same streamwise coordinates. By comparing successive planes
of data, the streamwise development of the wake characteristics both
with and without the canard can be observed.

Figures 10 and 11 describe the flow field for the wing/body at
the streamwise station of z=0. Figures 12 and 13 describe the flow
field for the canard/wing/body also at the streamwise station of z=0.
This streamwise station would have the data grid just touching the
trailing-edge tip of the wing at the y=3 point and was described
earlier. (See Figure 3.)

The cross velocity vectors of Figure 10 show the leading edge
separation vortex projection at about y=3.5 inches on the y axis and
the tip vortex at the -3 inch location. The rotational sense of each
vortex is consistent with the directions the flow field is attempting
to move the air. Note that at both the leading edge and tip, the wash
is moving air from the high pressure side of the wing (the negative x
face of this wing cross section) to the low pressure side of the wing

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Y-AXIS

Y-AXIS

X-AXIS

X-AXIS

-3.660
-3.439
-3.218
-2.997
-2.776
-2.555
-2.335
-2.114
-1.893
-1.672
-1.451
-1.230
-1.009
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-0.346
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0.537
0.759
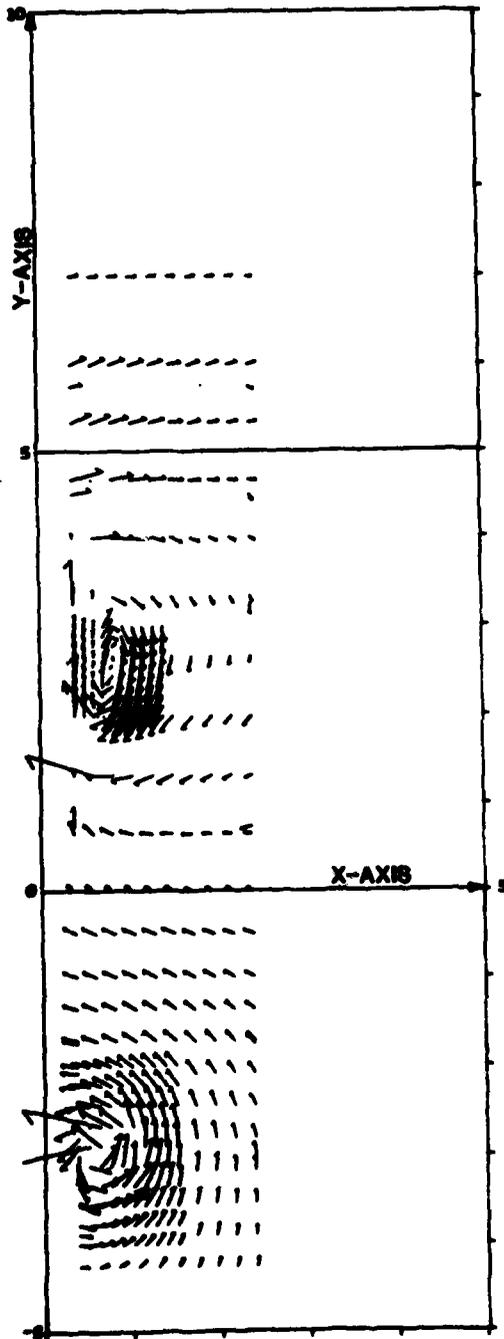
Figure 10: Cross Velocity
Vectors without
Canard
Z = 0 inches
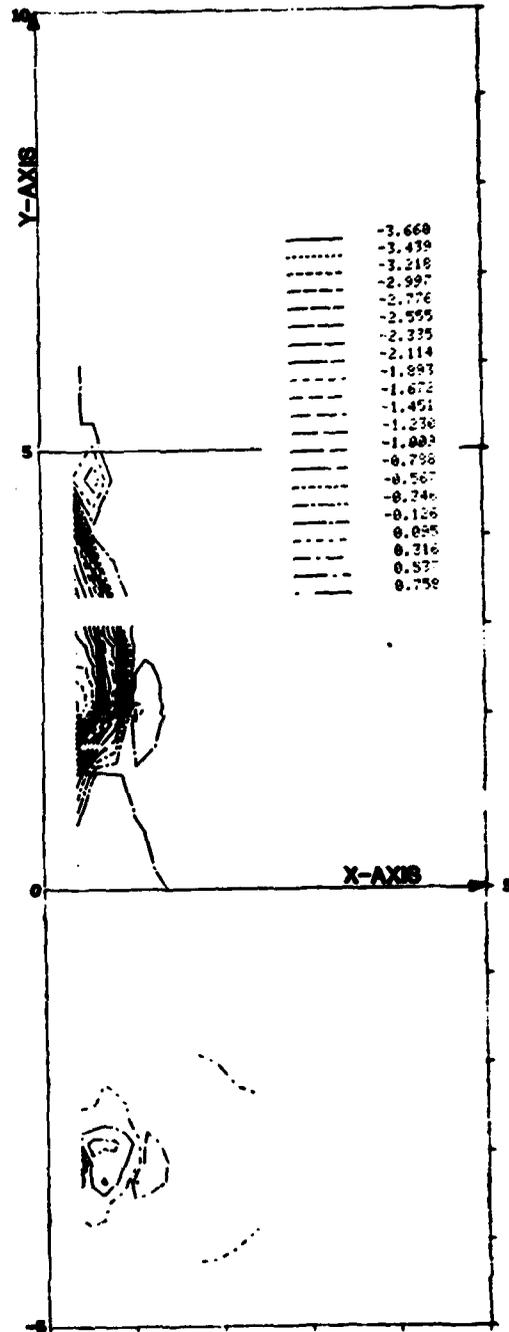
Figure 11: Total Pressure
Coefficient
Contours without
Canard
Z = 0 inches

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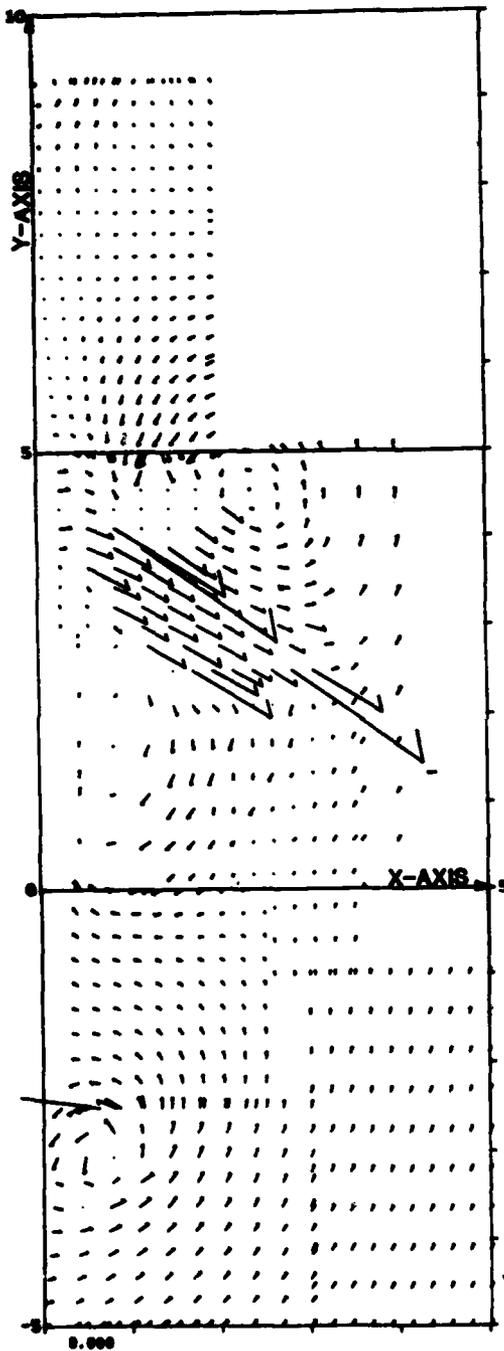
Figure 12: Cross Velocity
Vectors with
Canard
Z = 0 Inches
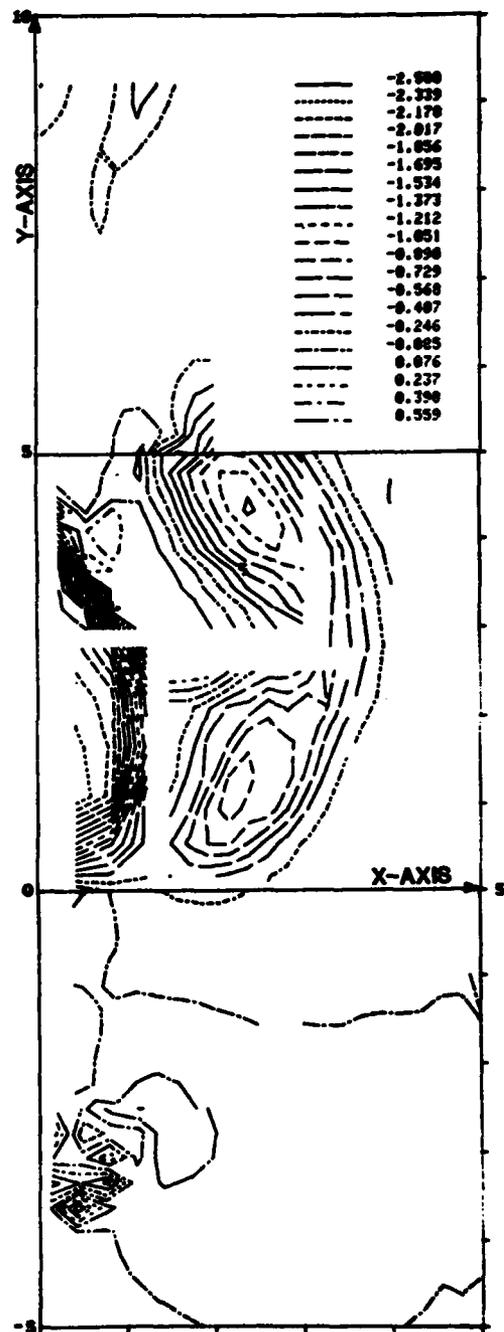
Figure 13: Total Pressure
Coefficient
Contours with Canard
Z = 0 Inches

(the positive x face of this wing cross section). The downwash field
on the wing is being influenced by both regions of vorticity, reducing
the apparent angle-of-attack of the flow that impinges the section of
the wing directly downstream of the canard. Contour plots of ΔC_{p_o} in
Figure 11 are for the same data points as those in Figure 10. Note
that two concentrations of loss in total pressure are found in the
regions where rotational flow from the tip and leading edge separation
vortices occur.

In Figures 12 and 13 the canard wake's effect can be seen in both
the velocity and pressure data. The canard tip is located upstream of
this station at 2.8 inches on the y axis.

Figure 14 is a composite plot of Figures 10, 11, 12, and 13.
Using this figure we can easily compare the two geometries tested. In
Figure 14, first compare the cross-velocity plots of the wing/body in
Figure 10 (Figure 14A) and the wing/body/canard in Figure 12 (Figure
14B). The canard tip vorticity is located at about y=4.5 inches and at
about x=2.5 inches or 2.5 inches above the wing leading edge. Note the
difference in wash inboard of the wing leading edge. While significant
upwash exists without the canard, the downwash is almost eliminated
with the canard in place.

The location of the leading edge separation vortex is more
outboard with the canard in place. Its rotational sense is opposite of
the canard vortex system. Note that the cross velocity between these
counter rotating systems is strongly enhanced (Figure 14B, y=2 to 4).
It should also be re-emphasized that the core of the leading edge
separation vortex is still nearly parallel to the wing leading edge
and is not perpendicular to this data plane.

Comparing the total pressure contours of the wing/body in Figure
14C and the wing/body/canard in Figure 14D shows the addition of the
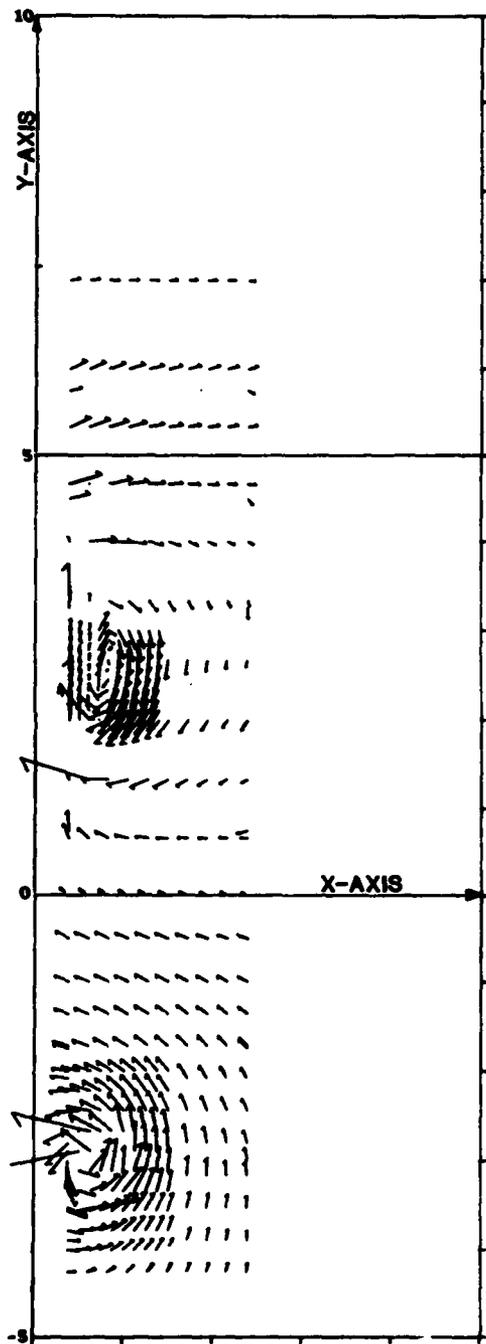
Figure 14A: Cross Velocity Vectors without Canard Z = 0 Inches
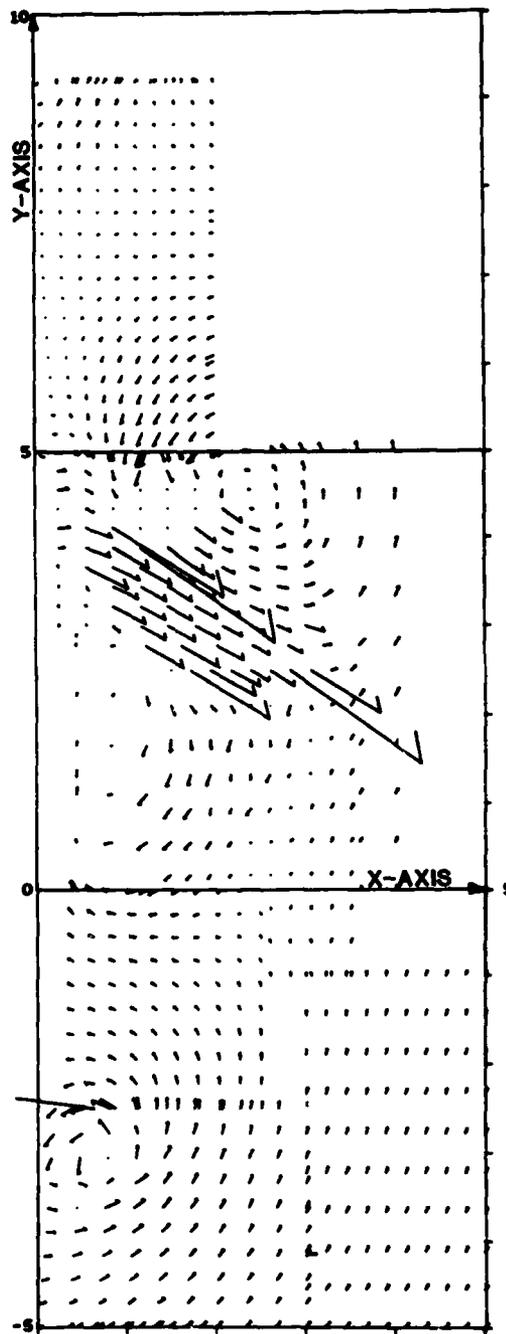
Figure 14B: Cross Velocity Vectors with Canard Z = 0 Inches

20

USAFA-TR-82-3
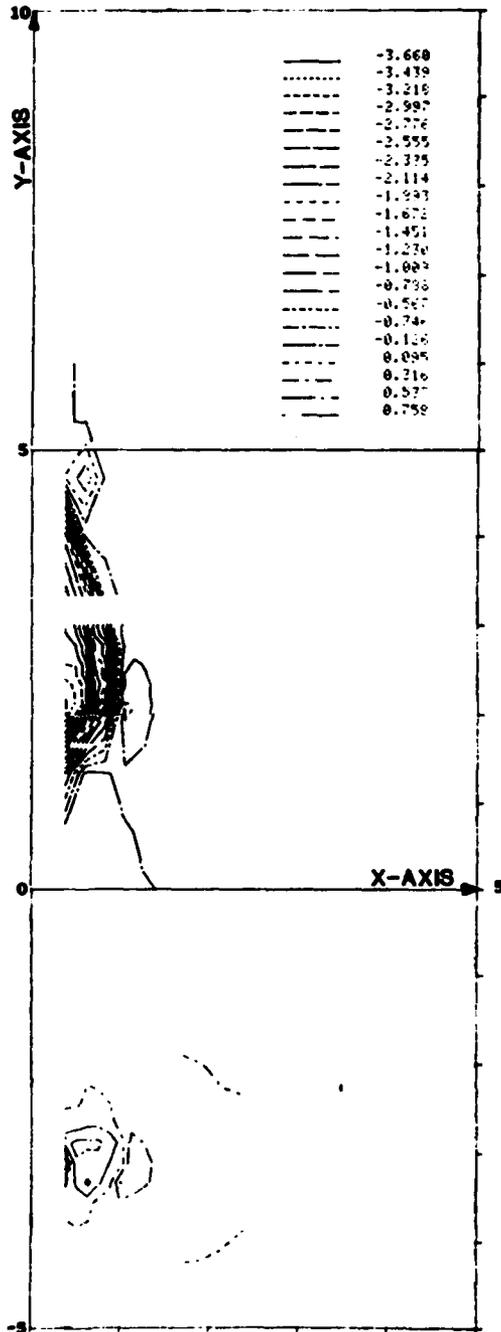
Figure 14C: Total Pressure
Coefficient
Contours without
Canard
Z = 0 Inches
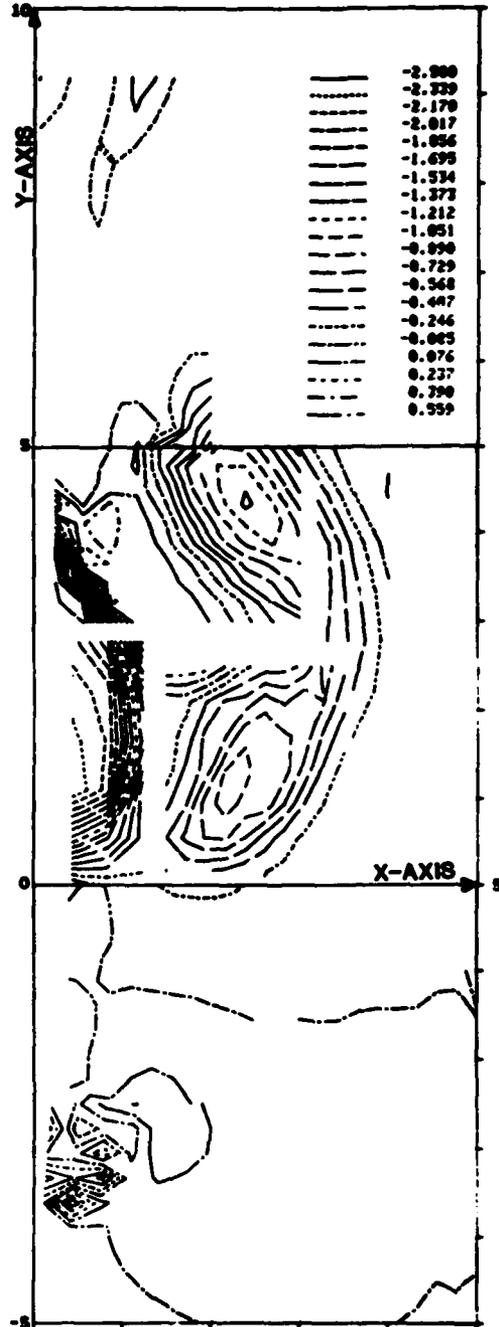
Figure 14D: Total Pressure
Coefficient
Contours with Canard
Z = 0 Inches

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canard vortex system. Note that the canard system has two areas of
concentric contours. The area centered about 2.5 inches (2.5, 1, 0)
above the x axis is the remnant of the weaker canard tip vortex, and
that centered at about 4.5 inches (2.5, 4.5, 0) is the canard leading
edge separation vortex.

In Figures 15 and 16 the wing/body data plane 4 inches downstream
of the wing tip trailing edge is shown. The wing intersection with
this data plane is at y=9 inches for the wing leading edge and y=-.7
inches on this axis for the trailing edge. The cross velocity plots
show the leading edge separation vortex core is now about 1.5 (1.5, 5,
-4) inches above the x axis. Outboard of this shows a wash that has
some inboard spanwise flow components. The wing tip vortex is still
essentially downstream of the wing tip. In Figure 16 the beginning of
the wing wake can be seen connecting the wing tip vortex and the
trailing edge of the wing in the region of (0, 2.5, -4).

The same data plane with the canard wake included is shown in
Figures 17 and 18. Note that the influence of the wing leading edge
vortex has been to move the canard vortex system (2.7, 4, -4) outboard
slightly and away from the wing.

The wing leading edge vortex has now been moved outboard to (1,
2.2, -4) 3 inches above the x axis even though the wing leading edge
is now at the 9 inch y location. The canard has essentially suppressed
this leading edge separation and thus the continuation of this wing
leading edge vortex inboard of the canard tip. The vortex core
remaining is that created outboard of the canard and has now been
turned essentially streamwise.

The wake of the canard as it rolls up into the canard vortex
system can be seen in Figure 18. The wing wake and associated tip
vortex is essentially unchanged with the canard addition. The wash

22
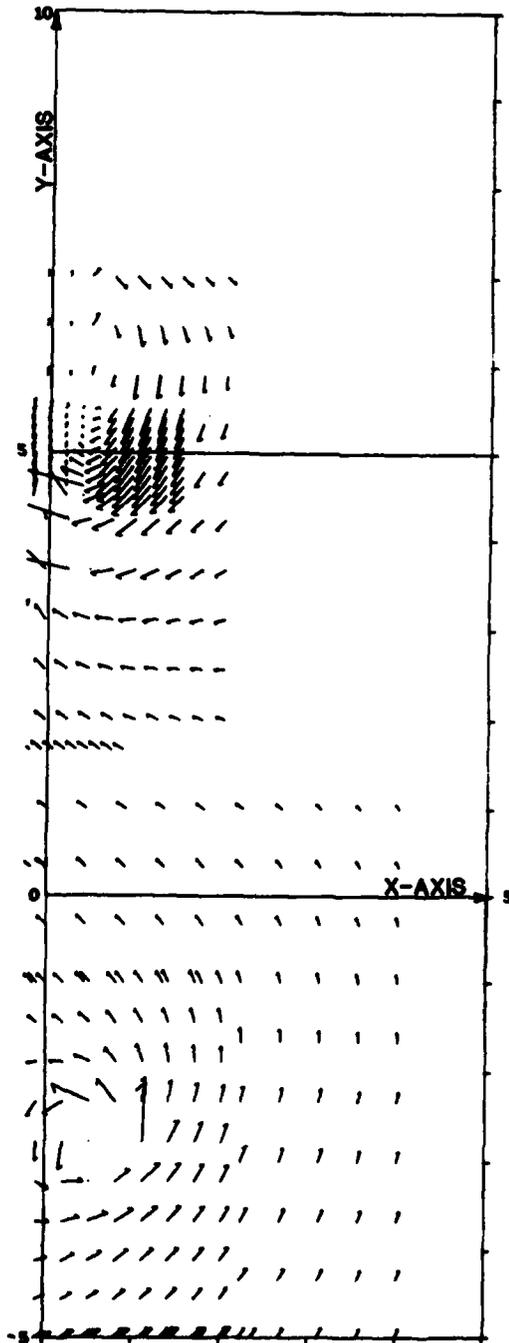
Figure 15: Cross Velocity
Vectors without
Canard
Z = -4 Inches
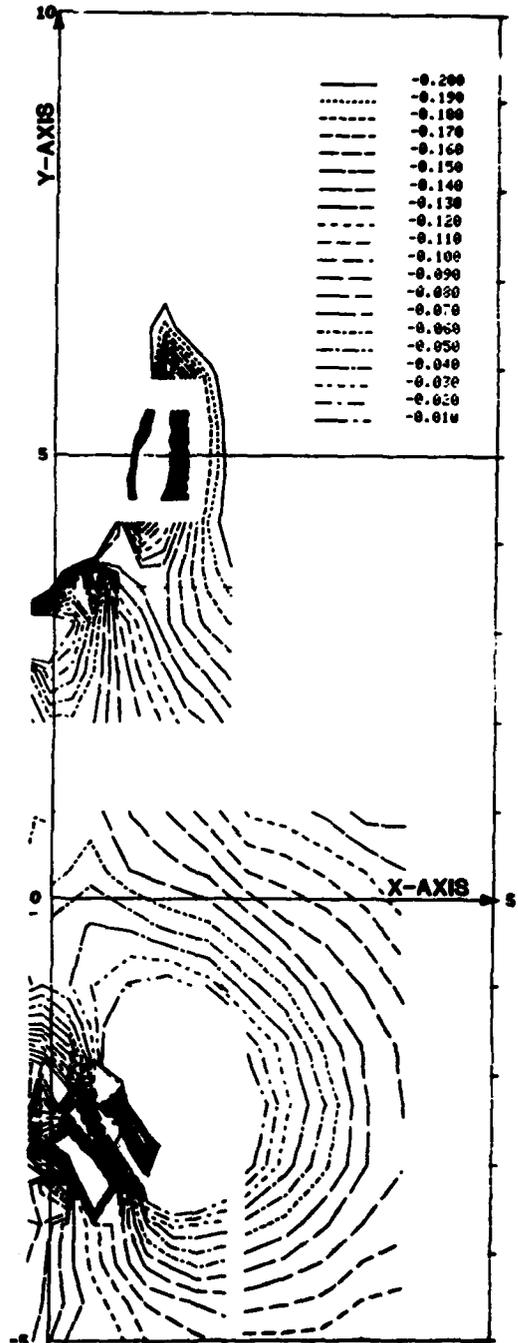
Figure 16: Total Pressure
Coefficient
Contours without
Canard
Z = -4 Inches

23
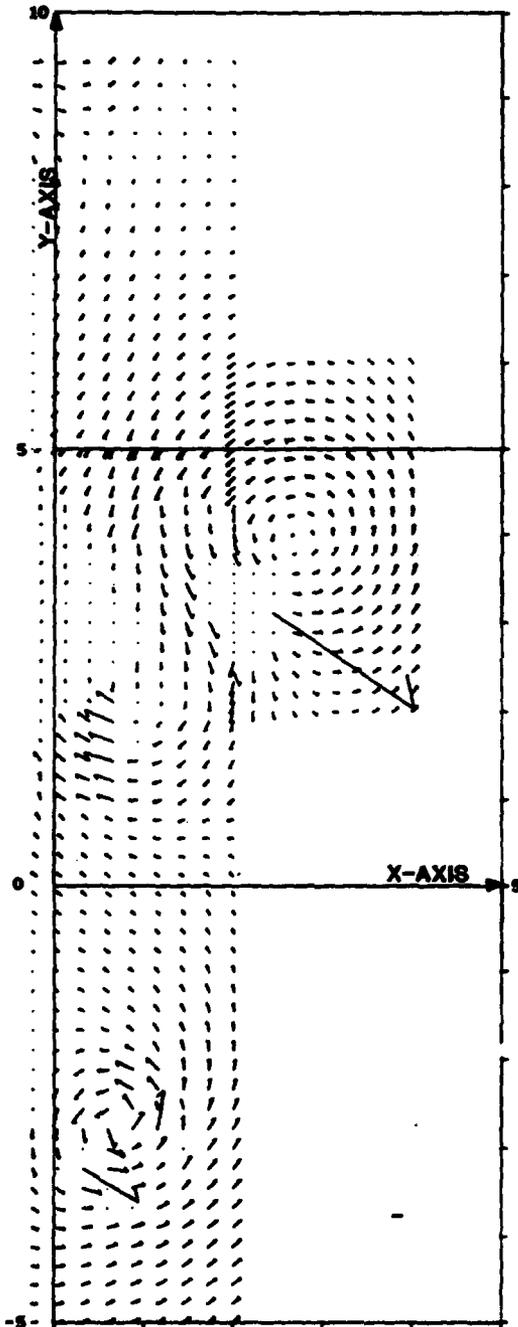
Figure 17: Cross Velocity
Vectors with
Canard
Z = -4 Inches
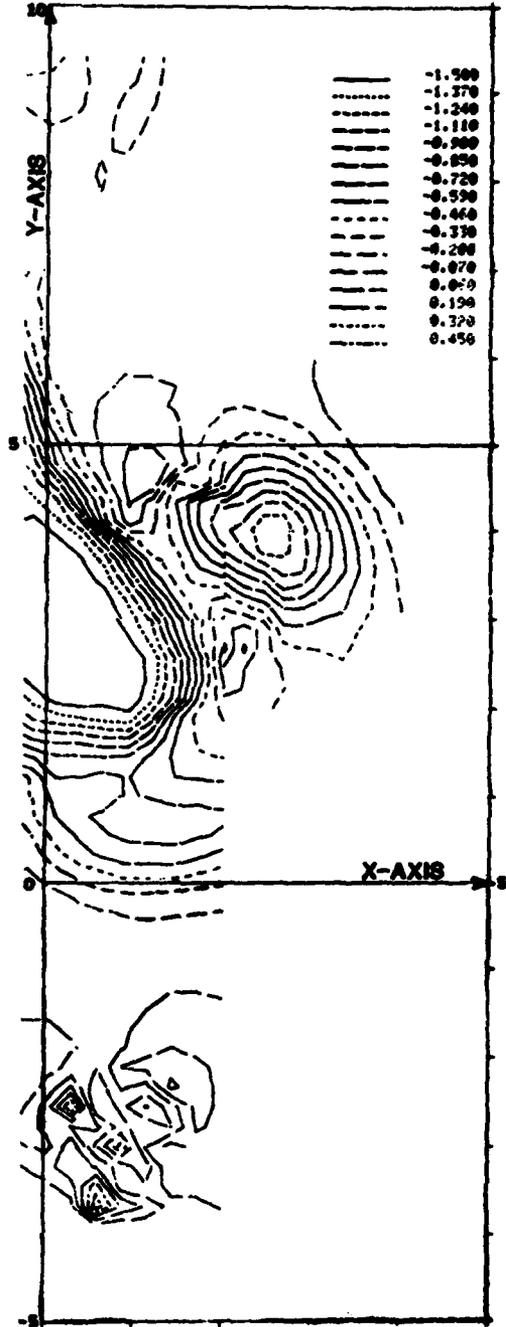
Figure 18: Total Pressure
Coefficient
Contours with
Canard
Z = -4 Inches

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over the wing directly downstream of the canard now has an outboard flow component as well as a downward component.

