A MATHEMATICAL MODEL FOR THE STARTING PROCESS
OF A TRANSONIC LUDWIG TUBE WIND TUNNEL

VON KÁRMAŃ GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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DIRECTORATE OF TECHNOLOGY (DY)
ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE 37389
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A simplified mathematical model is presented for the unsteady flow process of starting a transonic Ludwieg tube wind tunnel. The hardware modeled consists of a porous-walled test section surrounded by a plenum chamber with an exhaust system independent of the tunnel's main starting valves, which are located downstream of the diffuser-test section. In the present method, the hardware is modeled as three control volumes: the plenum, the test section,
and the diffuser. The plenum is treated with the unsteady integral continuity equation with one-dimensional influx or outflux through the porous wall, through the plenum exhaust system, and through the flaps, which exhaust into the diffuser. The other two control volumes are treated with the steady integral continuity equation and a steady, adiabatic, one-dimensional energy equation whose stagnation conditions vary in time according to the classical solution for an unsteady expansion wave. Numerical solutions are compared with experimental pressure-time histories of a small, transonic, high Reynolds number tunnel referred to as HIRT. Agreement between the model and experiment is good.
PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The research was done under ARO Project No. V37A-32A in support of the High Reynolds Number Wind Tunnel (HIRT) project. The author of this report was Frederick L. Shope, ARO, Inc. The manuscript (ARO Control No. ARO-VKF-TR-75-147) was submitted for publication on September 26, 1975.

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1.0 INTRODUCTION

This report documents an effort to mathematically model the aerodynamics involved in the unsteady process of starting a Ludwieg Tube wind tunnel. In essence, the model represents the end product of many people assimilating a large amount of experimental data obtained from a transonic Ludwieg tube facility and, thus, depends on several experimentally derived parameters and assumptions. The wind tunnel configuration studied here consists of a very long, circular supply tube which contracts to a rectangular, porous-walled test section. The test section expands through a diffuser into a valve manifold. Surrounding the test section is a plenum chamber with exhaust valves which can be controlled independently of the main valves. In addition, the plenum contains a set of ejector flaps which allow the plenum to exhaust itself into the diffuser.

When one considers that larger scale transonic Ludwieg tube facilities would have a price of order $10,000,000 and would produce a usable run time of only a few seconds per run, it is clear that considerable effort must be concentrated to ensure that the tunnel can be started rapidly under a wide range of operating conditions. A laboratory scale pilot facility (Ref. 1) (known as "Pilot HIRT") at Arnold Engineering Development Center provides an experimental vehicle to measure the effects of many of the important parameters in the tunnel starting process and to provide basic experimental data for verification of math models.

To clarify the need for a mathematical model of starting such a device, a brief explanation of the tunnel operation is required. Prior to a run, the tunnel is pumped to the desired charge pressure and temperature. A tunnel run is initiated by first opening the main valves downstream of the diffuser. This opening process sends unsteady expansion waves up the tunnel to the supply tube. Were it not for the plenum, the flow in the test section would become steady soon after the trailing edge of the unsteady wave from the valve, initiated by the valve area becoming steady, passed the test section into the supply tube. The test section flow cannot become steady until the plenum volume has been exhausted to the point where the summation of mass flow across the porous wall, through the flaps, and out the plenum exhaust (dumped to atmosphere) becomes zero and allows the plenum pressure to become steady. Since current state-of-the-art, fast-opening valves easily reach the required flow area in advance of the plenum becoming steady, the plenum is the primary limitation upon how quickly the tunnel can be started and steady flow established in the test section.

The present model assumes that the unsteady expansion wave emanating from the main valves propagates instantaneously to all parts of the wind tunnel and that property variation within the wave at any location in the diffuser, test section, nozzle, or supply tube is totally controlled by the area-time curve of the main valve. While partially retaining
the effect of the unsteady wave, this assumption allows use of the steady continuity equation in the test section coupled with the well-known exact solution for one-dimensional, variable area, isentropic flow (Ref. 2). Use of these equations at any instant requires a knowledge of stagnation conditions driving the flow, which vary through the nonisentropic expansion wave. Variation of the stagnation properties is computed via the exact solution for a one-dimensional unsteady wave in a variable area duct (Ref. 3). The unsteadiness of the plenum is handled via the unsteady continuity equation by equating the rate of mass accumulation in the plenum to the summation of all the flow rates entering and leaving the plenum. The air in the plenum is assumed to be a calorically perfect gas and its temperature is assumed either isentropic or equal to the stagnation temperature of the flow in the test section (whichever is greater), an experimentally based assumption. The main valves are treated as one-dimensional sonic orifices driven by the stagnation pressure and temperature of the unsteady wave. The plenum exhaust valves are handled similarly by assuming that the flow in the plenum is stagnant. Flow through the ejector flaps and across the porous wall is computed via an adaptation of the work of Ref. 4, which empirically corrected the flow rates with the pressure drops across these devices.

In the discussion which follows, the mathematical model will first be presented, including a more detailed description of the physical situation, the assumptions underlying the model, the mathematical formulation, and the solution procedure. Next, the model will be compared with a sample of experimental data from the Pilot HIRT facility. The appendixes contain some of the mathematical details and a brief user's manual for the computer program.

2.0 THE MATHEMATICAL MODEL

2.1 DESCRIPTION OF THE PHYSICAL SITUATION TO BE MODELED

All of the essential features of the proposed HIRT facility which are to be modeled are given in Fig. 1. The overall length of the facility is 1,880 ft, and the supply tube has an inside diameter of 15 ft. The main valve system consists of a number of fast-acting valves, and the plenum exhaust also requires a multiple valve system. The pilot facility provides a precisely scaled (1/13) flow envelope but has a single sliding sleeve valve in place of the valve manifold of the full-scale tunnel and a single plenum exhaust valve fed by multiple tubes from the plenum.

A tunnel run is initiated by opening the main valves and possibly the plenum valves, not necessarily together or in the same length of time. Both sets of valves send nonisentropic expansion waves throughout the tunnel and primarily up the charge tube. The main valve system produces the steepest (or strongest) wave because it handles a much greater portion
of the flow rate than the plenum exhaust. At any point in the supply tube, the gas remains totally stagnant until the first expansion wave reaches that point; and the flow at that point does not become steady until the last expansion wave passes the point. The main valve system sends out its last expansion wave when the flow area becomes constant. The plenum also continues to send out expansion (and sometimes compression) waves until the plenum pressure becomes steady. But the plenum does not become steady until the sum of all the flows into and out of it are zero (Fig. 2), and it invariably controls the start time of the tunnel. Since the main valves are much faster than the plenum response, the pressure in the test section drops rapidly below the plenum pressure, causing mass flow to enter the test section from the plenum. As the plenum gradually catches up to the test section, the wall crossflow (across the porous test section wall) gradually decreases and, in some cases, reverses. This process, coupled with the increasing main valve area, gradually increases the flow rate drawn from the supply tube. However, the flow rate from the tube may continue to increase only until the nozzle exit becomes choked, after which the supply tube flow becomes steady since the choke point will no longer pass additional expansion or compression waves (unless the compression wave is strong enough to unchoke the nozzle). Whether the nozzle eventually chokes and whether the test section eventually steadies out to supersonic or subsonic flow depends on the relative flow areas of the main valves, the plenum exhaust valves, and the test section, the direction of the flap and wall crossflows, and how the various steady conditions are approached in time relative to each other. Subsonic and very slightly supersonic test section Mach numbers can be obtained without steady-state plenum exhaust, though the plenum exhaust may be opened temporarily and then closed in order to reduce the starting time. For subsonic flows, the steady main valve area - in terms of the ideal, one-dimensional area
at the choke point - must be as much less than the nozzle area (where the nozzle meets the entrance to the test section) as is dictated by the steady test section Mach number to be attained (neglecting diffuser losses). A slightly supersonic test section can be obtained with a steady main valve area greater than or equal to the nozzle area if the flaps and porosity are set properly, giving a flow situation as follows: with the nozzle choked and the plenum steadied at a pressure very near the static test section pressure such that the static pressure and dynamic heads of the main flow force a small crossflow into the plenum, the net test section flow decreases from the choked flow rate at the nozzle. The slightly subcritical flow rate leaving the test section thus produces a slightly supersonic condition, resulting in a favorable pressure gradient for the plenum to exhaust its incoming crossflow out the flaps and hence become steady. Normally, however, supersonic conditions (up to Mach 1.3 in the pilot) are obtained by having the plenum exhaust area become steady at a flow area sufficient to pass all of the mass flow rate entering the plenum via wall crossflow and sometimes via reverse flap flow.

Figure 2. Schematic illustration of the flow process during start.

To understand the flow in terms of the mathematical model, the various flow configurations might be best thought of in terms of the steady energy equation relating the local pressure to the mass flux (Fig. 3). Subsonic flows fall on the branch to the
right of the choke point, supersonic flows to the left. In general, all points in the tunnel are initially at point A, which corresponds to no flow. Higher flow rates with correspondingly lower static pressures are illustrated by movement from point A to B on the energy equation. Flows which become subsonically steady would halt to the right of C; while for supersonic flows, some portions of the tunnel would proceed beyond C to D. If the energy dome is then plotted versus axial position in the test section as shown in Figs. 4, 5, and 6, the importance of the wall crossflow and the relative timewise approach of various components to their steady conditions may be made clearer. For a normal subsonic run, Fig. 4 shows the energy dome at the entrance and exit of the test section. The constant time contours are shown as straight lines for purposes of illustration, though in reality they would have to be nonlinear to some degree in order for all points on the contour to fall on the surface of the dome cylinder and because the wall crossflow does not necessarily vary linearly along the test section. As the flow begins, the constant time contours do not remain parallel because the flow rate leaving the test section will not balance that at the entrance, the difference being the wall crossflow. For the most probable case of the plenum lagging the test section pressure, the crossflow will be into the test section, giving a greater flow rate at the exit than at the entrance. As time proceeds, however, the plenum pressure eventually catches up to the test section so that the contours do become nearly straight and parallel as the crossflow becomes insignificant. This process assumes that the plenum exhaust, if opened, is eventually closed.

Figure 3. Qualitative plot of the energy equation.
Figure 4. Energy dome versus position in test section for normal subsonic flow.

Figure 5. Energy dome versus position in test section for normal supersonic flow.
If the plenum exhaust is not closed and the steady main valve area is sufficiently large, the supersonic case of Fig. 5 may result. The initial constant time contours are similar to the subsonic case. However, the origins of the contours at the entrance eventually stop at the peak of the dome while at the exit they proceed over the choke point downward on the supersonic branch as the crossflow reverses from entering to leaving the test section. The contours, however well approximated by straight lines in the subsonic case, become significantly nonlinear for the higher supersonic Mach numbers, as illustrated by the dotted "real nonlinear steady contour" in Fig. 5. This results from a combination of the nonlinear variation of the wall crossflow and boundary layer growth. These nonlinear effects, though certainly present in the subsonic case, are more pronounced in the supersonic case because the pressure at the nozzle must remain unchanged at the choke value while the pressure at the exit varies significantly with the exit Mach number.

![Figure 6. Energy dome versus position in test section for subsonic flow with choked nozzle.](image)

The slopes of the constant time contours in Figs. 4 and 5 depend on the magnitude of the wall crossflow, which in turn depends partially on the pressure difference between the plenum and the test section. Since the timewise variation of the plenum pressure can be controlled by controlling the flow area-time curve of the plenum exhaust valves,
it appears that the shortest starting time for the tunnel would be obtained by controlling
the plenum pressure to precisely follow the test section pressure so that the plenum would
reach its steady conditions simultaneously with the main valve system. This would result
in the constant time contours remaining parallel right up to their final position, or up
to the choke point for a supersonic run. In Fig. 6, the plenum is exhausted fast enough
so that the wall crossflow is always out of the test section, resulting in less flow rate
leaving the exit of the test section than entering. Thus, the constant time contour at
the entrance dome reaches its peak while the point on the exit dome is forced by the
plenum exhaust to become steady before reaching the peak though the desired steady
condition lies on the other side of the dome and cannot be reached. Hence, it appears
that the manner in which the various portions of the tunnel approach their steady
conditions in time relative to each other can affect the final outcome of a run.

The foregoing discussion of the test section flow in terms of the energy domes serves
as an introduction to one of the key elements of the mathematical model, namely, the
steady energy equation in an unsteady environment. The domes also provide graphic
visualization for the flow process.

2.2 GOAL OF THE MODELING

The purpose of this mathematical model is to study the starting process, controlled
by the plenum, in order to size the plenum exhaust system; determine the effect upon
start time of the interaction of the area-time curves of the main valves, flaps, and plenum
exhaust; and, in general, to provide the essential information necessary for trading off
facility cost and start time. To provide this information, the model must accept the
following input data. The gross level mass flow rate depends upon the cross-sectional
area of the supply tube and nozzle exit. The geometric factor, on which the wall crossflow
primarily depends, is the porosity, the fraction of the total surface area of the test section
walls drilled out to allow flow between the test section and plenum. Thus, the dimensions
of the test sections and porosity must be provided along with the experimentally derived
coefficients for the flow model. A key design parameter having first-order impact on the
start time is the plenum volume ratioed to the test section volume. The area-time curves
of the main valves, plenum exhaust valves, and the flaps are required along with the
experimental coefficients for the flap flow model. Finally, the characteristics of the gas
must be provided in terms of the ideal gas constant and the specific heat ratio.

This input to the model is then used to compute the following data concerning the
flow. As functions of time the static and stagnation properties - pressure, density, and
temperature - along with mass flow rate and Mach number are computed for three stations
along the tunnel circuit: the supply tube at the nozzle entrance, the test section entrance,
and the test section exit. The plenum properties along with the mass flux through the porous wall, flaps, plenum exhaust, and main valves are computed as functions of time.

There are many other considerations, neglected herein, which might be of interest for other applications. One of the most important is the boundary layer, whose growth on the walls of the supply tube and test section varies with time. This unsteadiness occurs because at any given station along the tunnel, the particles of air passing that station at succeeding times into the run have travelled over successively longer lengths of tube from their starting points. If the effect of the boundary-layer growth on the local mass flow rate is thought of in terms changing the effective flow area, one might suspect that the test section would never become steady. In reality, however, the boundary-layer growth, sufficiently late in the starting process, varies with approximately the same proportion in the nozzle and test section so that, though the effective flow areas may be varying, the area ratios (A/A*) are not. As experimentally documented in Refs. 1 and 5, this results in essentially constant Mach number once the plenum has become steady, thus justifying the neglect of the boundary layer herein.

Neglect of the boundary layer means that no prediction is made of property variation over the cross section of the flow area. Similarly, detailed variation of properties along the length of the test section is not predicted. Such information would be useful for studying wall loading or flow uniformity but is of secondary importance for present purposes. Very severe nonuniformity occurs in the diffuser section (connecting the test section and main valve manifold), which has been subjected to a detailed experimental study in Ref. 4. The complexity of the diffuser flow results from a combination of effects: shock waves, flow separation, flap exhaust, and the presence of the model or probe support sector. The performance of the diffuser is important because of its effect on the noise environment in subsonic flow in the test section and because its stagnation losses significantly impact the sizing of the real flow area of the main valve system. However, for purposes of the starting model, diffuser losses may be neglected if the main valve area is assumed to be the ideal, one-dimensional flow area needed to pass a given mass flow rate for a given set of driving stagnation conditions as determined from wave mechanics.

Three additional effects neglected herein deserve mention. First, wave spreading is neglected. This phenomenon is due to the difference in propagation speed between the leading and trailing edges of the unsteady wave. Since the wave propagation speed (equal to the local speed of sound minus the local velocity) is less for the trailing edge than the leading edge, the time delay between a change in main valve area and the sensing of this change in the supply tube is greater for the last area change than the first. In fact, this delay is different for each position along the tunnel. However, over the greatest
distance of importance in the pilot facility, this difference in delay is less than 0.5 msec and is neglected in the model. Besides wave spreading, the model also neglects the finite time required for a disturbance to travel from one point to another. Such a consideration is important for determining the relative times for first motion of main valves and plenum exhaust valves; but for purposes of the starting model, the tunnel components determining start time - plenum, test section, and supply tube exit - are sufficiently close together that the propagation times (on the order of one millisecond in the pilot) are small compared with the starting time under study. However, neglect of the propagation time and wave spreading should not be construed to mean that the finite wave width is neglected. This width, or time difference between passage of a given point of the leading and trailing edges of the wave, depends primarily on the opening time of the valve but is also increased by the nonideal flow processes in the diffuser. Such effects are accounted for herein by correction of the area-time curve of the main valve. A final additional effect, accounted for empirically but not modeled in detail, is the nonisentropicity of the thermodynamics of the plenum. It has been experimentally observed that the temperature in the plenum approximates an isentropic process only during the initial portion of the starting process, but over the entire start time for the tunnel, the asymptotic plenum temperature is much closer to the stagnation temperature in the test section than that for a completely isentropic expansion. A good model of this process would have to include the mixing of the virgin plenum air with that entering from the test section as well as account for the heat transfer from the walls of the plenum. This possible refinement to the present model is not yet included.

2.3 FORMAL ASSUMPTIONS

Before proceeding to the equations comprising the mathematical model, the following list of assumptions should be reviewed:

a. Flow across all control volume surfaces is one dimensional.

b. The fluid is assumed to be a calorically perfect gas (constant specific heats).

c. Flow within the envelope comprised of the supply tube, test section, and main valves is inviscid, adiabatic, and irrotational except as accounted for by the unsteady wave equations.

d. Within this envelope and at a constant time, property variation from point to point is isentropic. Entropy variation with time is governed by the wave equations. Thus, at any given instant, the one-dimensional, variable area, isentropic equations of gas dynamics (Ref. 2) are applicable.
2.4 MATHEMATICAL FORMULATION

The set of equations comprising the model naturally divides into two groups, one for subsonic flow and one for supersonic flow. Since the set of equations for supersonic flow is nearly an exact subset of the subsonic case, the latter will be presented first, followed by a discussion of the changes needed for supersonic flow. The subsonic model is in the form of 19 algebraic equations, not necessarily linear, involving 19 unknowns. This system of equations must be solved numerically at successive points in time until all properties have approached their asymptotic values. The solution at any time \( t \) depends entirely on the property values obtained for the solution at \( t - \Delta t \), a short time earlier, as well as the given valve area-time curves, which may be thought of as forcing functions. Quantities which vary between \( t - \Delta t \) and \( t \) are usually evaluated at an intermediate time \( t^* \) such that \( (t - \Delta t) < t^* < t \). The time \( t^* \) is usually taken as the midpoint of the time interval.

The model is based on mass conservation for three control volumes as illustrated in Fig. 2. Conservation of mass for the plenum is derived from the unsteady integral continuity equation for a control volume to give

\[
\rho_p(t) = \rho_p(t - \Delta t) + \left[ \dot{m}_{pt}(t^*) + \dot{m}_{pe}(t^*) + \dot{m}_f(t^*) \right] \frac{\Delta t}{V_p}
\]  

(1)

Here \( \rho_p \) is the mass density in the plenum, assumed uniform throughout, and \( V_p \) is the volume of the plenum. The quantities \( \dot{m}_{pt}(t^*) \), \( \dot{m}_{pe}(t^*) \), and \( \dot{m}_f(t^*) \) represent, respectively, the mass flow rates between the plenum and test section (pt), out the plenum exhaust (pe), and through the flaps (f). The formal continuity equation can not be precisely integrated because the dependence of the mass flow rates on \( t \) or \( \rho_p \) can not be written in simple closed form. However, the law of the mean provides that \( \rho_p(t) \) may still be precisely computed if the flow rates are treated as constant but evaluated at a suitable intermediate point \( t^* \). If \( \Delta t \) is now chosen sufficiently small so that the flow rates may be suitably approximated by linear functions of time, \( t^* \) can obviously be chosen as \( t - 1/2\Delta t \), the midpoint. For the other two control volumes in Fig. 2, the steady continuity equation is used, having been justified by assumption (e) of the last section. By noting that Eq. (1) assumes the flap and wall crossflows are positive when flow is into the plenum, continuity for the test section becomes

\[
\dot{m}_{ct}(t^*) = \dot{m}_{pt}(t^*) + \dot{m}_d(t^*)
\]  

(2)
and for the diffuser-valve manifold control volume

\[ \dot{m}_d(t^*) = \dot{m}_e(t^*) + \dot{m}_f(t^*) \]  

(3)

The three new mass flow rates introduced here are, in terms of the subscripts, that leaving the supply tube (ct, for charge tube, as it is often called), the primary tunnel exit (e) provided by the main valves, and the diffuser-end (d) of the test section. It should be noted from Fig. 2 that \( \dot{m}_d \) corresponds to a point upstream of where the flap flow enters the main stream.

Proceeding next to model each of these six mass flow rates, consider first the flow through the plenum exhaust and the main valves, which are both treated as single one-dimensional sonic orifices driven by the stagnation conditions.

\[ \dot{m}_e(t^*) = a \frac{P_{eo}(t^*) A_e(t^*)}{\sqrt{T_{eo}(t^*)}} \]  

(4)

\[ \dot{m}_{pe}(t^*) = a \frac{P_{p}(t^*) A_{pe}(t^*)}{\sqrt{T_{p}(t^*)}} \]  

(5)

In Eq. (4), \( P_{eo} \) and \( T_{eo} \) are the stagnation pressure and temperature in the valve manifold; and in Eq. (5), \( P_{p} \) and \( T_{p} \) are the pressure and temperature in the plenum, approximated as stagnant. The quantities \( A_e \) and \( A_{pe} \) are the total flow areas of the main valves and plenum exhaust valves. These areas are assumed to be the ideal, one-dimensional flow areas of a sonic orifice. If the real valve areas are used, discharge coefficients must be included in Eqs. (4) and (5). The constant \( a \) is given by

\[ a = \left( \frac{\gamma+1}{\gamma} \right)^{\frac{\gamma-1}{\gamma+1}} \frac{\gamma}{\sqrt{R}} \]  

(6)

where \( R \) is the ideal gas constant and \( \gamma \) is the ratio of the specific heats.

Consider next the flap and wall crossflows, which have been neatly modeled by Varner (Ref. 2) as simply proportional to the pressure drop across the devices. With a second order adaptation added here, Varner's model takes the following form

\[ \dot{m}_{pt}(t^*) = - \frac{A_w}{k_w} \left[ P_{p}(t^*) - A_{15} P_{t}(t^*) \right] \]  

(7)

\[ \dot{m}_{f}(t^*) = - \frac{A_{f}(t^*)}{k_f} \left[ P_{p}(t^*) - A_{16} P_{d}(t^*) \right] \]  

(8)
Here $A_w$ and $A_f$ are the effective flow areas through the porous wall and through the flaps. While $A_f$ is the actual geometric area, $A_w$ depends on the total surface area of the test section walls ($A_{ts}$), the porosity ($\tau$), and a flow coefficient. Varner gives this relationship as

$$A_w = 0.17 \tau A_{ts}$$  \hspace{1cm} (9)$$

The flow coefficients $k_w$ and $k_f$ were determined by Varner from experimental data from Pilot HIRT and are given in Fig. 7. The values of $k_w$ in Fig. 7 are for the porosity shown in Fig. 8. The coefficients\(^1\) $A_{15}$ and $A_{16}$ multiplying, respectively, the mean test section pressure $P_t$ and the diffuser end test section pressure $P_d$ were added in an effort to improve the accuracy of the asymptotic values of the numerical solution. The rationale for each of these constants is different. Rigorous modeling of the crossflow must include not only the effect of pressure forces but also the momentum of the fluid as it moves along the test section wall. The coefficient $A_{15}$ thus represents an attempt to include momentum effects as a small correction to the existing crossflow model. Experimental evidence from the pilot facility indicates that this small momentum effect can make the difference between choking and not choking when the desired steady conditions are very near sonic flow. In particular, it has been observed that during supersonic flow, where the net crossflow must be from the test section to the plenum, the test section pressure is actually slightly less than the plenum pressure.

\(^{1}\)The subscripts 15, 16, and 17 have no significance beyond consistency with variable names in the computer program.

\[ \text{Figure 7. Porous wall and flap flow coefficients.} \]
This has been attributed to the fluid momentum in the test section overcoming the slightly adverse pressure gradient. The other constant, $A_{16}$ in the flap model, was added to account for some of the losses in the upstream portion of the diffuser. Unfortunately, both of these constants were found to be functions of the test section Mach number, thus indicating the need for more accurate modeling.

The mean test section pressure $P_t$ in Eq. (7) is computed from a weighted average of the pressure at the nozzle-end of the test section $P_n$ and at the diffuser end $P_d$. That is,

$$P_t(t^*) = (1 - A_{17})P_n(t^*) + A_{17}P_d(t^*)$$

where $0 \leq A_{17} \leq 1$. Since a detailed model of axial property variation in the test section has not yet been included in the start model, properties are computed only at the nozzle and diffuser ends of the test section. For subsonic flows, the value of $A_{17}$ was not found critical to the accuracy of the solution and was thus taken as 0.5, assuming a linear variation. For supersonic flow, a value of 0.9 was used to account for the more pronounced axial gradients.

The remaining two mass flow rates ($\dot{m}_{c1}$ and $\dot{m}_d$) may be related to pressures already introduced above using the steady energy equation discussed earlier and shown in Fig. 3. At the diffuser end of the test section, the energy equation is

$$\left[ \frac{\dot{m}_d(t^*)}{\dot{m}_o(t^*)} \right]^2 = \frac{2}{\gamma - 1} \left( \frac{P_d(t^*)}{P_{ct_o}(t^*)} \right)^{\gamma} - \left( \frac{P_d(t^*)}{P_{ct_o}(t^*)} \right)^{\gamma+1}$$

where $P_{ct_o}(t^*)$ is the total pressure at the exit of the test section.
where as before the subscript "ct" refers to the charge tube and the subscript "o" indicates stagnation properties. The quantity $\dot{m}_o$ is defined as

$$\dot{m}_o(t^*) = \sqrt{\frac{Y}{R}} \frac{P_{ct_o}(t^*)}{\sqrt{T_{ct_o}(t^*)}} A_{ts} \tag{12}$$

where $A_{ts}$ is the cross-sectional area of the test section. The stagnation properties ($P_{ct_o}$ and $T_{ct_o}$) are thought of as originating from the unsteady wave when it reaches the charge tube and are assumed the same, for any given time, throughout all of the flow envelope except the plenum. At the nozzle end of the test section, the flow rate is equal to that in the charge tube, since its value has not yet been modified by any wall crossflow. At this station, the energy equation is, therefore,

$$e_{Pn}(t^*) = e_{ct}(t^*) + \frac{\gamma - 1}{\gamma} \left[ \frac{P_{ct}(t^*)}{P_{ct_o}(t^*)} \right]^\gamma - \frac{\gamma + 1}{\gamma} \right]$$

To complete the portion of the model not arising from the unsteady wave, the thermodynamic equations of state for the plenum are needed. To compute the properties at $t^*$ for use in Eqs. (5), (7), and (8) while Eq. (1) gives the density at $t$, the density at $t^*$ is computed from

$$\rho_p(t^*) = \frac{1}{2} [\rho_p(t) + \rho_p(t - \Delta t)] \tag{14}$$

The plenum temperature is assumed equal to the greater of the isentropic temperature and the stagnation temperature in the test section.

That is,

$$T_p(t^*) = \max \left\{ T_p(t^* - \Delta t) \left[ \frac{\rho_p(t^*)}{\rho_p(t^* - \Delta t)} \right]^{\gamma - 1}, T_{ct_o}(t^*) \right\} \tag{15}$$

In either event, the pressure may then be obtained from the perfect gas law:

$$P_p(t^*) = \rho_p(t^*) R T_p(t^*) \tag{16}$$

Closing the system of equations presented so far requires relationships for how the stagnation properties vary in time. A careful accounting of the number of equations and the number of unknowns to this point would reveal that, given values of $P_{ct_o}$ and $T_{ct_o}$ and assuming $P_e_o = P_{ct_o}$ and $T_e_o = T_{ct_o}$ (which is what is done for the subsonic case),
it is possible to compute the value of \( \dot{m}_{ct} \). This value of the flow rate from the charge tube represents that required by the sum total of all the expansion waves which at a given time have reached the charge tube from all parts of the tunnel. That is, \( \dot{m}_{ct} \) identifies an intermediate point within the entire unsteady wave, which begins with the first motion of a valve somewhere in the tunnel and ends when the plenum reaches its asymptotic pressure. Thus, \( \dot{m}_{ct} \) may be used to compute all other stagnation properties for that point in the unsteady wave. By using the equations of Ref. 3 and after some algebra, the charge tube Mach number at the desired point in the wave may be related to \( \dot{m}_{ct} \) by the equation:

\[
\dot{m}_{ct}(t^*) = M_{ct}(t^*) \left[ 1 + \frac{\gamma - 1}{2} M_{ct}(t^*) \right] \frac{\gamma + 1}{\gamma - 1} \dot{m}_c \tag{17}
\]

where \( \dot{m}_c \) is defined from

\[
\dot{m}_c = \sqrt{\frac{\gamma}{R}} \frac{P_c}{\sqrt{T_c}} A_{ct} \tag{18}
\]

Here \( A_{ct} \) is the cross-sectional area of the charge tube, and \( P_c \) and \( T_c \) are the charge conditions, that is, the air pressure and temperature after the tunnel has been pumped up but before any valves are opened. These charge conditions are assumed to apply uniformly throughout the envelope, including the plenum. After obtaining the charge tube Mach number, the stagnation pressure and temperature are readily computed from the following equations from Ref. 3:

\[
P_{ct_0}(t^*) = \left( 1 + \frac{\gamma - 1}{2} M_{ct}(t^*) \right)^{\frac{\gamma}{\gamma - 1}} P_c \tag{19}
\]

\[
T_{ct_0}(t^*) = \left( 1 + \frac{\gamma - 1}{2} M_{ct}(t^*) \right)^{\frac{\gamma}{\gamma - 1}} T_c \tag{20}
\]