The last and most downstream data plane is illustrated by data plots in Figures 19 and 20 for the wing/body and Figures 21 and 22 for the wing/body/canard configuration. This plane is 8 inches downstream of the wing tip trailing edge. The wing intersection of this plane lies from the wing root at $y=9.8$ inches to the $z=-8$ inch location of the wing trailing edge at $y=1.6$ inches.

Figure 19 presents the cross velocity field for the wing/body configuration. Note that the leading edge separation vortex has moved to the wing root/fuselage junction, $y=-9.8$ inches, and the wing tip vortex remains essentially downstream of the wing tip, $y=-3$ inches. The wash over the wing is downward with a very small inboard component.

The wing wake can be see in Figure 20 from the wing trailing edge and wrapping up into the wing tip vortex. This is best seen using the narrow range of ΔC_{P_O} presented in Figure 20.

Figure 21 shows the effect that the canard wake has had on the wing flow field. The wash seen by this spanwise section of the wing has a strong inboard component which runs counter to the wash just above the wing due to the canard wake. The canard vorticity appears to be high enough away from the wing to lose some of its influence on the flow field near the wing. The cross flow due to the wing leading edge separation vortex is now very weak. This vortex system has been greatly weakened by the presence of the counter rotating canard system.

The wing wake can be observed in the cross flow velocity in Figure 21 by noting the region in the flow field where the spanwise component of the wash abruptly changes sign. Above the wing wake, in

25
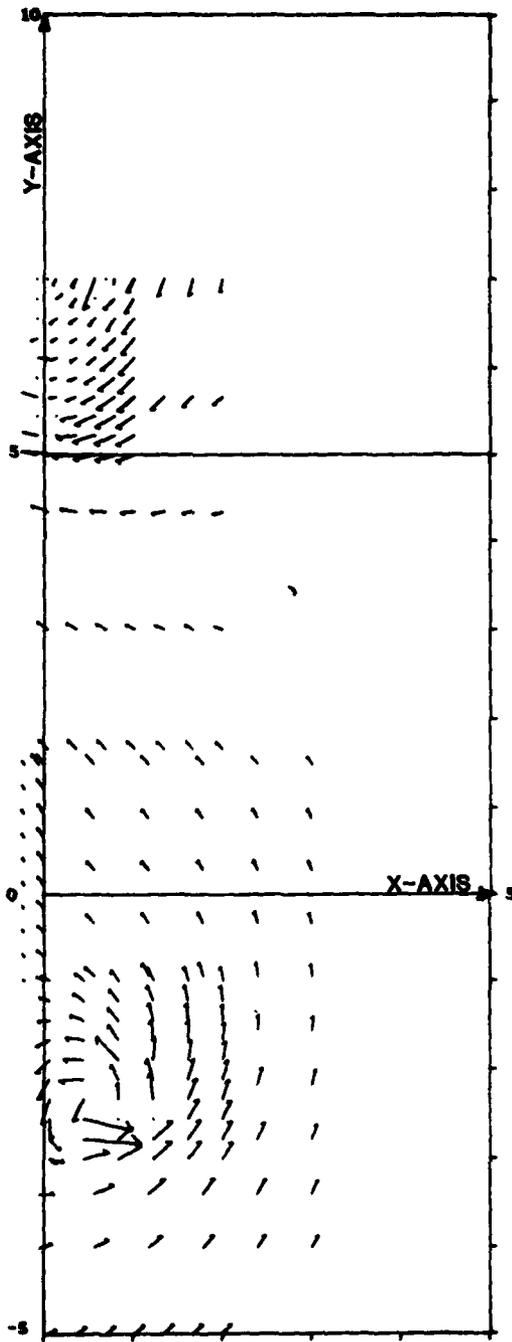
Figure 19: Cross Velocity
Vectors without
Canard
Z = -8 Inches
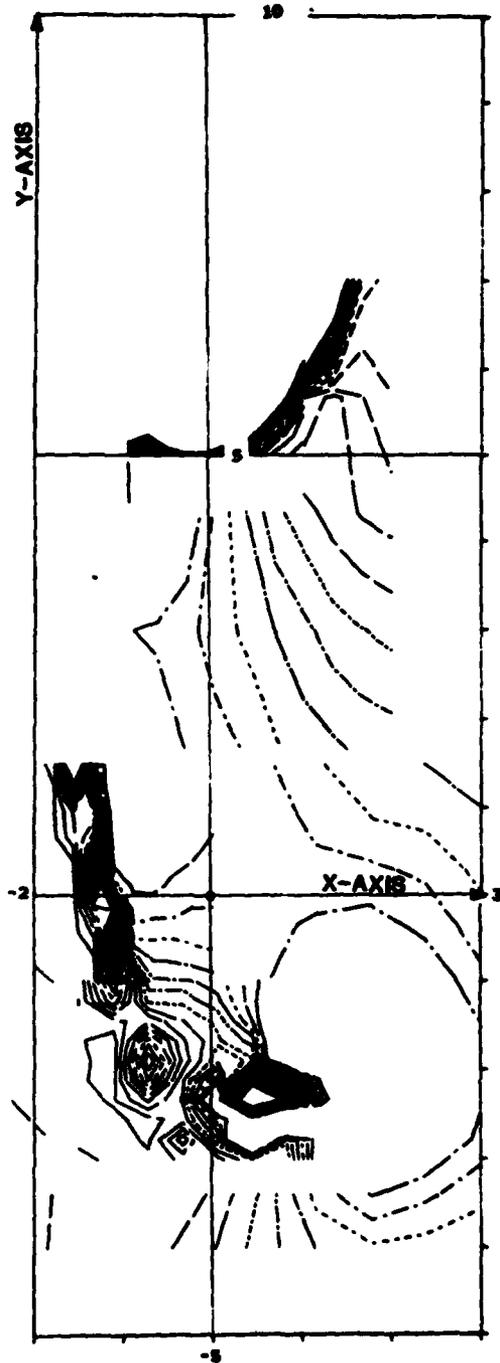
Figure 20: Total Pressure
Coefficient
Contours without
Canard
Z = -8 Inches

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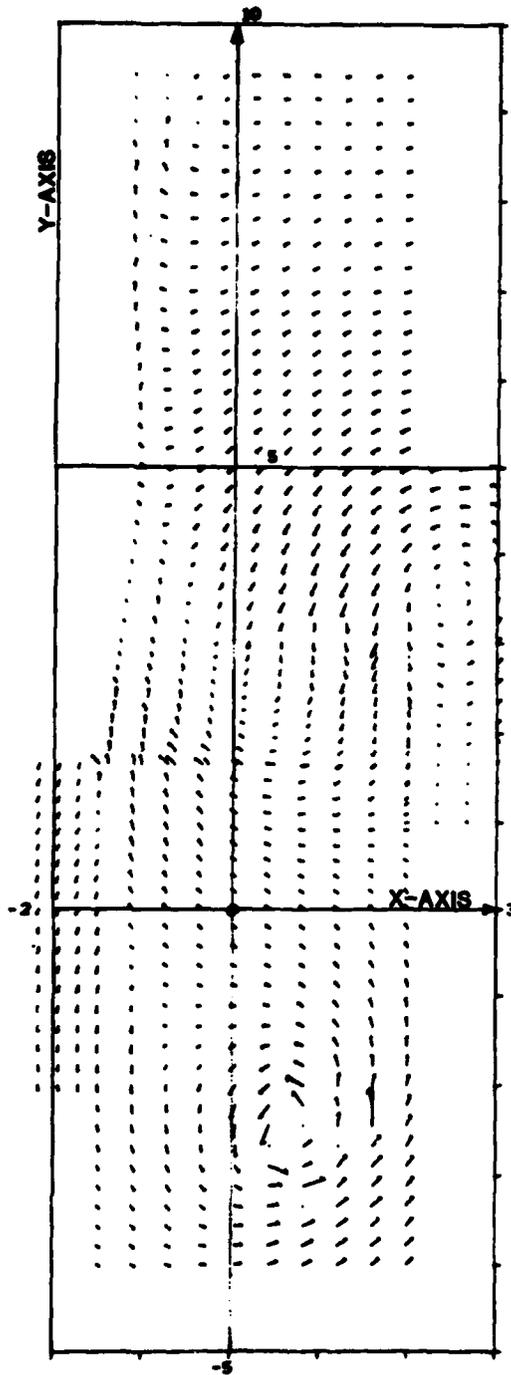
Figure 21: Cross Velocity
   Vectors with
            Canard
            Z = -8 Inches
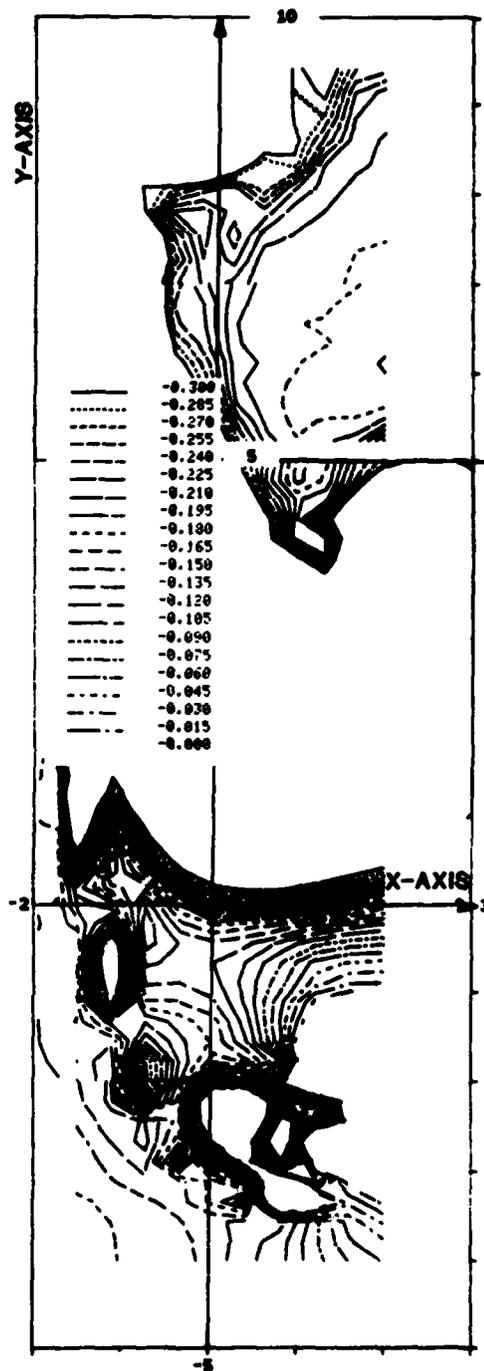
Figure 22: Total Pressure
            Coefficient
            Contours with
            Canard
            Z = -8 Inches

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the region of (-1, -1, -8), the wash has an inboard component. Below
it the wash is outboard. The wing tip vortex is unchanged in location.
Figure 22 presents a narrow range of ΔC_{P_0} contours in order to
emphasize the wing wake location. Note the large wake and vortex
system above the wing due to the canard vortex system centered at
approximately (2, 3, -8). The center of this system would require much
larger values of loss in total pressure tc be included in the plot.

D. General Airflow Characteristics around the Model

The airflow which developed in the test model's wake had flow
characteristics typical of sharp leading edge lifting surfaces. Both
the canard and the wing developed two concentrations of vorticity as
their angle-of-attack was increased: the usual tip vorticity and a
leading edge separation vortex caused by their sharp leading edge.
Their streamwise development was strongly influenced by the leading
edge sweep of each surface.

With the negative leading edge sweep of the wing, the leading
edge separation vortex of the wing moved inboard as it developed
streamwise. This moved it away from the tip vorticity that develops at
the wing tip. Near the fuselage the core of this leading edge vortex
is forced toward the streamwise direction due to the fuselage
interference effects. The resulting rotational sense downstream in the
wake for this separation vortex was opposite of the tip vortex and its
core widely separated from the tip vortex core.

The canard leading edge had positive sweep causing a different
movement in its leading edge separation vortex core. As this
positively swept leading edge separation vortex developed downstream,
it moved outboard of the fuselage toward the vortex system being
developed at the canard tip. As the canard leading edge intersected

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with the canard tip, the leading edge separation vortex core turned streamwise and combined with canard tip vorticity to form a large concentration of vorticity downstream of the canard tip. Due to the orientation of the canard leading edge and its separation vorticity, its rotational sense was the same as the canard tip vortex when it turned streamwise. Thus, the flow influence from these vortices blended into a large system of vorticity aft of the canard tip.

V.   Conclusions

The ability to locate the wakes of lifting surfaces in the free stream has been shown. The pressure loss coefficient, ΔC_{p_o} , plotted spatially, located the exact position of the canard wake. Other related data have shown that the wake signature can be observed even for lifting surfaces with zero angle-of-attack.

Vortical flow can also be observed. The organized energy losses in the core regions of vortices due to viscous effects can be observed as total pressure losses. The tip vorticity produced by all the lifting surfaces has been observed, and the wrapping up of the wing wake around the tip vortex core has been shown as the transition from the free wake to the tip vortex. Leading edge separation vorticity has also been documented using the seven-hole probe. Its formation on both forward and aft swept lifting surfaces has been documented, and its movement spanwise is consistent with the leading edge sweep. Its interaction with other wake flow fields such as the canard vorticity has also been shown.

With the above capability to observe the wake characteristics of lifting surfaces, several observations are noted of the canard wake, the wing wake, and their effect on each other.

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The canard wake illustrates the type of wake that should be expected from an aft swept, sharp leading edge lifting surface. A large concentration of vorticity downstream of the canard tip exists due to both tip pressure recovery and the streamwise remnants of the leading edge separation vortex. This vortex system has a wake of pressure loss inboard of its location which manifests itself as a downwash velocity field aft of the canard trailing edge. This wake is bounded at the fuselage by a weak fuselage interference disturbance. The spanwise velocity component in the wake reflects that expected of aft swept wings.

The wing wake illustrates the type of wake that should be expected aft of a forward swept, sharp leading edge lifting surface. The wake of pressure loss aft of the wing trailing edge is bounded by two concentrations of counter rotating vorticity. The outboard concentration is due to the tip pressure recovery. The inboard concentration is due to the wing leading edge separation vortex that has been turned streamwise by the fuselage at the wing and fuselage junction. The spanwise velocity components of the wake show an inboard flow movement on the upper surface of the forward-swept wing.

The wake of the canard changed the flow field seen by the wing and the resulting wake due to the wing. The downwash from the canard prevented the formation of a leading edge separation vortex over the immediate downstream portion of the wing. Thus, the wing leading edge separation vortex turned downstream at the span location aft of the canard tip and the vortex system from the canard was translated and weakened when it intersected the area of the wing leading edge separation vortex.

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5. Gerner, A.A., and C.L. Maurer. "Calibration of Seven-Hole Probes Suitable for High Angles and Subsonic Compressible Flow." Aeronautics Digest, USAFA-TR-81-4, USAF Academy, May 1981.

EXPERIMENTAL FLOW FIELD MEASUREMENTS OF THREE-DIMENSIONAL
SQUARE CROSS-SECTION MISSILES AT MODERATE ANGLES OF ATTACK

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Abstract

This paper describes an investigation conducted to analyze the subsonic aerodynamic flow field characteristics of square cross-sectioned missile bodies. Leeside pressure and velocity measurements as well as surface oil flow and tuft grid flow patterns were obtained for the square missile bodies, which were tested at various roll angles and angles of attack. The results indicate that the body vortex flow field is highly dependent on roll angle, body corner radius, and angle of attack.

I.   Introduction

Submunitions have typically been placed in circular

cross-sectioned housings. However, these housings create problems of

efficient packing and have led munitions designers to investigate the

use of rectangular or square cross-sectioned munitions shells. These

rectangular housings permit easier packaging of the rectangular-shaped

modular components and yield a greater usable volume for a given

frontal area. This packaging advantage, however, must be weighed

against the potentially detrimental aerodynamic effects caused by the

rectangular shape of the munitions shell. Unfortunately, data

concerning the aerodynamic characteristics of square cross-sectioned

bodies is limited. The limited data that does exist includes the

two-dimensional studies of Polhamus (Refs. 1 and 2), the high angle of

attack work by Clarkson et al (Ref. 3), and the most recent work by

Knoche (Ref. 4).

In an attempt to gather more information about the aerodynamic

performance of square-shaped missile bodies, the United States Air

Force Armament Laboratory and the United States Air Force Academy have

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been conducting a research program to analyze the aerodynamic
characteristics of square cross-sectioned munitions containers. The
initial work in this effort (Ref. 5) was mainly concerned with
measurement of the forces and moments acting on square cross-sectioned
bodies in a freestream airflow. Current research, described in this
paper, analyzes the subsonic flow field characteristics created in the
vicinity of the leeward side of the missile body. We obtained flow
field pressures and velocities for a variety of roll angles, angles of
attack, and cross-sectional shapes. The flow field was also
investigated by observing oil patterns on the surface of various
missile configurations. In addition, we placed a grid of wool tufts in
the flow field and photographed the tuft patterns. The experimental
data measured from the flow field was correlated with force data
obtained during last year's research (Ref. 5). This paper also
contains a description of the wind tunnel test models, the test
facility and the equipment used, and an analysis of all test results.

II. Test Facilities

   A. Wind Tunnel

      The experimental data for this investigation was obtained in
the subsonic wind tunnel at the U.S. Air Force Academy. The tunnel is
a continuous flow, closed circuit facility which has a test section
measuring 2 feet by 3 feet. It is capable of operating at Mach numbers
ranging from .04 to .35 at atmospheric pressure. At maximum operating
conditions, the tunnel is capable of operating at a unit Reynolds
number of 1.6 million per foot (Ref. 6).

   B. Wind Tunnel Models

      The various munitions models used in this investigation are

shown in Figure 1. This figure depicts the cross-sections of the four munitions bodies tested, each with a different cross-section corner radius, r, and a blunted tangent-ogive nose. The body corner radius was non-dimensionalized by the round body diameter. The body corner radius ratios, r/b, investigated were 0.0, 0.1, 0.2, and 0.5.
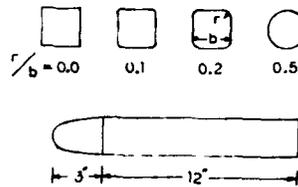
Figure 1. Model Cross-Sections and Planform
r - Cross-Section Corner Radius
b - Body Diameter

Each of the munitions containers that was tested measured 12 inches in length and 2 inches in diameter. In addition, the blunted tangent-ogive nose was 3 inches in length with a 69 percent bluntness. All components were made of aluminum. Figure 2 shows a typical testing setup.
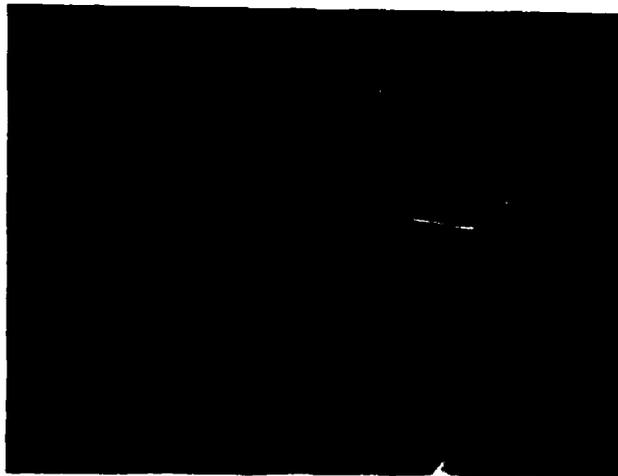
Figure 2. Typical Wind Tunnel Model Setup Showing
a Side View of a Model in the Wind Tunnel

C. Test Apparatus

To measure the leeside pressure and flow velocities on the square-shaped munitions containers, a seven-hole probe developed at the Air Force Academy was used (Ref. 7). The seven-hole probe is capable of recording total pressure, static pressure, and fluid velocity in all three axes and has been calibrated for incompressible fluid flows up to 80 degrees, measured from the flow direction to the probe axis.

To position the probe on the leeward side of the missile body, a three-directional traverse mechanism was used. For all flow field measurements taken, the traverse mechanism was used and was positioned to place the probe in a plane behind the model, approximately one-half inch behind the model base.

A .75 inch diameter, steady state, internally mounted strain gauge balance was used to measure the force and moment components on the square-shaped missile bodies in all three axes. The balance is capable of measuring forces to an accuracy of 0.1 percent. All forces and moments were recorded in both the body- and wind-axis systems with the axis origin at the balance center. The positive force directions in the wind axis system are presented in Figure 3.
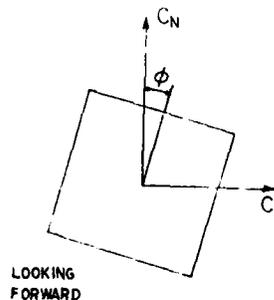
LOOKING
FORWARD

Figure 3.   Wind-Axis System (Looking at the Aft-Side of the Model). Direction of Airflow is out of the Plane of the Paper.

III. Test Result

The results obtained with the pressure probe included flow field measurements which permitted plotting of pressure contours and velocity patterns at the aft plane of the tested model. All flow field data was collected at a freestream Mach number of approximately 0.10 and a Reynolds number of 0.43 million per foot. Data was taken at 280 points in the flow field planes, which measured 5 inches by 6 inches. All four bodies investigated were tested at angles of attack of 15 degrees and 25 degrees, and at roll angles of 0 degrees, 22.5 degrees, and 45 degrees.

To enhance our understanding of the flow field pressure and velocity patterns obtained by the pressure probe, tuft grid tests and oil flow tests were also conducted. The tuft grid tests were conducted at the same test conditions as the probe tests described in the preceding paragraph. Figure 4 shows a schematic representation of the tuft grid test setup. Oil flow tests were conducted at approximately Mach 0.3 at angles of attack of 10 degrees, 15 degrees, 20 degrees, and 25 degrees. Although obtained at a different Mach number than the tuft grid and flow field pressure measurement data, the oil flow patterns provide insight into the vortex build-up and shedding phenomena caused by the square missile bodies in an airstream.
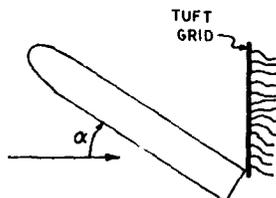
Figure 4. Side View of Tuft Grid Test Setup

Force and moment data were taken at Mach 0.3 for all test
configurations. Because the force and moment measurements were
obtained at a different Mach number than the flow field pressure
measurements, only a qualitative comparison of the two sets of data is
possible.

IV. Analysis

A. Roll Angle Effects

The three roll angles tested (0 degrees, 22.5 degrees, and 45
degrees) yielded widely varying results, as would be expected from a
non-circular cross-sectioned body. Figure 5 illustrates this point.
The tuft grid patterns shown in the figure were obtained by
positioning the 10 percent corner radius body at an angle of attack of
25 degrees and making measurements at each of the 3 roll angles. For
the zero degree roll case, very little vortex activity is evident, as
illustrated in Figure 5a. However, at roll angles of 22.5 degrees and
45 degrees, strong vortex action is present. Figure 5b shows a strong
vortex on the right leeward side of the body with a weaker but
developing vortex along the left side. At a 45 degree roll, shown in
Figure 5c, two strong vortices are evident on the leeward side of the
body of apparently equal strength and symmetry.

The relative strength of the vortex patterns in Figure 5 can be
better defined by the total pressure contours shown in Figure 6. The
pressure contours were measured at the aft plane of the zero percent
corner radius body at a 25 degree angle of attack for all three roll
angles. The contours indicate how the total pressure coefficient
varies in the flow field plane. As shown in Figure 6, the minimum
total pressure (which is labeled for each vortex) occurs at the center

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of the vortex. The magnitude of this central pressure (C$_p$) for each

vortex provides an indication of the strength of the vortex -- the

more negative the total pressure, the greater the vortex strength. It

is evident that the vortices become stronger as the body is rolled to

45 degrees.

(a) $\phi = 0°$

$\alpha = 25°$

$r/b = 0.10$

(b) $\phi = 22.5°$

(c) $\phi = 45°$
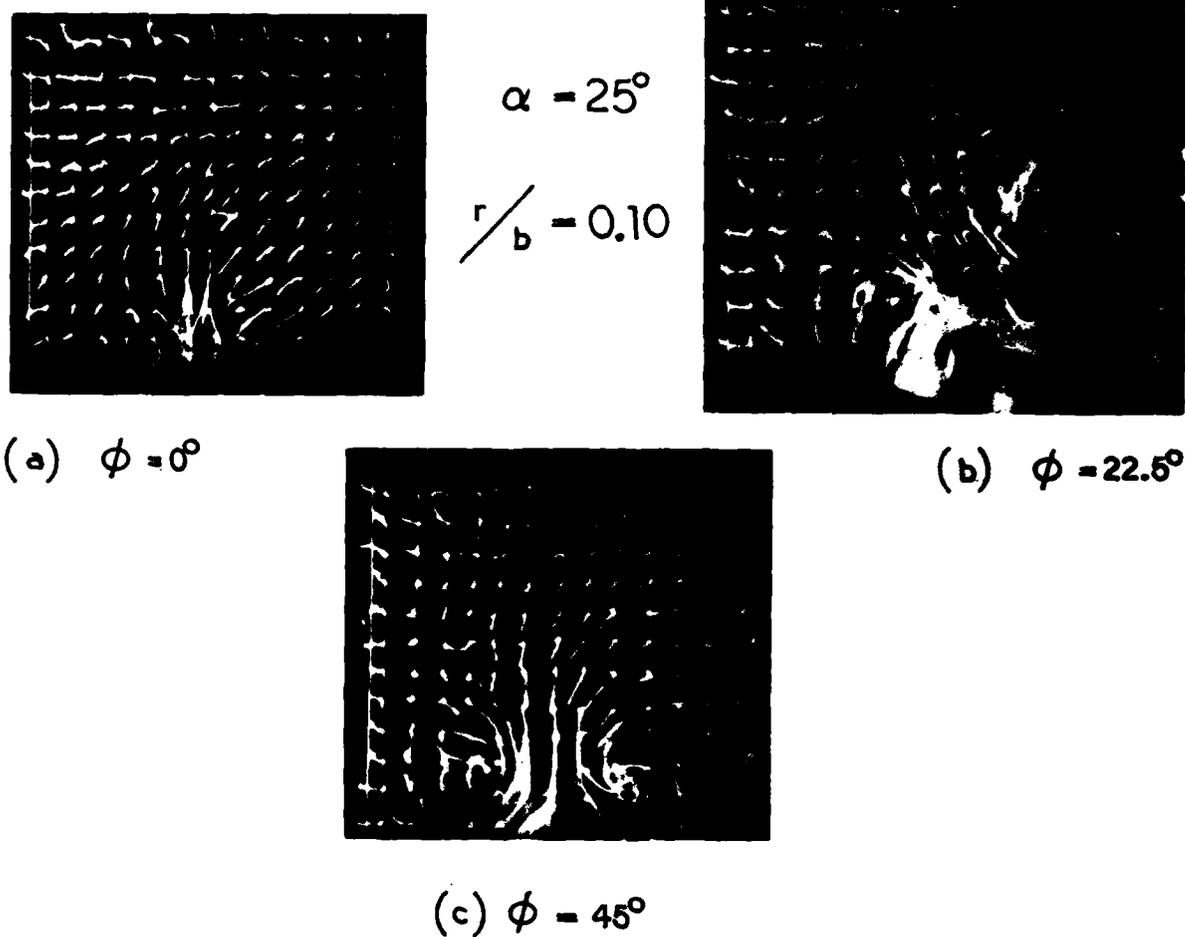
Figure 5. Tuft Grid Flow Patterns for Three Roll Angles
for the 10 Percent Body (r/b = 0) at an Angle
of Attack of 25 Degrees

Figure 6a shows the total pressure contour for a munitions casing

tested in a zero roll case, and it indicates that relatively weak

vortices occur with the lowest central pressure, -0.51. Figure 6b

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illustrates the strong vortex on the right leeward side and the
developing vortex along the left side that were shown by the tuft grid
tests (Figure 5b) when the munitions housing was tested at 22.5
degree roll angle. The right vortex shows an increase in strength from
the vortices at zero roll. Finally, the contour lines and the low
central pressure shown in Figure 6c indicate that the vortices which
develop when the missile body has a 45 degree roll angle in the flow
stream are much stronger than the vortices that occurred at the other
two roll angles shown in Figures 6a and 6b.

AFT STATION LOOKING FORWARD
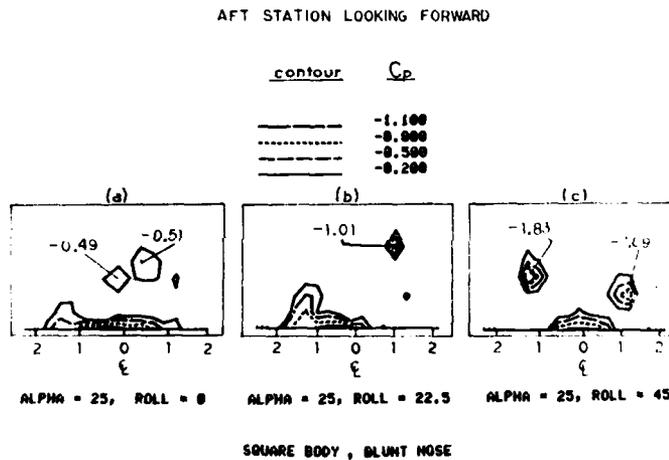
contour   C_p

Figure 6.   Total Pressure Contours for Three Roll Angles of
            the 0 Percent Body (r/b = 0) at an Angle of Attack
            of 25 Degrees. The Closed Contours on Each Graph
            Represent Vortices in the Flowfield. The Value of
            the Coefficient of Pressure (C_p) for the Center of
            Each Vortex is Labeled.

Also, the graphic plots illustrated in Figure 6 show that even
though the orientations of the body cross-sections at the 0 degree and
45 degree roll angles are symmetric, the vortex patterns are slightly
asymmetric. This phenomenon can be attributed to an inaccuracy in
setting the roll angle. This inaccuracy is estimated to be less than

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one degree. Another possibility is that the asymmetry is caused by an instability in the flow pattern due to the nature of the body cross-section.