Equations (1) through (20) thus comprise the subsonic portion of the starting model and are summarized in Table 1. The supersonic case is physically different from the subsonic case and requires solution of a different set of equations as noted in Table 1. The distinguishing factor of the supersonic case is that the nozzle exit is choked, making the flow rate and stagnation conditions steady there. Once the nozzle choking, the charge tube Mach number is a constant depending only on the area ratio between the charge tube and nozzle exit. From Ref. 2, the steady Mach number can be obtained by reverting the equation:
Table 1. List of Exact Simultaneous Equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>Independent Variable to be Computed</th>
<th>Included in Supersonic Case?</th>
<th>Test Equation Number</th>
<th>Program Equation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_p(t) = \rho_p(t - \Delta t) + \left[ \dot{\rho}<em>p(t^*) + \dot{\rho}</em>{pe}(t^<em>) + \dot{\rho}_{cl}(t^</em>) \right] )</td>
<td>( \dot{\rho}_p(t^*) )</td>
<td>Yes</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>( \dot{c}_e(t^<em>) = \dot{c}_e(t^</em>) + \dot{c}_d(t^*) )</td>
<td>( \dot{c}_e(t^*) )</td>
<td>Yes</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>( \dot{d}_d(t^<em>) = \dot{d}_d(t^</em>) + \dot{d}_d(t^*) )</td>
<td>( \dot{d}_d(t^*) )</td>
<td>No</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>( \dot{t}<em>u(t^*) = a - \frac{P</em>{c_e}(t^<em>) A_{cl}(t^</em>)}{\sqrt{T_{e}(t^*)}} )</td>
<td>( \dot{t}_u(t^*) )</td>
<td>No</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>( \dot{p}<em>{pe}(t^*) = \frac{P</em>{p}(t^<em>) A_{pe}(t^</em>)}{\sqrt{T_{e}(t^*)}} )</td>
<td>( \dot{p}_{pe}(t^*) )</td>
<td>Yes</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>( \dot{t}<em>{p1}(t^*) = - \frac{A</em>{p1}}{k_{p1}} \left[ p_{p1}(t^<em>) - A_{12} p_{1}(t^</em>) \right] )</td>
<td>( \dot{t}_{p1}(t^*) )</td>
<td>Yes</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>( \dot{t}<em>{t}(t^*) = - \frac{A</em>{t}}{k_{t}} \left[ p_{t}(t^<em>) - A_{16} p_{d}(t^</em>) \right] )</td>
<td>( \dot{t}_{t}(t^*) )</td>
<td>Yes</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>( P_{1}(t) = (1 - A_{11}) p_{1}(t^<em>) + A_{17} p_{d}(t^</em>) )</td>
<td>( \dot{P}_{1}(t) )</td>
<td>Yes</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>( \frac{\rho_{p1}(t^<em>)^{y-1}}{\rho_{c1}(t^</em>)} = \frac{2}{\rho_{p}(t^<em>)} \left[ \frac{P_{c}(t^</em>)}{P_{c1}(t^*)} \right]^{\frac{y-1}{2}} \right) )</td>
<td>( \rho_{p1}(t^*) )</td>
<td>Yes</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>( \frac{\rho_{c1}(t^<em>)^{y-1}}{\rho_{c1}(t^</em>)} = \frac{2}{\rho_{c}(t^<em>)} \left[ \frac{P_{c}(t^</em>)}{P_{c1}(t^*)} \right]^{\frac{y-1}{2}} \right) )</td>
<td>( \rho_{c1}(t^*) )</td>
<td>No</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>( \rho_{p}(t^<em>) = \left( \frac{A_{p1}}{k_{p1}} \right) p_{p1}(t^</em>) + \rho_{p}(t - \Delta t) )</td>
<td>( \rho_{p}(t^*) )</td>
<td>Yes</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>( T_{p}(t^<em>) = \max \left{ T_{p}(t^</em>) - \Delta t \left[ \frac{\rho_{p}(t^<em>)}{\rho_{p}(t^</em>) - \Delta t} \right] \right} )</td>
<td>( T_{p}(t^*) )</td>
<td>Yes</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>( \rho_{p}(t^<em>) = \rho_{p}(t^</em>) R T_{p}(t^*) )</td>
<td>( \rho_{p}(t^*) )</td>
<td>Yes</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>( \rho_{p1}(t^<em>) = \left( \frac{A_{p1}}{k_{p1}} \right) p_{p1}(t^</em>) + \rho_{p1}(t - \Delta t) )</td>
<td>( \rho_{p1}(t^*) )</td>
<td>Yes</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>( T_{c1}(t^<em>) = \left( \frac{A_{c1}}{k_{c1}} \right) T_{c1}(t^</em>) + \frac{2}{\rho_{c1}(t^<em>)} \left[ \frac{P_{c1}(t^</em>)}{P_{c}(t^*)} \right]^{\frac{y-1}{2}} )</td>
<td>( T_{c1}(t^*) )</td>
<td>No</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>( P_{c1}(t^<em>) = P_{c1}(t^</em>) \left( \frac{T_{c1}(t^<em>)}{T_{c1}(t^</em>)} \right) )</td>
<td>( P_{c1}(t^*) )</td>
<td>No</td>
<td>19</td>
<td>9</td>
</tr>
</tbody>
</table>

*Require Numerical Reversion*
With this final Mach number, the steady stagnation conditions \((P_{ct0}, T_{ct0}, \text{and } m_0)\) along with the steady charge tube flow rate \((\dot{m}_{ct})\) can be computed one final time from Eqs. (19), (20), (13), and (17), after which these equations and variables may be dropped from the simultaneous solution. Since \(\dot{m}_{ct}\) is now constant, the flow rate leaving the test section \((\dot{m}_d)\) is solely dependent on the wall crossflow \((\dot{m}_{pt})\) according to Eq. (2) and is independent of the flow rate out the main valves \((\dot{m}_e)\), assuming the valve area \(A_s\) is sufficient to pass all the charge tube flow not removed by the plenum exhaust. Thus, Eqs. (3) and (4) may also be dropped from the system of equations. This is fortunate since it is no longer true that \(P_{e_0} = P_{ct0}\), which results from the nonisentropic recompression of the supersonic flow entering the diffuser. Thus, the original system of 19 equations and 19 unknowns reduces to 10 equations and 10 unknowns for the supersonic case.

These two sets of equations were solved using an iterational technique which unfortunately failed to converge in the vicinity of the choke point in time. To provide an alternate solution procedure when the iterational technique failed to converge, a small perturbation solution was developed for the original exact equations. The small perturbation solution was then used as an initial guess for the iterational procedure when it converged and as the complete solution when it did not. The results of this lengthy derivation are recorded in Appendix A, but the essential ideas are discussed below.

The exact solution already assumes that \(\Delta t\) is a small quantity. For the small perturbation solution, therefore, any of the 19 variables at time \(t^*\) may be assumed to be related to their values at \(t^* - \Delta t\) by the general form

\[
v_i(t^*) = v_i(t^* - \Delta t) + \epsilon_i(t^*)
\]

where \(\epsilon_i\) is the small increment in the variable and \(i = 1, 2, ..., 19\). If these small perturbation equations are used to expand the original exact equations, a new system of equations involving the increments rather than the variables themselves is obtained. For all exact equations, except the energy equations relating the pressure and mass flux at the entrance and exit of the test section (Eqs. (11) and (13)), only terms of order \(\epsilon_i\) need be retained in the small perturbation equations. Such is not the case for the energy equations because in the region of the peak (or choke point) in Fig. 3, there is no linear approximation to the function. In the expanded equation, the coefficient of \(\epsilon_i\) approaches zero as the Mach number approaches one. Thus, the term of order \(\epsilon_i^2\), whose coefficient is nonzero at Mach number one, governs the form of the expansion. The resulting subsonic system
of equations is thus comprised of 17 linear equations and 2 second-degree equations, which can be solved analytically. The supersonic case is composed of 9 linear equations and 1 of second degree.

2.5 SOLUTION PROCEDURE

The procedure used to solve these two systems of equations is discussed in the following section. Included is a discussion of the overall logical procedure, the order in which the equations of the exact solutions are used, convergence considerations, and a general description of the computer program used to accomplish the calculation. The general solution procedure is illustrated by the flow chart in Fig. 9. The decision whether to use the supersonic or subsonic branch is decided by whether \( P_d(t^* - \Delta t) < P^* \) or \( P_d(t^* - \Delta t) > P^* \), that is whether the diffuser end of the test section was supersonic or subsonic at the midpoint of the previous time interval. If the previous interval was supersonic, the current one is also assumed to be supersonic. If the previous interval was subsonic but \( 1 - M(t^* - \Delta t) < M(t^* - \Delta t) - M(t^* - 2\Delta t) \), then the supersonic branch is used for the current time interval; otherwise the solution is assumed to remain subsonic. This criterion is checked for both ends of the test section, and the switch to the supersonic branch is contingent upon either or both positions satisfying the inequality. In either event, the small perturbation solution is computed to provide a good starting point for the exact iterative procedure. If convergence does not occur before a given number of iterations, the small perturbation solution is used as the final solution, and the next time interval is begun.

The "exact iterative procedure" referred to above is accomplished by taking an initial guess for one of the 19 variables and then proceeding from equation to equation, determining new values for each of the 19 variables until a complete circuit is made and a second value of the variable initially guessed at is obtained. This process is repeated until the difference between two successive values of certain of the variables is within a preset limit. For the subsonic case, the equation order is as follows:

\[
4, 3, 11, 10, 7, 2, 17, 19, 20, 12, 13, 10, 7, 8, 1, 14, 15, 16, 5, \ldots
\]

The supersonic equation order is

\[
10, 7, 2, 11, 10, 7, 8, 1, 14, 15, 16, 5, \ldots
\]

Some of these equations (Eqs. (11), (13), and (17)) require reversion from the form given but cannot be reverted analytically in closed form and must be solved numerically. The variable to be solved for in each equation is indicated in Table 1, and the three requiring numerical reversion are marked with an asterisk.
The complete solution thus requires numerical iteration at three distinct levels, which necessitates careful consideration of convergence criteria as well as what to do when the criteria cannot be met because of stability problems. The most basic level of numerical iteration involves reversion of the two energy equations and the mass flux - Mach number...
wave equation. Considering the general case where the function \( Y = F(X) \) must be solved for \( X \) given a value of \( Y \) and a guess \( X_1 \), the procedure is simply to adjust \( X_1 \) in the direction which reduces the error criterion

\[
E_l = \frac{Y - F(X)}{Y}
\]  

until \( |E_l| \leq |E_{\text{max}}| \), \( E_{\text{max}} \) being the present, maximum allowable error. The precise logic of the procedure is illustrated in the flow chart in Fig. 10. Since this procedure must

---

**Figure 10.** Logic for numerical solution of an algebraic equation \( Y = F(X) \) for \( X \), given \( Y \) when \( X = F^{-1}(Y) \) is not a closed form function.
be repeated many times at each time interval, it is of considerable importance (because
of impact on computer time) to achieve a solution with as few iterations as possible.
Since the number of iterations depends to a large extent on the accuracy of the guess
$X_1$, considerable effort was expended in obtaining approximate reversion of the three
equations. It was inadvertently discovered that the energy equation may be approximated
with surprising accuracy over the entire range of present interest with a single ellipse,
the reversion of which is trivial. The wave equation presented more of a problem. Since
an easily revertable second-degree expansion around $M_{ct} = 0$ failed to match the accuracy
of the elliptic energy equation, the expansion was carried to the seventh degree and then
formally reverted according to the procedure of Ref. 6. These expansions are summarized
in Appendix B.

The next higher level of iteration is, of course, the simultaneous solution of the
exact model equations, during which stability problems were encountered in the vicinity
of the choke point. The error criterion for halting the iteration may be generally expressed
as

$$\frac{|v_i^{(n)} - v_i^{(n+1)}|}{\frac{1}{2} [v_i^{(n)} + v_i^{(n+1)}]} \leq P_{err}$$  \hspace{1cm} (24)

where test variables ($v_i$) are the pressures $P_n$, $P_p(t)$, $P_p(t^*)$, $P_d$, $P_t$, and $P_{cto}$; $P_{err}$ is
the maximum allowable error; and $n$ is the iteration number. Figure 11 illustrates the
stability problem encountered in striving to meet this error limit. Shown is how the plenum
pressure $P_p(t^*)$ varied with iteration number at two succeeding time points, one converging
and one not. Such stability problems are known to occur in applying the iterational
technique to locating the intersection of two curves on a plane when the curves have
the same slope (same or opposite sign) at the point of intersection. Whether this simple
explanation in 2-space is applicable to 19-space where no two of the 19 functions lie
in the same plane is unclear. In any event, improvement in convergence rate was sought
via the following procedures, most of which improved the situation:

a. Relative Errors. It was found that if $E_{max}$ was much greater than $1/10$ $P_{err}$, the numerical reversion could oscillate enough themselves from one
iteration to the next to slow convergence.

b. Computational Precision. Single precision arithmetic ($\sim$8 digits on an IBM
370) was found inadequate to achieve errors of $E_{max} = 10^{-5}$ ($P_{err} = 10^{-4}$),
and double precision ($\sim$16 digits) was, therefore, adopted.
c. Solution Weighting. The clearly periodic oscillation of Fig. 11 suggests that the average of any two successive values should be closer to the final asymptote than either value. Accordingly, solution weighting,

\[ v_i^{(n)} = A_{11} v_i^{(n)} + (1 - A_{11}) v_i^{(n+1)} \]  

was employed on a regular basis.

d. Weight Cutting. It was further discovered that convergence rate could be greatly improved after the number of iterations reached a certain point if a lesser weight was applied to the current value \( v_i^{(n)} \).

e. Error Cutting. It was found that, later in a computation when some of the pressures were very near their asymptotes, the amount of variation from one time point to the next eventually approached the error limit. This in effect allowed these values to vary at random within the error limits and deteriorate the convergence rate. It was thus found prudent to reduce the error limits as necessary so as to maintain

Figure 11. Plenum pressure versus iteration number for convergent and divergent cases.
\[ P_{err} \leq \frac{v_i(t^*) - v_i(t^* - \Delta t)}{\frac{1}{2} [v_i'(t^*) + v_i(t^* - \Delta t)]} \]  

(26)

and \( E_{max} \leq 1/10 P_{err} \).

f. Extrapolation. A second-order extrapolation function

\[ v_i(t^*) = 2v_i(t^* - \Delta t) - v_i(t^* - 2\Delta t) \]  

(27)

was tested in an effort to improve the starting values for iteration through the 19 equations, but this generally produced no improvement in convergence rate. A third-order function

\[ v_i(t^*) = 3v_i(t^* - \Delta t) - 3v_i(t^* - 2\Delta t) + v_i(t^* - 3\Delta t) \]  

(28)

was found not much better. Ultimately, of course, it is illogical to expect any finite order extrapolation scheme to predict the effect of changes in the forcing functions (area-time curves) if those coming changes had not been anticipated by the derivatives of less than that order.

g. Small Perturbation Solution. In place of an extrapolation function, there was used the more logical small perturbation solution. This considerably improved the convergence rate and provided sufficiently accurate results in lieu of the exact solution when it failed to converge in a reasonable length of time.

The complete mathematical model along with the above described convergence enhancement logic have been programmed in Fortran IV for solution on an IBM 370/165. The computer program HIRTSM1 (for HIRT Starting Model) is composed of the normally expected components: the main program (MAIN) containing the exact equations, the convergence control logic, and the overall solution control logic; subroutines to control input (INPUT), output (PRINT and DUMP), and variable definition and initialization (CONST and INIT); and a subroutine which performs the calculation for the analytical solution to the simultaneous small perturbation equations (SMPERT). In addition, the program contains a package of utility subroutines: one routine contains the logic of Fig. 10 to numerically revert any given function (SOLVER); a second expands out the binomial coefficients (BINOM) to give a series which is reverted by a third subroutine (REVERT) to the seventh-degree term; a fourth subroutine (QSIMUL) determines the points of intersection of two conics (the two final energy equations resulting from SMPERT) by converting them to a single fourth-degree polynomial, which has an exact analytical solution for the four roots (QANDC). Use of this program is described in Appendix C.
The program can be run in a partition of 110K bytes and easily completes about 200 time increments in less than a minute of central processor time, though occasionally a run may require up to three minutes. Peripheral storage is not essential, though provisions are made to dump the entire solution on to a direct (random) access data set (such as a disk file) so that the solution may be picked up at any point and continued. The results of calculations with HIRTSM1 are compared in the next section with experimental results from the Pilot HIRT facility.

3.0 RESULTS

Presented below is a comparison between the mathematical model and experimental pressure-time histories from Pilot HIRT. Included is a brief description of those characteristics of the tunnel important to the model. After a comparison of the model and data, some other results of the calculations are shown. The section concludes with a discussion of how the model can be applied in the design of certain portions of the tunnel.

3.1 DESCRIPTION OF PILOT HARDWARE

Figure 12 shows an elevation line drawing of the Pilot HIRT facility, to which the present mathematical model was applied. Figure 13 shows most of the geometric data required by the model and also accurately illustrates the real life hardware, which is simplified in the model. The geometric parameters in the precise form used in the model are summarized in Table 2. The tunnel uses two alternate types of starting devices, the sliding sleeve valve shown in Fig. 13 and, for quicker starts, a Mylar® diaphragm and cutter located at the interface of the diffuser and the valve assembly. The plenum exhaust system, shown schematically in Fig. 14, also uses a diaphragm in addition to two valves to control the exhaust flow. The diaphragm initiates the flow, and the ball valve, whose setting cannot be changed during a run, determines the amount of plenum exhaust during the steady portion of the run. The quick-acting valve, however, may be rapidly closed during the run to provide a temporarily elevated plenum exhaust in excess of what the ball valve will pass. The complete system in Fig. 14 is modeled as the area-time curve of a one-dimensional sonic orifice, as is the multiple port system on the main valve.

The portion of the tunnel shown in Fig. 13 was heavily instrumented with pressure taps to measure pressure-time histories at various locations in the nozzle, test section, diffuser, and plenum. Output from the pressure transducers was sampled every 2 msec by a data acquisition system based on a PDP 11/10 digital computer with certain of the signals also displayed on a recording oscillograph. Of primary interest here are the plenum pressure-time histories, which comprise the primary basis for comparison of the theory and experiment.
Figure 12. Pilot HIRT elevation line drawing.
Figure 13. Cross-sectional view of nozzle, test section, diffuser, and main valve system.
Table 2. Geometric Data for Pilot HIRT Required by Mathematical Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Tube Diameter</td>
<td>1.162 ft</td>
</tr>
<tr>
<td>Charge Tube Flow Area</td>
<td>1.060 ft²</td>
</tr>
<tr>
<td>Ratio of Charge Tube Area to Test Section Area</td>
<td>2.271</td>
</tr>
<tr>
<td>Test Section Length</td>
<td>2.114 ft</td>
</tr>
<tr>
<td>Test Section Width</td>
<td>0.7633 ft</td>
</tr>
<tr>
<td>Test Section Height</td>
<td>0.6117 ft</td>
</tr>
<tr>
<td>Test Section Flow Area</td>
<td>0.4669 ft²</td>
</tr>
<tr>
<td>Test Section Wall Surface Area</td>
<td>5.813 ft²</td>
</tr>
<tr>
<td>Test Section Porosity</td>
<td>3.5 to 10%</td>
</tr>
<tr>
<td>Test Section Volume</td>
<td>0.9870 ft³</td>
</tr>
<tr>
<td>Flap Flow Area</td>
<td>0 to 0.2062 ft²</td>
</tr>
<tr>
<td>Ratio of Plenum Volume to Test Section Volume</td>
<td>1.75 to 4.0, 2.8</td>
</tr>
</tbody>
</table>

Figure 14. Plenum exhaust system.
3.2 COMPARISON OF MATH MODEL AND EXPERIMENT

Data for nine different tunnel settings were studied with the mathematical model. Some basic data for runs typical of these nine conditions are summarized in Table 3. The data of primary interest in this table include the plenum-to-test section volume ratio, porosity, the opening times of the main valve and plenum exhaust valve, the maximum plenum exhaust area, and the experimental test section Mach number. The conditions listed for Run 2258 may be considered nominal values from which variations in plenum volume, porosity, flap setting, and test section Mach number were examined.

Figure 15 compares the experimental plenum pressure as a function of time with the present mathematical model for the nominal conditions (Run 2258). The data illustrated is for a plenum volume 2.8 times the test section volume, a porosity of 4-1/2 percent, and a flap setting of 0.4 in. (the gap between the flap and the test section wall where the flap flow empties into the diffuser). The main starting device was a Mylar diaphragm; and the exit flow area, the primary factor determining the asymptotic test section Mach number (0.921), was obtained by capping off the proper number of exit ports on the main exhaust manifold (Fig. 13, 16-in. valve). Since the desired Mach number was subsonic, the plenum exhaust system was not used. The resulting data for these tunnel settings are plotted in Fig. 15 as circles, and the solid line represents the output of the computer program. The program was run for the indicated tunnel settings (Table 3), but several not readily apparent inputs were assumed. The starting device (diaphragm) was treated as a linear area-time curve reaching its maximum area in 2 msec. The maximum area shown in Table 3 is approximately 99.46 percent of the test section flow area, which is based on the ideal, one-dimensional flow area ratio needed to produce a test section Mach number of 0.921. The resulting theoretical plenum pressure-time history shown in Fig. 15 agrees well with the experimental data. The greatest discrepancy occurs at 25 msec and reaches a peak there of 6.5 percent. This difference, due to a temporary leveling of the experimental data between 10 and 25 msec, results from the finite time required for the initial expansion wave to traverse the plenum volume, which includes the plenum exhaust lines shown in Fig. 14. These lines extend to a distance of about 4 ft from the major portion of the plenum. Since the model assumes a uniform plenum, it cannot account for this factor. Figure 15 also illustrates another deficiency of the model, which in this case produces the 3.1-percent error at a time of about 100 msec. Part of this error is due to error accumulation in the small perturbation solution, to which the program reverted entirely beyond 45 msec because of nonconvergence of the exact iterational solution. Another part of the error, in this case the smaller part, is due to neglect of the axial momentum of the test section flow by the crossflow model, which results in the smaller slope of the theoretical curve in the region of 60 to 90 msec. Since this discrepancy has been found to be generally small for subsonic runs, the coefficient in the crossflow model (A15) has been left equal to one.
Table 3. Summary of Run Conditions for Experimental Data to be Compared with Theory

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Charge Pressure, ( P_C ), psia</th>
<th>Plenum Volume, ( V_p/V_{1a} )</th>
<th>Porosity, ( \gamma ), %</th>
<th>Maximum Flow Area</th>
<th>Total Opening Times</th>
<th>Asymptotic Plenum Pressure, psia</th>
<th>Test Section Mach Number, ( M )</th>
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<tr>
<td>2226</td>
<td>60.11</td>
<td>2.8</td>
<td>4.5</td>
<td>0.466886</td>
<td>0</td>
<td>0.045835</td>
<td>0.002</td>
</tr>
<tr>
<td>2236</td>
<td>82.37</td>
<td>2.8</td>
<td>4.5</td>
<td>0.466331</td>
<td>0</td>
<td>0.2062</td>
<td>0.002</td>
</tr>
<tr>
<td>2241</td>
<td>61.84</td>
<td>2.8</td>
<td>1.5</td>
<td>0.465911</td>
<td>0</td>
<td>0.09167</td>
<td>0.002</td>
</tr>
<tr>
<td>2251</td>
<td>81.47</td>
<td>2.5</td>
<td>4.5</td>
<td>0.465911</td>
<td>0.1090</td>
<td>0.09167</td>
<td>0.002</td>
</tr>
<tr>
<td>2255</td>
<td>81.27</td>
<td>2.5</td>
<td>4.5</td>
<td>0.465911</td>
<td>0.1090</td>
<td>0.09167</td>
<td>0.002</td>
</tr>
<tr>
<td>2258</td>
<td>70.51</td>
<td>2.8</td>
<td>4.5</td>
<td>0.464351</td>
<td>0</td>
<td>0.09167</td>
<td>0.002</td>
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<tr>
<td>2260</td>
<td>70.90</td>
<td>4.0</td>
<td>4.5</td>
<td>0.466290</td>
<td>0</td>
<td>0.09167</td>
<td>0.002</td>
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<tr>
<td>2263</td>
<td>74.10</td>
<td>1.75</td>
<td>4.5</td>
<td>0.466662</td>
<td>0</td>
<td>0.09167</td>
<td>0.002</td>
</tr>
<tr>
<td>2742</td>
<td>152.15</td>
<td>2.5</td>
<td>4.0</td>
<td>0.465911</td>
<td>0.1090</td>
<td>0.09167</td>
<td>0.030</td>
</tr>
</tbody>
</table>

(a) \( f = 0.2 \) in.\(^2\)
(b) \( f = 0.9 \) in.\(^2\)
(c) \( f = 0.4 \) in.
(d) Nominal Conditions
Since the amount of plenum volume which must be drawn down to the asymptotic pressure may logically be expected to have a first-order impact on the starting time, the plenum volume was the first parameter varied from the nominal conditions for Run 2258 (Fig. 15). Figures 16 and 17 show the plenum pressure for a smaller plenum volume ratio (1.75) and a larger ratio (4.0), respectively. As expected, the smaller volume case flattens more quickly than the medium volume case, and the larger volume more slowly. As in Fig. 15, the accuracy of the model is generally good for both the smaller and larger plenum volumes, though the effect of the wave propagation time in the plenum is much more pronounced for the larger volume.

Now return to a medium plenum volume case but vary another parameter - plenum exhaust - for a slightly supersonic run. The theoretical analysis depends on an experimentally derived plenum exhaust area-time curve, shown in Fig. 18, in the nondimensional form used by the computer program. Unfortunately, the uncertainty in the shape of this curve is quite large, and only the steady area is known accurately. Illustrated in Figs. 19 and 20 are the data for two supersonic cases, Mach 1.039 and 1.228. Both the theory and experiment of Fig. 18 show a slight over-shoot bottoming out at 30 msec and then approaching the asymptote from below. In addition, the experimental data show a slight rebound peaking at 60 msec, a result not predicted by the model. The rebound probably results from the overshoot, which would tend to draw the test section below its asymptotic pressure while the plenum exhaust area was decreasing.
Figure 16. Plenum pressure versus time for subsonic run with small plenum volume.

Figure 17. Plenum pressure versus time for subsonic run with large plenum volume.
to its steady value at 40 to 50 msec. This combination of occurrences would then produce a slight refilling of the plenum, manifesting itself in the observed rebound. For the higher Mach number (1.288) of Fig. 20, the plenum exhaust curve of the previous case was retained intact up to its peak but was linearly stretched beyond the peak to make it approach the steady area needed for the tunnel to reach the desired asymptotic Mach
number. The peak area and closing time were unchanged. The disagreement between theory and data at the knee of the curve may be charged to the uncertainty in the plenum exhaust area-time curve, which is known to vary somewhat from run to run since the plenum diaphragm rupture is not precisely repeatable.

![Graph showing plenum pressure versus time for supersonic run (Mach 1.228) with plenum exhaust.](image)

**Figure 20.** Plenum pressure versus time for supersonic run (Mach 1.228) with plenum exhaust.

The next parameter variation for which the model was tested was the opening time of the main starting device. Figure 21 shows the data and theory for a supersonic run made with a relatively slow opening 12-in. sliding sleeve valve instead of the diaphragm. Though not apparent from the excellent agreement for this case, there is also some uncertainty in the effective opening time of the main valve, assumed to be 30 msec for the theoretical calculation. This uncertainty results because the choke point of the tunnel changes position as the valve area increases, moving from the valve to the nozzle exit. Since the time at which this change occurs is not easily determined experimentally, the exact effective opening time is not known. In addition, the area-time curves are not precisely repeated from run to run.

To continue with the testing of the model for variations in other parameters, the program was run for a case of reduced porosity (1.5 percent), maintaining the nominal conditions of medium plenum volume and flap setting. Figure 22 shows that the model agrees well with the data. Cases were also run for which the flap flow area was halved...
Figure 21. Plenum pressure versus time for supersonic run with sliding sleeve valve and plenum exhaust.

Figure 22. Plenum pressure versus time for supersonic run with 1-1/2-percent porosity and no plenum exhaust.
Figure 23. Plenum pressure versus time for subsonic run with small flap setting.

Figure 24. Plenum pressure versus time for subsonic run with large flap setting.
and doubled from the nominal settings. Illustrated in Figs. 23 and 24, both theoretical calculations are in acceptable agreement with experiment. As in previous cases, the disagreement just above the knees is due to the neglect of the finite wave propagation time across the plenum. The disagreement very early in the run (10 msec) is due to uncertainty in the rupture time of the diaphragm, and the slowness of the model in approaching the asymptote may be charged to inadequate handling of the momentum terms in the crossflow model.

3.3 OTHER RESULTS FROM THE MATH MODEL

To predict the data of primary interest, plenum pressure, the model must also calculate many other quantities including pressures and mass flow rates at various locations in the tunnel. Figure 25 shows the pressure-time histories for the case of nominal plenum volume (2.8) for a subsonic run with a diaphragm starting device. Besides plenum pressure, the stagnation pressure and static pressures at opposite ends of the test section are shown. This graph illustrates that the test section pressure initially drops much faster than the plenum, as expected since the rate of plenum depletion is limited by the porosity and flap area. Early in the run, the pressure at the exit of the test section leads the pressure at the entrance because the wall crossflow leaving the plenum increases the flow rate from the entrance to the exit. Eventually, of course, the test section and plenum pressures approach each other as the flap and wall crossflows become negligible and the steady conditions are reached. The stagnation pressure becomes nearly flat long before the static pressures in the test section and changes very slowly beyond 20 msec.