Figures 7b, 7d, 8b, and 8d illustrate the vortex patterns shown by the velocity vector patterns for two of the corner radii (r/b = 0, .2) at a 25 degree angle of attack. Figure 7 shows the zero roll angle case, while Figure 8 illustrates the 45 degree roll angle. For the zero percent corner radius (sharp-cornered square cross-sectioned) body, asymmetric vortex patterns are clearly evident, as shown in Figures 7b and 8b. However, no asymmetry is seen for the more rounded 20 percent corner radius body as shown in Figures 7d and 8d.
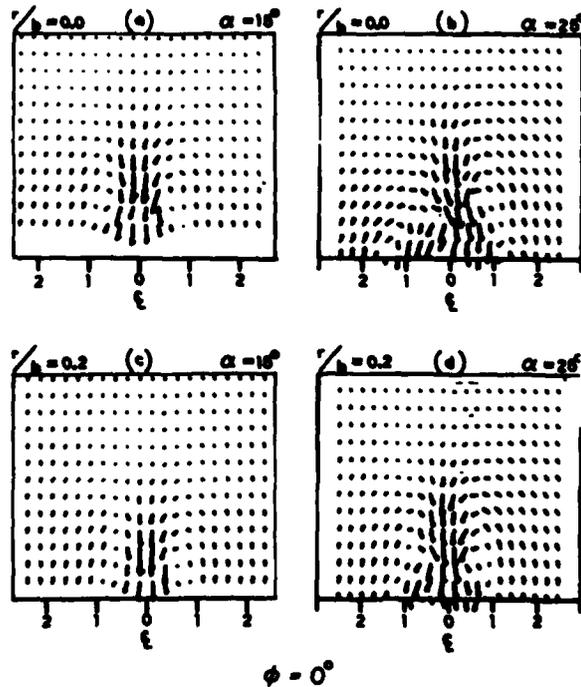
Figure 7. Velocity Patterns behind Two Body Cross-Sections (with Cross-Section Corner Radii of 0 Percent and 20 Percent) at Two Angles of Attack (15 Degrees and 25 Degrees) and a Roll Angle of 0 Degrees

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Similarly, flows at a lesser angle of attack of 15 degrees do not show these asymmetric patterns as illustrated in Figures 7a, 7b, 8a, and 8b. Thus, the asymmetric vortex patterns generated by the symmetric bodies occur only at higher angles of attack for the zero or near zero body corner radii shapes. An investigation will be made into the cause of the asymmetric vortex patterns at the symmetric roll conditions.

$$\phi = 45°$$
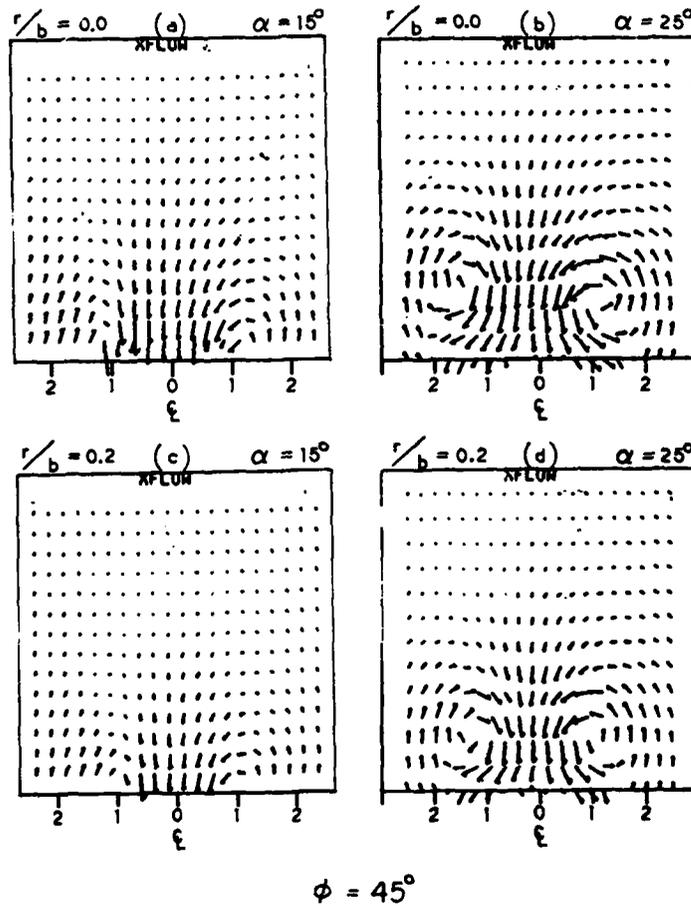
Figure 8.   Velocity Patterns behind Two Body Cross-Sections
(with Cross-Section Corner Radii of 0 Percent and
20 Percent) at Two Angles of Attack (15 Degrees and
25 Degrees) and a Roll Angle of 45 Degrees

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B. Corner Radius Effects

The effect of variations of corner radius on the vortex flow
patterns can be seen by comparing Figures 7a and 7c, 7b and 7d, 8a and
8c, and 8b and 8d. Each of these pairs of figures shows the tuft grid
patterns for the zero percent and 20 percent corner radii bodies at
the same roll angle and angle of attack. In all four cases, the vortex
activity is greatest for the zero percent corner radius body. Thus,
for the symmetric roll cases of zero degrees and 45 degrees, the
vortex flow patterns become more pronounced as the body becomes more
square. This tendency is also evident from the oil flow patterns shown
in the photographs in Figures 9 and 10. By successively comparing the
surface oil flow patterns shown in cases (a), (b), (c), and (d) of
Figures 9 and 10, one can see that the vortex separation line on the
leeward side of the body becomes less distinct as the body becomes
more round. A typical separation line is labeled in Figure 9b. The
vortex separation line is consistently generated at the nose-body
junction and is caused by the flow on the windward side separating at
the body corners, curling up, and reattaching as a vortex along the
leeward side of the body. The location of the separation line does not
appear to move as r/b goes from 0.0 to 0.5, but the change in the
sharpness of the line seems to indicate that the strength of the
vortex diminishes as r/b approaches 0.5. Figure 11 confirms this
observation by displaying pressure contours for three of the corner
radii oil flows seen in Figure 10. The strongest vortex, indicated by
the most negative value of central pressure, -1.67, occurred when the
10 percent corner radius body was tested. (See Figure 11a.) Figures
11b and 11c illustrate that the vortex strength decreases with
increasing corner radius as shown by a central pressure of -1.41 for
the 20 percent body and only -0.81 for the round (50 percent) body.

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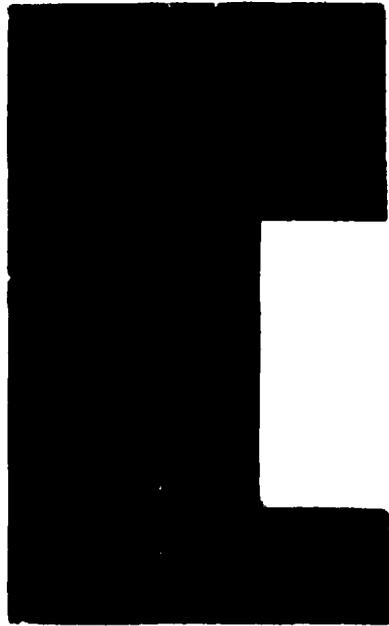
(a) $r/b = 0.00$

(b) $r/b = 0.10$

(c) $r/b = 0.20$

(d) $r/b = 0.50$

$\alpha = 15°$ $\phi = 45°$

Figure 9.   Surface Oil Flow Patterns for Four Body Cross-Sections
at an Angle of Attack of 15 Degrees and a Roll
Angle of 15 Degrees
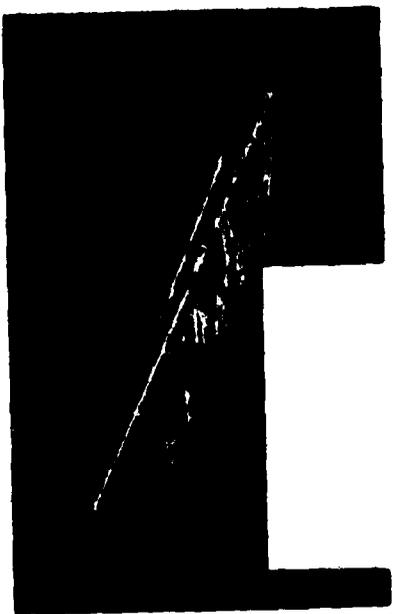
(a) r/b = 0.00

(b) r/b = 0.10
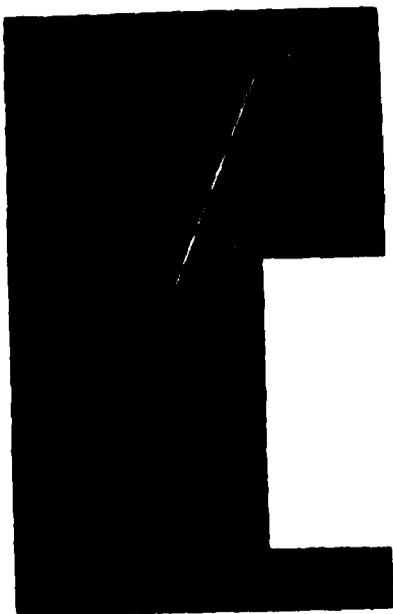
(c) r/b = 0.20

(d) r/b = 0.50

$\alpha = 25°$ $\phi = 45°$

Figure 10.   Surface Oil Flow Patterns for Four Body Cross-
Sections at an Angle of Attack of 25 Degrees and
a Roll Angle of 45 Degrees

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AFT STATION LOOKING FORWARD
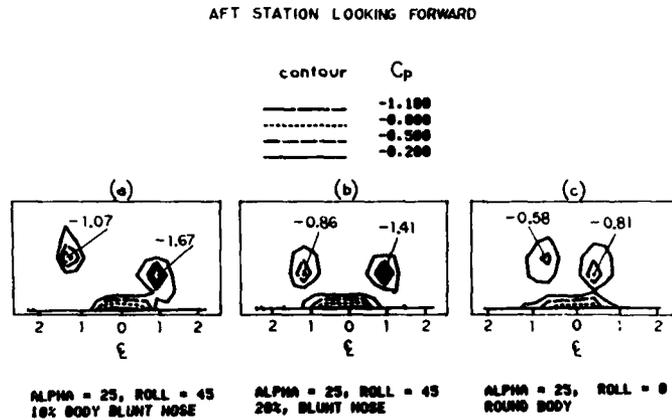
Figure 11. Total Pressure Contours for Three Body Cross-Sections
(r/b = 10 Percent, 20 Percent, 50 Percent) at an
Angle of Attack of 25 Degrees and a Roll Angle
of 45 Degrees.

At the unsymmetric roll angle of 22.5 percent shown in Figure 12,
interesting flow patterns exist. This figure illustrates the vortex
patterns at a 25 degree angle of attack for the square, zero degree
corner radius, and the 20 percent corner radius bodies. Strong vortex
action exists for both bodies with the more developed, stronger
vortices evident in the zero percent corner radius case of Figure 12a.
This is consistent with the data represented in Figures 7 through 11
for the symmetric roll angles of zero degrees and 45 degrees, where
the vortex strength increased as the corner radius decreased to zero.
In addition, when comparing the tuft grid patterns in Figures 12a and
12b, we observe that the vortices tend to move closer to the body as
the corner radius increases (that is, as the body becomes more round).
As a result, the vortices stay attached to the body longer and become
hindered in their effort to develop and strengthen due to the
proximity of the body. Figure 13, which shows oil flow patterns on the
right leeward side of the body for three different corner radii at a
roll angle of 22.5 degrees, confirms this observation. The zero corner

45

radius body, Figure 13a, corresponds to the tuft grid pattern in
Figure 12a and shows the vortex separation line extending halfway back
to the body. This indicates an early separating vortex that can be
seen on the upper right side of the body in Figure 12a. For the more
rounded, 20 percent corner radius body, Figure 13c shows that the
vortex separation line extends farther back on the body, nearly to the
body base. This phenomenon indicates that a vortex is attached to the
missile body for its entire length. This observation is supported by
the Figure 12b tuft grid pattern for the 20 percent corner radius
body, where the vortex along the right leeward side remains close to
the body.
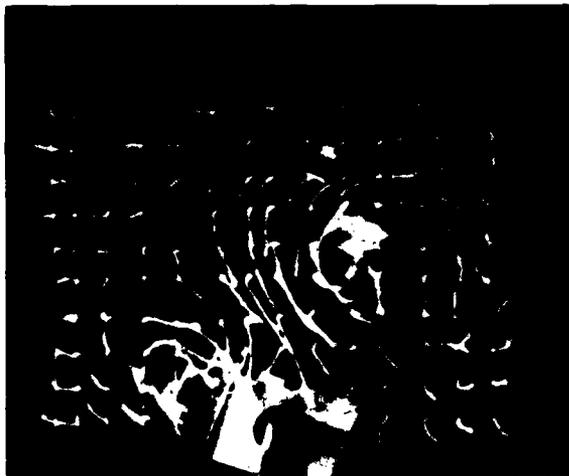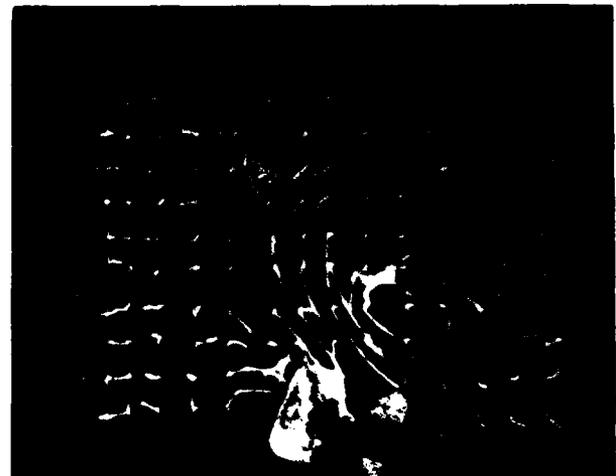
(a) $r/b = 0.00$ (b) $r/b = 0.20$

$$\alpha = 25°$$

$$\phi = 22.5°$$

Figure 12. Tuft Grid Patterns for Two Body Corner Radii
(r/b = 0 Percent, 20 Percent) at an Angle of
Attack of 25 Degrees and a Roll Angle of 22.5 Degrees

(a) $r/b = 0.00$

(b) $r/b = 0.10$
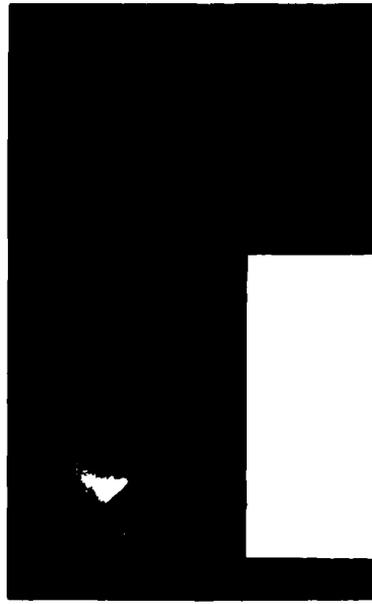
(c) $r/b = 0.20$

$\alpha = 25^\circ$

$\phi = 22.5^\circ$

Figure 13.   Surface Oil Flow Patterns (Top View) of Three
Body Cross-Sections (r/b = 0 Percent, 10 Percent
20 Percent) at an Angle of Attack of 25 Degrees
and a Roll Angle of 22.5 Degrees

Figure 14 illustrates the variations of normal and side forces
with corner radius, roll angle, and angle of attack. Normal force
decreases as corner radius increases for all roll angles and angles of
attack (Figures 14a and 14c). This is expected since the more rounded
bodies allow increased pressure relief around the body corners
reducing the normal force. In general, the normal force increases for
any given corner radius as the body is rolled from zero degrees to 45
degrees. This can be expected since the planform area of the
non-circular body increases as it is rolled to 45 degrees.
The side force coefficient behaves quite predictably at the symmetric
roll cases of zero degrees and 45 degrees. The side force coefficient
stays close to zero (Figures 14b and 14d), with the deviation from
zero possibly explained by the slightly asymmetric flow patterns seen
in Figures 6, 7, and 8. The unsymmetric roll angle of 22.5 degrees
shows that there is a significant side force present for all
non-circular body corner radii. Undoubtedly, the side force is a
result of the asymmetric vortex flow field patterns generated by the
non-circular cross-sections as seen in Figures 5, 6, and 12.

C. Angle of Attack Effects

By comparing Figures 14a and 14c, one can see the effect of
angle of attack on the normal force on a missile in an airstream.
Normal force increases with increasing angle of attack as expected.

The side force on the missile (Figures 14b and 14d) exhibits the same
behavior, increasing with increasing angle of attack, although the
zero degree and 45 degree roll angle cases show only small increases
in magnitudes. The difference in side force at the 15 degree and the
25 degree angle of attack for a 22.5 degree roll angle can be
explained by observing the flow field shown in Figure 15.

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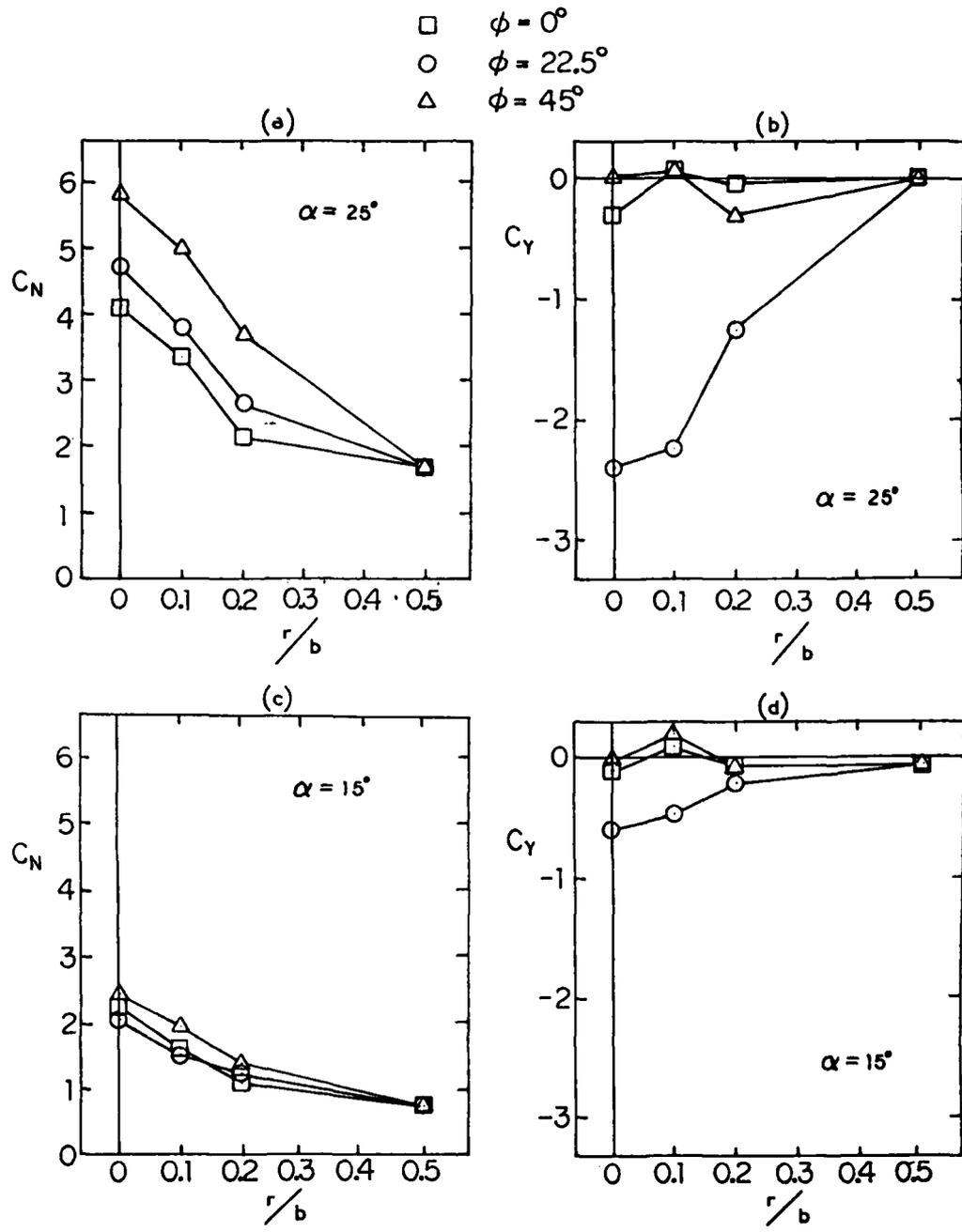
Figure 14. Normal Coefficients (C_N) and Side Force Coefficients
(C_y) for All Four Body Cross-Sections at Three
Roll Angles and Two Angles of Attack

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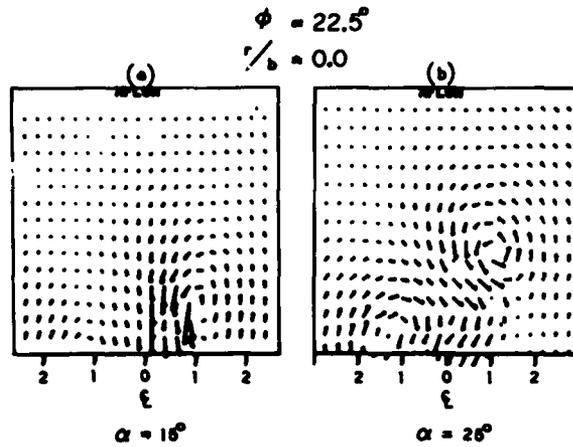
Figure 15. Flow Field Velocity Patterns for the 0 Percent
Corner-Radius Body (Sharp-Cornered Square
Cross-Section) at a Roll Angle of 22.5 Degrees
and Two Angles of Attack

Figure 15a shows the right leeside vortex of the zero corner
radius body developing and strengthening close to the body, which is
at a 15 degree angle of attack. The left vortex is just beginning to
develop. At a 25 degree angle of attack, the right leeside vortex is
fully developed and is stronger and farther from the body. The left
vortex has also developed and strengthened. This increased vortex
development and strengthening at a 25 degree angle of attack agrees
with the side force curves in Figures 14b and 14d.

The increase of side force with angle of attack for the 22.5
degree role case can also be seen in the oil flow patterns shown in
Figure 16. The three pictures in Figure 16 sequentially portray the
air flow over the square missile as angle of attack increases from 10
degrees to 20 degrees. At a 10 degree angle of attack (Figure 16a),
the vortex separation line extends rearward from the nose-body
junction on the upper portion of the leeward side and is weak but
extends the length of the body. At a 15 degree angle of attack shown

in Figure 16b, the separation line appears better defined than at 10 degrees. The separation line becomes sharply defined, but shorter, at a 20 degree angle of attack as shown in Figure 16c. This observation of the sharpness and length of the vortex separation lines illustrates the strengthening of the vortex and its earlier separation from the body as angle of attack increases. Figure 13a, which shows the surface oil flow patterns at an even higher angle of attack (25 degrees), continues the same trends. At a 25 degree angle of attack, the vortex separation line remains sharply defined and shorter than at 20 degrees as shown in Figure 16c.
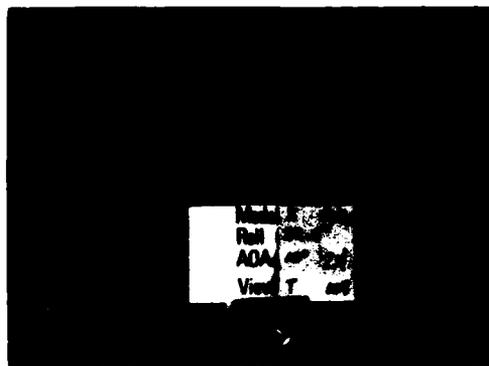
(a) $\alpha = 10^{\circ}$
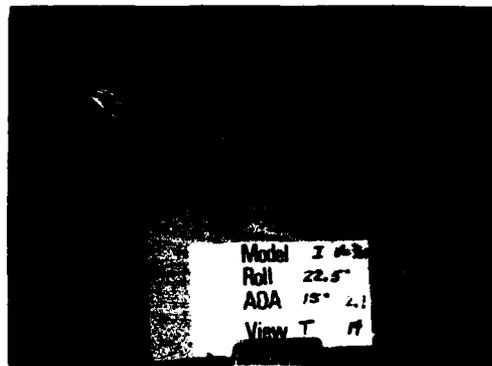
(b) $\alpha = 15^{\circ}$

$^{r}/_{b} = 0.0$

$\phi = 22.5^{\circ}$
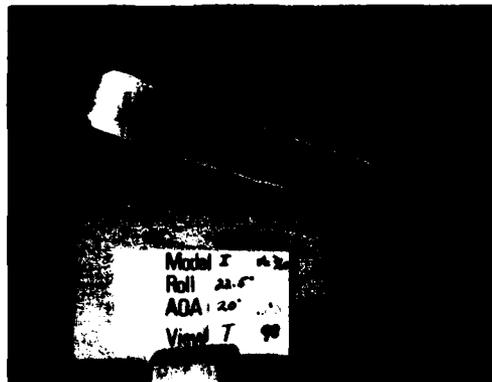
(c) $\alpha = 20^{\circ}$

Figure 16.   Surface Oil Flow Patterns for the 0 Percent Corner Radius Body at a Roll Angle of 22.5 Degrees and Three Angles of Attack

V.   Conclusions

The qualitative and quantitative flow field wind tunnel tests of a family of square cross-sectioned missile bodies revealed a number of important aerodynamic phenomena. Surface oil flow and tuft grid patterns resulting from the tests indicate that strong vortex flows occur around square cross-sectioned missile bodies at moderate angles of attack and non-zero roll angles. These vortices increased in strength as the roll angle was increased to 45 degrees. Similarly, a decrease in body corner radius toward a perfectly square cross-section also resulted in increased vortex strength. These trends, found in both oil flow and tuft grid patterns, were confirmed by total pressure contours. The vortex flow patterns generated at the nose-body junction build up and separate from the missile body as a function of body corner radius and angle of attack. As the body corner radius decreases to zero, or the angle of attack increases, the vortices strengthen at an earlier point on the body and separate into the flow sooner. When this occurs for the unsymmetric roll angle case of 22.5 degrees, the unsymmetric vortex patterns that are generated result in large side forces. This is particularly important to a missile designer, since the strong vortex flow fields and associated side force variations can have a significant impact on stability and control of non-circular vehicles in flight.

Symbols

α	angle of attack (degrees)
b	body diameter
C_N	normal force coefficient
C_p	total pressure coefficient
C_y	side force coefficient

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ϕ roll angle (degrees)

r   body corner radius

Acknowledgements

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SECTION II

Propulsion

WHAT MAKES THE AIRCRAFT GAS TURBINE ENGINE SO GOOD AT ALTITUDE?

Gordon C. Oates* and John M. Fabian**

Abstract

In this paper several aspects of the design and off-design behavior of aircraft gas turbine engines are analyzed, with particular emphasis on the high altitude behavior of such engines. Engine design limitations, as well as the reasons for various engineering design trade-offs are discussed, along with a description of the historical background and current trends in aircraft engine development.

I.   Introduction

The question raised by the title of this essay is one we have often been asked to answer. After reflecting on the subject, however, it became evident that there are several possible interpretations of the actual intent of the question. For example, we could consider the following three related questions, which actually are implied by the basic question:

1. Why does the gas turbine engine outperform other engine types at high altitude?

2. How does the turbofan engine performance compare to turbojet engine performance at high altitude?

3. Why does the performance of a given gas turbine engine improve with increase in altitude?

In the latter sections of this paper, we provide some simplified analytical (mathematical) methods for answering Questions 2 and 3. First, however, we think it could be of some interest to address all three questions in general terms, with the intent of describing some of the reasons which dictate that engineers make design trade-offs in order to build practical, efficient aircraft engines. We also describe some of the important historical decisions which occurred when pioneering engineers

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were forced to solve some of these design trade-off problems.

II. Discussion

Engineers, especially thermodynamicists, are partial to viewing problems in terms of "control volumes", such as that in Figure 1.
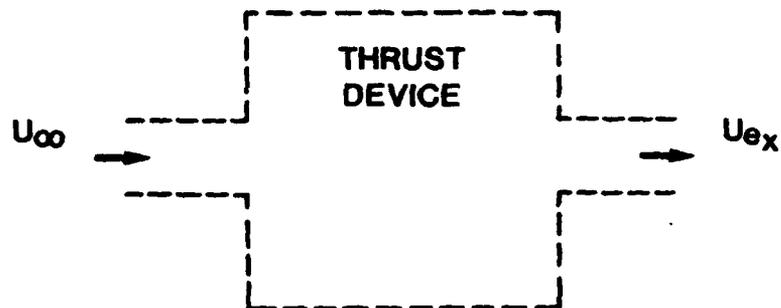
Figure 1. Propulsion as Viewed by the Thermodynamicist

The "control volume" is some region in space (usually defined by the external surface of the engine) and U_∞ is the velocity of the air entering the thrust device (engine) and U_{ex} is the velocity of the exhaust of the thrust device. Once the engine has been idealized as a control volume, the thermodynamicist is most interested in the control volume's interaction with the environment rather than with the internal working of the device. Thus, the task of the "thrust device" is to ingest a stream of air and to eject the air at an increased velocity obtaining a thrust from the change of momentum. It would seem that the amount of thrust provided should be a measure of the performance of the device, as would the fuel flow rate required to sustain the thrust. Because the thrust device must accompany the airplane, the weight of the device is also important.

Dr. Hans von Ohain, inventor and developer of the first aircraft gas turbine engine to power an aircraft in flight, is fond of asking the

question: "What two attributes of the gas turbine engine (turbojet or
fanjet) truly set it apart from competing types of aircraft propulsion
systems?" (Ref. 1) He, and we, think that these two distinguishing
attributes are: first, the enormously high thrust-to-weight ratio of the
aircraft gas turbine engine, and second, the effect of the inlet cowl on
the incoming airflow. The cowl has a very large influence, particularly
in transonic flows, because of the induced diffusion of the inlet air
prior to entry into the engine's compressor or fan. Because of this
airflow diffusion, it is the compressor operating condition (RPM), and
not the aircraft's flight Mach number, that actually determines the air
flow Mach number at the compressor's entrance or face. To understand this
concept clearly, note that an installed fan or compressor will create a
unique air flow Mach number at its face for a given engine RPM. The air
flow from the inlet plane of the engine to the compressor's face is
essentially an ideal flow (no losses in energy), so the given compressor
RPM fixes the engine's inlet Mach number also. It is the job of the cowl
to provide this Mach number "smoothly", independent of the flight Mach
number. As Dr. von Ohain has stated, "The compressor makes its own wind."
This relationship between the compressor's RPM and the inlet Mach number
obviates the need for variable pitch rotors, which considerably
simplifies the design requirements for the engine. Further benefits of
the cowl appear in the very much reduced compressor blade tip loss which
occurs because, unlike unshrouded propellers, compressor blades operate
with no induced drag (there is no flow around the blade tip leading to
the tip vortex).

Significant as the effect of the cowl is, it really is not a device
that could only be associated with a gas turbine engine. We could easily
place a cowl around a piston driven fan and, in fact, an Italian patent
was granted in the 1930s for a concept that matched a piston driven fan
to a cowl.

The real significance of the gas turbine engine is its enormous thrust-to-weight ratio. This fact was clearly recognized by both Sir Frank Whittle and Dr. Hans von Ohain at the time they began their design of the gas turbine engine (Ref. 2 and 3).

It is quite obvious that a large thrust-to-weight ratio will be of great benefit to combat aircraft at any altitude, but the benefits for transport aircraft are not quite so clear. The following question might be asked of an engine designer, "Who needs all that power -- After all, some guy just peddled across the English Channel?!"

In reply we cite Professor E.S. Taylor, who, in a wonderfully readable article (Ref. 4), revealed the benefits of high available power. In his analysis, he referred to the Breguet Range equation, which may be written in the following form:

$$\text{Range} = n_p n_{th} Q_R \ \frac{L}{D} \ \ln \frac{W_i}{W_f} \qquad (1)$$

In Eqn (1) η_p = propulsive efficiency, η_{th} = thermal efficiency, Q_R = fuel energy content/weight, L/D = Lift-to-drag ratio, and W_i/W_f = initial weight/final weight.

It is apparent from Eqn (1) that to achieve maximum range for a given weight ratio W_i/W_f, the overall efficiency of propulsion, $\eta_p \eta_{th}$, and the lift-to-drag ratio, L/D, should be maximized. It is notable, however, that the aircraft's flight speed does not appear explicitly in the expression for the range, nor does the flight altitude. So Eqn (1) indicates that it might be possible to fly at high speed and therefore shorten the flight time while still being able to obtain a large range for the aircraft.