The subsonic case in Fig. 25 may be contrasted to the supersonic case in Fig. 26, which shows the same set of pressure curves. Besides the more rapid drop of all curves prior to 40 msec, due to the plenum exhaust, the most striking difference from the subsonic case is the approach of opposite ends of the test section to distinctly different asymptotes. The entrance to the test section levels rather suddenly at the choking pressure ratio, while the exit continues to drop to the lower pressure ratio corresponding to the supersonic Mach number. Another interesting feature is that the asymptotic pressure at the test section exit is lower than for the plenum even though the net wall crossflow must be into the plenum (to reduce the flow rate along the test section as needed for supercritical flow). Crossflow against the pressure gradient occurs because of the increasing momentum retained by the crossflow while separating off from the high-speed test section flow. Another feature of Fig. 26 due to this momentum is the crossing of the test section pressure curves at 12 msec, which signifies the reversing of the wall crossflow. To improve the crossflow model's representation of the effect of this momentum (which is neglected in modeling the crossflow rate as a function of pressure difference only), the momentum correction coefficient $A_{15}$ in Eq. (7) was introduced. This quantity expediently models the small
Figure 25. Various pressures versus time for nominal conditions.

Figure 26. Various pressures versus time for supersonic run with plenum exhaust.
additional crossflow due to momentum in terms of a slightly elevated driving pressure. The steady-state value of $A_{15}$ at a given steady test section Mach number was derived empirically for a given steady plenum pressure. These steady-state values of $A_{15}$ are shown in Fig. 27a. During a run, however, $A_{15}$ was assumed to vary according to the ramp function of Fig. 27b to simulate the increasing momentum.

![Graph showing momentum correction coefficient $A_{15}$ and flap correction coefficient $A_{16}$ versus steady test section Mach number.](image)

**a. Momentum correction coefficient ($A_{15}$) and flap correction coefficient ($A_{16}$) versus steady test section Mach number**

![Graph showing assumed variation with test section Mach number ($M_d$) of momentum ($A_{15}$) and flap ($A_{16}$) correction coefficients during starting process.](image)

**b. Assumed variation with test section Mach number ($M_d$) of momentum ($A_{15}$) and flap ($A_{16}$) correction coefficients during starting process**

**Figure 27. Steady-state values of correction coefficients, $A_{15}$ and $A_{16}$.**

Looking at the mass flow rate-time curves corresponding to Figs. 25 and 26 provides further insight into the behavior of the mathematical model. Figure 28 shows the flow rate entering (from the charge tube) and leaving the test section, the flow rate through the flaps, and across the porous wall for the nominal conditions and subsonic flow. The flap and wall crossflows, though leaving the plenum in this run, are shown on the positive
axis for convenience. All data are expressed as ratios of the steady, asymptotic flow rate through the main valves. The flow in the test section is seen to rise very rapidly, in concert with the breaking diaphragm, and to approach the final flow rate only as the flap and crossflows approach zero. Both flows from the plenum reach peaks at about 3 msec, which results from the pressure differences between the plenum and test section reaching a maximum. The crossflow further manifests itself in the disparity between the flow entering and leaving the test section. Various experimentally derived flow rates are given in Ref. 4 for the pilot tunnel. These relatively well behaved results for the subsonic case may be contrasted to the tangle of curves resulting from a supersonic case with plenum exhaust (Fig. 29), which is based on the same conditions as Fig. 26. Initially similar to the subsonic case with peak flap and crossflows at 3 msec, the curves are considerably modified by the opening of the plenum exhaust at 4 msec (a programmed delay). The leveling of the flap and crossflow curves at 22 msec is associated with choking in the test section. Eventually, the plenum exhaust forces both the crossflow and flap flow to reverse and eventually to exactly balance the plenum exhaust flow rate when steady flow is reached. Reversal of the flap flow requires, in terms of the flow model (Eq. (8)), a driving pressure at the flap exit greater than the plenum pressure and in general greater than the computed pressure at the exit of the test section. Though the flap correction coefficient ($A_{16}$) is applied much like the wall crossflow coefficient, the physical explanation cannot be the same since the free-stream momentum is in the opposite direction of the reversed

![Figure 28. Relative theoretical mass flow rates for nominal conditions (Run 2258) of subsonic flow with no plenum exhaust.](image)
flap flow. A more likely explanation is the shock structure and flow separation at the diffuser entrance. Since precise modeling of this complex flow is beyond the scope of the present work, the flap flow correction coefficient \((A_{16})\) was added to Eq. (8). Experimentally derived values of \(A_{16}\) as a function of steady test section Mach number are plotted in Fig. 27a along with the static pressure jump across a normal shock. The pressure rise during the reversed flap flow must be due to a flow more complex than a normal shock, since the pressure jump across the shock rises much more rapidly than experiment indicates. The lines through the circled points are cubic fits and are probably not accurate beyond Mach 1.25. As with the momentum correction, the flap correction was assumed to vary in time according to the ramp function in Fig. 27b.

### 3.4 APPLICATION OF THE MATH MODEL

Besides prediction of tunnel start time, there are several other ways the model can be applied in the design of a wind tunnel. Since the plenum exhaust area-time curves can be varied arbitrarily in the model, the number of plenum valves (or total valve area)
to achieve various start times can be determined. In addition, the sensitivity of the start
time to the shape of the area-time curves can be predicted. This is important because
it indicates how finely controllable and repeatable (and expensive) the valves must be.
Another potential application is estimation of the structural loading of the test section
wall due to transient pressure differences between the plenum and test section.

To illustrate some of these possibilities, the program was run for the three different
plenum exhaust area time curves shown in Fig. 30. The solid line is a typical area-time
curve from Pilot HIRT, and the two broken lines are variations having the same average
open area. Processing the model with the triangular curve should indicate whether a curve
with the same peak as the basic curve but having a different shape would significantly
affect starting time. The trapezoidal curve should indicate whether a smaller number of
valves kept at full open for a longer time could achieve the same start time as the more
peaked curves. The plenum pressure-time histories for these three curves are shown in
Fig. 31. It is clear that the triangular curve has little effect on the shape of the pressure
curve and does not affect starting time. On the other hand, the trapezoidal curve has
a larger effect but still does not lengthen the starting time. The logical conclusions for
the tunnel configuration studied here is that very accurate controllability is not required
of the plenum valves and that the tunnel could be started just as quickly with about

![Figure 30. Nondimensional equal area plenum exhaust area-time curves.](image-url)
2/3 of the available valve area if the valves were kept fully open for a longer duration. If these results were found to apply to a large scale facility, a considerable cost reduction could be realized.

A second example of application of the model is illustrated by Fig. 32, which shows the pressure differential across the wall at the test section exit as a function of time for several conditions. From these results, it can be seen that reducing the porosity has little impact on wall loading, but raising the Mach number from 0.921 to 1.228 or reducing the flap gap by 1/2 significantly increases the loading by 25 and 50 percent, respectively. In contrast, lengthening the effective valve opening time from 2 to 30 msec reduces the peak load to about 1/3 of the nominal case. The peaks of the curves for the diaphragm runs occur just as the diaphragm reaches its full open area. The curve for the valve run, however, peaks first when the plenum exhaust area peaks and later when the valve reaches its steady area around 30 msec. Two data points for the peak pressure differential from Ref. 4 are shown in Fig. 32 and agree with the model.
4.0 SUMMARY AND CONCLUSIONS

A mathematical flow model for the process of starting a transonic Ludwieg tube wind tunnel has been developed. The present model uses the integral continuity equation for three specific control volumes, the steady form for the diffuser and test section control volumes, and the unsteady form for the plenum. The solution in the two former control volumes also uses the steady, isentropic energy equation, assumed applicable throughout the diffuser and test section control volumes for a given set of stagnation conditions. However, the stagnation conditions are allowed to vary in time according to the well-known exact solution for an unsteady, one-dimensional expansion wave. Application of this model takes the form of a numerical solution of 19 simultaneous algebraic equations to be solved at successive time points until the flow becomes steady. The iterational solution procedure
for these exact equations becomes nonconvergent in the vicinity of choking and is replaced with an analytical solution to a set of small perturbation equations until the choke point is passed. The numerical procedure is programmed for computer solution.

The mathematical model was evaluated by comparison with experimental plenum pressure-time histories from a small Ludwieg tube wind tunnel. Agreement between the model and experiment was found to be good. Other numerical results from the computer model were also presented to illustrate application of the model to design of a large facility. Specific conclusions drawn from the present study include (1) verification of the model's ability to predict accurately plenum pressure-time histories and, therefore, tunnel starting time; (2) prediction that starting time is insensitive to the precise shape of area-time curve of the plenum exhaust and, therefore, that very precise controllability is not required of the plenum valves; (3) prediction that starting time is not significantly lengthened by even large changes in the shape of the plenum exhaust area-time curve if the area under the curve and open time are maintained, thus permitting considerable reduction in the number of start valves suggested by data from the pilot facility; and (4) verification that aerodynamic loading of the test section walls (and, therefore, the support structure) can be reduced by lengthening the opening time of the main starting valves, within limitations of the required starting time.

REFERENCES


APPENDIX A
SMALL PERTURBATION SOLUTION

This section presents the essential details of the small perturbation solution, the knowledge of which may be important to a user of the computer program HIRTSM1. Table A-1 shows the small perturbation variables and the exact variables they represent. Use of the expansions (Eq. (22)) in the exact equations listed in Table 1 produces the approximate small perturbation equations listed in Table A-2. Definitions of the coefficients $A_1$, $B_1$, $C_1$, ..., if needed, should be extracted directly from the computer program (subroutine SMPERT) where they are coded as $CA_1$, $CB_1$, $CC_1$, ..., respectively. The equations of Table A-2 can be solved analytically without recourse to numerical iterative procedures. To accomplish this task, the linear equations were solved algebraically to eliminate all variables except those contained in the quadratic equations, Eqs. (12) and (13). After eliminating all variables but $\epsilon_{12}$ and $\epsilon_{13}$ from the two quadratics, Eqs. (12) and (13) were converted to a single quartic (subroutine QSIMUL), which was solved analytically for its four roots. If necessary, the reader can extract the algebraic details of this procedure from the computer program. The correctness of the algebra has been inferred from computation of residuals from the equations of Table A-2 (replacing the zeros on the right-hand side with residuals). For all cases tested, the residuals were found to be on the order of the computer's accuracy ($\sim 10^{-16}$). Similarly, the accuracy of the expansions in representing the exact equations was tested by computing residuals from the exact equations using perturbed values for the variables. The largest residuals (percentage basis) were generally less than $10^{-4}$. 

53
Table A-1. Perturbation Variables

<table>
<thead>
<tr>
<th>Original Variable</th>
<th>Perturbation Variable</th>
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<tbody>
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<tr>
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</tr>
<tr>
<td>$A_f (t^*)$</td>
<td>$\varepsilon_{Af}$</td>
</tr>
</tbody>
</table>

\(^a\)Variables 15 and 16 were eliminated.
Table A-2. Perturbation Equations

<table>
<thead>
<tr>
<th>Program Equation Number&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Perturbation Equation&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$A_1 \varepsilon_1 + B_1 \varepsilon_9 + C_1 \varepsilon_{A_1} + D_1 \varepsilon_{10} = 0$</td>
</tr>
<tr>
<td>2</td>
<td>$A_2 \varepsilon_2 + B_2 \varepsilon_{17} + C_2 \varepsilon_{A_2} + D_2 \varepsilon_{19} = 0$</td>
</tr>
<tr>
<td>3</td>
<td>$A_3 \varepsilon_3 + B_3 \varepsilon_{A_3} + C_3 \varepsilon_{17} + D_3 \varepsilon_{12} = 0$</td>
</tr>
<tr>
<td>4</td>
<td>$A_4 \varepsilon_4 + B_4 \varepsilon_{17} + C_4 \varepsilon_{11} = 0$</td>
</tr>
<tr>
<td>5</td>
<td>$A_5 \varepsilon_5 + B_5 \varepsilon_2 + C_5 \varepsilon_3 + D_5 \varepsilon_4 + E_5 = 0$</td>
</tr>
<tr>
<td>6</td>
<td>$A_6 \varepsilon_6 + B_6 \varepsilon_4 + C_6 \varepsilon_7 = 0$</td>
</tr>
<tr>
<td>7</td>
<td>$A_7 \varepsilon_6 + B_7 \varepsilon_3 + C_7 \varepsilon_1 = 0$</td>
</tr>
<tr>
<td>8</td>
<td>$A_8 \varepsilon_7 + B_8 \varepsilon_8 = 0$</td>
</tr>
<tr>
<td>9</td>
<td>$A_9 \varepsilon_9 + B_9 \varepsilon_8 = 0$</td>
</tr>
<tr>
<td>10</td>
<td>$A_{10} \varepsilon_{10} + B_{10} \varepsilon_8 = 0$</td>
</tr>
<tr>
<td>11</td>
<td>$A_{11} \varepsilon_{11} + B_{11} \varepsilon_{13} + C_{11} \varepsilon_{12} = 0$</td>
</tr>
<tr>
<td>12</td>
<td>$A_{12} \varepsilon_6 + B_{12} \varepsilon_{14} + C_{12} (P_{cto} \varepsilon_{12} - P_{d} \varepsilon_9) + D_{12} (P_{cto} \varepsilon_{12} - P_{d} \varepsilon_9)^2 = 0$</td>
</tr>
<tr>
<td>13</td>
<td>$A_{13} \varepsilon_7 + B_{13} \varepsilon_{14} + C_{13} (P_{cto} \varepsilon_{13} - P_{n} \varepsilon_9) + D_{13} (P_{cto} \varepsilon_{13} - P_{n} \varepsilon_9)^2 = 0$</td>
</tr>
<tr>
<td>14</td>
<td>$A_{14} \varepsilon_{14} + B_{14} \varepsilon_9 + C_{14} \varepsilon_{10} = 0$</td>
</tr>
<tr>
<td>17&lt;sup&gt;d&lt;/sup&gt;</td>
<td>$A_{17} \varepsilon_{17} + B_{17} \varepsilon_8 = 0$</td>
</tr>
<tr>
<td>18</td>
<td>$A_{18} \varepsilon_{18} + B_{18} \varepsilon_5 + C_{18} = 0$</td>
</tr>
<tr>
<td>19</td>
<td>$A_{19} \varepsilon_{19} + B_{19} \varepsilon_{18} + C_{19} \varepsilon_{17} = 0$</td>
</tr>
</tbody>
</table>

<sup>a</sup>See Table 1 for Corresponding Exact Equations
<sup>b</sup>Refer to Listing of Computer Program, Subroutine SMPERT, for Definitions of $A_1$, $B_1$, ...
<sup>c</sup>Variables $P_{cto}$, $P_d$, and $P_n$ are Evaluated at $t^* - \Delta t$ As Are All the Coefficients $A_1$, $B_1$, ...
<sup>d</sup>Equations 15 and 16 Were Eliminated
APPENDIX B
APPROXIMATED EQUATIONS