The aircraft airspeed at which the maximum lift-to-drag ratio occurs increases with altitude, i.e., decreasing density. Therefore, the higher we fly, the faster we can fly and still be at the airspeed for maximum

L/D. The result of flying at higher altitudes then, is that the aircraft does not have to sacrifice any range capability to fly at a faster velocity. In fact, an additional benefit occurs by flying at higher altitudes because the overall efficiency of propulsion, $\eta = \eta_p \eta_{th}$, increases, as will be shown in the following analysis. It is interesting to note that the airspeed for maximum L/D is only slightly above the aircraft's stall speed and at high altitudes, cruise speed and stall speed may differ by only a few knots! The point of this discussion, however, is that all air breathing engines lose thrust capacity with increased altitude, so that at extreme altitudes, only the highest thrust-to-weight ratio engines are suitable, and it is in this region that the gas turbine engine reigns supreme.

The high thrust-to-weight gas turbine engine thus made very high speed flight possible, but it also introduced a related problem. Detailed design studies make it clear that the optimal aircraft configuration for high cruise speed flying would be one with a high wing-loading. This, of course, is necessary to reduce cruise drag. Unfortunately, a low wing-loading is required to obtain low landing speeds. It was difficult indeed to design for the low landing speeds of the time -- dictated by both government decree and by the availability of only very limited length runways. For example, in the 1940s, it was the lack of long runways together with the nonavailability of large aircraft with pressurized cabin capability necessary to fly at the required "extreme" altitudes that led to the conclusion from an expert committee of highly respected individuals (Ref. 2) that commercial transport with gas turbine engines would not be commercially feasible.

Eventually, of course, successful cabin pressurization was achieved, longer runways were constructed, and the gas turbine era was under way.

The advent of the longer runways, built principally to accommodate the landing requirements of jet aircraft, introduced a related design problem, however. This was because the "new" runway lengths set the requirement for takeoff thrust. Even though the increased runway lengths appeared substantial at the time, attainment of sufficient take-off thrusts for heavily loaded long range aircraft was anything but a trivial problem in the early days of commercial jet transportation.

This conflict between take-off thrust demand and cruise thrust demand brings us back to Questions 2 and 3 listed earlier. As we demonstrate in our Analysis section of this paper, if an engine is to be designed to provide a given take-off (zero flight velocity) thrust, the power required to provide the thrust varies inversely with the mass flow handled by the engine. Or equivalently, the engine power required increases linearly with the exit velocity of the gas leaving the engine. Furthermore, we will show that the thrust capability of the more powerful gas turbine engines decreases more slowly with increase in flight speed than does the thrust capability of the less powerful engines.

As a result of the relationships discussed in the previous paragraph, a turbojet engine, when compared to a turbofan engine that could be used to produce the required thrust for a given aircraft at take-off, must be very powerful. This is because a turbojet has a relatively small exit mass flow and a high exhaust velocity. Since it is very powerful, the turbojet engine's thrust decreases very slowly with flight speed. The resulting design compromises were unpleasant indeed, in that the early turbojets were very marginal in take-off thrust, but had to be operated in a throttled-back position (and hence low thermal efficiency) at aircraft cruise, because of the excess power of the engine. The engines could, of course, be made more powerful (bigger) to

accommodate the take-off thrust requirement, but they would then be even
more inefficient at the cruise condition. In the early days of jet
propulsion, aircraft pressurization and lift limits would not allow
flight at even higher altitudes and the flight regime was limited to
subsonic speeds. It is a terrible irony that the three Comet disasters
were in fact identified with the aircraft encountering the engineering
limits discussed here.

These disasters occurred in the pioneering days of commercial jet
transportation (early 1950s) as British Overseas Airways (BOAC) was
extending jet transportation around the world with the Comet aircraft.
Two of these disasters occurred within months of each other in early
1954, because of explosive decompression of the tragically undesigned
structure. Both aircraft fell into the Mediterranean Sea. The third
occurred at Karachi, Pakistan, because of the inadequate take-off margin
from a hot airfield (the aircraft engine's thrust was inadequate for the
runway length).

The advent of fan jets (turbofans) led to a superb resolution of the
cruise power and take-off thrust requirements problem. Thus, by judicious
choice of the "by-pass ratio" for the engine (defined as the mass flow
rate of air through the fan duct divided by the mass flow rate of air
through the "core" engine), the fan jet could be designed so that it
satisfied both the take-off thrust requirement and the requirement that
the engine operate near maximum power during aircraft cruise.

As a final comment before considering some analysis to support the
general principles of gas turbine engines described above, it is
interesting to consider where the turboprop fits in the gas turbine
aircraft engine hierarchy. It is clear that by removing the cowl, the
advantages created by a cowl which we have described will be lost.
However, when very high "by-pass ratios" are considered, the required

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cowl will be very large and therefore very heavy and, because of its
large surface and projected areas, will create a significant amount of
aerodynamic drag. If we remove the cowl, we lose the diffusion of the air
stream approaching the "fan" blades, which would cause large Mach numbers
to occur near the blade tips with resultant shock losses and decrease in
propeller efficiency. However, if we use fuel efficiency as the primary
design consideration, it appears that for by-pass ratios in excess of
about twenty and flight speeds up to a Mach number of about 0.8, the
performance losses created by the use of a cowl outweigh the benefits.
Consequently, because of the high propulsion efficiency of such engines,
the turboprop is once again being considered for propulsion of subsonic
transports. With such engines the problem of achieving the required
take-off thrust is enormously reduced, because of the low "exhaust"
velocity of the gases leaving the engine. As a result, the design
requirements for this type of gas turbine engine are primarily dictated
by the high-speed flight regime. In fact, the ease of achieving large
take-off thrusts led to turboprops being far less powerful than turbofans
and, therefore, incapable of providing the required power for cruise at
high Mach numbers (0.8). It is from these design choices that the myth of
turboprops being "underpowered" has arisen. In fact, of course, if flight
at high subsonic Mach number and high altitude is to be provided by a
turboprop, it is only necessary to design a large (powerful) engine.
Unlike the experience with the turbojet, however, when such an engine is
operated in the take-off condition the thrust that would be available if
the engine were operated at full thermodynamically available power is far
in excess of that required. As a result, such engines are operated
enormously "de-rated", i.e. their thrust is intentionally limited at
take-off in order to allow the use of acceptably light gear boxes and to
prevent propeller blade stalling. To illustrate the magnitude of this

"problem," a business turboprop currently under development, capable of
flight at Mach number 0.8 at 39,000 feet altitude, will have its engine
flat rated to 20,000 feet! (By flat rated, we mean the engine power
output is constant in that range.)

III. Analysis

In this section we will provide support for our preceding
observations. We begin by describing the effect of flight speed variation
on a given gas turbine engine's specific thrust. This analysis employs a
control volume representation of the gas turbine engine and simply
analyzes the changes in velocity of the gas flow into and out of the
engine. In the next section we will illustrate the mathematical
techniques used to determine the off-design performance of an ideal
turbojet. In this analysis it is necessary to determine the effects of
each of the gas turbine engine's components (compressor, burner, turbine,
etc.) on the engine's performance. Therefore, we will examine fthe
effects of variations in such parameters as the temperature at the outlet
of the burner and the flight Mach number.

A. Variation of Specific Thrust with Flight Velocity

We will use a very simplified approximate analysis to estimate
the variation of specific thrust with aircraft velocity. The object of
this analysis is to provide some insight into the selection process for
obtaining the best gas turbine configuration (turboprop, turbofan, etc.)
for use in a particular aircraft design. If we assume for the moment that
high altitude implies a high airspeed for the aircraft (low altitude here
would imply low airspeed or landing), we are, in fact, providing an
answer to Question 2 above. The geometry of the engine and the pertinent
symbols are shown in Figure 2.
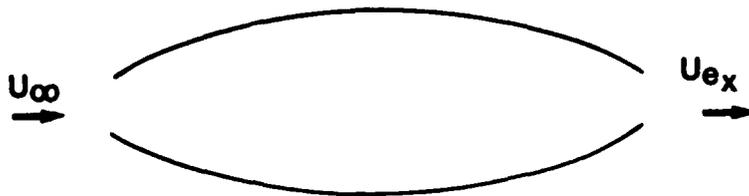
Figure 2. Fanjet Geometry

Here U_∞ is the velocity of the inlet airstream (velocity of the aircraft) and U_{ex} is the velocity of the exhaust stream. If this geometry simulates a fanjet, we consider, for simplicity, the case where the fan stream and the core stream are fully mixed prior to passing through the propelling (exhaust) nozzle. In addition, we assume that the nozzle exhaust is perfectly expanded, so that the pressure at the nozzle exit equals the ambient pressure. When viewed as a thermodynamic device, the power of the engine P, appears simply as the increase of kinetic energy of the gas flow, so we can immediately write

$$P = \frac{\dot{m}}{2}\left(U_{ex}^2 - U_\infty^2\right) \tag{2}$$

Here $\dot{m}$ is the mass flow rate of the air passing through the engine. Also for simplicity, we consider the engine to be ideal and therefore neglect the extra mass flow of the fuel.

For the momentum equation we obtain

$$T = \dot{m}\left(U_{ex} - U_\infty\right) \tag{3}$$

Remember, we are considering perfectly expanded flow, so that the pressure terms normally in the momentum equation go to zero. We can digress for a moment at this point to consider Eqns (2) and (3) at

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take-off $(U_\infty \cong 0)$ to find

$$P = \frac{\dot{m}}{2}U_{ex}^2 = \frac{TU_{ex}}{2} = \frac{T^2}{2\dot{m}} \qquad (4)$$

Eqn (4) is the equation we used to determine the relationship between engine power and thrust we discussed earlier (page 61). From Eqn (4), for example, it is clear that for a given level of thrust required at take-off, the power of the engine is directly proportional to the exit velocity of the engine.

    To consider how thrust varies with flight velocity we first rearrange Eqn (2) to obtain

$$U_{ex}^2 = 2P/\dot{m} + U_\infty^2 \qquad (5)$$

We then use a subscript o to denote conditions corresponding to zero flight velocity and compare Eqn (5) for conditions at other flight speeds to those at take-off to find

$$\left(\frac{U_{ex}}{U_{ex_o}}\right)^2 = \frac{P/\dot{m}}{\left(P/\dot{m}\right)_o} + \frac{U_\infty^2}{U_{ex_o}^2} \qquad (6)$$

For take-off $U_\infty \cong 0$ so that $U^2_{ex_o} = (2P/\dot{m})_o$. Similarly for Eqn (3).

$$\frac{T/\dot{m}}{T_o/\dot{m}_o} = \frac{U_{ex}}{U_{ex_o}} - \frac{U_\infty}{U_{ex_o}} \qquad (7)$$

Combining Eqn (6) and (7) we find

$$\frac{T/\dot{m}}{T_o/\dot{m}_o} = \left[\frac{P/\dot{m}}{P_o/\dot{m}_o} + \frac{U_\infty^2}{U_{ex_o}^2}\right]^{\frac{1}{2}} - \frac{U_\infty}{U_{ex_o}} \qquad (8)$$

This last expression reveals the important relationship between the thrust provided by the engine (momentum change of airflow entering and exiting the engine) and the power supplied to the engine (energy flow to air from fuel). Supposing for the moment that the power per mass flow of air per second is a constant over the velocity range of the aircraft, then we obtain the relationship between specific thrust ratio and velocity ratio, U_∞/U_{ex_0} , shown in Figure 3.
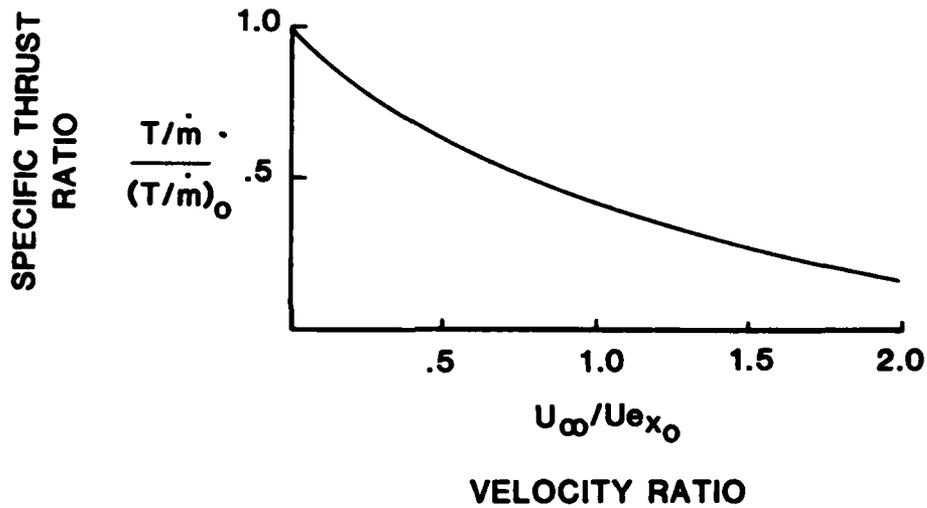
Figure 3. Thrust versus Velocity

Therefore, as an example, if we consider a typical turbojet with $U_{ex_0} \cong$ 3000 fps and a typical high-bypass ratio turbofan with $U_{ex_0} \cong$ 760 fps, we find for a flight velocity of $U_\infty \cong$ 850 fps

$$\left\{ \frac{T/\dot{m}}{(T/\dot{m})_0} \right\}_{\text{Turbojet}} = .76 \qquad (9)$$

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and

$$\left\{ \frac{T/\dot{m}}{(T/\dot{m})_o} \right\}_{\text{Turbofan}} = .38 \tag{10}$$

Thus, as we previously indicated, for equal thrust levels required
for take-off, the thrust of the turbofan drops off much more rapidly from
the required take-off thrust with flight speed than does that of the
turbojet. It is true that for both of these gas turbine engines, as with
other engine types, the power per mass flow per second, for a given
turbine inlet temperature and flight Mach number, will increase with
increasing altitude up to the tropopause. This is because the decreased
inlet temperature to the compressor causes much less work interaction to
be required for the compressor to attain a given pressure ratio. As a
result, the compressor pressure ratio increases, leading not only to
greater power per mass flow per second, but also to an increased
compressor air demand. As a result, $\dot{m}$ decreases less rapidly with
altitude than would otherwise be the case. These altitude effects help
gas turbines increase efficiency and specific power with altitude which
further enhances their attractiveness.

B. Off-Design Performance of a Turbojet

The concluding paragraph of the preceding section described,
qualitatively, the effect of altitude variation on a given gas turbine
engine. The procedure for mathematically predicting the performance of a
given engine is quite straightforward and is described in Refs. 3 and 4.
We will illustrate the techniques involved by considering the off-design
performance of an ideal turbojet. By "off-design" performance, we mean
the performance of the engine at some operating point other than the
reference point where the engine's operating parameters are known. The

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term "ideal" means we are not considering certain engine "loss" terms,
such as the combustion efficiency of a burner or the mechanical
efficiency of the turbine-compressor coupling. Of course, by making these
simplifying assumptions, we are creating a mathematical model of the
engine that is not as accurate as it could be, but our objective here is
to illuminate the off-design analysis technique.

A schematic diagram of our ideal turbojet is shown in Figure 4 and
the various elements of the engine are noted along with station numbers
at various points within the engine.
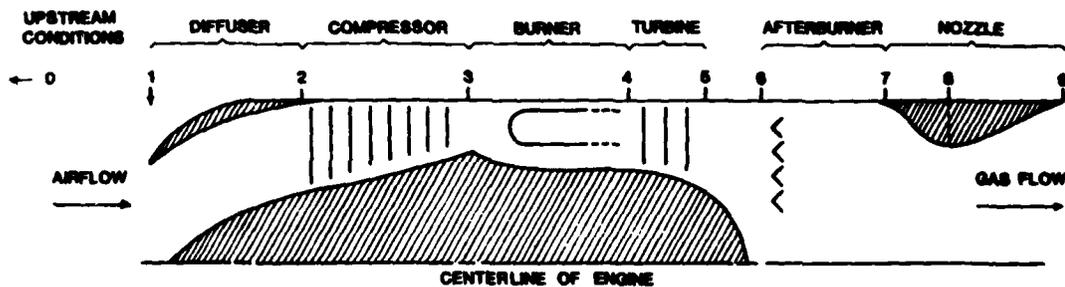
Figure 4. The Turbojet

For example, the number "0" refers to ambient air conditions far upstream
of the engine and station 8 refers to the exhaust nozzle's throat. Also,
we will use the shorthand technique used in Refs. 3 and 4 in order to
simplify the mathematical expressions that will follow. These shorthand
expressions are shown below, where the τ's are total temperature ratios
and the π's are total pressure ratios. τ_c would be the total temperature
ratio across the compressor, and if we refer to Figure 4, we see that

$$\tau_c = \frac{T_{t_3}}{T_{t_2}} \qquad (11)$$

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Notice that the T_{t_3} term would represent the total temperature of the air at the compressor's exit, station 3. In a similar manner then

$$\tau_t = \frac{T_{t_5}}{T_{t_4}} , \tag{12}$$

$$\pi_c = \frac{P_{t_3}}{P_{t_2}} = \tau_c^{\frac{\gamma}{\gamma-1}} \tag{13}$$

and

$$\pi_t = \frac{P_{t_5}}{P_{t_4}} = \tau_t^{\frac{\gamma}{\gamma-1}} \tag{14}$$

In Eqns (13) and (14), the isentropic flow relationship between total temperature ratio and total pressure ratio has been inserted. Here γ is the specific heat ratio.

In addition to these component ratios, it is customary to also define the following terms which define the aircraft's flight conditions. First we define

$$\tau_r = \frac{T_{t_0}}{T_0} = 1 + \frac{\gamma-1}{2} M_0^2 \tag{15}$$

Where M_0 is the free-stream Mach number of the air (aircraft flight speed) and T_0 is the air's static temperature. We can then also define

$$\pi_r = \frac{P_{t_0}}{P_0} = \tau_r^{\frac{\gamma}{\gamma-1}} \tag{16}$$

Finally we define a parameter that indicates the throttle setting of the engine as

$$\tau_\lambda = \frac{T_{t_4}}{T_0} \tag{17}$$

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Notice that T_{t_4} is the total temperature of the burner exit and, as such, is a direct measure of the throttle setting.

With these definitions we can begin our analysis. This analysis is greatly facilitated if it is assumed that the gas flow is choked at stations 4 and 8. This assumption is valid over a wide operating range in modern turbojets. With this assumption, continuity of mass flow at stations 4 and 8 gives:

$$\dot{m}_4 = \dot{m}_8 \sim \frac{P_{t_8} A_8}{\sqrt{T_{t_8}}} = \frac{P_{T_4} A_4}{\sqrt{T_{t_4}}} \tag{18}$$

This may be rearranged to give:

$$\frac{\tau_t^{\frac{1}{2}}}{\pi_t} = \frac{A_8}{A_4} \sqrt{\frac{T_{t_5}}{T_{t_8}}} = \pi_t^{-\left(\frac{\gamma+1}{2\gamma}\right)} \tag{19}$$

In non-afterburning engines $T_{t_5} = T_{t_8}$, and in afterburning engines A_8 is usually varied to give "returned engine conditions," which means simply that A_8 is varied so as to keep

$$\frac{A_8}{A_4} \sqrt{\frac{T_{t_5}}{T_{t_8}}} = \text{Constant} \tag{20}$$

Thus it can be seen that with afterburning engines operating in the returned engine condition, or with conventional (fixed A_8 and A_4), turbojets operating without afterburner the turbine expansion ratio remains constant over the operating range! This very convenient result allows us to obtain other properties of interest very simply. Thus, a power balance between the compressor and turbine leads quickly to:

$$\tau_c = \pi_c^{\frac{\gamma-1}{\gamma}} = 1 + \frac{\tau_\lambda}{\tau_r}\left(1 - \tau_t\right) \tag{21}$$

Note that τ_t would itself be given from the reference (design)

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point. Thus

$$\tau_t = 1 - \frac{\tau_{c_R} - 1}{\left(\tau_\lambda / \tau_r\right)_R} \tag{22}$$

In Eqn (22) the subscript R refers to reference conditions. Thus, if we calculate τ_t from Eqn (22) we can then determine the off-design performance of the engine, because Eqn (21) will give us the off-design (new) value of the compressor ratio that results from a change in Mach number (τ_r), a change in throttle setting (T_{t_4} and therefore T_λ), a change in ambient temperature (T_o), or a combination of the three. With the "new" value of compressor pressure ratio, we can continue with the analysis to find other engine performance parameters such as engine thrust. We will not continue this development here, however, but will refer to the reader to Refs. 3 and 4 for this development.

As an illustrative calculation, consider an engine to operate over a range of Mach numbers such as the SR-71 "Blackbird." Let us consider the zero Mach number, sea level conditions to be the reference conditions and take:

$$T_{o_R} = 520°R, \ \tau_{\lambda_R} = 6, \ \pi_{cR} = 9 \tag{23}$$

Assume also that at the altitude of interest, $T_o = 390$ degrees R and $M_o = 3$. Then assuming that the turbine inlet temperature (throttle setting) remains constant we find from Eqns (21) and (22)

$$\tau_c = 1 + \frac{\tau_\lambda}{\tau_{\lambda R}} \frac{\tau_{rR}}{\tau_r} \left(\tau_{cR} - 1\right)$$

$$= 1 + \frac{T_{oR}}{T_o} \frac{1}{1 + \frac{M_o^2}{5}} \left\{ \pi_{cR}^{\frac{1}{3.5}} - 1 \right\} \tag{24}$$

hence $\tau_c = 1.4159$ for the conditions given here.

We then find that the compressor pressure ratio has dropped from

$$\pi_{cR} = 9 \quad \text{to} \quad \pi_r = \tau_c^{3.5} = 3.378 \tag{25}$$

The result would at first seem a little disappointing -- and it is to the compressor designer who has to design the compressor to operate over such a range -- but from the ideal cycle analysis point of view, the result is anything but discouraging. Thus, we note that the cycle thermal efficiency depends upon the <u>overall</u> pressure ratio, ram compression times compressor compression, such that:

$$\eta_{th} = 1 - \frac{1}{\left(\pi_r \pi_c\right)^{\frac{\gamma-1}{\gamma}}} \tag{26}$$

Thus, we note that $(\pi_r \pi_c)_R = 9$, whereas $(\pi_r \pi_c) = 124!$

Thus

$$\eta_{thR} = 0.466 \quad \text{but} \quad \eta_{th} = 0.748 \tag{27}$$

Therefore the effects of both the increased Mach number (which increases π_r even more than it decreases π_c), and the decreased ambient temperature with altitude (which reduces the decrease in π_c), both lead to increased thermal efficiency of the engine.

Further beneficial effects, such as those described in Section II, (which include an increase in propulsive efficiency with Mach numbers) are evident from further calculation. Rather than pursue such calculations here, however, we are hopeful that the reader would find it more edifying and more enjoyable to program the simple summary we have included as the Appendix and work a few example cases for his own amusement. The relationships in the summary follow very easily using

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conventional cycle analysis techniques as developed in Refs. 3 and 4.

IV. Epilogue

As a closing thought, we would like to emphasize that in writing this paper, we have endeavored to describe the design concepts involved in aircraft gas turbine engines in as simple a manner as possible. It is obvious that no aircraft operates only at cruise conditions, so design decisions will in fact be much affected by other segments of a typical flying mission as well as the cruise requirements. The extent of the effect of such other considerations on engine and aircraft design and performance can be inferred from such examples as the Concorde, which uses 39 percent of its fuel in reaching flight altitude and Mach number (for Paris to New York), or a typical fighter aircraft, which uses about 25 percent of its fuel for aircraft taxi, take-off, and climb to altitude portion of a typical mission, while traveling only 100 miles of the available range of the aircraft. Finally, of course, one does have to land eventually, and the hour or two circling around in thunderstorms waiting to get into O'Hare Airport, Chicago also has to be considered carefully in any aircraft engine design!

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Appendix

SUMMARY OF THE EQUATIONS FOR THE OFF-DESIGN ANALYSIS OF
AN IDEAL TURBOJET WITH EXIT PRESSURE MATCHED TO AMBIENT PRESSURE

INPUTS: $\tau_{\lambda R}$, M_{oR}, π_{cR}, T_{oR}, P_{oR}, T_{t_4}, M_o, T_o, P_o

OUTPUTS: η_{thR}, η_{th}, T/T_R, S/S_R

(T = Thrust, S = Specific Fuel Consumption)

EQUATIONS: $\tau_r = 1 + \frac{\gamma-1}{2} M_o^2$, $\pi_r = \tau_r^{\frac{\gamma}{\gamma-1}}$

$$\tau_{rR} = 1 + \frac{\gamma-1}{2} M_{oR}^2 \quad , \quad \pi_{rR} = \tau_{rR}^{\frac{\gamma}{\gamma-1}}$$

$$\tau_{cR} = \pi_{cR}^{\frac{\gamma-1}{\gamma}}$$

$$\tau_t = 1 - \frac{\tau_{cR}-1}{\left(\tau_\lambda/\tau_r\right)_R}$$

$$\tau_\lambda = T_{t_4}/T_o$$

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$$\tau_c = 1 + \frac{\tau_\lambda/\tau_r}{\left(\tau_\lambda/\tau_r\right)_R}\left(\tau_{cR} - 1\right)$$

$$\pi_c = \tau_c^{\frac{\gamma}{\gamma-1}}$$

$$M_0\,\frac{U_9}{U_0} = \left\{\frac{2}{\gamma-1}\,\tau_\lambda\,\tau_t\,\left[1 - \frac{1}{\tau_r\tau_c\tau_t}\right]\right\}^{\frac{1}{2}}$$

$$M_0\left(\frac{U_9}{U_0}\right)_R = \left\{\frac{2}{\gamma-1}\,\tau_{\lambda R}\,\tau_t\left[1 - \frac{1}{\tau_{rR}\,\tau_{cR}\,\tau_t}\right]\right\}^{\frac{1}{2}}$$

$$\frac{\dot{m}}{\dot{m}_R} = \frac{P_0\,\pi_r\,\pi_c}{\left(P_0\,\pi_r\,\pi_c\right)_R}\,\left\{\frac{\left(T_0\,\tau_\lambda\right)_R}{T_0\,\tau_\lambda}\right\}^{\frac{1}{2}}$$

$$\frac{T}{T_R}\quad\frac{\dot{m}}{\dot{m}_R}\left\{\frac{M_0\,\dfrac{U_9}{U_0} - M_0}{\left(M_0\,\dfrac{U_9}{U_0}\right)_R - M_{0R}}\right\}\sqrt{\frac{T_0}{T_{0R}}}$$

$$\frac{S}{S_R}\quad\frac{T_0}{T_{0R}}\frac{\left(\tau_\lambda - \tau_r\tau_c\right)}{\left(\tau_\lambda - \tau_r\tau_c\right)_R}\frac{\dfrac{\dot{m}}{\dot{m}_R}}{\dfrac{T}{T_R}}$$

$$\eta_{thR} = 1 - \frac{1}{\left(\tau_r\tau_c\right)_R}$$

$$\eta_{th} = 1 - \frac{1}{\tau_r\tau_c}$$

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SECTION III

Instrumentation and Hardware

DETERMINATION OF THE FREQUENCY RESPONSE CHARACTERISTICS
OF A REDESIGNED SEVEN-HOLE PRESSURE PROBE

Scott R. Schlapkohl[*] and William A. Buzzell[**]

Abstract

This paper discusses the redesign of a seven-hole pressure
probe. The objective of this redesign project was to achieve better
flow field pressure measurement resolution by reducing the size of
the pressure probe tip while maintaining a system frequency response
equivalent to that of the current probe. The reduction in the probe
tip size necessitated reduction of the internal diameters of the
seven individual sampling port tubes from .018 inches to .004 inches,
and the incorporation of the pressure transducers into the probe
assembly to reduce overall tubing length. Different configurations of
the tube diameter and tubing length were also investigated
experimentally. The objective of this investigation was to achieve a
smooth dimensional transition from the .004 inch sampling port
internal diameter to the .093 inch transducer face diameter while
minimizing the probe dwell time at each measurement location in the
flow field to achieve a 99 percent pressure amplitude ratio. The
results of this investigation are presented as well as a comparison
between the original and redesigned probe.

I.   Introduction

The Department of Aeronautics at the United States Air Force

Academy is deeply involved in aerodynamic testing, and much of this

testing uses different types of pressure measurement probes to

analyze the aerodynamic characteristics of various wind tunnel test

models. These probes are particularly useful in mapping vortex flow

fields produced by the test models.

A grid-plane approach is usually used to map these flow fields.

By grid-plane approach, we mean that a plane is defined at some

location in the flow field (these planes are usually perpendicular to

the free-stream flow) and data is recorded at equally spaced points

within this plane. These points form a grid, hence the term

"grid-plane". The probe is moved from point to point within the plane

and from plane to plane by a three dimensional (X,Y,Z) traverse. A

typical test set-up is illustrated in Figure 1.

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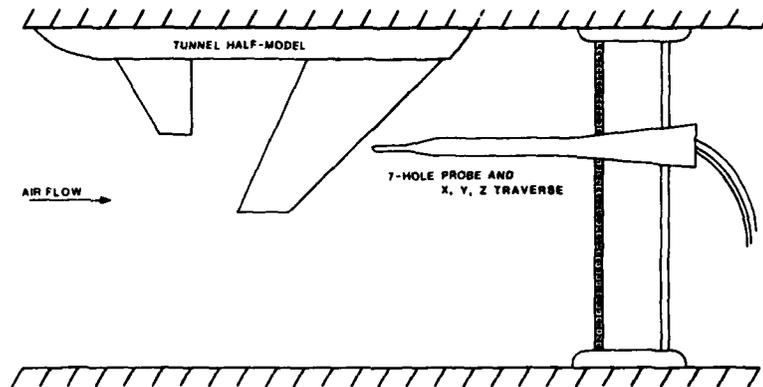
SCHEMATIC OF TYPICAL PROBE/TEST MODEL
INSTALLATION

Figure 1:   Current Seven-Hole Probe Cross-Section and Hole
Configuration

In making grid-point measurements, there are two distinct time
periods which must be considered if one wants to rapidly record
accurate data.   One is the physical time period required to move the
probe between grid-points. This is fixed due to mechanical
limitations of the traverse. The second time period is the "dwell
time" of the probe at a grid-point. The probe must remain at a
grid-point until the pressure on the tip of the probe has time to be
transmitted down the length of the probe and be sensed at the
transducer face. This transmission time must be minimized, of course,
if one wants to shorten the required dwell time of the probe at each
grid-point and therefore shorten the wind tunnel run time.

There are generally two types of pressure variations that are
encountered when grid-point measurements in vortex flow fields are
made and these are: the variation in pressure from grid-point to
grid-point (the pressure at each grid-point is constant or steady)

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and the variation of pressure at a grid-point. In this paper we are
concerned with measuring pressure variations between grid-points
where, for our tests, the pressure at each grid point is unchanging.
In moving the pressure probe from one grid-point to the next, the
"worst case" pressure measurement that could arise would be one in
which a large pressure differential exists between grid-points. This
large difference in pressures would be analogous to a "step function"
pressure input to the probe system. This pressure step could be
encountered, for example, when a shear flow boundary exists between
respective grid-points. This large difference in pressure between
grid-points would require the longest dwell time to allow the
pressure at the face of the pressure transducer to adjust to the much
different "new" pressure at the pressure probe's tip. If the pressure
probe measurement system is properly designed, it must be able to
accurately sense this "step function" pressure variation between
grid-points in the allotted dwell time.