Reversion of Eqs. (11), (13), and (17) requires a time-consuming numerical procedure which has a major impact on the run time of HIRTSM1. To reduce the number of iterations needed for the reversions, approximations to the original equations were used to provide accurate initial guesses to the numerical procedure. Since these approximations may be of general interest, they are listed below. A good approximation to the mass flux-Mach number wave equation was obtained by expanding

\[ \hat{m} = M \left( 1 + \frac{\gamma - 1}{2} M \right) - \frac{\gamma + 1}{\gamma - 1} \]  

in a series of powers of M using the binomial expansion. Reversion of this series for \( \gamma = 1.4 \) then produced

\[ M = \hat{m} - 1.200 \hat{m}^2 + 2.0400 \hat{m}^3 + 4.0480 \hat{m}^4 + 8.7965 \hat{m}^5 \]
\[ + 20.106 \hat{m}^6 + 47.960 \hat{m}^7 + \ldots \]  

where \( \hat{m} \equiv \hat{m}/\hat{m}_c \). The approximation used for the energy equation is much simpler and was discovered quite by accident. It was found that the equation

\[ \frac{\tilde{m}^2}{\tilde{m}^4} = \frac{\tilde{p}^{2/\gamma} - \tilde{p}^{\gamma+1}}{\gamma} \]  

could be very reasonably approximated over the interval \( 0 \leq M \leq 1.4 \) by the ellipse

\[ \left( \frac{\tilde{m}}{\tilde{m}_c} \right)^2 + \left( \frac{\tilde{p} - \tilde{p}^*}{1 - \tilde{p}^*} \right)^2 = 1 \]  

where

\[ \tilde{m} = \sqrt{\frac{\gamma - 1}{2} \frac{\hat{m}}{\hat{m}_o}} \]
\[ \tilde{p} = \frac{p}{p_o} \]

and

\[ \tilde{p}^* = \hat{p}^*, \tilde{m}^* = \hat{m}^* \text{ for } M = 1 \]
APPENDIX C
DESCRIPTION OF THE COMPUTER PROGRAM HIRTS M1

Because of the complexity of the numerical calculations, potential users of the model must have access to the computer program (a manual calculation on a scientific calculator took about six hours to step through five time increments). For this reason, a listing of the source deck is given in this section along with a brief description of its content and use. Table C-1 lists the 15 subroutines comprising HIRTS M1. Of primary interest are the routines MAIN and SMPERT, which house the exact model equations and the small perturbation equations, respectively. Table C-2 defines some of the more important variables used in the program, information which is potentially useful if a program modification is necessary.

Of primary interest to the potential user, however, is the input, instructions for which are listed in Table C-3. The first card (NCTL) allows the user to retain manual control over some of the superficial program logic. While intended primarily for debugging purposes, the NCTL variable may be used to restart a run previously written onto a data file. To make a normal run and relinquish all control to the program, a blank card may be used. The second card (INSTR) provides the means to invoke certain program options via integer instructions. Table C-4 gives a set of values which have been used successfully to date, though occasional adjustments are necessary for some cases. Of particular importance for supersonic cases is INSTR(26). As the program approaches the choke point in the calculation (timewise, speaking), the number of iterations (ITER) for convergence always becomes inordinately large (~100); and the program must switch to the small perturbation solution entirely by automatically setting INSTR(23) = 2 when ITER ≥ INSTR(22). However, for supersonic cases, the solution is often not close to its asymptote, and significant error can accumulate from the small perturbation solution. To reduce this error, INSTR(26) may be used to direct the program to attempt to revert back to the exact solution a certain number of time increments (the input value of INSTR(26)) beyond the choke point. Sometimes the attempted reversion will be unsuccessful because the solution is either still too close to the choke point or is already too close to its asymptote; in which case ITER ≥ INSTR(22) will occur, and the program will continue with the small perturbation solution. When this situation occurs, the exact solution is not given a chance to correct the accumulated error, which may affect the asymptote by as much as 10 percent. If this result is encountered, different values of INSTR(26) should be tried, since even a temporary successful reversion to the exact solution can improve the accuracy of the solution considerably.

The remaining data cards constitute primarily a description of the tunnel and its geometry. While most of the table entries are self explanatory, some of them deserve more emphasis. On card number 4, the values of A15 and A16, if used, should be entered...
as negative to invoke the use of ramps. On card number 5, the weight used in computation of the test section pressure for subsonic flow is programmed as 0.5. The input value is used only in supersonic flow. On card number 6, the variable A14 is used to sort the roots from the quartic. A value of -0.2 has been found more effective than -0.1. If the root sorting logic finds more than one value of $\epsilon_{13}$ acceptable, the program will halt in bewilderment, requiring some trial and error adjustment of A14 by the user. On card number 7, it has been found best to keep $\delta_{EMAX} \leq \delta_{PERR}/10$. The quantity A10 is used to obtain debugging information when $T > A10$. Following card number 10, three separate decks for the nondimensional area-time curves for the main valves, plenum exhaust valves, and flaps must be provided. Each deck must contain the number of cards entered on card number one. The times and areas must be nondimensionalized by the values entered on card numbers 9 and 8, respectively, and, therefore, will vary only between zero and one. The times must proceed in ascending order. Table C-5 gives recommended values for some of these entries. The remaining input instructions (11, 12, ...) may be ignored unless NCTL has been entered as other than zero, in which case the user is invited to decipher the program logic in order to determine the endless uses to which this option may be put.

Table C-6 presents a sample job stream and data deck. The first four cards are peculiar to the computer facility. The first "GO" card designates data set 03 a dummy in order to suppress debugging printouts sent to DSRN* IDEBUG. The remaining data cards may be understood via Table A-3.

A portion of the output from this run is shown in Table A-7. The first four pages show the input data along with the initial values of most program variables. In addition, an interpretation of the INSTR(I) options selected is printed. The flow area-time curves are the redimensionalized form in units of seconds and square feet (or whatever units are used in the input data). The form of the remaining output is that due to the selection of INSTR(5) = 2 and generally displays all computed properties at the midpoint or end of each time interval. Each five lines of data separated by a space corresponds to a single time interval, and each block of five numbers corresponds to the similarly positioned block of five variable names in the page heading. Interpretation of these names may be accomplished via Table C-2. The illustrated run went to 180 msec, generated about 1,700 records (lines of print), and required 42.6 sec of central processor (CPU) time on an IBM 370/165. This run may be used as a check case by potential users.

Table C-8 presents a machine listing of the final source deck. All necessary subprograms are included except those available from the IBM subroutine library, from which HIRTS M1 uses DABS, DSQRT, DSIN, DCOS, DATAN2, CDSQRT, and CDABS.

*Data Set Reference Number
Table C-1. Description of Subroutines

**PRIMARY MODEL SUBROUTINES**

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Function</th>
</tr>
</thead>
</table>
| MAIN            | 1. Overall program control  
|                 | 2. Exact model equations  
|                 | 3. Convergence control     |
| SMPERT          | Small perturbation equations |

**SPECIALIZED UTILITY SUBROUTINES**

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT</td>
<td>Obtains initial data from DSRN IIN</td>
</tr>
<tr>
<td>CONST</td>
<td>Defines certain program constants</td>
</tr>
<tr>
<td>INIT</td>
<td>Initializes certain program variables</td>
</tr>
<tr>
<td>DUMP</td>
<td>Prints out all program variables at beginning and end of run and as needed for debugging</td>
</tr>
<tr>
<td>PRINT</td>
<td>Prints numerical solution and controls paging</td>
</tr>
</tbody>
</table>

**GENERAL UTILITY SUBROUTINES**

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLVER</td>
<td>Provides logic for numerical reversion of a function (see Fig. 10)</td>
</tr>
<tr>
<td>BINOM</td>
<td>Expands a binomial to seven terms</td>
</tr>
<tr>
<td>REVERT</td>
<td>Reverts a series to seven terms</td>
</tr>
<tr>
<td>QSIMUL</td>
<td>Converts two conics to a quartic</td>
</tr>
<tr>
<td>QANDC</td>
<td>Computes the exact roots of a quartic</td>
</tr>
<tr>
<td>CUBRT</td>
<td>Computes the exact roots of a cubic</td>
</tr>
<tr>
<td>DREAL</td>
<td>Returns the real part of a double precision complex number</td>
</tr>
<tr>
<td>DIMAG</td>
<td>Returns the imaginary part of a double precision complex number</td>
</tr>
</tbody>
</table>
Table C-2. Definition of Major Program Variables

**REAL ARRAYS**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA</td>
<td>Input nondimensional area-time curves for main valves, flaps, and plenum exhaust valves</td>
</tr>
<tr>
<td>AREATS</td>
<td>Interpolated areas for time t*</td>
</tr>
<tr>
<td>AREAM</td>
<td>Peak of area-time curves (dimensional)</td>
</tr>
<tr>
<td>TV</td>
<td>Nondimensional times for area-time curves</td>
</tr>
<tr>
<td>E</td>
<td>Convergence criteria errors</td>
</tr>
<tr>
<td>TVF</td>
<td>Total time for main valves, flaps, and plenum exhaust valves (dimensional)</td>
</tr>
<tr>
<td>TDELAY</td>
<td>Delays times for first motion of valves and flaps</td>
</tr>
<tr>
<td>RW</td>
<td>Coefficients for the reverted expansion of the mass Flux-Mach number wave equation</td>
</tr>
<tr>
<td>V</td>
<td>Array equivalenced to major property values</td>
</tr>
<tr>
<td>RSTR</td>
<td>Array equivalenced to certain real commoned variables to simplify writing of solution onto a storage device for restarting a run</td>
</tr>
<tr>
<td>ISTR</td>
<td>Array equivalenced to certain integer variables for storage and restarting</td>
</tr>
</tbody>
</table>

**REAL SCALARS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pxi</td>
<td>Pressure</td>
</tr>
<tr>
<td>MDxi</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>Txi</td>
<td>Temperature</td>
</tr>
<tr>
<td>Rxi</td>
<td>Density</td>
</tr>
<tr>
<td>Mxi</td>
<td>Mach number</td>
</tr>
<tr>
<td>Axi</td>
<td>Flow areas</td>
</tr>
</tbody>
</table>
Table C-2. Continued.

x-codes:

x = N          Nozzle exit (test section entrance)
   = P          Plenum
   = PT         Plenum at time t (PPT) or wall crossflow (MDPT)
   = D          Diffuser entrance (test section exit)
   = T          Test section midpoint (PT)
   = CTO        Stagnation condition, charge tube
   = CT         Charge tube
   = E          Main valve exit
   = F          Flaps
   = PE         Plenum exhaust
   = C          Charge conditions

i - codes:

i = blank      Values at current time interval and current iteration
i = 1          Converged values from last time interval
i = 2          Values from last iteration, current interval
i = 3          Scratch area
   G           Specific heat ratio (γ)
   R           Ideal gas constant
   PERR        Error limit on pressures
   KF          Flap flow coefficient
   KW          Wall crossflow coefficient
   TSL         Test section length
   TSH         Height
### Table C-2. Continued.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSW</td>
<td>Width</td>
</tr>
<tr>
<td>TSP</td>
<td>Perimeter</td>
</tr>
<tr>
<td>TSA</td>
<td>Flow area</td>
</tr>
<tr>
<td>TSWA</td>
<td>Wall surface area</td>
</tr>
<tr>
<td>TSV</td>
<td>Volume</td>
</tr>
<tr>
<td>CTD</td>
<td>Charge tube diameter</td>
</tr>
<tr>
<td>CTA</td>
<td>Charge tube flow area</td>
</tr>
<tr>
<td>PV</td>
<td>Plenum volume</td>
</tr>
<tr>
<td>PVOTSV</td>
<td>Plenum: test section volume ratio</td>
</tr>
<tr>
<td>TAUW</td>
<td>Porosity</td>
</tr>
<tr>
<td>T</td>
<td>Time at end of current interval (t)</td>
</tr>
<tr>
<td>Tl</td>
<td>Time at end of last interval (t - Δt)</td>
</tr>
<tr>
<td>DT</td>
<td>Time increment</td>
</tr>
<tr>
<td>TSTR</td>
<td>Midpoint of current interval (t*)</td>
</tr>
<tr>
<td>TSTOP</td>
<td>Time for termination of run</td>
</tr>
<tr>
<td>Ai</td>
<td>Miscellaneous program constants</td>
</tr>
</tbody>
</table>

#### INTEGER ARRAYS

- **INSTR**: Program control instructions (see input)
- **NVT**: Number of time points in each of three input area-time curves

#### INTEGER SCALARS

- **IDEBUG**: Data set reference number (DSRN) for debugging output, normally dummied
- **IIN**: DSRN of input data (usually 05 for card reader)
- **IOUT**: DSRN of primary output data (usually 06 for line printer)
- **ITER**: Number of iterations
### Table C-2. Concluded.

NP  
**Printing time interval**

IFLGi  
**Miscellaneous program control flags**

### Table C-3. Description of Program Input

#### a. Main Program

<table>
<thead>
<tr>
<th>Variable</th>
<th>Index</th>
<th>Value</th>
<th>Action</th>
<th>Default Value</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCTL</td>
<td>0</td>
<td>Proceed through normal programmed solution procedure</td>
<td>0</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Read INSTR(*)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Write heading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Read data file and print results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Proceed to normal calculation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Call INPUT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Call INIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Call CONSRT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Call DUMP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Call SOLVER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Call PRINT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Call BINOM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Call REVERT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Stop</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**INSTR**

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
<th>Action</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>06</td>
<td>Print debugging data</td>
<td>(One Card)</td>
</tr>
<tr>
<td>03</td>
<td>Skip debugging prints (DSRN 03 is dummy)</td>
<td>03</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Input DSRN</td>
<td>05</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Output DSRN</td>
<td>06</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Printing time interval</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pressures in psf</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Extrapolate to next time interval as an initial guess</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Do not extrapolate</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Use reverted series from mass flux - Mach number wave equation</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Use second-degree approximation</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Use iterative solution to energy and wave equations</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Use approximate expansions for energy and wave equations</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Average current value with previous average value</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Average current value with previous unaveraged value</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Do not invoke option</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Continued

a. Concluded

<table>
<thead>
<tr>
<th>Variable</th>
<th>Index</th>
<th>Value</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>INSTR</td>
<td>11</td>
<td>&gt;0</td>
<td>iteration limit beyond which current weight is halved</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>1</td>
<td>Do not invoke option</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>&gt;1</td>
<td>Divide error limits PERR and $EMAX$ by INSTR(12) if the fractional difference between successive time intervals is less than (errors) x (INSTR(12))</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>#0</td>
<td>Print only time and pressure data</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0</td>
<td>Print everything</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>&gt;1</td>
<td>Set DT = DT*INSTR(14) based on INSTR(12) criteria, do not cut error limits</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1</td>
<td>Do not invoke option</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>#03</td>
<td>Read solution from DSRN = INSTR(15), skip other input</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>0</td>
<td>Do not read solution</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>[1,1000]</td>
<td>First record number to be read</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>[1,1000]</td>
<td>Last record number to be read</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>#03</td>
<td>Write solution on DSRN = INSTR(18)</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>0</td>
<td>Do not write solution</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>[1,1000]</td>
<td>First record number to be written</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0</td>
<td>Do not invoke option</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>&gt;0</td>
<td>When weight is halved, increment INSTR(11) by INSTR(20)</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>0</td>
<td>Do not invoke option</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>&gt;0</td>
<td>Set INSTR(7) = 2 to extrapolate next time interval when weight is halved</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>#0</td>
<td>Do not use small perturbation expansion</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>Use small perturbation initial guess for next time interval</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>&gt;0</td>
<td>Use small perturbation expansions as solution</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>#0</td>
<td>SMPERT prints small perturbation results</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>0</td>
<td>Does not print without error</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>1</td>
<td>Use isentropic solution in plenum</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>2</td>
<td>Use anisentropic solution in plenum</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>0</td>
<td>Do not invoke option</td>
</tr>
<tr>
<td></td>
<td>37</td>
<td>&gt;0</td>
<td>Revert to exact equation after the input number of time increments beyond choking</td>
</tr>
</tbody>
</table>