For our tests, we define the pressure measurement to be accurate
when the pressure sensed by the transducer is within 1 percent of the
actual pressure at the grid-point during a specified dwell time (also
called "rise time"). The probe's system frequency response can then
be determined by taking the inverse of this dwell time. Stated
another way, the frequency response of our probe system is the
inverse of the maximum dwell time necessary for the probe system to
react to the maximum pressure difference expected where the pressure
sensed by the pressure transducer reaches 99 percent of the actual
pressure at the measurement grid-point during this dwell time.

Since we want to minimize wind tunnel run time, we want to
minimize the maximum dwell time required. We therefore want to

maximize the probe's frequency response. The unit for frequency
response is cycle per second or Hertz (HZ).

One type of probe which we use in the Air Force Academy wind
tunnels is a seven-hole pressure probe. A schematic diagram of the
seven-hole probe currently used is shown in Figure 2. This probe has
the ability to measure local total pressure as well as to determine
the angle of flow relative to the probe, even when the flow is as
much as 80 degrees off the axis of the probe. The frequency response
of the current probe is such that we must allow it to dwell for 1 to
2 seconds at each grid point in order to allow the sensed pressure to
reach the actual pressure at the probe's tip before moving to measure
the pressure at the next grid-point. This current probe design has
been very successful, but we want to improve the design to permit
increased measurement resolution when testing complex vortex flow
fields associated with advanced wing designs. The reasons we need the
increased resolution capability are: (1) to more accurately locate
the boundaries of very strong vortices, which are due to large
velocity gradients or shear flow conditions, and (2) to find the
location of small vortices. To accomplish these tasks, we essentially
want to make the probe tip smaller. This can be done by decreasing
the size of the individual tubes and packing them closer together.
From previous experience, we know that as the tubing diameter
decreases, the frequency response of the probe system decreases,
thereby causing a longer dwell time to be required to make each
grid-point measurement.

This paper discusses the results of a recent effort to redesign
the seven-hole pressure probe, in which the main design consideration
was to decrease the probe tip size, while insuring that the frequency
response of the new probe is greater than, or equal to, the current
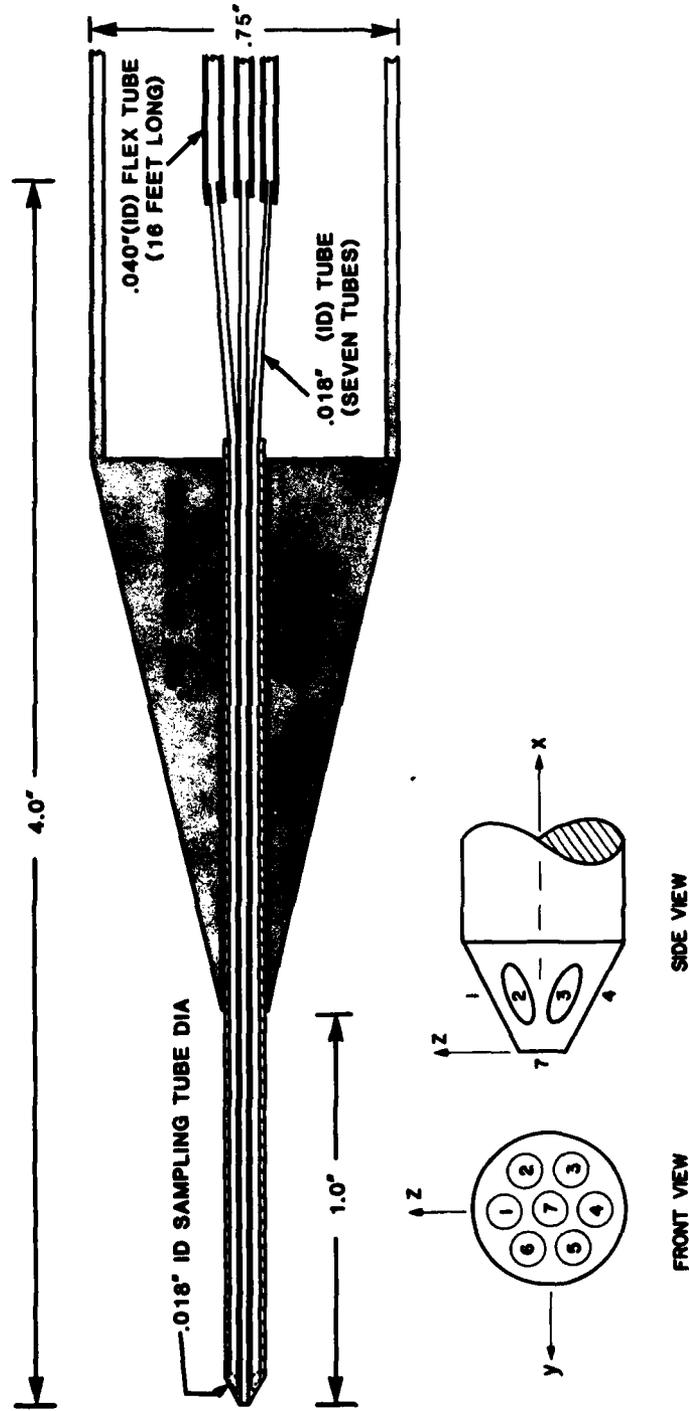
CURRENT SEVEN-HOLE PROBE CROSS-SECTION

Figure 2: Schematic of a Typical Tunnel Installation Using
the Current Seven-Hole Probe

probe. Before discussing the design process, however, two other areas must be discussed: (1) the factors which affect system frequency response, and (2) the basic seven-hole pressure probe operation.

II. Background

A. Factors which Affect the Frequency Response of the Probe System

There are several factors which will affect the frequency response of a pressure measuring system that uses a pitot tube probe. These include:

1. Tubing length

2. Tubing diameter

3. Transducer volume

4. Pressure differential between probe tip and transducer face

5. Fluid Density

The first three factors are characteristics of the measurement system. An increased probe tubing length and a decreased probe tubing diameter both act to enhance the viscous effects of the fluid flow, which acts to reduce the frequency response of the system. As the transducer volume increases, a larger "fill time" is necessary for the pressure pulse to be transmitted across the cavity, also yielding a decreased frequency response.

The final two factors which affect the frequency response of a pressure probe system are the aerodynamic properties of the fluid flow. First, the pressure differential between the fluid flow pressure and the pressure at the transducer face acts as the driving potential for the probe system, and for the tests, it would generally act to increase the frequency response. Second, the density of the

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flow is dependent on temperature differentials, and the greater the
density the greater the frequency response.

B. Current Seven-Hole Probe Configuration

The current seven-hole probe consists of seven ports which
are arranged in a hexagonal configuration. The center port is
perpendicular to the probe's main axis, while the other six ports are
offset by an angle of 25 degrees relative to the main axis (Figure
2).

The probe can be calibrated to give accurate readings for the
angle of attack, angle of sideslip, and velocity of the airflow at
the probe tip location. This calibration is accomplished by first
placing the probe in various known airflows and relating the
pressures at the probe ports to the flow conditions. Once these
relationships between the pressures at the probe tip and the various
flow properties are known, the probe can be placed in various unknown
flows and the flow properties can be determined.

The primary advantage of the seven-hole probe is that it does
not have to be aligned with the flow before data can be recorded. In
fact, the flow direction may be up to 80 degrees off the probe axis
(see Figure 3), with airflow separation at the probe tip, and the
probe can still accurately measure the flow conditions. Thus, the
seven-hole probe can be used in either high or low angle flow
measurement regions and in either compressible or incompressible
flow. A complete description and theory of the operation of this
probe design, along with a detailed description of the calibration
procedure, can be found in Refs. 1 and 2.

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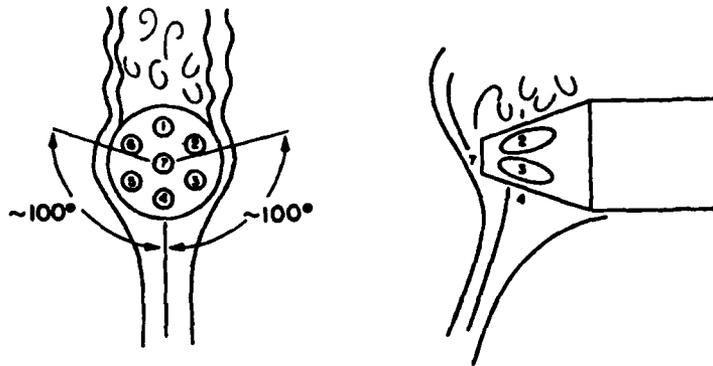
Figure 3:   Flow over Probe at High Angle of Attack

III. Redesign Procedure

A. Criteria for Redesign

To extend the capability of the seven-hole probe as a flow measurement device, the decision was made to modify the current probe in the following way:

1. Decrease the probe tip size. This would reduce the sampling area of the probe tip and thus would increase the measurement resolution of the probe. It is especially critical in the investigation of canard/wing designs to be able to locate both large and small vortex regions and their relative strengths and a smaller probe tip will enhance the probe's capability to accomplish this task.

2. Increase the probe length. The current probe has a short, fixed length, which limits the capability of interrogating over or under wing surfaces or near fuselage/wing intersections due to the mechanical interference of the probe mounting structure with the wind tunnel model. An increase in probe length would provide greater

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separation between the mounting structure and the probe tip and would enhance this measurement capability.

3. The pressure transducers for the current design are located external to the wind tunnel, connected to the probe by 16 feet of .040 inch internal diameter (ID) flex tubing. This length of tubing reduces the frequency response of the probe system and has limited the data acquisition sample rate due to the dwell time necessary to achieve a .99 pressure amplitude ratio. Any probe modifications should at least match or increase the overall system frequency response of the current system to assure that the redesigned probe does not require more wind tunnel test time.

Of the changes suggested above, reduction of the probe tip size was the primary consideration in the redesign of the seven-hole probe. Laboratory manufacturing trials demonstrated that .004 inch ID stainless steel tubing could be handled and formed into a seven-hole configuration. A comparison of the tubing dimensions of the current probe and a probe using the .004 inch ID tubing is shown in Figure 4.

CURRENT PROBE DIMENSIONS   **REDESIGNED PROBE DIMENSIONS**
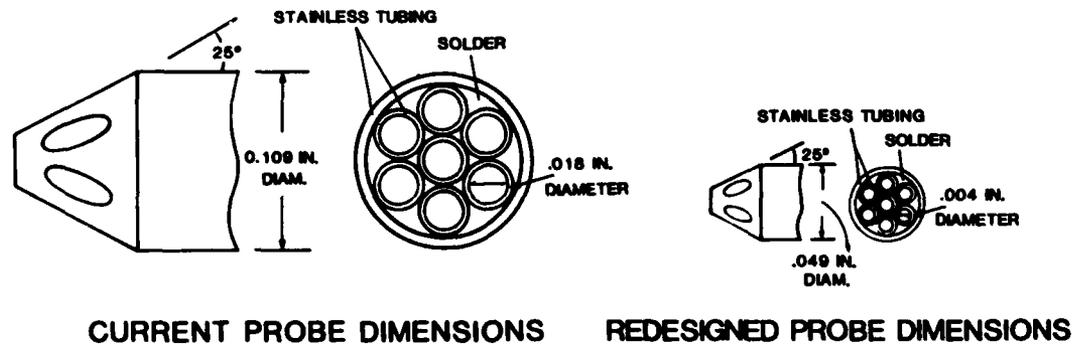
Figure 4:   Comparison of Current Versus Redesigned Probe
            Dimensions

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The new design configuration would significantly reduce probe hole size and sp   ng. However, as stated above, it was known from previous test experience that the use of tubing with such a small diameter could severely affect the frequency response of the pressure measurement system. Therefore, it was determined that an experimental program would be needed to optimize the tubing configuration that would yield the maximum frequency response for the new probe design utilizing the .004 inch ID tubing. In addition to the .004 inch ID sample port tubing, we determined that certain other parameters were important in the redesign of the probe. Therefore, we required the following:

1) A transducer face diameter of .093 inches

2) An overall probe diameter of .75 inches
   (to allow use of existing probe sting)

3) The location of the transducers within
   the probe

4) An adjustable probe length

5) For a step function input pulse, a .99 pressure
   amplitude ratio reached in 0.5 seconds or less
   (frequency response 2.0 Hz)

Locating the transducers in the probe reduces the overall tubing length and was considered a major step in helping to compensate for the reduced frequency response due to use of the .004 inch ID sampling port tubing. Pressure transducers with a .093 inch face diameter would be used, since seven transducers would fit easily into the .75 inch diameter of the probe base. The adjustable length of the probe was a compromise between achieving a mechanically rigid probe, yet allowing for the capability of extending the tip of the probe

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away from the .75 inch overall probe diameter. This would increase
test engineers' ability to interrogate over or under wing surfaces
during wind tunnel tests.

B. Method of Analysis

We decided to conduct experimental test using various
configurations of the probe system to determine its frequency
response. We chose this experimental approach for the following
reasons:

1. To determine a baseline frequency response level for the
current probe configuration, the most accurate method is by direct
experimentation.

2. The minimum tubing diameter of .004 inch ID for the
redesigned probe was chosen based on mechanical constraints.
Therefore, this parameter was fixed.

3. The maximum tubing diameter was also fixed, based on existing
transducer dimensions.

4. Based on previous work, the redesigned system is considered
to be heavily damped due to the imposed tubing diameter constraints.
The viscous effects would be difficult to model accurately without an
empirical data base.

IV. Description of the Experimental Test Program

A. Probe Tube Modeling

The first step in the testing process was to model a pressure
sampling port from the probe. To do this we manufactured test "plugs"
which used different lengths of the .004 inch ID tubing as a base
dimension. Each model of the sampling port was tested with its own

specific tubing configuration. A schematic diagram of a typical
tubing configuration is shown in Figure 5.

THREADED PLUG

BRASS COLLAR

STEEL TUBING

FLEX TUBING

TRANSDUCER

X

Y

Z
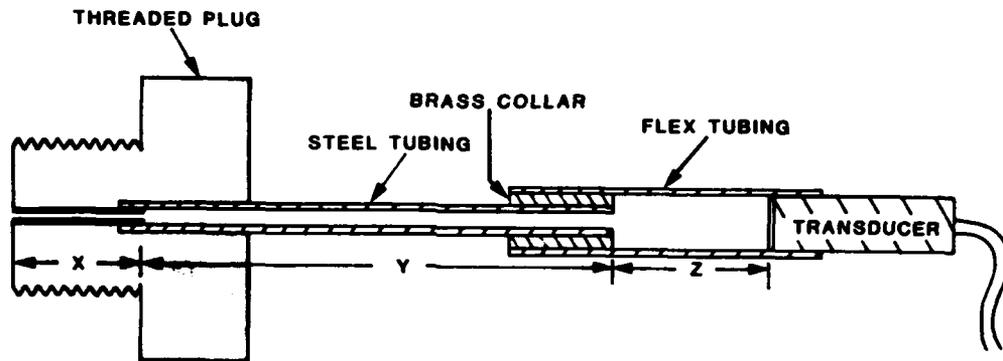
TUBING TEST CONFIGURATIONS

X (.004" ID)	.25, .50, .75 IN
Y (.010" ID)	1.0, 3.0, 5.0, 7.0 IN
Z (.080" ID)	.1, .2, .4, .6, .8, 1.0, 1.2 IN

Figure 5:   Schematic of the Test Tubing Configuration

The test configuration was composed of three different sizes of
tubing. For ease of discussion, these were labeled "X, Y, and Z":

1. Length "X" was the .004 inch ID sampling port tubing length.
This length was minimized since we knew that this tubing could
greatly reduce the system frequency response.

2. Length "Y" was .010 inch ID steel tubing. It provided the
transition between the sampling port tubing and the larger transducer
tubing "Z". The "Y" length must permit a longer probe length (and

therefore an adjustable length). Since the "Y" tubing ID is over twice the diameter of the sampling port tubing, it would have a much smaller effect on the overall probe frequency response. A "Y" length of 7.0 inches was used initially with each of the three "X" test lengths. The tubing was subsequently shortened to achieve each of the different "Y" lengths.

3. Length "Z" created the transducer sensing volume. Flexible tubing of .080 inch ID was chosen not only to make it easy to install and seal the transducer, but to provide electrical insulation for the transducer case. In addition, during the test program, the "Z" length was easily changed by simply sliding the transducer inside the tubing to the desired length.

The different dimensions for each of the lengths described above is also listed in Figure 5, and formed the matrix of tubing configurations tested.

B. Test Apparatus

To test each of the tubing configurations, an experimental apparatus was assembled. A schematic diagram of this apparatus is shown in Figure 6. A regulated pressure source was used to impress a constant pressure upon the solenoid-activated pressure valve. The valve system was configured in such a manner as to cause a step function pressure pulse to be impressed on the tubing "plug." The pressure pulse amplitude was either .25, .50, or 1.0 PSIG. These levels were chosen based on previously measured wind tunnel testing values using the current seven-hole probe configuration. The size of the pressure valve cavity was sufficiently large to insure little attenuation of the pressure pulse. This small attenuation was
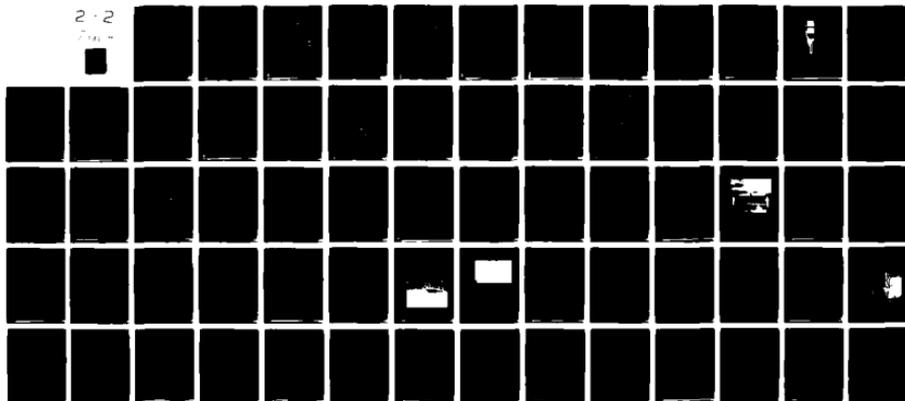
verified during testing. A water manometer was used to set the
pressure differential between the atmospheric pressure and the
regulated pressure source (Figure 6). A difference of +.5 inches of
water (+.018 PSIG) in pressure differential between similar tests was
considered adequate to insure that different tubing configurations
were exposed to a repeatable pressure pulse.
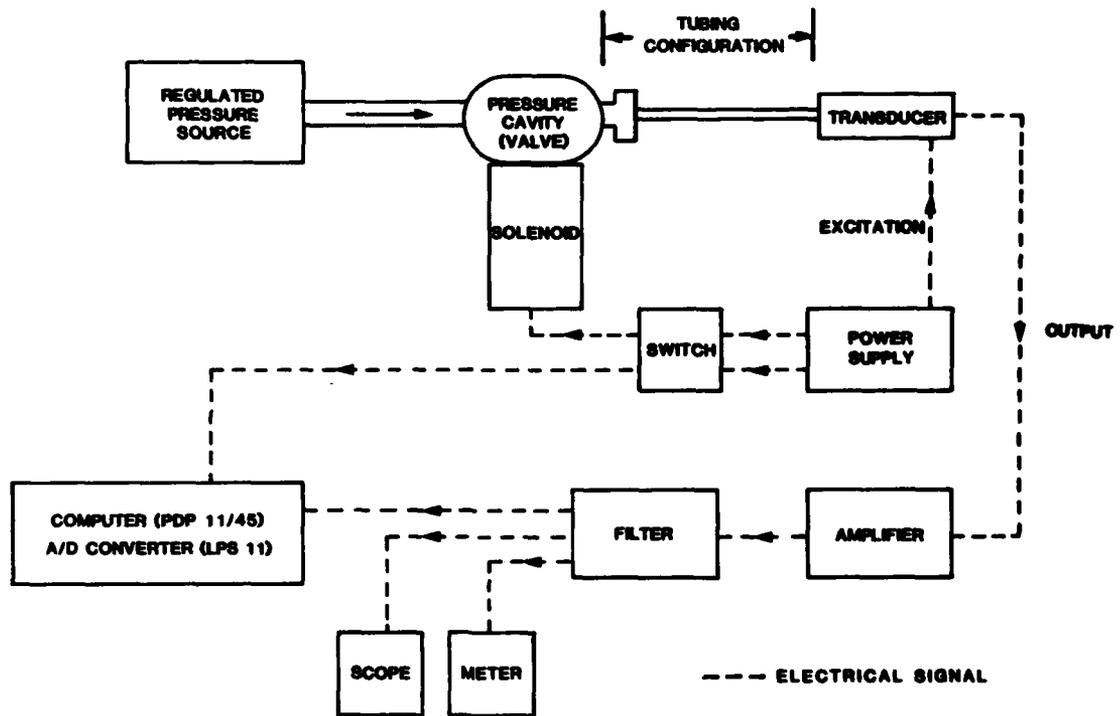
Figure 6:   Schematic of the Experimental Test Apparatus

A single pressure transducer was used to measure the change in
pressure due to the pressure pulse. The transducer has a frequency
response of 3.5 KHZ (well above the expected system frequency range),
and it outputs an analog electrical signal. The analog signal of the

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transducer was digitized with an LPS 11 Laboratory Peripheral System, which was controlled by a Digital PDP 11/45 computer. A control program sampled the changes in pressure level in the tubing at a rate of 10,000 samples per second. A manual switch was used to initiate the time clock of the PDP 11/45 and to activate the pressure valve solenoid simultaneously. The signal from the transducer was then amplified and filtered. This conditioned signal could then be sent to an oscilloscope or a digital volt meter for readout if desired.

C. Computer Control Program

A computer program was written to record and display the digitized transducer output. Figure 7 is a block diagram of the program. This "on-line" program gave us a distinct advantage in that immediately after data acquisition was completed, we were able to plot the results. The plot routine divided the pressure data points by the average peak pressure reading reached at the end of the run, so that each data point was expressed as a percent of the peak pressure (i.e. the pressures were normalized) instead of the absolute value. Once the pressures were normalized, a plot of normalized pressure versus time (rise time) was plotted. Also displayed on the plot was the calculated frequency response (the inverse of the rise time). The "on-line" capability of the plotting routine allowed us to immediately detect tube clogging or any other anomalies in the system. The computer also calculated the dwell time necessary for the pressure to reach a .99 pressure amplitude ratio. The final value of the pressure was based on the average of the last 256 of the 10,000 data samples. This was the pressure which was used to normalize all of the other data points. The analysis program also had the ability

to print out all of the 10,000 normalized data samples.
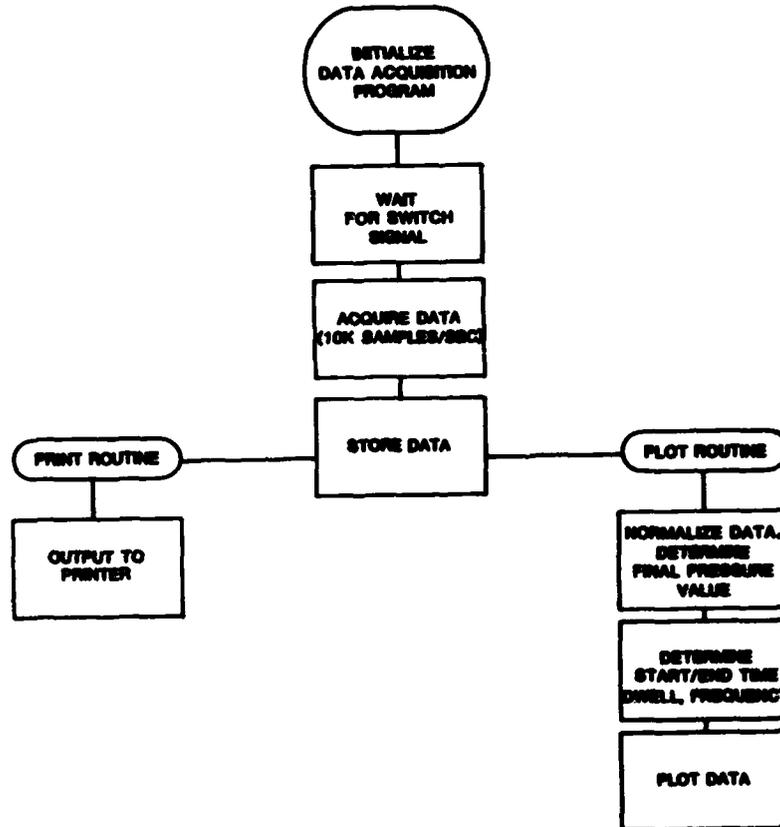
Figure 7: Block Diagram of the Computer Control Diagram

D. Test Procedure

The experimental test program was divided into three parts:

1. A test to verify that a step function was being impressed upon the tubing configuration was run to insure that we were testing the "worst case" situation. This was accomplished by placing the pressure transducer directly into the pressure valve cavity.

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2. The frequency response of the current probe was tested so
that a minimum frequency response requirement for our new probe could
be set. In addition, the effect of both the signal filtering strength
and the magnitude of the pressure pulse impressed on the current
probe was examined.

3. Finally, each of the tubing configurations in the tubing
configuration matrix (Figure 5) was tested. The effect of changing
the magnitude of the pressure pulse was also examined.

V.   Results

A. Frequency Response Trends

As stated in the test procedures, the frequency response of
the valve cavity was found by placing a pressure transducer in it.
Testing indicated that a fill time (the time it takes for the
pressure in the cavity to equal the source pressure) of less than 2
milliseconds was necessary to arrive at the .99 amplitude ratio. We
considered this pressure rise time to represent an adequate step
function for the test program.

The frequency response of the current probe was checked to
determine the baseline frequency response. This was done by inserting
the probe tip into the valve cavity and connecting the pressure
transducer at the end of the 16 foot tubing length of the center port
of the probe. Frequency responses ranging from 1.3 to 1.7 HZ were
recorded for the impulse pressures of .25, .50, and 1.0 PSIG. These
results indicated that the magnitude of the impulse pressure had
little effect on the system's frequency response. In addition, the
transducer input signal was filtered with three different filters (10
HZ, 100 HZ, 1000 HZ). However, only small changes in the frequency
response (less than 5 percent) were noted for the different filters.

Therefore, the 1000 HZ filter was used for all subsequent tests. The
plot of pressure measured by the probe versus time for the current
probe configuration at 1.0 PSIG is shown in Figure 8.

TIME (SECONDS)
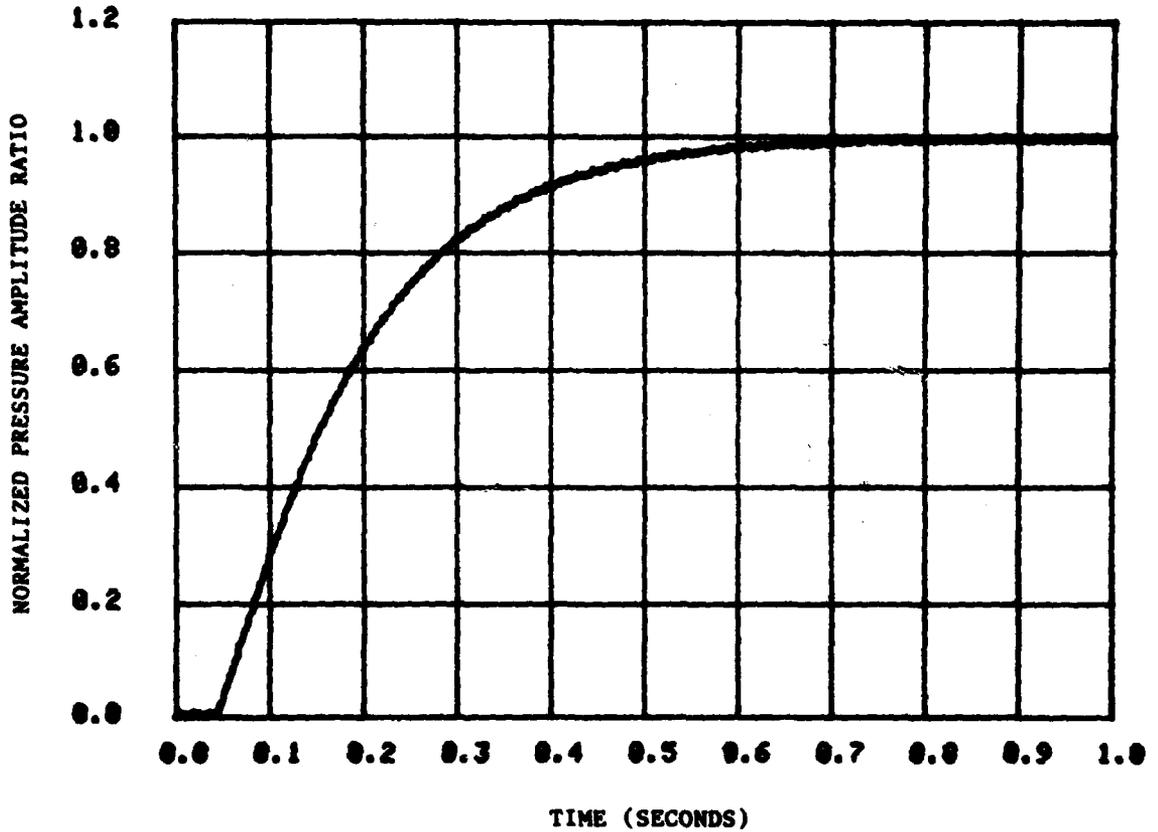
Figure 8:   Pressure Response Time for the Current Seven-Hole
Probe (1.0 PSIG Amplitude Pulse)

The test results for the redesigned tubing test configurations
are shown in Figures 9 and 10 for a 1.0 PSIG amplitude pulse. As in
the case with the current probe, we observed that there was little
difference in the pressure response rate for a given tubing
configuration between the .25, .50, and 1.0 PSIG pulses. Therefore,
only the 1.0 PSIG pressure pulse results are given. Figure 9 shows
frequency response plotted against "Z" lengths for different values
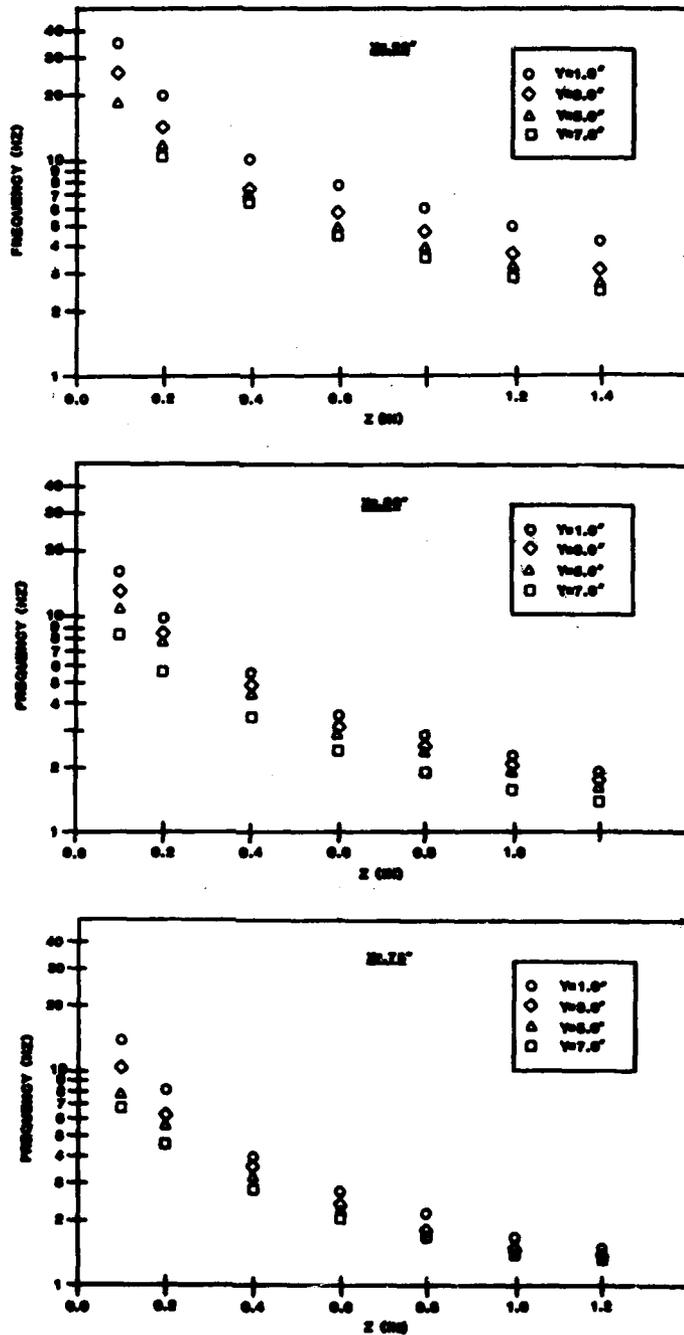
Figure 9: Frequency Response Results for the Test Tubing
Configurations (Constant "x" Length Plots)

of "Y" length with the "X" length held constant. Figure 10 shows
similar plots, except that the "Y" length is held constant in each
plot and the family of "X" length curves are shown.