\*Square brackets [ ] indicate the range of the variable.
Table 3. Concluded

b. Subroutine INPUT

<table>
<thead>
<tr>
<th>Variable, units</th>
<th>Card Number</th>
<th>Value</th>
<th>Meaning</th>
<th>Default Value</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVT(1)</td>
<td>1</td>
<td>[2,50]</td>
<td>Number of area-time points for main valve</td>
<td>2613</td>
<td>SE16.8</td>
</tr>
<tr>
<td>NVT(2)</td>
<td>2</td>
<td>[2,50]</td>
<td>Number of area-time points for plenum exhaust valve</td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>NVT(3)</td>
<td>3</td>
<td>[2,50]</td>
<td>Number of area-time points for flaps</td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>PC, psia</td>
<td>2</td>
<td>Charge pressure</td>
<td></td>
<td>2613</td>
<td>SE16.8</td>
</tr>
<tr>
<td>TC, °K</td>
<td></td>
<td>Charge temperature</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TSL, ft</td>
<td>3</td>
<td>Test section length</td>
<td></td>
<td>2613</td>
<td>SE16.8</td>
</tr>
<tr>
<td>TSN, ft</td>
<td></td>
<td>Test section height</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TSW, ft</td>
<td></td>
<td>Test section width</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>CTD, ft</td>
<td></td>
<td>Charge tube diameter</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>PVOTSV</td>
<td></td>
<td>Ratio of plenum volume to test section volume</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TA0W</td>
<td>4</td>
<td>Porosity (fraction, not percent)</td>
<td></td>
<td>1.0</td>
<td>SE16.8</td>
</tr>
<tr>
<td>KW, ft/sec</td>
<td>5</td>
<td>Perfect gas constant</td>
<td></td>
<td>1.0</td>
<td>SE16.8</td>
</tr>
<tr>
<td>KF, ft/sec</td>
<td></td>
<td>Ratio of specific heats (γ)</td>
<td></td>
<td>0.5</td>
<td>SE16.8</td>
</tr>
<tr>
<td>A15b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>A16b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A17</td>
<td>6</td>
<td>Time increment for numerical calculation</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>DT, sec</td>
<td></td>
<td>Time to halt calculation</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>TSTOP, sec</td>
<td></td>
<td>Maximum allowable error - used in SOLVER</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>$NMAX</td>
<td></td>
<td>Maximum allowable error - used in MAIN</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>A10, sec</td>
<td></td>
<td>Time at which INSTR(8) is set different from zero</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>AREA(1), ft²</td>
<td>8</td>
<td>Maximum main valve flow area</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>AREA(2), ft²</td>
<td></td>
<td>Maximum plenum exhaust flow area</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>AREA(3), ft²</td>
<td></td>
<td>Maximum flap flow area</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TVF(1), sec</td>
<td>9</td>
<td>Final time in main valve area-time curve</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>TVF(2), sec</td>
<td></td>
<td>Final time in plenum exhaust area-time curve</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TVF(3), sec</td>
<td></td>
<td>Final time in flap area-time curve</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TOELAY(1), sec</td>
<td>10</td>
<td>Time delay for main valve</td>
<td></td>
<td>1.070</td>
<td>SE16.8</td>
</tr>
<tr>
<td>TOELAY(2), sec</td>
<td></td>
<td>Time delay for plenum exhaust</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TOELAY(3), sec</td>
<td></td>
<td>Time delay for flaps</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td>TV(1,1)</td>
<td></td>
<td>Non-dimensional time (final = 1.0) and non-dimensional area (maximum = 1.0)</td>
<td></td>
<td>2613</td>
<td>SE16.8</td>
</tr>
<tr>
<td>AREA(1,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV(2,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA(2,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TV(3,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AREA(3,1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td>1</td>
<td>Return 1</td>
<td></td>
<td>2613</td>
<td>SE16.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Read ISTR(12)</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Read RSTR(12)</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indices of array elements to be read</td>
<td></td>
<td></td>
<td>SE16.8</td>
</tr>
</tbody>
</table>

*a Card Order is Input Deck
*b if less than Zero, Ramps of Fig. 27b Will Be Used
*c Round Brackets Exclude End Points
*d These Cards Omitted Unless NCTL ≠ 0

Note: If INSTR(9) = 1, any set of units for which $\xi_a = 1$ in $T = 1/\xi_a$ ma will work properly.
Table C-4. Suggested Values for INSTR(I)

<table>
<thead>
<tr>
<th>I</th>
<th>Suggested Value of INSTR(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>03</td>
</tr>
<tr>
<td>2</td>
<td>05</td>
</tr>
<tr>
<td>3</td>
<td>06</td>
</tr>
<tr>
<td>4</td>
<td>01</td>
</tr>
<tr>
<td>5</td>
<td>02</td>
</tr>
<tr>
<td>6</td>
<td>00</td>
</tr>
<tr>
<td>7</td>
<td>02</td>
</tr>
<tr>
<td>8</td>
<td>01</td>
</tr>
<tr>
<td>9</td>
<td>01</td>
</tr>
<tr>
<td>10</td>
<td>01</td>
</tr>
<tr>
<td>11</td>
<td>40&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>13</td>
<td>0 or 1</td>
</tr>
<tr>
<td>14</td>
<td>01</td>
</tr>
<tr>
<td>15</td>
<td>03</td>
</tr>
<tr>
<td>16</td>
<td>00</td>
</tr>
<tr>
<td>17</td>
<td>00</td>
</tr>
<tr>
<td>18</td>
<td>03</td>
</tr>
<tr>
<td>19</td>
<td>00</td>
</tr>
<tr>
<td>20</td>
<td>10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>00</td>
</tr>
<tr>
<td>22</td>
<td>01</td>
</tr>
<tr>
<td>23</td>
<td>01</td>
</tr>
<tr>
<td>24</td>
<td>00</td>
</tr>
<tr>
<td>25</td>
<td>02</td>
</tr>
<tr>
<td>26</td>
<td>09&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Adjustment May Be Necessary for Specific Cases
Table C-5. Recommended Values for Certain Variables

<table>
<thead>
<tr>
<th>Variable Names</th>
<th>Recommended Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KW, KF</td>
<td>See Fig. 7</td>
</tr>
<tr>
<td>A15, A16</td>
<td>See Fig. 27a, Enter Negative 0.5 or Leave Blank</td>
</tr>
<tr>
<td>A11</td>
<td>0.9</td>
</tr>
<tr>
<td>A13</td>
<td>Leave Blank</td>
</tr>
<tr>
<td>A14</td>
<td>-0.2</td>
</tr>
<tr>
<td>PERR</td>
<td>0.49999999E-05</td>
</tr>
<tr>
<td>$EMAX</td>
<td>0.49999999E-04</td>
</tr>
</tbody>
</table>

Table C-6. Sample Jobstream and Input Data Deck

```plaintext
/*PRIORITY 2
/*VKF05145 JOB (ARO
// VRV00090+01+V37A=31A) 40962SHDE+MSLEVEL=(2.0)+CLASS=A+TIME=3
// EXEC FORTEPOS,PGMNO=VRV00090
/*GO,FT03F901 DD DUMMY
/*GO,FT05F901 DD *
000
02 10 02
0.15215000E+03 0.53000000E+03
2.11400000E 00 0.61170000E 00 0.76330000E 00 1.16200000E 00 2.50000000E 00
0.04000000E 00 0.31000000E+03 0.20000000E+03 1.04988410E 00 -1.06312800E 00
0.00000000E 00 0.17176000E+04 1.40000000E 00 0.49999999E-04 0.49999999E-05
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00 0.00000000E 00
*/
```
TABLE C-7
SAMPLE OUTPUT FROM HIRTSM1 FOR RUN 2742
INSTRU(1)= 3  SEND DEBUGGING OUTPUT TO DSRN 3
INSTRU(2)= 5  OBTAIN INPUT FROM DSRN 5
INSTRU(3)= 6  SEND REGULAR OUTPUT TO DSRN 6
INSTRU(4)= 1  PRINTING TIME INTERVAL 1
INSTRU(5)= 2  INPUT AND OUTPUT PRESSURES IN PSI
INSTRU(6)= 0  PRINT DATA ONLY WHEN CONVERGED
INSTRU(7)= 2  DO NOT extrapolate TO NEXT TIME INTERVAL
INSTRU(8)= 1  USE SEVENTH DEGREE REVERSED SERIES AS INITIAL GUESS TO MASS FLUX-MACH NUMBER WAVE EQUATION
INSTRU(9)= 1  USE ITERATIVE SOLUTION TO ENERGY AND WAVE EQUATIONS
INSTRU(10)= 1  AVERAGE VALUES OF CURRENT ITERATION WITH AVERAGE VALUES OF PREVIOUS ITERATION
INSTRU(11)= 20  CURRENT WEIGHT IS HALVED BEYOND 20 ITERATIONS
INSTR(22) = 20 SET INSTR(22) = 2 WHEN ITER >= 9
INSTR(23) = 1 USE SMALL PERTURBATION EXPANSIONS AS INITIAL GUESS FOR NEXT TIME INTERVAL
INSTR(24) = 0 RESULTS FROM SIMPER NOT PRINTED
INSTR(25) = 2 SET TDF AND TPT = MAX [TDF, TPT]
INSTR(26) = 9 REVERT TO ACTUAL SUPERSONIC SOLUTION 9 TIME INCREMENTS AFTER CHOKE

```
J 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

FLOW AREAS VERSUS TIME

|   | TV(1|1) | ASEA(1|1) | TV(2|1) | ASEA(2|1) | TV(3|1) | ASEA(3|1) |
|---|------|--------|------|--------|------|--------|--------|
| 1 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 2 | 0.3000000000-01 | 0.6659111750 | 0.0 | 0.5000000000-02 | 0.0 | 0.0 | 0.0 | 0.9107000000-01 |
| 3 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 4 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 5 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 6 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 7 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 8 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 9 | 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 10| 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
| 11| 0.0  | 0.0    | 0.0  | 0.0    | 0.0  | 0.0    | 0.0    |
```

INSTR(12) = 10 DIVIDE ERRORS BY 10 WHEN TIME-DIFFERENCES ARE LESS THAN 10 TIMES THE ERRORS
INSTR(13) = 0 PRINT ALL DATA
INSTR(14) = 1 DO NOT INVOKE DT-RAISING OPTION
INSTR(15) = 3 DO NOT READ SOLUTION FROM PERMANENT DATA SET
INSTR(16) = 0 FIRST RECORD TO BE READ: 0
INSTR(17) = 0 LAST RECORD TO BE READ: 0
INSTR(18) = 3 DO NOT WRITE SOLUTION ON PERMANENT DATA SET
INSTR(19) = 0 FIRST RECORD TO BE WRITTEN: 0
INSTR(20) = 10 INCREMENT INSTR(11) BY 10 WHENEVER WEIGHT IS MALVED
INSTR(21) = 0 DO NOT CHANGE Extrapolation OPTION (INSTR(7))
INSTR(23) = 2 SET TP AND TPT = MAX [TDF, TPT]
INSTR(26) = 9 REVERT TO ACTUAL SUPERSONIC SOLUTION 9 TIME INCREMENTS AFTER CHOKE
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<thead>
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<th>PCTO</th>
<th>T1</th>
<th>TI</th>
<th>PP</th>
<th>PD</th>
<th>PN</th>
<th>TPT</th>
<th>NO</th>
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<tbody>
<tr>
<td>PC0</td>
<td>PE0</td>
<td>MCT</td>
<td>MCT</td>
<td>MCTS</td>
<td>MCTO</td>
<td>TP</td>
<td>TEO</td>
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<tr>
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<td>MDE</td>
<td>MDPE</td>
<td>MCTS</td>
<td>MCTO</td>
<td>AL</td>
<td>AF</td>
<td>IER</td>
</tr>
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<td>TCTO</td>
<td>RP</td>
<td>RP</td>
<td>TPT</td>
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<table>
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PERR CUT TO 0.49999999999 AND BESAM CUT TO 0.49999999999
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<td>PEU</td>
<td>MCT</td>
<td>P1</td>
<td>PP</td>
<td>PD</td>
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**Switching to Small Perturbation Solution Entirely**

| 0.3300000 | 0.3200000 | 0.3200000 | 0.7083500 | 0.7975000 | 0.7726000 | 0.7841000 | 0.10 |
| 0.1127130 | 0.1127130 | 0.2429950 | 0.8082600 | 0.7738500 | 0.5405800 | 0.6795000 | 0.5473800 | 0.16 |
| 0.4864100 | 0.4864100 | 0.1304500 | 0.1942600 | 0.1942600 | 0.8591100 | 0.8591100 | 0.8591100 | 0.19 |
| 0.3798900 | 0.3798900 | 0.9915100 | 0.4749400 | 0.7385100 | 0.5385200 | 0.5385200 | 0.5385200 | 0.19 |

**List of Equations**

1. \( T \)
2. \( PCTO \)
3. \( PEU \)
4. \( MCT \)
5. \( P1 \)
6. \( PP \)
7. \( PD \)
8. \( PMPT \)
9. \( PPT \)
10. \( NO \)

**Parameters**

- **T**: Temperature
- **PCTO**: Perturbation Control Parameter
- **PEU**: Perturbation Excess Unit
- **MCT**: Main Control Parameter
- **P1**: Perturbation Initial
- **PP**: Perturbation Final
- **PD**: Perturbation Deviation
- **PMPT**: Perturbation Main Parameter
- **PPT**: Perturbation Total
- **NO**: Number of Observations

---

The table above provides a comprehensive overview of the parameters and equations relevant to the study. Each entry corresponds to a specific value or calculation, contributing to a detailed analysis of the system under examination.
<table>
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**AEDC-TR-76-39**
TABLE 8
LISTING OF THE COMPUTER PROGRAM HIRTS M1
AEDC-TR-76-39

DATE = 75157
11/58/40

C HIRTSI = HIRTS STARTING MODEL

IMPLICIT REAL*8 (A-H,M-O-Z)$

COMMON AREA(3,50),AREAT(3),AREAT(3),TV(3,50),A(10),E(7),B(30),
1 TV(3),TVLAY(3),RIW(2)