The figures show some specific trends:

1. The effect of the probe tip length, the "X" dimension, on
frequency response is nearly independent of the rest of the system.
This can be seen in Figure 10. If we double the probe tip's length,
we reduce the frequency response of the probe to one half its
previou value, regardless of the values of "Y" and "Z".

2. The length of the connecting tubing, the "Y" length, between
the probe tip and the transducer cavity volume has the least effect
on the system's frequency response. This is because of the reduced
effect of viscosity in the connecting tubing, due to its larger
diameter relative to the probe tip tubing, "X" length (Figure 9).

3. The effect of the cavity volume in front of the transducer
face, the "Z" length, is similar to the effect of the probe tip
length, since doubling the cavity volume results in a reduction of 50
percent in the frequency response of the probe assembly. This can be
seen in Figures 9 and 10.

B. Probe Tip Clogging

Tube clogging was a major problem. For example, just the
simple wiping of the tube's opening with a finger caused the .004
inch tubes to become clogged with flakes of skin. We cleared the
system by using a high pressure source or by threading a .003 inch
diameter wire through the tubes. As it was obvious that this clogging
problem would persist and probably increase in an actual wind tunnel
testing environment, we realized that a means of rapidly clearing the
probe tip must be incorporated into our redesigned system.
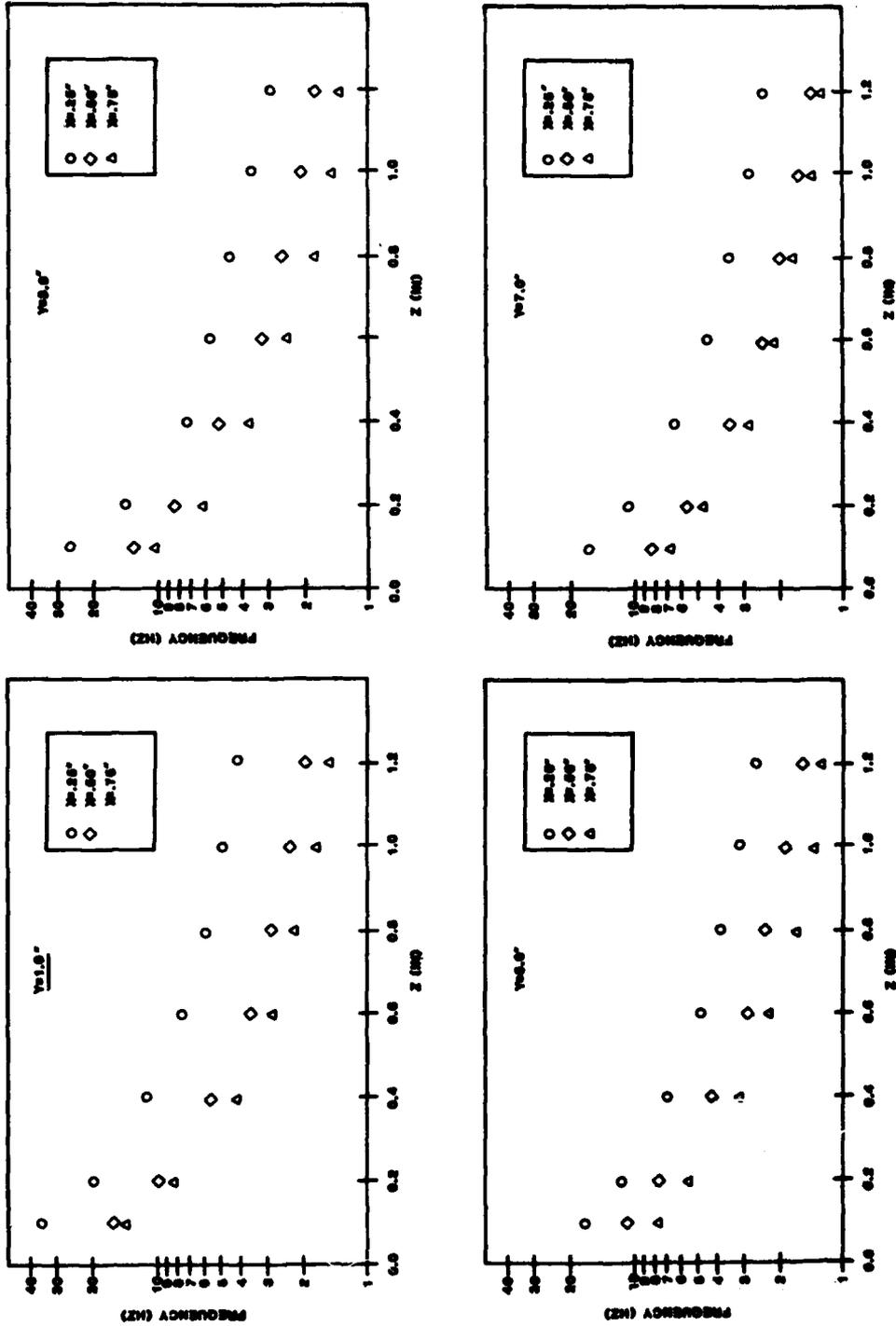
Figure 10: Frequency Response Results for the Test Tubing
Configurations (Constant "y" Length Plots)

C. Recommended Configuration

Based on the test results and the mechanical requirements we discussed earlier, the following lengths were chosen for the new probe configuration:

$$X = .75 \text{ inches}$$
$$Y = 7.0 \text{ inches}$$
$$Z = 0.1 \text{ inches}$$

The major mechanical design constraint is that, for ease of construction, the "X" length must be at least .75 inches long. The other mechanical design requirement is that the "Y" length must be large, so that the probe will be able to interrogate vortex flow fields over and under wings. Therefore, the "Y" length was chosen as 7.0 inches. The "Z" length has a lower limit of 0.1 inches due to construction limitations, and an upper limit of 0.6 inches due to the frequency response requirement that the probe's frequency response be greater than 2 HZ. Since the best frequency response is desired, 0.1 inches was chosen for the "Z" length value. This particular configuration of the overall probe assembly gives a frequency response between 6.0 and 7.0 HZ. Figure 11 shows the pressure versus time response of this configuration plotted against the response performance of the current seven-hole probe configuration.

A schematic diagram of the redesigned probe is shown in Figure 12. One feature that has been incorporated into the new design is a tubing disconnect between the "Y" and "Z" lengths. This was deemed necessary in order to have an easy means to clear the .004 inch ID tubing in case of plugging.
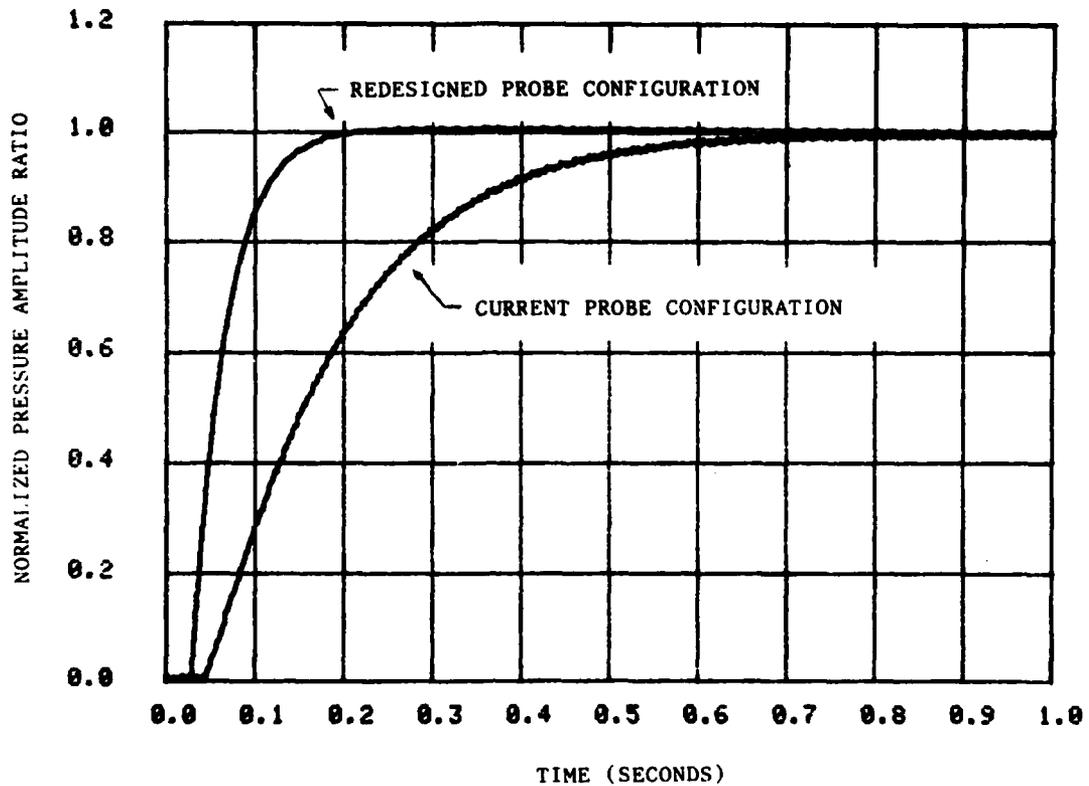
Figure 11: Comparison of the Pressure Response Time,
Current Probe Versus Redesigned Probe Final
Configuration (1.0 PSIG Amplitude Pulse)

V.   Summary

Based on the results of the experimental frequency response
tests of the redesigned seven-hole probe system, a probe
configuration has been designed that not only has a smaller tip
(better resolution), but also has a better frequency response than
the current seven-hole probe configuration. This newly designed probe
also meets the other mechanical restraints which were imposed, such
as a flexible length which allows pressure sensing at various points
near a wind tunnel model without sting interference. A comparison of
the current and redesigned probe configurations is given below:

100
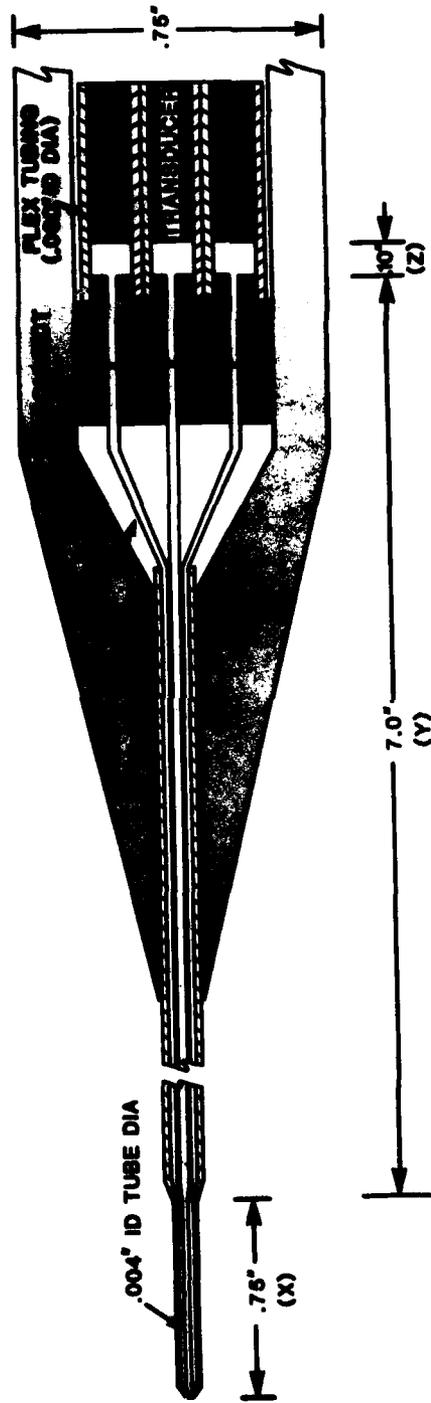
REDESIGNED SEVEN-HOLE PROBE CROSS SECTION

Figure 12:   Redesigned Seven-Hole Probe Cross-Section

	Current Probe	Redesigned Probe
Frequency Response	1.3 - 1.7 HZ	6.0 - 7.0 HZ
Tip Diameter	.109 inches	.049 inches
Effective Probe Length	1.0 inches	approx. 5.0 inches

Potential plugging problems associated with using the .004 inch ID sampling port tubing should be resolved by incorporation of a tubing disconnect assembly in the probe that will allow a "blow back" operation to clear the tubing.

The smaller probe tip will allow sampling of a smaller region in the flow field and therefore will improve measurement resolution of the seven-hole probe. This in turn will allow better data resolution in the complex flow fields associated with advanced wing/canard designs. The data resulting from this test program will provide a valuable and useful base for future analytical work. We do plan ultimately to complete a theoretical analysis that will allow us to predict the frequency response of various tubing combinations.

VI. Acknowledgements

We wish to acknowledge the assistance of several individuals without whose help and expertise this redesign effort would have been impossible. Mr. Calvin Westover was the technician who constructed all of the test "plugs". Captain Thomas Bolick wrote the computer software program which performed the data acquisition and the plot programs for the research tests. Finally, Major A.M. Higgins provided help and guidance which were essential to the completion of this project.

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SECTION IV

Engineering Education

THE AERONAUTICS DEPARTMENT AND CORE COURSES
AT THE UNITED STATES AIR FORCE ACADEMY*

Daniel H. Daley**

I learned from the last Convocation that the two prerequisites
needed to be a speaker here are a bit of magic and a quotation. I
asked the officers in the Department if they could come up with some
magic, and two volunteered to make a model of the Stealth Bomber to
display here. It's on the desk in front, and we will leave it there
for you to look at more closely after the presentation. For a
quotation, I have a quote from the famous infamous Chairman of the
Faculty Convocation, Jim Wright, so we'll begin with that. Figure 1
is a quote from Jim's memo telling me that I would have the
opportunity to acquaint this Convocation with the Aero Department and
our core courses.

. . . **IMPROVING AWARENESS OF OUR FACULTY**

IN AREAS OUTSIDE OF THEIR OWN DEPARTMENTS.

— JAMES WRIGHT

Figure 1. Purpose of Convocation

First, I will give you a little background on the Department and how
we operate. Then I'll discuss our Department's philosophy concerning
core courses.

We begin with a brief history of the Department. When the Academy
was started, there was a Department of Thermodynamics and a Department
of Aeronautics as shown in Figure 2.

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*This paper is a slightly revised version of remarks delivered to the
Faculty Convocation at the United States Air Force Academy on 3
February 1982.
**Colonel, USAF, Professor of Aeronautics, DFAN
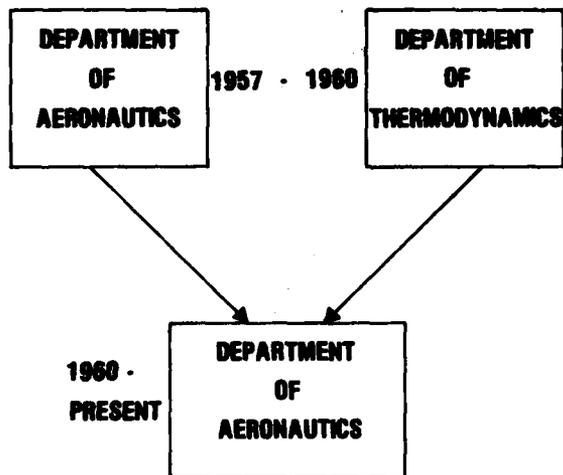
Figure 2. Evolution of Department of Aeronautics.

The Department of Thermodynamics handled the propulsion, thermodynamics, heat transfer, and gas dynamics -- what you might call the heart of an airplane -- while the Department of Aeronautics handled the skeleton and the airframe. They were really two incomplete departments. In 1960, these departments were combined into the Department of Aeronautics that we still have today. It's the whole airplane now -- the aircraft's propulsion system and the airframe. That is the reason why thermodynamics is a core course in the Department of Aeronautics.

DFAN MEMBERS

ASSIGNED

    ACTIVE DUTY   34

                            34

NOT ASSIGNED

    ACTIVE DUTY   53

    RETIRED   66

    VISITING FACULTY 5

    RESIGNED   21

    DECEASED   8

                         153
                         187

Figure 3. Department of Aeronautics (DFAN) Members (3
February 1982).

The Department membership, which is outlined in Figure 3, is much
larger than it appears on the surface. Since I have been head of the
Department, my policy has been, "Once a member of the Department;
always a member of the Department." The words "former member" are not
in the lexicon of the Department of Aeronautics. We talk about
"assigned members" and "not-assigned members". Therefore, we now have
187 members in the Department. To illustrate that this is not just a
bookkeeping process, three weeks ago I asked all the members of the
Department to keep a log of their contacts with not-assigned members.
I was really amazed at the number of contacts we've had in the past
three weeks -- 65! Now those 65 contacts were between 16 of the 34
assigned members and 30 not-assigned members. Of those 30 not-assigned
members, 18 were active duty not-assigned, 5 were retired, 4 were DVPs
(Distinguished Visiting Professors), and 3 were resigned members.
Thirty not-assigned members made a total of 65 contacts. The topics of
those conversations ranged from personal matters to the most prominent
subject, which was research. Other frequently mentioned subjects were
recommendations and leads on future members of the Department. Thus it

is a very active membership, and we get some tangible results from keeping in touch with all the not-assigned members.

The day before yesterday, when I was assembling these numbers, I got a call from a not-assigned member, who was not among the 65 just mentioned. When I told him how many people had called back in the last three weeks, he pointed out that on that day he planned to call three not-assigned members whom he had met while he was at the Department. I got to thinking that one excellent reason for attending the senior service schools is having the opportunity to meet other people in the service. Well, one benefit of being assigned to the Department of Aeronautics is that one meets people who will help one later in one's Air Force career.

In addition to these informal contacts which are made during the year, we have at least 3 formal contacts which are initiated by the Department to keep in touch with the not-assigned members. These contacts are listed in Figure 4.

DFAN ANNUAL CONTACTS

APRIL · NEWSLETTER

OCTOBER · ADVISORY PANEL/DINING-IN

DECEMBER · ADDRESS ROSTER

Figure 4. Contacts Made with Department Members.

As you see, in April we will send out our 16th Annual Newsletter and in August we will send out invitations to the 14th Annual Advisory Panel and the the 16th Annual Fall Dining-In. After the second Dining-In, when we first invited not-assigned members back, some said

that they would have come if there had been a reason for TDY. So we
decided to have an Advisory Panel meet the Friday afternoon before the
Dining-In. As it turns out, it has been a most helpful Advisory Panel.
For example, we cut five courses from the aero major about five years
or so ago when we were working on the curriculum. We were gnashing our
teeth and so on about how we were going to drop all these courses and
would have no electives in the new curriculum for the aero major. In
October we had many members back for the Advisory Panel and went over
the curriculum with them. The panel members advised us against
dropping all electives, so we put in two electives, which turned out
to be the right way to go. Each year we review various aspects of our
program here with the Advisory Panel. Then at the end of November or
in early December, we send a current address roster in time for
Christmas cards.

Finally, I thought you might be interested in our organizational
structure -- it's very simple. As you see in Figure 5, we put all the
well-rounded people in a circle and a square in a square.
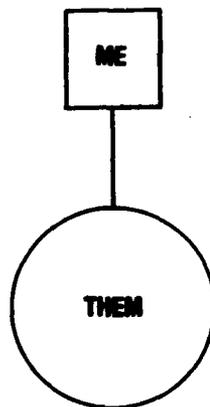
Figure 5. Department of Aeronautics Organizational Chart.

Now I'll turn to the core courses. From 1959 to 1965, we had two

thermodynamics courses, which were an outgrowth of the original

Department of Thermodynamics. They were presented in the second class

(junior) year. These were followed by two courses in aeronautics in

the first class (senior) year. From 1966 to the present, we have had

the one aero core course and the engineering thermodynamics course.

This arrangement is shown in Figure 6.

THERMO/AERO CORE COURSES

CLASSES OF '59 - '65:

2 THERMO
2 AERO
—
4

CLASS OF '66 TO PRESENT:

1 AERO
1 THERMO
—
2

Figure 6. Thermo/Aero Core Courses.

Now I'll discuss briefly my philosophy about core courses in the

Aero Department. I'm a firm believer that the presentation of a

technical subject, at least in the core program here, should be

three-dimensional, covering the technical, historical, and issues

axes. Figure 7 illustrates this three-dimensional axis system.

I think we at the Academy are in a particularly good position to teach

a technical subject using a three-dimensional approach because of the

fine support we get from the other core courses. Certainly the social

sciences and the humanities core programs support the historical and

issues axes, and the engineering sciences and basic sciences core

courses are a necessity for us to advance on the technical axis. I

would say that in the first twenty years we've been oscillating on
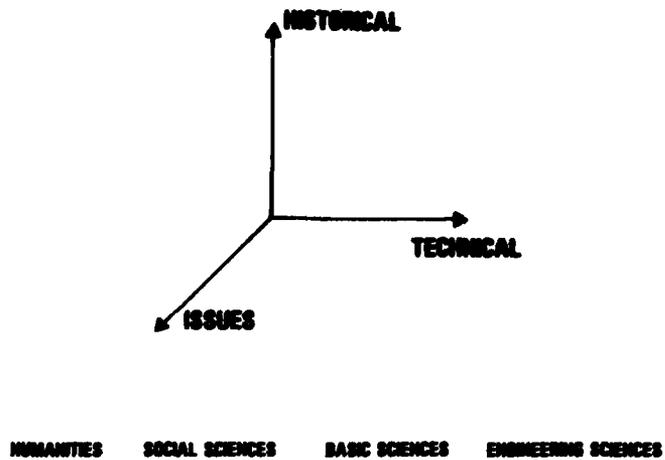
Figure 7. Subject Space of Core Aeronautics Courses.

that technical axis, trying to decide what we ought to teach on that axis. I think that in the last five years we've pretty well stabilized what we ought to be teaching in the technical area. Now it's time to start making some excursions off the technical axis. We've already moved into the technical-historical plane with the first core course we teach, because four years ago John Anderson of the University of Maryland published a text which is an introduction to flight with some historical perspective. The topics are listed in Figure 8: first history, then the technical subjects.

Only the first chapter (34 pages) is all history; however, at the end of each technical chapter, there are historical notes. Figure 9 presents a list of the historical notes that occur in the text. I don't want you to think that 90 percent of the course is history. Ten percent would be a more accurate estimate, but the idea is that we are enriching the technical axis. I think that an historical perspective makes a very interesting and useful background for a future Air Force officer.

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AERO 311 - FUNDAMENTALS OF AERONAUTICS

TEXT: "INTRODUCTION TO FLIGHT" BY ANDERSON

TOPICS: HISTORY
  INTRODUCTORY FLUID MECHANICS
  AIRFOIL AND WING AERODYNAMICS
  AIRCRAFT PERFORMANCE
    STEADY
    ACCELERATED
  STABILITY AND CONTROL

Figure 8. Fundamentals of Aeronautics (Aero 311) Course
Topics.

HISTORICAL NOTES

· THE NACA AND NASA

· THE STANDARD ATMOSPHERE

· THE PITOT TUBE

· THE FIRST WIND TUNNELS

· AIRFOILS AND WINGS

· DRAG REDUCTION (THE NACA COWLING AND FILLET)

· EARLY PREDICTIONS OF AIRPLANE PERFORMANCE

· BREGUET AND THE RANGE FORMULA

THE WRIGHT BROTHERS PHILOSOPHY ON STABILITY AND CONTROL

· THE DEVELOPMENT OF FLIGHT CONTROLS

· THE "TUCK-UNDER" PROBLEM

Figure 9. Historical Notes Included in Fundamentals of
Aeronautics Text.

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That third note from the bottom in Figure 9 -- the Wright
Brothers' philosophy on stability and control -- is the historical
note at the end of chapter 7 (chapter 7 deals with stability and
control). If you read that note you learn that the Wright Brothers, in
all of their airplanes, sacrificed static stability in pitch for
maneuverability. No other airplanes have done that until recently.
That means that all the Wright-designed airplanes were statically
unstable in pitch. I didn't know that until I read it in this text.

With the F-16 we have come full circle. The F-16 is statically
unstable in pitch -- and why? Because it needs to be highly
maneuverable. And that's exactly what the Wright Brothers did. The
Wright Brothers' airplane was very difficult to fly because it was
statically unstable; but that has been corrected in the F-16 by black
boxes, electronics, and fly-by-wire. With the advent of that
sophisticated technology, we can have a statically unstable airplane
such as the F-16.

Figure 10 gives you an idea of one technical topic which we
discuss in our Aero 311 course. This graph is a plot of altitude
versus Mach number. The heavy line shows the flight schedule required
for an F4E to get to Mach 2 at 35,000 feet in the shortest possible
time. The interesting thing about this schedule is that it calls for
take-off and level flight to a Mach number of 0.9, then a climb to
about 25,000 feet, followed by a dive to 20,000 feet to attain a Mach
number of 2. After this the plane again climbs to 40,000 feet, and
then dives to 35,000. By doing this, one will get there in the
shortest time. We explain why that's so in our Aero 311 course, and we
do that by using the contours of specific excess power which you see
on the graph along with contours of constant energy height. It's
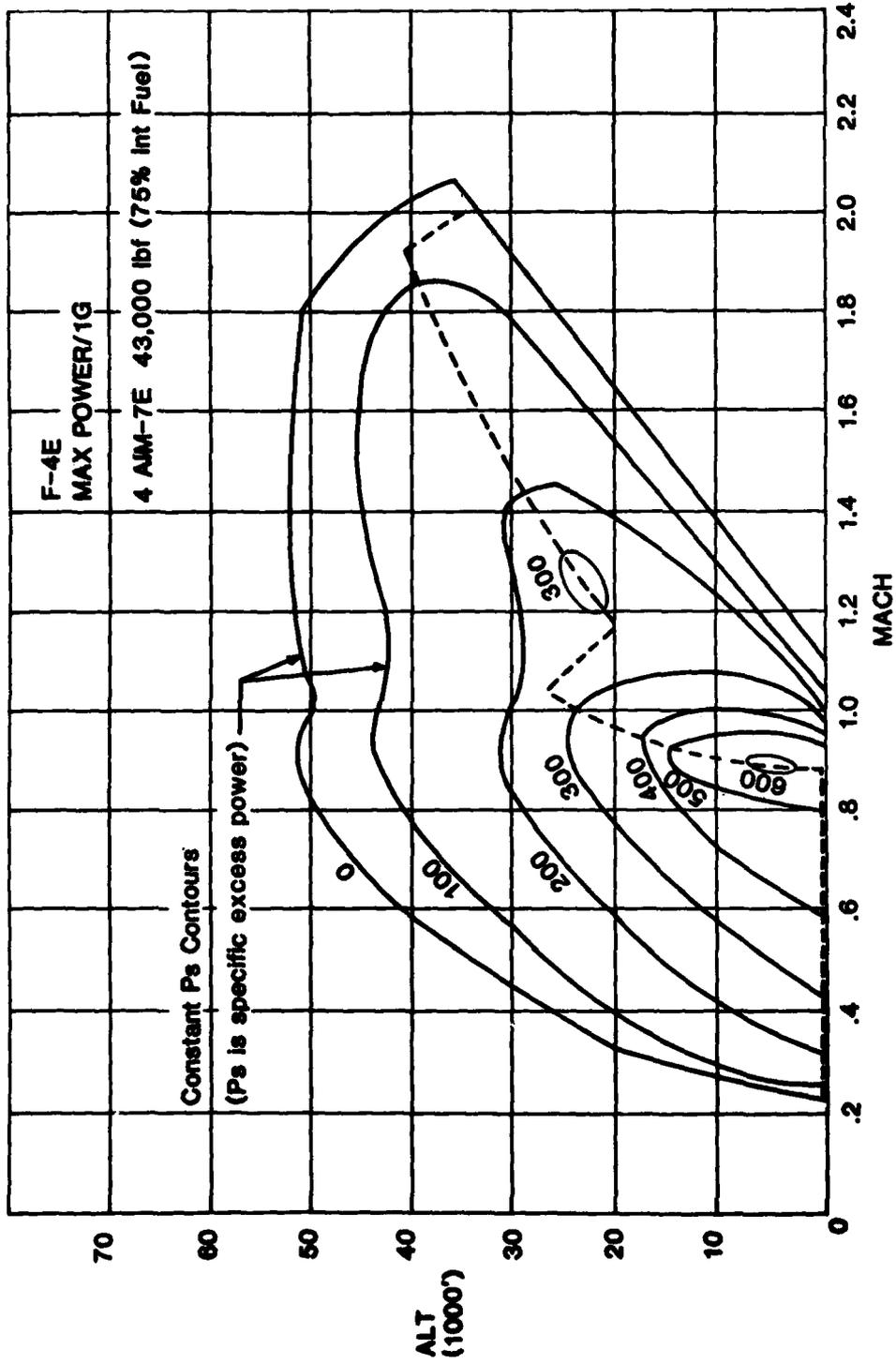
Figure 10. Typical Specific Excess Power Plot from Aero 311 Course.

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rather interesting that to get to an altitude of 35,000 feet in the
shortest time, you must overshoot a couple of times and dive as shown.

Now we look at Aero 312, our engineering thermodynamics course.
The topics listed in Figure 11 are taught in that course.

AERO 312 · INTRODUCTORY ENGINEERING THERMODYNAMICS

TEXT: *"ENGINEERING THERMODYNAMICS"*
        BY REYNOLDS AND PERKINS

TOPICS: FIRST LAW AND ENERGY
        WORKING FLUIDS FOR CYCLES
        SECOND LAW AND ENTROPY
        CYCLES
                RANKINE
                VAPOR COMPRESSION
                BRAYTON (LAB EXERCISE)
                OTTO
                DIESEL

Figure 11. Introductory Engineering Thermodynamics (Aero
312) Course Topics.

We've been using this text for five years, and it is excellent. I'd
like to discuss the cycles a little. The Rankine cycle is the cycle
that produces approximately 90 percent of the world's electricity.
It's the cycle that is used by a steam power plant. The vapor
compression cycle is a cycle that is found in a heat pump, air
conditioner, or refrigerator. The Brayton cycle is the cycle that is
used by a turbojet or turbofan engine. We have some fine engine test
cells in our Aeronautics Laboratory, just south of Fairchild Hall. In
the test cells we have a J-69 engine which is the engine in the T-37,
and a J-85 engine which is the engine in the T-38. Each thermodynamics
class learns to analyze the jet engine; then we run the J-69 engine
during a laboratory period. Every class goes through this laboratory

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exercise. The other cycles we discuss are the Otto and Diesel cycles.
The Otto cycle is the one that gasoline engines in automobiles use,
and the Diesel cycle is used generally in locomotives and in some cars
and trucks.

From some of your reactions to Figure 12, it occurs to me that we
might not need a policy to conserve energy when we have a natural law
that guarantees that it is conserved.

NATIONAL POLICY

ENERGY WILL BE CONSERVED

NATURAL LAW

ENERGY IS CONSERVED

ENERGY = EXERGY + ANERGY

Figure 12. An Issue Clarified in Aeronautics 312.

This is an issue that we try to clarify in our engineering
thermodynamics course, by indicating that the layman's definition of
energy is different from that of the engineer or scientist. To a
politician or a layman, energy is that portion of the engineer's
energy that is available to do work. In Europe that is clarified by
terms which will probably be creeping into our textbooks in the next
few years. That is, energy is the sum of exergy and anergy. What
we want to conserve is exergy. Exergy is that portion of energy that
is available to do work. When you turn off a light switch you are
really conserving exergy, because all the electricity flowing through
a light switch is exergy. It's available to do work, run a motor, and
lift a weight. This is an illustration of one issue which we clarify

in our thermodynamics course. To conclude, I might point out that in this thermodynamics course we are still pretty much on the technical axis. However, this summer I plan to work with some people in the Department to use 312H (honors) to introduce the history of some of the cycles and some of the ideas of thermodynamics.

Question and Answer Period

Question:

Colonel Daley, one of the questions that I have is this: most of the students you teach are second class en. How do you keep them motivated and interested in taking courses like thermodynamics?

Answer:

Well, the Arabs helped us very much, beginning in 1973, by making people aware of our limited exergy resources. Also, the students are all very much interested in airplanes and the engines that power the airplanes and they all are going to have or do have a car. They are interested in the performance of the engines in their cars, so it is really not all that difficult to hold their interest.

Question:

How do cadets who are more interested in majoring in something other than engineering sciences handle aero?

Answer:

Before they take the first core course in aero, they've had a fine exposure to physics, chemistry, and engineering mechanics courses, and we build on that. I don't think that the subject matter that we teach in the core aero courses is any more difficult than the subject matter that we teach in other core courses. Are you from the Physics department? I doubt that the cadet who is more interested in the humanities has any more trouble in aero than he had in physics. I

think that we are lucky in the aero courses. Sixty-five percent or so

of our students will be going to pilot training, so it's a natural --

we're talking about things related to the airplanes that they will be

flying. Maybe in that sense, we have less difficulty in interesting

them. However, when you get into some of the details of the equations

that describe the motions that we're interested in and so on, they

become impatient. They'd like to get the answers without the reasons.

SECTION V

Aeronautical History

SOME AERONAUTICAL EXPERIMENTS.

By Wilbur Wright, Dayton, U.S.A.

Editor's Note

This paper was read before the American Western Society of Civil Engineers in Chicago on September 18, 1901. It was subsequently published serially in the British Publication The Automotor Journal in February and March of 1902. The photographs in the original paper could not be used in the Aeronautics Digest because of their quality. The photos you see here are similar photographs from the Wright Brothers' collection in the Library of Congress.

The difficulties which obstruct the pathway to success in flying machine construction are of three general classes: (1) those which relate to the construction of the sustaining wings, (2) those which relate to the generation and application of the power required to drive the machine through the air, (3) those relating to the balancing and steering of the machine after it is actually in flight. Of these difficulties two are already to a certain extent solved. Men already know how to construct wings or aeroplanes, which, when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed. As long ago as 1893, a machine, weighing 8,000 pounds demonstrated its power both to lift itself from the ground and to maintain a speed of from thirty to forty miles per hour; but it came to grief in an accidental free flight, owing to the inability of the operators to balance and steer it properly. This inability to balance and steer still confronts students of the flying problem, although nearly ten years have passed. When this one feature has been worked out, the age of flying machines will have arrived, for all other difficulties are of minor importance.

The person who merely watches the flight of a bird gathers the

impression that the bird has nothing to think of but the flapping of its wings. As a matter of fact this is a very small part of its mental labor. To even mention all the things the bird must constantly keep in mind in order to fly securely through the air would take a considerable part of the evening. If I take this piece of paper, and after placing it parallel with the ground, quickly let it fall, it will not settle steadily down as a staid, sensible piece of paper ought to do, but it insists on contravening every recognized rule of decorum, turning over and darting hither and thither in the most erratic manner, much after the style of an untrained horse. Yet this is the style of steed that men must learn to manage before flying can become an everyday sport. The bird has learned this art of equilibrium, and learned it so thoroughly that its skill is not apparent to our sight. We only learn to appreciate it when we try to imitate it. Now, there are two ways of learning how to ride a fractious horse; one is to get on him and learn by actual practice how each motion and trick may be best met; the other is to sit on a fence and watch the beast awhile, and then retire to the house and at leisure figure out the best way of overcoming his jumps and kicks. The latter system is the safest; but the former, on the whole, turns out the larger proportion of good riders. It is very much the same in learning to ride a flying machine; if you are looking for perfect safety, you will do well to sit on a fence and watch the birds; but if you really wish to learn, you must mount a machine and become acquainted with its tricks by actual trial.

Herr Otto Lilienthal seems to have been the first man who really comprehended that balancing was the <u>first</u> instead of the <u>last</u> of the great problems in connection with human flight. He began where others left off, and thus saved the many thousands of dollars that it had theretofore been customary to spend in building and fitting expensive engines to machines which were uncontrollable when tried. He built a pair

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of wings of a size suitable to sustain his own weight, and made use of
gravity as his motor. The motor not only cost him nothing to begin with,
but it required no expensive fuel while in operation, and never had to be
sent to the shop for repairs. It had one serious drawback, however, in
that it always insisted on fixing the conditions under which it would
work. These were that the man should first betake himself and machine to
the top of a hill and fly with a downward as well as a forward motion.
Unless these conditions were complied with, gravity served no better than
a balky horse -- it would not work at all. Although Lilienthal must have
thought the conditions were rather hard, he nevertheless accepted them
till something better should turn up; and in this manner he made some two
thousand flights, in a few cases landing at a point more than a thousand
feet distant from his place of starting. Other men, no doubt, long before
had thought of trying such a plan. Lilienthal not only thought, but
acted; and in so doing probably made the greatest contribution to the
solution of the flying problem that has ever been made by any one man. He
demonstrated the feasibility of actual practice in the air, without which
success is impossible. Herr Lilienthal was followed by Mr. Pilcher, a
young English engineer, and by Mr. Chanute, a distinguished member of the
society I now address. A few others have built machines, but nearly all
that is of value is due to the experiments conducted under the direction
of the three men mentioned.

The balancing of a gliding or flying machine is very simple in
theory. It merely consists in causing the center of pressure to coincide
with the center of gravity. But in actual practice there seems to be an
almost boundless incompatibility of temper which prevents their remaining
peaceably together for a single instant, so that the operator, who in
this case acts as peacemaker, often suffers injury to himself while
attempting to bring them together. If a wind strikes a vertical plane,

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the pressure on that part to one side of the center will balance that below. This point we call the center of pressure. But if the plane be slightly inclined, the pressure on the part nearest the wind is increased, and the pressure on the other part decreased, so that the center of pressure is now located, not in the center of the surface, but a little toward the side which is in advance. If the plane be still further inclined the center of pressure will move still farther forward. And if the wind blow a little to one side, it will also move over as if to meet it. Now, since neither the wind nor the machine for even an instant maintains exactly the same direction and velocity, it is evident that the man who would trace the course of the center of pressure must be very quick of mind; and he who would attempt to move his body to that spot at every change must be very active indeed. Yet this is what Herr Lilienthal attempted to do, and did do with the most remarkable skill, as his two thousand glides sufficiently attest. However he did not escape being overturned by wind gusts several times, and finally lost his life through a breakage of his machine, due to defective construction. The Pilcher machine was similar to that of Lilienthal, and, like it, seems to have been structurally weak; for on one occasion, while exhibiting the flight of his machine to several members of the Aeronautical Society of Great Britain, it suddenly collapsed and fell to the ground, causing injuries to the operator which proved sadly fatal. The method of management of this machine differed in no important respect from that of Lilienthal, the operator shifting his body to make the centers of pressure and gravity coincide. Although the fatalities which befell the designers of these machines were due to the lack of structural strength rather than to lack of control, nevertheless, it had become clear to the students of the problem that a more perfect method of control must be evolved. The Chanute machines marked a great advance in both respects. In

the multiple wing machine the tips folded slightly backward under the
pressure of wind gusts, so that the travel of the center of pressure was
thus largely counterbalanced. The guiding of the machine was done by a
slight movement of the operator's body toward the direction in which it
was desired the machine should go. The double deck machine built and
tried at the same time marked a very great structural advance, as it was
the first in which the principles of the modern truss bridges were fully
applied to flying machine construction. This machine, in addition to its
greatly improved construction and general design of parts, also differed
from the machine of Lilienthal in the operation of its tail. In the
Lilienthal machine the tail, instead of being fixed in one position, was
prevented by a stop from folding downward beyond a certain point, but was
free to fold upward without any hindrance. In the Chanute machine the
tail was at first rigid, but afterward, at the suggestion of Mr. Herring,
it was held in place by a spring that allowed it to move slightly either
upward or downward with reference to its normal position, thus modifying
the action of the wind gusts upon it very much to its advantage. The
guiding of the machine was effected by slight movements of the operator's
body, as in the multiple wing machines. Both these machines were much
more manageable than the Lilienthal type, and their structural strength,
notwithstanding their extreme lightness, was such that no fatalities, or
even accidents, marked the glides made with them, although winds were
successfully encountered much greater in violence than any which previous
experimenters had dared to attempt.

My own active interest in aeronautical problems dates back to the
death of Lilienthal in 1896. The brief notice of his death which appeared
in the telegraphic news at that time aroused a passive interest which had
existed from my childhood, and led me to take down from the shelves of
our home library a book on "Animal Mechanism," by Prof. Marey, which I

had already read several times. From this I was led to read more modern
works, and as my brother soon became equally interested with myself, we
soon passed from the reading to the thinking, and finally to the working
stage. It seemed to us that the main reason why the problem had remained
so long unsolved was that no one had been able to obtain any adequate
practice. We figured that Lilienthal in five years of time had spent only
about five hours in actual gliding through the air. The wonder was not
that he had done so little, but that he had accomplished so much. It
would not be considered at all safe for a bicycle rider to attempt to
ride through a crowded city street after only five hours' practice,
spread out in bits of ten seconds over a period of five years; yet
Lilienthal with this brief practice was remarkably successful in meeting
the fluctuations and eddies of wind gusts. We thought that if some method
could be found by which it would be possible to practice by the hour
instead of by the second, there would be hope of advancing the solution
of a very difficult problem. It seemed feasible to do this by building a
machine which would be sustained at a speed of 18 miles per hour, and
then finding a locality where winds of this velocity were common. With
these conditions, a rope attached to the machine to keep it from floating
backward would answer very nearly the same purpose as a propeller driven
by a motor, and it would be possible to practice by the hour, and without
any serious danger, as it would not be necessary to rise far from the
ground, and the machine would not have any forward motion at all. We
found, according to the accepted tables of air pressure on curved
surfaces, that a machine spreading 200 square feet of wing surface would
be sufficient for our purpose, and that places could easily be found
along the Atlantic coast where winds of 16 to 25 miles were not at all
uncommon. When the winds were low, it was our plan to glide from the tops
of sand hills, and when they were sufficiently strong, to use a rope for

our motor and fly over one spot. Our next work was to draw up the plans
for a suitable machine. After much study, we finally concluded that tails
were a source of trouble rather than of assistance; and therefore we
decided to dispense with them altogether. It seemed reasonable that if
the body of the operator could be placed in a horizontal position,
instead of upright, as in the machines of Lilienthal, Pilcher, and
Chanute, the wind resistance could be very materially reduced, since only
one square foot instead of five would be exposed. As a full half
horsepower could be saved by this change, we arranged to try at least the
horizontal position. Then the method of control used by Lilienthal, which
consisted of shifting the body, did not seem to be quite as quick or
effective as the case required; so after long study, we contrived a
system consisting of two large surfaces on the Chanute double deck plan,
and a smaller surface placed a short distance in front of the main
surfaces in such a position that the action of the wind upon it would
counterbalance the effect of the travel of the center pressure on the
main surfaces. Thus, changes in the direction and velocity of the wind
would have little disturbing effect, and the operator would be required
to attend only to the steering of the machine, which was to be effected
by curving the forward surface up or down. The lateral equilibrium and
the steering to right or left was to be attained by a peculiar torsion of
the main surfaces, which was equivalent to presenting one end of the
wings at a greater angle than the other. In the main frame a few changes
were also made in the details of construction and trussing employed by
Chanute. The most important of these were: (1) The moving of the forward
main cross-piece of the frame to the extreme front edge; (2) The encasing
in the cloth of all cross-pieces and ribs of the surfaces; (3) A
re-arrangement of the wires used in trussing the two surfaces together,
which rendered it possible to tighten all the wires by simply shortening

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two of them.

With these plans we proceeded in the summer of 1900 to Kitty Hawk,
North Carolina, a little settlement located on the strip of land that
separates Albemarle Sound from the Atlantic Ocean. Owing to the
impossibility of obtaining suitable material for a 200 square-foot
machine, we were compelled to make it only 165 square feet in area,
which, according to the Lilienthal tables, would be supported at an angle
of three degrees in a wind of about 21 miles per hour. On the very day
that the machine was completed the wind blew from 25 to 30 miles per
hour, and we took it out for trial as a kite. We found that, while it was
supported with a man on it in a wind of about 25 miles, its angle was
much nearer 20 degrees than three degrees. Even in gusts of 30 miles the
angle of incidence did not get as low as three degrees, although the wind
at this speed has more than twice the lifting power of a 21 mile wind. As
winds of 30 miles per hour are not plentiful on clear days, it was at
once evident that our plan of practicing by the hour, day after day,
would have to be postponed. Our system of twisting the surfaces to
regulate the lateral balance was tried, and found to be much more
effective than shifting the operator's body. On subsequent days, when the
wind was too light to support the machine with a man on it, we tested it
as a kite, working the rudders by cords reaching to the ground (Figure 1). The
results were very satisfactory, yet we were well aware that this method
of testing is never wholly convincing until the results are confirmed by
actual gliding experience.

We then turned our attention to making a series of actual
measurements of the lift and drift of the machine under various loads. So
far as we were aware this had never previously been done with any
full-size machine. The results obtained were most astonishing, for it
appeared that the total horizontal pull of the machine, while sustaining

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Figure 1. Wilbur and Orville Wright Flying 1901 Glider as a Kite

a weight of 52 pounds, was only 8.5 pounds, which was less than had

previously been estimated for head resistance of the framing alone.

Making allowance for the weight carried, it appeared that the head

resistance of the framing was but little more than 50 percent of the

amount which Chanute had estimated as the head resistance of the framing

of his machine. On the other hand it appeared sadly deficient in lifting

power as compared with the calculated lift of curved surfaces of its

size. This deficiency we supposed might be due to one or more of the

following causes: (1) that the depth of the curvature of our surfaces was

insufficient, being only about 1 in 22, instead of 1 in 12, (2) that the

cloth used in our wings was not sufficiently airtight, (3) that the

Lilienthal tables might themselves be somewhat in error. We decided to

arrange our machine for the following year, so that the depth of

curvature of its surfaces could be varied at will, and its covering

air-proofed.

Our attention was next turned to gliding, but no hill suitable for

the purpose could be found near our camp at Kitty Hawk. This compelled us

to take the machine to a point four miles south, where the Kill Devil

sand hill rises from the flat sand to a height of more than 100 feet. Its

main slope is toward the north-east, and has an inclination of 10

degrees. On the day of our arrival the wind blew about 25 miles per hour,

and as we had no experience at all in gliding, we deemed it unsafe to

attempt to leave the ground. But on the day following, the wind having

subsided to 14 miles per hour, we made about a dozen glides. It had been

the original intention that the operator should run with the machine to

obtain initial velocity, and assume the horizontal position only after

the machine was in free flight. When it came time to land he was to

resume the upright position and light on his feet, after the style of

previous gliding experimenters. But on actual trial we found it much

better to employ the help of two assistants in starting, which the

peculiar form of our machine enabled us readily to do, and in landing we

found that it was entirely practicable to land while still reclining in a

horizontal position upon the machine. Although the landings were made

while moving at speeds of more than 20 miles per hour, neither machine or

operator suffered any injury. The slope of the hill was 9.5 degrees, or a

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drop of 1 foot in 6. We found that after attaining a speed of about 25 or
30 miles with reference to the wind, or 10 to 15 miles over the ground,
the machine not only glided parallel to the slope of the hill, but
greatly increased its speed, thus indicating its ability to glide on a
somehwat less angle than 9.5 degrees, when we should feel it safe to rise
higher from the surface. The control of the machine proved even better
than we had dared to expect, responding quickly to the slightest motion
of the rudder. With these glides our experiments for the year 1900
closed. Although the hours and hours of practice we had hoped to obtain
finally dwindled down to about two minutes, we were very much pleased
with the general results of the trip, for setting out as we did, with
almost revolutionary theories on many points, and an entirely untried
form of machine, we considered it quite a point to be able to return
without having our pet theories completely knocked on the head by the
hard logic of experience and our own brains dashed out in the bargain.
Everything seemed to us to confirm the correctness of our original
opinions that, (1) practice is the key to the secret of flying; (2) it is
practicable to assume the horizontal position; (3) a smaller surface set
at a negative angle in front of the main bearing surfaces, or wings, will
largely counteract the effect of the fore and aft travel of the center of
pressure; (4) steering up and down can be attained with a rudder, without
moving the position of the operator's body and (5) twisting the wings so
as to present their ends to the wind at different angles is a more prompt
and efficient way of maintaining lateral equilibrium than shifting the
body of the operator.

When the time came to design our new machine for 1901, we decided to
make it exactly like the previous machine in theory and method of
operation. But as the former machine was not able to support the weight
of the operator when flown as a kite, except in very high winds and at

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very large angles of incidence, we decided to increase its lifting power. Accordingly, the curvature of the surfaces was increased to 1 in 12, to conform to the shape on which Lilienthal's table was based, and to be on the safe side, we decided also to increase the area of the machine from 165 square feet to 308 square feet, although so large a machine had never before been deemed controllable. The Lilienthal machine had an area of 151 square feet; that of Picher, 165 square feet; and the Chanute double decker, 134 square feet. As our system of control consisted in a manipulation of the surfaces themselves instead of shifting the operator's body, we hoped that the new machine would be controllable, notwithstanding its great size. According to calculations it would obtain support in a wind of 17 miles per hour with an angle of incidence of only 3 degrees.

Our experience of the previous year having shown the necessity of a suitable building for housing the machine, we erected a cheap frame building, 16 feet wide, 25 feet long, and 7 feet high at the eaves. As our machine was 22 feet wide, 14 feet long (including the rudder), and about 6 feet high, it was not necessary to take the machine apart in any way in order to house it. Both ends of the building, except the gable parts, were made into doors which hinged above, so that when opened they formed an awning at each end, and left an entrance the full width of the building. We went into camp about the middle of July, and were soon joined by Mr. E.C. Huffaker, of Tennessee, an experienced aeronautical investigator in the employ of Mr. Chanute, by whom his services were kindly loaned, and by Dr. G.A. Spratt, of Pennsylvania, a young man who has made some valuable investigations of the properties of variously curved surfaces and the travel of the center of pressure thereon. Early in August, Mr. Chanute came down from Chicago to witness our experiments,

and spent a week in camp with us. These gentlemen, with my brother and
myself, formed our camping party, but in addition we had in many of our
experiments the valuable assistance of Mr. W.J. Tate and Mr. Dan Tate, of
Kitty Hawk.

The machine was completed and tried for the first time on the 27th
of July in a wind blowing about 13 miles per hour. The operator having
taken a position where the center of pressure was supposed to be, an
attempt at gliding was made, but the machine turned downward and landed
after going only a few yards. This indicated that the center of gravity
was too far in front of the center of pressure. In the second attempt the
operator took a position several inches further back, but the result was
much the same. He kept moving further and further back with each trial,
till finally he occupied a position nearly a foot back of that at which
we had expected to find the center of pressure. The machine then sailed
off and made an undulating flight of a little more than 300 feet. To the
onlookers this flight seemed very successful, but to the operator it was
known that the full power of the rudder had been required to keep the
machine from either running into the ground or rising so high as to lose
all headway. In the 1900 machine one-fourth as much rudder action had
been sufficient to give much better control. It was apparent that
something was radically wrong, though we were for some time unable to
locate the trouble. In one glide the machine rose higher and higher till
it lost all headway. This was the position from which Lilienthal had
always found difficulty to extricate himself, as his machine then, in
spite of his greatest exertions, manifested a tendency to dive downward
almost vertically and strike the ground head on with frightful velocity.
In this case a warning cry from the ground caused the operator to turn
the rudder to its full extent and also to move his body slightly forward.

The machine then settled slowly to the ground, maintaining its horizontal position almost perfectly, and landed without any injury at all. This was very encouraging, as it showed that one of the greatest dangers in machines with horizontal tails had been overcome by the use of a front rudder. Several glides later the same experience was repeated with the same result. In the latter case the machine had even commenced to move backward, but was nevertheless brought safely to the ground in a horizontal position. On the whole, this day's experiments were encouraging, for while the action of the rudder did not seem at all like that of our 1900 machine, yet we had escaped without difficulty from positions which had proved very dangerous to preceding experimenters, and after less than one minute's actual practice had made a glide of more than 300 feet at an angle of descent of 10 degrees, and with a machine nearly twice as large as had previously been considered safe. The trouble with its control, which has been mentioned, we believed could be corrected when we should have located its cause. Several possible explanations occurred to us, but we finally concluded that the trouble was due to a reversal of the direction of the travel of the center of pressure at small angles. In deeply curved surfaces the center of pressure at 90 degrees is near the center of the surface, but moves forward as the angle becomes less, till a certain point is reached, varying with the depth of curvature. After this point is passed, the center of pressure, instead of continuing to move forward, with the decreasing angle, turns and moves rapidly toward the rear. The phenomena are due to the fact that at small angles the wind strikes the forward part of the surface on the upper side instead of the lower, and thus this part altogether ceases to lift, instead of being the most effective part of all, as in the case of the plane. Lilienthal had called attention to the danger of using surfaces with a curvature as great as one in eight,

on account of this action on the upper side; but he seems never to have
investigated the curvature and angle at which the phenomena entirely
ceases. My brother and I had never made any original investigation of the
matter, but assumed that a curvature of one in twelve would be safe, as
this was the curvature on which Lilienthal based his tables. However, to
be on the safe side, instead of using the arc of a circle, we had made
the curve of our machine very abrupt at the front, so as to expose the
least possible area to this downward pressure. While the machine was
building, Messrs. Huffaker and Spratt had suggested that we would find
this reversal of the center of pressure, but we believed it sufficiently
guarded against. Accordingly, we were not at first disposed to believe
that this reversal actually existed in our machine, although it offered a
perfect explanation of the action we had noticed in gliding. Our peculiar
plan of control by forward surfaces, instead of tails, was based on the
assumption that the center of pressure would continue to move farther and
farther forward, as the angle of incidence became less, and it will be
readily perceived that it would make quite a difference if the front
surface instead of counteracting this assumed forward travel, should in
reality be expediting an actual backward movement. For several days we
were in a state of indecision, but were finally convinced by observing
the following phenomena (Figure 2). We had removed the upper surface
from the machine, and were flying it in a wind to see at what angles
it would be supported in winds of different strengths. We noticed that
in light winds it flew in the upper position shown in the figure, with
a strong upward pull on the cords. As the wind became stronger, the
angle of incidence became less, and the surface flew in the position
shown in the middle of the figure, with a slight horizontal pull. But
when the wind became still stronger, it took the lower position shown
in the figure, with a strong downward pull. It at once occurred to me

that here was the answer to our problem, for it is evident that in the
first case the center of pressure was in front of the center of
gravity, and thus pushed up the front edge; in the second case, they
were in coincidence, and the surface in equilibrium; while in the
third case the center of pressure had reached a point even behind the
center of gravity, and there was therefore a downward pull on the
cord. This point having been definitely settled, we proceeded to truss
down the ribs of the whole machine, so as to reduce the depth of
curvature. In Figure 3, line 1 shows the original curvature; line 2,
the curvature when supporting the operator's weight; and line 3, the
curvature after trussing.

P-CENTER OF PRESSURE
G-CENTER OF GRAVITY
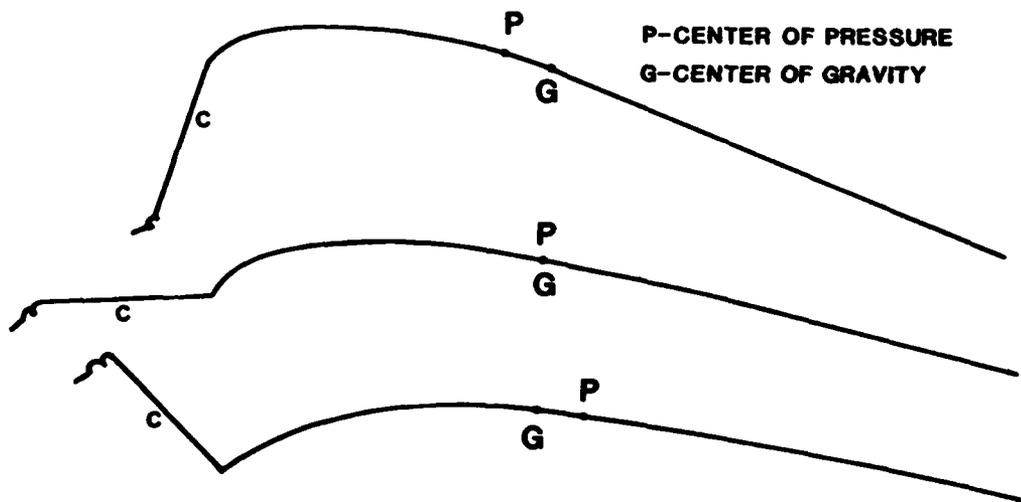
Figure 2:   Wing Attitude at Various Wind Speeds

center of gravity, and there was therefore a downward pull on the cord.
This point having been definitely settled, we proceeded to truss down the
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Figure 3, line 1 shows the original curvature; line 2, the curvature when

supporting the operator's weight; and line 3, the curvature after
trussing.
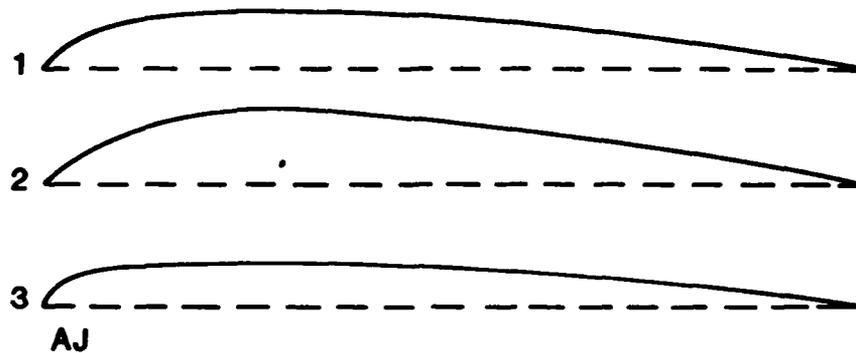
Figure 3. Evolution of the Wing's Cross-Section

On resuming our gliding we found that the old conditions of the
preceding year had returned, and after a few trials made a glide of 366
feet, and soon after one of 389 feet. The machine with its new curvature
never failed to respond promptly to even small movements of the rudder.
The operator could cause it to almost skim the ground, following the
undulations of its surface, or he could cause it to sail out almost on a
level with the starting point, and passing high above the foot of the
hill gradually settle down to the ground. The wind on this day was
blowing 11 to 14 miles per hour. The next day, the conditions being
favorable, the machine was again taken out for trial. This time the
velocity of the wind was 18 to 22 miles per hour. At first we felt some
doubt as to the safety of attempting free flight in so strong a wind,
with a machine of over 300 square feet, and a practice of less than five
minutes spent in actual flight. But after several preliminary experiments
we decided to try a glide. The control of the machine seemed so good that
we then felt no apprehension in sailing boldly forth. And thereafter we

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made glide after glide, sometimes following the ground closely, and sometimes sailing high in the air. Mr. Chanute had his camera with him, and took pictures of some of these glides... Figures 4 and 5 .
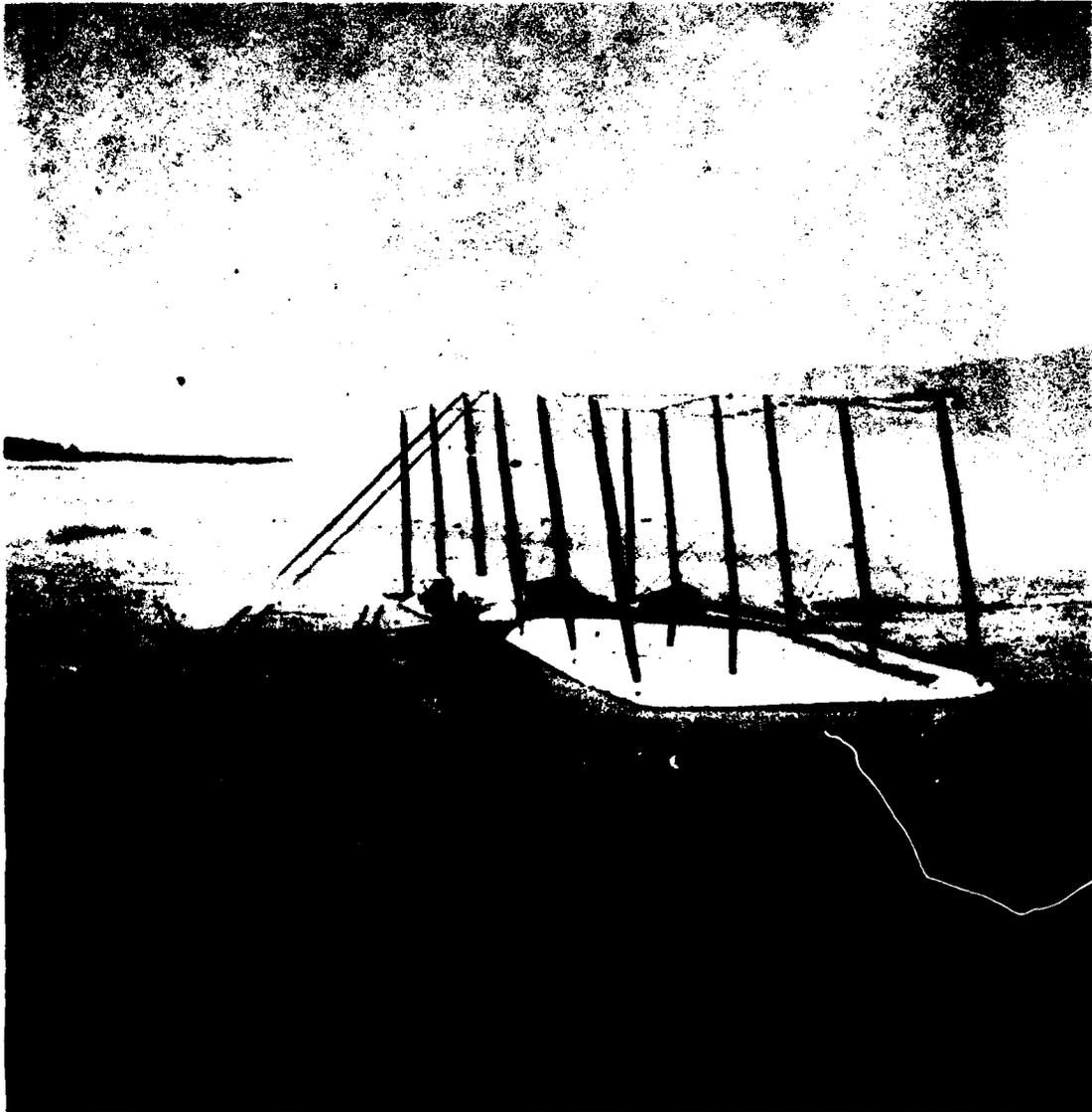
Figure 4. Wilbur Wright in 1901 Glider.
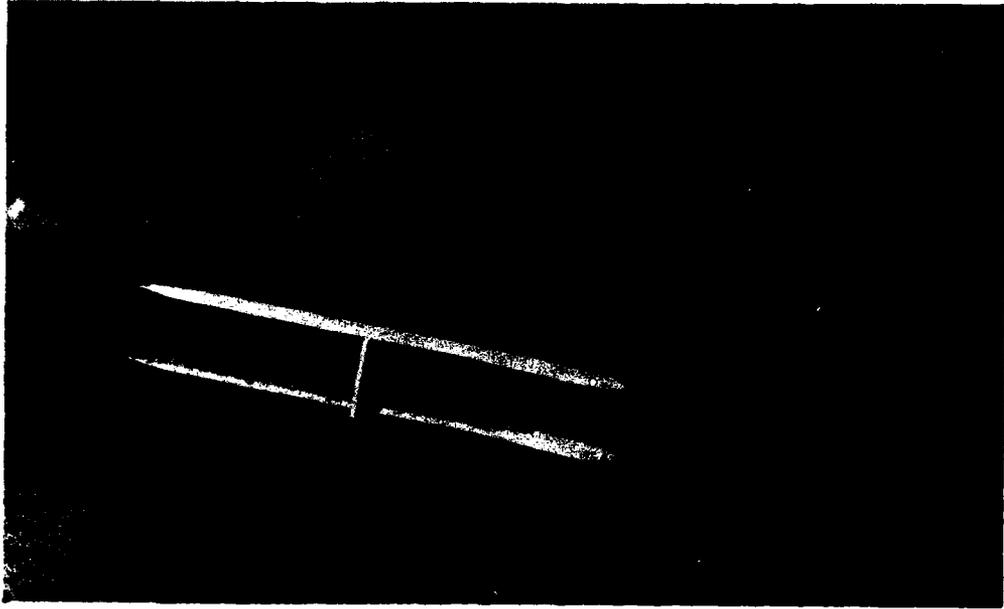
Figure 5. Wilbur Wright at Hill No. 2, October 24, 1902

We made glides on subsequent days, whenever the conditions were favorable. The highest wind thus experimented in was a little over 12 meters per second -- nearly 27 miles per hour.

It had been our intention when building the machine to do the larger part of the experimenting in the following manner: -- When the wind blew 17 miles per hour, or more, we would attach a rope to the machine, and let it rise as a kite with an operator upon it. When it should reach a proper height the operator would cast off the rope and glide down to the ground just as from the top of a hill. In this way we would be saved the trouble of carrying the machine up hill after each glide, and could make at least ten glides in the time required for one in the other way. But when we came to try it we found that a wind of 17 miles, as measured by Richard's anemometer, instead of sustaining the machine with its

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operator, a total weight of 240 pounds, at an angle of incident of 3
degrees, in reality would not sustain the machine alone -- 100 pounds --
at this angle. Its lifting capacity seemed scarcely one third of the
calculated amount. In order to make sure that this was not due to the
porosity of the cloth, we constructed two small experimental surfaces of
equal size, one of which was air-proof and the other left in its natural
state, but we could detect no difference in their lifting powers. For a
time we were led to suspect that the lift of curved surfaces little
exceeded that of planes of the same size, but further investigation and
experiment led to the opinion that (1) the anemometer used by us
over-recorded the true velocity of the wind by nearly 15 percent; (2)
that the well-known Smeaton coefficient of $.005 \ V^2$ for the wind pressure
at 90 degrees is probably too great by at least 20 percent; (3) that
Lilienthal's estimate that the pressure on a curved surface having an
angle of incidence of 3 degrees equals .545 of the pressure at 90 degrees
is too large, being nearly 50 percent greater than very recent
experiments of our own with a special pressure testing machine indicate;
(4) that the superposition of the surfaces somewhat reduced the lift per
square foot, as compared with a single surface of equal area.

In gliding experiments, however, the amount of lift is of less
relative importance than the ratio of lift to drift, as this alone
decides the angle of gliding descent. In a plane the pressure is always
perpendicular to the surface, and the ratio of lift to drift is therefore
the same as that of the cosine to the sine of the angle of incidence. But
in curved surfaces a very remarkable situation is found. The pressure
instead of being uniformly normal to the chord of the arc, is usually
inclined considerably in front of the perpendicular. The result is that
the lift is greater and the drift less than if the pressure were normal.

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Lilienthal was the first to discover this exceedingly important fact,
which is fully set forth in his book, <u>Bird Flight the Basis of the Flying
Art</u>, but owing to some errors in the methods he used in making
measurements, question was raised by other investigators not only as to
the accuracy of his figures, but even as to the existence of any
tangential force at all. Our experiments confirm the existence of this
force, though our measurements differ considerably from those of
Lilienthal. While at Kitty Hawk we spent much time in measuring the
horizontal pressure on our unloaded machine at various angles of
incidence. We found that at 13 degrees the horizontal pressure was about
23 pounds. This included not only the drift proper, or horizontal
component of the pressure on the side of the surface, but also the head
resistance of the framing as well. The weight of the machine at the time
of this test was about 108 pounds. Now, if the pressure had been normal
to the chord of surface, the drift proper would have been to the lift
(108 pounds) as the sine of 13 degrees is to the cosine of 13 degrees, or

$$\frac{.22 \times 108}{97} = 24 + \text{lbs.} \tag{1}$$

but this slightly exceeds the total pull of 23 pounds on our scales.
Therefore, it is evident that the average pressure on the surface instead
of being normal to the chord was so far inclined toward the front that
all the head resistance of framing and wires used in the construction was
more than overcome. In a wind of 14 miles per hour, resistance is by no
means a negligible factor, so that the tangential force is evidently a
force of considerable value. In a higher wind which sustained the machine
at an angle of 10 degrees, the pull on the scales was 18 pounds. With
the pressure normal to the chord, the drift proper would have been

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$$\frac{\cdot 17 \times 98*}{\cdot 97} = 17 \text{ lbs.} \tag{2}$$

so that although the higher wind velocity must have caused an increase in the head resistance, the tangential force still came within one pound of overcoming it. After our return from Kitty Hawk we began a series of experiments to accurately determine the amount and direction of the pressure produced on curved surfaces when acted upon by winds at the various angles from zero to 90 degrees. These experiments are not yet concluded, but in general they support Lilienthal in the claim that the curves give pressures more favorable in amount and direction than planes; but we find marked differences in the exact values, especially at angles below 10 degrees. We were unable to obtain direct measurements of the horizontal pressures of the machine with the operator on board, but by comparing the distance traveled in gliding with the vertical fall, it was easily calculated that at a speed of 24 miles per hour the total horizontal resistances of our machine, when bearing the operator amounted to 40 pounds, which is equivalent to about $2\frac{1}{3}$ horsepower. It must not be supposed, however, that a motor developing this power would be sufficient to drive a man-bearing machine. The extra weight of the motor would require either a larger machine, higher speed, or a greater angle of incidence, in order to support it, and therefore more power. It is probable, however, that an engine of 6 horsepower, weighing 100 pounds, would answer the purposes. Such an engine is entirely practicable. Indeed, working motors of one-half this weight per horsepower (9 lbs. per horsepower) have been constructed by several different builders. Increasing the speed of our machine from 24 to 33 miles per hour reduced

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*The travel of the center of pressure made it necessary to put sand on the front rudder to bring the centers of gravity and pressure into coincidence, consequently the weight of the machine varied from 98 pounds to 108 pounds in the different tests.

the total horizontal pressure from 40 to about 35 pounds. This was quite

an advantage in gliding as it made it possible to sail about 15 percent

further with a given drop. However, it would be of little or no advantage

in reducing the size of the motor in a power driven machine, because the

lessened thrust would be counterbalanced by the increased speed per

minute. Some years ago Prof. Langley called attention to the great

economy of thrust which might be obtained by using very high speeds, and

from this many were led to suppose that high speed was essential to

success in a motor driven machine. But the economy to which Prof. Langley

called attention was in foot pounds per mile of travel, not in foot

pounds per minute. It is the foot pounds per minute that fixes the size

of the motor. The probability is that the first flying machines will have

a relatively low speed, perhaps not much exceeding 20 miles per hour, but

the problem of increasing the speed will be much simpler in some respects

than that of increasing the speed of a steamboat; for, whereas in the

latter case the size of the engine must increase as the cube of the

speed, in the flying machine, until extremely high speeds are reached,

the capacity of the motor increases in less than simple ratio; and there

is even a decrease in the fuel consumption per mile of travel. In other

words, to double the speed of a steamship (and the same is true of the

balloon type of air ship) eight times the engine and boiler capacity

would be required, and four times the fuel consumption per mile of

travel; while a flying machine would require engines of less than double

the size, and there would be an actual decrease in the fuel consumption

per mile of travel. But looking at the matter conversely, the great

disadvantage of the flying machine is apparent; for in the latter no

flight at all is possible unless the proportion of horsepower to flying

capacity is very high; but on the other hand, a steamship is a mechanical

success if its ratio of horsepower to tonnage is insignificant. A flying machine that would fly at a speed of 50 miles per hour with engines of 1,000 horsepower, would not be upheld by its wings at all at a speed of less than 25 miles per hour, and nothing less than 500 horsepower could drive it at this speed. But a boat which could make 49 miles per hour with engines of 1,000 horsepower, would still move 4 miles an hour even if the engines were reduced to 1 horsepower. The problems of land and water travel were solved in the 19th century because it was possible to begin with small achievements and gradually work up to our present success. The flying problem was left over to the 20th century, because in this case the art must be highly developed before any flight of any considerable duration at all can be obtained.

However, there is another way of flying which requires no artificial motor, and many workers believe that success will first come by this road. I refer to the soaring flight, by which the machine is permanently sustained in the air by the same means that are employed by soaring birds. They spread their wings to the wind, and sail by the hour, with no perceptible exertion beyond that required to balance and steer themselves. What sustains them is not definitely known, though it is almost certain that it is a rising current of air. But whether it be a rising current or something else, it is as well able to support a flying machine as a bird, if man once learns the art of utilizing it. In gliding experiments it has long been known that the rate of vertical descent is very much retarded and the duration of the flight greatly prolonged, if a strong wind blows up the face of the hill parallel to its surface. Our machine, when gliding in still air, has a rate of vertical descent of nearly 6 feet per second, while in a wind blowing 26 miles per hour up a steep hill, we made glides in which the rate of descent was less than 2

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feet per second. And during the larger part of this time, while the machine remained exactly in the rising current, there was no descent at all, but even a slight rise. If the operator had had sufficient skill to keep himself from passing beyond the rising current, he could have been sustained indefinitely at a higher point than that from which he started. The illustration, Figure 6, shows one of these very slow glides at a time when the machine was practically at a standstill.
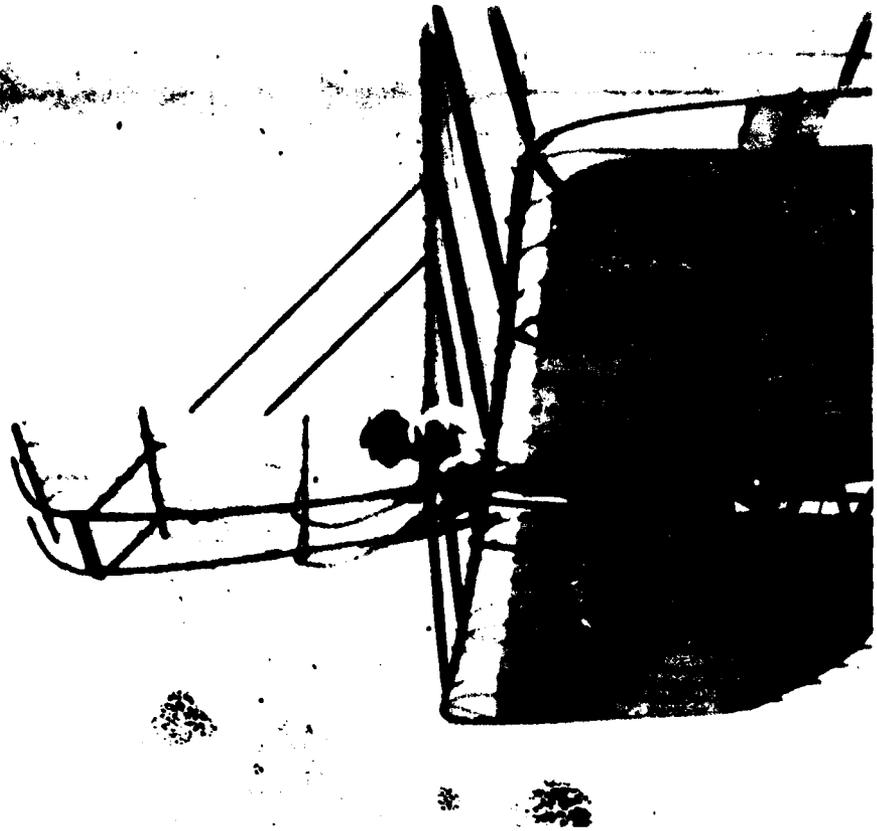

Figure 6. Wilbur Wright Gliding, 1901

The failure to advance more rapidly causes the photographer some trouble in aiming, as you will perceive. In looking at this picture you will readily understand that the excitement of gliding experiments does not

entirely cease with the breaking up of camp. In the photographic dark
room at home we pass moments of as thrilling interest as any in the
field, when the image begins to appear on the plate and it is yet an open
question whether we have a picture of a flying machine, or merely a
patch of open sky. These slow glides in rising currents probably hold out
greater hope of extensive practice than any other method within man's
reach, but they have the disadvantage of requiring rather strong winds
and very large supporting surfaces. However, when gliding operators have
attained greater skill, they can, with comparative safety, maintain
themselves in the air for hours at a time in this way, and thus by
constant practice so increase their knowledge and skill that they can
rise into the higher air and search out the currents which enable the
soaring birds to transport themselves to any desired point by first
rising in a circle, and then sailing off at a descending angle. We have
flown the unoccupied machine ... in a wind of 35 miles per hour on the
face of a steep hill, 100 feet high. ... The machine not only pulls
upwards, but also pulls forward in the direction from which the wind
blows, thus overcoming both gravity and the speed of the wind. We tried
the same experiment with a man on it, but found danger that the forward
pull would become so strong that the men holding the ropes would be
dragged from their insecure foothold on the slope of the hill. So this
form of exerimenting was discontinued after four or five minutes' trial.

In looking over our experiments of the past two years, with models
and full size machines, the following points stand out with clearness: --

1. That the lifting power of a large machine, held stationary in a
wind at a small distance from the earth, is much less than the Lilienthal
table and our own laboratory experiments would lead us to expect.

2. That the ratio of drift to lift in well shaped surfaces is less

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at angles of incidence of 5 degrees to 12 degrees than at an angle of 3 degrees.

3. That in arched surfaces the center of pressure at 90 degrees is near the center of the surface, but moves slowly forward as the angle becomes less, till a critical angle varying with the shape and depth of the curve is reached, after which it moves rapidly toward the rear till the angle of no lift is found.

4. That with similar conditions, large surfaces may be controlled with not much greater difficulty than small ones, if the control is effected by manipulation of the surfaces themselves, rather than by a movement of the body of the operator.

5. That the head resistances of the framing can be brought to a point much below that usually estimated as necessary.

6. That tails, both vertical and horizontal, may with safety be eliminated in gliding and other flying experiments.

7. That a horizontal position of the operator's body may be assumed without excessive danger, and thus the head resistance reduced to about one-fifth that of the upright position.

8. That a pair of superposed, or tandem surfaces, has less lift in proportion to drift than either surface separately, even after making allowance for weight and head resistance of the connections.

SECTION VI

The Engineer's Bookshelf

THE ENGINEER'S BOOKSHELF

James M. Kempf*

Editor's Note

This essay-review column is intended by the editors to be a recurring feature of the Aeronautics Digest to encourage readers to expand their familiarity with works that are well written and which, at the same time, relate technical subjects to their larger context, such as defense policy and even social philosophy and history.

One day during the summer of 1981, Mike Higgins, Eric Jumper and I were sitting around a desk in the Aeronautics Department at the United States Air Force Academy reflecting, with great relief, on our past year's accomplishments in putting together several issues of the Academy's Aeronautics Digest. Since I had been involved with the Digest for only one year, while Eric and Mike had been "seasoned" by their work for almost two years (Eric since the inception of the journal), our conversation inevitably turned to a discussion of why it was so time consuming and often downright frustrating to deal with technical essays submitted by engineers.

While listening to Eric and Mike describe their many hours spent cajoling other engineers to rewrite essays so as to make them intelligible to the wider audience of the Digest, I thought I detected a few traces of resignation amidst their general frustration. The cause of that resignation, I sensed, was their belief that there was no way to make the job of editing a technical journal easier, given the fact that most engineers and scientists who are forced to sit down and describe their technical research find the task about as enjoyable as being forced to do a mating dance with an angry rattlesnake. Mike and Eric had concluded that the only way to make many of the articles submitted to their journal publishable was to roll up their sleeves, hitch their belts tighter, and do a whole lot

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of collaborative revising, redesigning, and editing, both with the
original writers and with other editors. They often ended by "ghost
writing" a major part of tho essays. Welcome to the world of editing,
I remarked. Little credit, lots of work.

Thus, they turned their weary gazes to me and asked if I had any
advice. Not being hesitant to offer opinions, I answered that of
course I did. My more pungent advice will have to be ascertained by
talking to them personally, but as a result of our conversation I gave
them an essay describing my experiences in private industry as a
technical editor, which they later requested for publication in the
Digest. My consent being duly profferred, they duly published that
essay in the 1981 Spring/Summer issue of the Digest. Whereupon Eric
left the Academy and Mike began looking for people to replace him. So
much for advice for technical editors offered by English professors.

But my main advice to Eric and Mike led to the essay you are now
reading. My own experiences with engineering writing confirmed to me
that most engineers trained in America (and elsewhere) today are
wholly unprepared for, and even unaware of, the important role that
technical writing will play in their engineering careers. Indeed, most
engineers receive little formal training in writing due to the
extraordinarily rigorous demands made on students by contemporary
engineering curriculums. Furthermore, most engineers are totally
oblivious to the fact that in the real world of practical engineering,
research and design projects, solicitations of contracts, and grant
applications require written reports to allow second parties to
evaluate, buy, or learn about engineering work. Having spent years
acquiring the specialized knowledge of an engineering profession,
student engineers are often abruptly thrown into a situation where
their work will be judged not only by the successful working of

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machinery, hardware, or software programs they have developed, but also by a written report which is evaluated by numbskull bureaucrats who are irritated by such seemingly superfluous matters as spelling and punctuation. To all these engineers, a teacher can only say, welcome to the real world of engineering.

What, then, do I advise that engineers do to make the unpleasant task of technical writing easier? First, the bad news. The most important attitude one should bring to the task of writing a technical essay is an expectation that the job will not be easy. Indeed, it should be viewed as an extremely important act of communication, and therefore worthy of hard work, a significant expenditure of time, and a serious passion to explain technical concepts, issues, and thought processes with great clarity. The "difficulty" of this writing job should not surprise or irritate engineers. For, in general, engineers of all kinds are known to be fastidious creatures, perfectionists who, like absent-minded professors, will lose themselves in painstaking efforts to design, redesign, test, and retest a given experiment or engineering project. Given this personality trait which most engineers possess -- a willingness to expend as much time as necessary to insure that a project is done with maximum efficiency, elegance, and durability -- it is curious that engineers are often cavalier about taking the same care to write about their work. Indeed, they often scribble off some pages and then complain that no one understands their efforts and that this misunderstanding is largely due to the "ignorance" of the uneducated, unwashed, general, non-technical public. My answer to such an attitude is that if engineers built bridges or airplanes with such lack of concern for detail they would lead us all into Hades.

Yet I know from my own experiences as a technical editor that the defensiveness of most engineers about their writing results from a belief that criticism of their verbal skills implies criticism of either their intelligence or their education. Thus, their initial response to a suggestion that a technical essay needs rewriting is one of wounded pride, and they lash out at the perceived foe, editors. This response, like that of a wounded lion, is more instinctive than rational and takes the form of a standard riposte: "English majors (presumably most editors are creatures of this species--though in fact this is not the case) and Humanities students do not have the technical background that engineers do, so why should we be expected to be perfect grammarians or prose writers? In fact, Humanities students can't even understand most of our disciplines, so how can we expect them to understand our writing?" What most engineers don't realize when they make comments like the one above is that, far from being original, they are merely repeating an argument that has been made for decades.

For the simple truth is that editors (Humanities students?) who are justifiably frustrated by the technical jargon and incoherence of much technical writing, and engineers or scientists who are baffled by the complex technical rules of language are both suffering from a failure of modern civilization and modern education: we no longer even try to approach our professional areas of knowledge as if knowledge should benefit and be available to all mankind.

The only way to overcome this division of knowledge (other than by a wholesale restructuring of the political and economic rationale of "professions") is to attempt to find and use a common language which permits communication across disciplines of learning. For engineers and Humanities scholars in America, whether they like it or

<u>not</u>, that language must be English. The implication of this bald truth is that engineers cannot avoid the "laws" of the English language any more than they can avoid the laws of Newtonian mechanics. To do so is to create chaos and incoherence.

Thus, along with developing an attitude that one must expect to work hard on writing, engineers must accept the premise that in order to communicate clearly the fruits of their complex, specialized research, they must approach their writing task with a belief that the written description of engineering research is as important as, or even more important than, the research itself. In fact, without the act of communication to a wider audience, the research would have no value or utility.

If a positive, enthusiastic attitude about the importance of technical writing is accompanied by a willingness to work hard to communicate to a non-specialized audience, 95 percent of the "problems" of technical writing will be overcome. However, no one would argue that the average technical person will, if motivated by these attitudes, instantly become a successful writer and correct the common faults of technical writing. Like any discipline, writing takes much train...g to master. But the typical faults of most technical writers, such as unstructured thought, sloppy prose, lack of an outline or organization of information, and failure to remember that the audience of technical writing is not as steeped in the research as the writer, are serious and persistent. They exist because technical writers today may spend two years developing a project but only twenty minutes writing about it, with the expectation that they will be universally understood. The faults also reoccur because engineering and most scientific education today is badly deficient in the practice of the "liberal arts" skills by which educated persons historically

were distinguished. And this is not the fault of engineering students alone. It is a failure of their educational system, whereby their teachers are often worse writers than their students and therefore hardly capable of improving student communication skills.

If rhetoric, the study of communication, is an art rather than a science, it is nevertheless a demanding mental discipline which was seen by the ancient Greeks as a central characteristic of an educated citizenry. That engineering curriculums today neglect the study of rhetoric speaks less about the historical changes of modern technical education and culture than it does about our failure to remember the profound wisdom of the ancients.

Yet with effort, any engineer and all engineers can significantly improve their technical writing, which is, in fact, only writing about technical subjects and thus no different from writing about any other subject.

What can be done to achieve such improvement? First, engineers who are about to embark on an essay or report about a technical subject should expect to spend considerable time in preparing, writing, and revising the essay. They should expect to collaborate with the editors who will often require them to rewrite, reorganize, expand, and clarify issues in the essay. The editors, after all, receive feedback from their audience, and it is they who are held responsible by that audience to insure that the journal is readable and intelligible.

Second, engineers who intend to write about technical subjects should do all they can to master the "laws of the English language," which can be regarded as a "code" which governs the interpretation, the "decoding" of a technical essay by a reader, just as it does the interpretation of an essay on any subject. Assuming that most

engineers won't be masters of the English language, they can nonetheless do their best and willingly collaborate with editors, who are supposed to be experts in precisely that language "code."

And finally, there is one other technique that should significantly improve one's ability to write clearly about technical subjects. That technique is to study models of good technical writing. This idea too is a precept of the ancient Greeks and Romans. Like Aristotle and Demosthenes, Vergil and Cicero, good communicators have always been good readers and constantly studied the best models of writing in order to develop their own oratorical and rhetorical skills.

Whence we come to the purpose of the "Engineer's Bookshelf" in this journal. In the next few issues of the journal I shall be recommending technical articles, essays, and books that are extremely well written in the hope that engineers will begin to recognize excellent writing and to demand the same high standards of themselves and their colleagues. The works I will recommend are, of course, technical in nature (since most engineers are particularly interested in technical subjects), but they are not limited to specialized or narrow technical issues. For technology today is hardly neutral or uninvolved in wider social implications. Indeed, any practicing engineer knows that design decisions are often constrained as much by economic, environmental or political issues as by technical limitations. That is why I believe that the best written works on technical subjects today also deal with those subjects in terms of public policy, history, or social philosophy. They must, since the interaction between technology and policy occurs at the point where the general public is affected, and it is that audience that requires and deserves technical writing that is accessible to all. If we read

works targeted for the general public, then an appreciation for good writing will be easy to develop.

We are fortunate also that in contemporary America there is a flourishing interest in scientific and technical writing on subjects that affect almost everyone. New scientific journals are being launched almost every few months, and some with astonishing success, including adaptation by publishers in Japan and Europe. And technology, which affects public life in every sphere, from computer automation to nuclear weapons, from electric power generation to business productivity, has created a flourishing interest among the contemporary reading public in all kinds of technical issues.

Where to begin. First, I recommend that an engineer who wishes to improve his technical writing (and his breadth of knowledge) subscribe to, and carefully read on a regular basis, one or all of several eminent American technical publications. The foremost, of course, is Scientific American. Its chief virtue remains its rigorous editorial standards. The editors publish only clearly written articles permitting readers of all backgrounds to be enlightened on subjects as diverse as particle physics and the sex life of dung beetles. The magazine's chief weakness is that specialists sometimes find the smorgasbord of essays too bland for their taste. But at least one article of broad public policy interest discussed from a technical perspective is contained in almost every issue. In the last two years, for example, military weapons technology and technical developments affecting military strategy and tactics have been the subject of several lead essays in Scientific American. I call your attention especially to the following: "Precision-Guided Weapons" by Paul F. Walker (August 1981). This article, recently cited by the New York Times columnist Tom Wicker in regard to the Falkland Islands

battles, predicted that the cost-effective yet extremely destructive power of guided-missile technology will (or should) change an entire generation's thinking about the strategy of naval and air warfare.

An equally influential article was published in the November 1979 issue of Scientific American by MIT physicists Bernard T. Feld and Kosta Tsipis. Titled "Land-Based Intercontinental Ballistic Missiles," the article analyzed the technical factors that, according to the authors, made the MX missile, indeed all land-based missiles, a less effective strategic force than its proponents claimed. The article also argued that the threat to such missiles from first strike launches was less probable and effective than a number of defense proponents claimed. In recent months, during the continuing debates over strategic missile technology and strategy, the arguments of Feld and Tsipis have been rehashed almost constantly.

Tsipis also analyzed the physical limitations of laser weapon technology in an article, "Laser Weapons," in the December 1981 issue of Scientific American. Three other recent Scientific American articles of special note to defense engineers include: "Intermediate-Range Nuclear Weapons" by Kevin N. Lewis (December 1980); "Advances in Antisubmarine Warfare" by Joel S. Wit (February 1981); and "A Ban on the Production of Fissionable Material for Weapons" by William Epstein (July 1980).

Another journal that publishes articles about technology and public policy is Technology Review. The writing in this journal, edited at MIT, is characterized by intelligence, a broad perspective, and rigorous editorial standards of clarity. Technology Review is expensive but valuable, and it too periodically prints essays by many writers that deal with a single issue, including defense technology. Of particular interest in recent months have been the following

essays: "Living with Technology: Trade-Offs in Paradise" by Samuel L.
Florman (August-September 1981); "The Ultimate Battleground: Weapons
in Space" by Gerald Steinberg (October 1981); "Debunking the Window of
Vulnerability: A Comparison of Soviet and American Military Forces" by
Michael W. Johnson, along with "Yesterday, Today, and Tomorrow in
Command, Control, and Communications" by Robert R. Everett (January
1982); and "The Threat of Biological Weapons" by Jonathan King
(May-June 1982).

Technology Review proves that serious and complicated
technological subjects can e written about with such clarity that any
intelligent reader can follow the discussion, and without simplifying
the technical analysis too much for a non-technical audience.

Other valuable, well written scientific journals include a
little-known weekly magazine called Science News, the venerable
journal of the Society of Sigma-Psi, The American Scientist, and the
weekly British journal Science.

Several general interest magazines of eminent American
intellectual standing are also valuable reading, especially for their
essays which periodically discuss issues of defense policy and
technology. The monthly journals The Atlantic and Harper's
continually publish articles on national defense issues. For example,
in recent months The Atlantic serialized chapters of National
Defense, a widely discussed book written by one of its editors. James
Fallows' study particularly dealt with the relationship between the
defense department bureaucracy, the exotic engineering of high
technology weapons systems, and economic and political factors that
influence military engineering projects and decision-making. (Cf.
"America's High-Tech Weaponry" by James Fallows, The Atlantic, May
1981 and "M-16: A Bureaucratic Horror Story," June 1981).

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Harper's magazine too, constantly deals with defense issues and technology as it affects public policy, from solar energy to military budgets. I recommend two articles of special merit in particular: John Keegan, "Soviet Blitzkrieg: Who Wins?" (Harper's, May 1982) and "Shreds of Evidence: Science Confronts the Miraculous -- The Shroud of Turin," by Cullen Murphy (Harper's, November 1981). The latter is an article of particular interest to engineers at the Air Force Academy since it discusses both the Academy and the wide-ranging, sometimes bizarre, issues that defense department engineers can get involved with. In particular, this essay discusses a former member of the Academy's Aeronautics Department, who was a founding editor of this journal.

Finally, I recommend two books of wide and longstanding influence that might be useful in introducing engineers to the issue of the conflict between technology and modern civilization which has dominated discussions of cultural critics for decades. First, the late C.P. Snow's The Two Cultures and A Second Look, Cambridge University Press, 1959 (reprinted 1980), and second, J. Bronowski's Science and Human Values, Harper and Row, 1965. Both of these books describe the issues that have placed science and technology at the forefront of debate about the nature and historical character of modern civilization during the past four hundred years. With grace, lucidity, and expansive learning, both men cut across the barriers of the scientific and literary cultures to define what they believe is common to both "cultures" and what the two intellectual communities, the technical and the humanistic, misperceive about each other. Although brief, these books are seminal introductions to issues which every engineer would do well to be acquainted with. They are also books which should drive one to further reading.