COMMON PC,RC,TC,AC,MODCTCE(3),

1 SODR

COMMON G,GM1,G1P1,GG1P2,GG1P2,G1P2,G1P1,G1P1,G1P1,G1P1,G1P1,
1 G,GM1,G1P1,GG1P2,GG1P2,G1P2,G1P1,G1P1,G1P1,G1P1,

2 G,GM1,G1P1,GG1P2,GG1P2,G1P2,G1P1,G1P1,G1P1,G1P1,

COMMON T41,DTSTRB,DT02,DT01,OD01,OD01,OD01,OD01,

COMMON A,1,A0,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,A17,

COMMON PN, PV, PT, PCT0, PE0, MDE,

M, VDF, MDP, MCT, MDF, MDTSO + MDT, TE0, TP,

- TP1, TCT0, AP, RPT, R00, RCT0, ACT0, MCT, AE,

- APE, AF, NN, MN

COMMON PN1, PP1, PP1, PD1, PT1, PCT01, PE01, MDE1,

- MDP1, VDF1, MDP1, MCT1, MDF1 + MDT01, TE01, TP1,

- TP01, TCT01, AP1, RPT1, R001, RCT01, ACT01, MCT1, AE1,

- APE1, AF1, NN1, MN1,

COMMON PN2, PP2, PP2, PD2, PT2, PCT02, PE02, MDE2,

- MDP2, VDF2, MDP2, MCT2, MDF2 + MDT02, TE02, TP2,

- TP2, TCT02, AP2, RPT2, R002, RCT02, MCT2, AE2,

- APE2, AF2, MN2, MDP3, VDF3, MDP3, MCT3, MDF3,

- TP3, TCT03, AP3, RPT3, R003, RCT03, MCT3, AE3,

- APE3, AF3, MN3, MDP3

COMMON PD0, PS0, PS0, TS0, TS0, TS0, TS0, TS0

COMMON SY, SYL, SYZ, SYZ, SDX, SE1, SE2, SMAX, SDF

COMMON INSTR(26), TIN, OUT, NP, IP, P, TEP, NVT(3), EXT, NPT(3),

INPAP, NINT(3), J1, J10, J11, J11, J12, J12, J13, J13, J14, J13, J15, J16, J17

 drug

1 J18, J19, J20, J21, J22, J23, J24, J25, J26

COMMON NCTL

DIMENTION (30,4), RSTR(520), ISTR(35), IETPN(7), JV(26)

DIMENTION (4,2)

ENIPT(1), ARE(1), ARE(1), T((ISTR(1), NP)), (P/N=1), (J-V(1), J1)

INTEGER SY

REAL KF, KW

DATA IEXT(1), 12, 6, 7, 10, 14, 16

DATA C1=-1.14853817,2,453750102e,4353067302e,106855402

1.=-1.5523304372e,1693984372e,1328817903e,3091333207

DEFINE FILE 01(1300,1206,140,116)

G, GM1, G1P1, G1P2, G1P2, G1P1, G1P1, G1P1, G1P1, G1P1,

COMMON MDPT(01,02) = AWOKW*(D1-D2*A15)*A2

ITMP=0

ITFH=1

TFLG0=1

TFLG0=1

TFLG0=1

TFLG0=1

TFLG0=1

TFLG0=1

TFLG0=1

TFLG0=1

DEFINE(0)
IIN=05
TOUT=06
NP=1
T5=0
10 READ(I14,120)NCTL
C---------------
C MANUAL PROGRAM CONTROL
C---------------
IF(NCTL.EQ.0)GO TO 100
WRITE(IOUT,15)NCTL
15 FORMAT(*0*NCTL=*I3)
C---------------
1 2 3 4 5 6 7 8 9 10 11 12 13 14
GO TO(100,125,129,1116,20,30,40,50,60,70,80,90,151,95)*NCTL
20 CALL: INPUT(410)
30 CALL: INIT(110)
40 CALL: CONST(110)
50 CALL: DUMP(110)
50 CALL: SOLVSTR(110)
70 CALL: PRINT(110)
90 CALL: INVERT(110)
95 CALL: SMPERT(110)
C-----------------
.C READ AND DEFINE DEFAULT RUN CONTROL INSTRUCTIONS
C-----------------
100 READ(I1N,120)INSTR
120 FORMAT(26I3)
IF(INSTR(1),NE,0)INSTR(1)=DEBUG=INSTR(1)
IF(INSTR(2),NE,0)INSTR(1)=IN=INSTR(2)
IF(INSTR(2),EQ,0)INSTR(2)=IIN
IF(INSTR(3),NE,0)INSTR(3)=INSTR(3)
IF(INSTR(3),EQ,0)INSTR(3)=IOUT=INSTR(3)
IF(INSTR(4),NE,0)INSTR(4)=INSTR(4)
IF(INSTR(4),EQ,0)INSTR(4)=IIN
IF(INSTR(5),NE,0)INSTR(5)=IOUT=INSTR(5)
IF(INSTR(5),EQ,0)INSTR(5)=0
IF(INSTR(7),EQ,0)INSTR(7)=2
IF(INSTR(8),EQ,0)INSTR(8)=1
IF(INSTR(9),EQ,0)INSTR(9)=1
IF(INSTR(12),EQ,0)INSTR(12)=1
IF(INSTR(14),EQ,0)INSTR(14)=1
IF(INSTR(15),EQ,0)INSTR(15)=03
IF(INSTR(18),EQ,0)INSTR(18)=03
IF(INSTR(22),EQ,0)INSTR(22)=999999
IF(INSTR(25),EQ,0)INSTR(25)=2
IF(INSTR(26),EQ,0)INSTR(26)=999999
DO 121 I=1,76
121 JV(I)=INSTR(I)
125 IF(NCTL.NE,0)GO TO 10
C---------------
C PRINT HEADING
C---------------
130 WRITE(IOUT,130)
130 FORMAT(15+29X*415)}/30X*5+7X*5/30X*5 HIRSM1 = MATHEMATICAL STARTING MODEL FOR A LUNWIG TUBE WIND TUNNEL $*/30X*5
MAIN

DATE = 75157  11/58/40

272X*5+30X*5  ARNOLD RESEARCH ORGANIZATION, ARNOLD AIR FORCE STA
3710X+*12X*5+30X*5+72X*5+30X*7A(*511)

IF(NCTL,NC,.EQ.0)GO TO 10

129 IF(J15.EQ.031560) TO 135

C READ SOLUTION FROM DATA FILE AND PRINT
C-------------------------------

K1=0

131 IF(J15,NE,.07)GO TO 128
    READ(J15,END=132)RSTR,ISTR
    J16=J16+1
    GO TO 127
128 READ(J15,J16)RSTR,ISTR
    FIND(J15,J16)

127 IF(K1,LT,0)CALL DUMP
    IPAGE=K1
    CALL PRINT
    K1=IPAGE
    IF(J16-1,EQ,J17)GO TO 132
    GO TO 13

132 IF(INSTR(J15,EQ.0))GO TO 134
    WRITE(OUT,J133)

133 FORMAT(*11*)
    CALL DUMP
    IPAGE=0
    CALL PRINT

134 J19=J19
    WRITE(OUT,J136)

136 FORMAT(*11*)
    DMT=MD-M9
    DNN=MN-M9
    IF(NCTL,NC,.NE.0160)GO TO 10
    GO TO 1116

C-------------------------------

C READ INPUT, INITIALIZE VARIABLES, AND PRINT RESULTS

C-------------------------------

135 J16=J16
    IF(S=0)
    CALL INPUT
    CALL CONST
    CALL INIT
    CALL DUMP
    IF(A15,AT,0,00)GO TO 140
    IF(S=1)
    IF(A16,GE,0,00)GO TO 139
    A15=DARS(A15)
    A16=DARS(A16)
    IF(S=2)
    139 A15=1,00
    A16=1,00

140 CALL PRINT
    IF(J18,EO,.EQ.03)GO TO 150
    IF(J18,NE,.EQ.03)GO TO 145
    WRITE(J18,J161)

141 FORMAT(32(*11*),*45,*,*11*)),*45,*,*11*)
    WRITE(J18,J161)
J16=J16+1
GO TO 150

145 WRITE(J10+J16)ISTR,TSTR

C START NEW TIME INTERVAL

150 T1=T1+DT
  IF(FLG1.EQ.0) GO TO 280
  GO TO (269,282,276) IF(FLG1)

269 IF(M01.GE.1.00) GO TO 270
A15=1.00
A16=1.00
GO TO 276

270 A(1)=0.00
A(2)=0.00
DO 274 I=1,6
A(3)=MD1*(I-1)
DO 272 J=1,2

272 A(J)=A(J)+C(I,J)*A(3)

274 CONTINUE
  A15=A(1)
  A16=A(2)
  GO TO 276

242 IF(M01.GE.1.00) GO TO 284
  A15=(A15-1.00)*MD1+1.00
  A16=(A16-1.00)*MD1+1.00
  GO TO 275

284 A15=A15A
A16=A16A
IFLAG1=3

276 WRITE(1,DEBUG)MD1,A15,A16

278 FORMAT(6E16.8) A15=*,E16.8, A16=*,E16.8)

280 IF(ISTR(26)) GO TO 143

INSTR(23)=1
WRITE(OUT,142)

142 FORMAT(10,REVERTING TO EXACT SUPERSONIC SOLUTION')

143 IF((INSTR(10).EQ.0).OR.(ITER.LT.INSTR(1))) GO TO 152

C WEIGHT CUTTING

151 5=ALL
A2=0.1*ALL
INSTR(11)=INSTR(11)+INSTR(20)
WRITE(OUT,1205)ITER=ALL,INSTR(11)

1205 FORMAT(6I6)ITER=*,E13.5, WT HALVED TO *F5.3,* INSTR(11) RAISED
1D TO *F1.17
1PAGE=1PAGE+2

152 IF(T*60+CHANGEMOD) OUT

130 TST=1+DT02
TIME=TIME+1

10 IF(IFLAG1.EQ.2) IFLAG4=1

C SET PRESSURES OF LAST ITERATION TO INFINITY FOR ERROR COMPUTATION

DO 153 ITER=1,7
   V(I)=INFIN
   ITER=0
   IF(IFLAG1.EQ.0) GO TO 155

153 V(I)=1
155 V(I)=INFIN

ITER=0
AEDC-TR-76-39

---

C COMPUTE AREAS OF VALVES AT TSTR

C---------------------------------------------

155 DO 220 J=1,3
   11=NVT(J)
   IF(TSTR(GT-TV(J,I1))) GO TO 200
   12=I(I)
   DO 160 I=12,11
   14=I-1
   IF((TSTR LE TV(J+1M1)),OR,(TSTR GT TV(J,I1))) GO TO 160
   15=I1
   IF(L31=3
   A(1)=TSTR-TW(J+1M1)
   A(2)=1./(TV(J,I)-TV(J+1M1))
   AREA(J)=AREA(J,I)+AREA(J+1M1) *A(1)*A(2)+AREA(J,1M1)
   GO TO 220
   160 CONTINUE
   WRITE(TOUT*190)
   190 FORMAT(*STOP AT 190*)
   STOP
   200 AREAS(J)=AREA(J,NVT(J))
   GO TO(210,220+220)*IFLG1
   210 IFLG1=2
   220 CONTINUE
   IF(IFLG1=EQ.3 IFLG1=1

C---------------------------------------------

C BEGIN NEXT ITERATION AT SAME TIME INTERVAL

C---------------------------------------------

240 ITER=ITER+1
   244 IF(ITEP.LT.INSTR(22)) GO TO 242
   INST=23
   IF(IFLG1.EQ.1) WRITE(TOUT*245)
   245 FORMAT(*SWITCHING TO SMALL PERTURBATION SOLUTION ENTIRELY*)
   IFLG1=2
   241 ITER=1
   242 N=0
   QN=0
   NCT=0
   IF(ITEP.GE.INSTR(22)) INST=2
   243 IF(IFLG1.EQ.1) GO TO 250

C---------------------------------------------

C SFT CHARGE TURF AND NOZZLE VARIABLES TO STEADY CHOKED VALVES

C---------------------------------------------

250 IF(IFLG6*EQ.2) GO TO 250
   IFLG6=2
   $Y=CTA/TS
   IFLG=3
   IFLG2=1
   CALL SOLVER
AEDC-TR-76-39

MCT=SN
A(1)=(1.+GM12*MCT**2)/(1.+GM12*MCT)**2

TC0=TC+A(1)

V0=TC0

PC0=PC+A(1)**20GM1

ACT0=DSQRT(ACT0*ACT0)

MDT0=MDT0*ACT0*TS0

MXT0=MDT0*ACT0*TS0

MN=1.

PN=50POP*PC0

MDT0=MDT0*DSQRT(TS0*TST0)*ACT0*TS0

IF(LG2=1)

WRITE(TOUT=249)

FORMAT(10,WOZZLE HAS CHOKED!)

MCT1=MCT

TC01=TC0

ACT01=ACT0

MN1=MN

PN1=PN

MDT1=MDT1

MDT01=MDT0

PT1=A17*PD+(1.0D0-A17)*PN

PT2=PT

IF(INST(23),EQ,0)GO TO 255

IF((IT,6T,A13)INSTR(23)=2

IF((INSTR(23),EQ,31)AND.(ITER.GE.INSTR(11)))GO TO 253

252 IF((ITER,NE,1160)GO TO 255

C---------------------------

C CALL SMALL PERTURBATION PACKAGE

C---------------------------

253 DO 260 I=1,3

II=I+25

V(II,1)=AREAS(1)

EA(1)= V(II,1)-V(II,2)

260 CONTINUE

IF((ARFATS(3),EQ,0,D0).AND.((EA(3),EQ,0,D0))MDF1=0.00

IF((AREAS(2),EQ,0,D0).AND.((EA(2),EQ,0,D0))MDF1=0.00

CALL SMPERT

K1=SIGN(1.500)+PT-ACT0*PD0P01

IF((1,F0.50,FILG2)GO TO 256

IF((FILG10,EQ,2)GO TO 258

IFLS10=2

IF((FILG2,EQ,11)IFLG2=K1

IF((FILG2,EQ,11)GO TO 241

258 IFLS10=1

256 IF((INSTR(23),EQ,31)AND.(ITER,GE,INSTR(11)))GO TO 254

IF((INSTR(23),EQ,2)GO TO 254

GO TO 255

254 IF((J118,EQ,0)GO TO 1190

WRITE(J118,J16)IRSTR,ISTR

90
FIN87(J1A1,J1A1)
GO TO 1190
255 IF(FLG2)500,9999,251
C------------------------
C SUBSONIC BRANCH
C------------------------
251 MDF=A1*RE0*AREA*(1)/DSRT(TF0)*A2
IFLG2=1
IFLG6=1
MDN=MDF*MTF
C DIFFUSER MACH NUMBER AND PRESSURE
SY=MDN/MDT50
IFL3=2
CALL SOLVER
MD=XL
ND=$N
PD=CT0*PO00(MD)
PT=5*(PD+PN)
MDPT=MDF*PT0(PD+PT)
MDCT=MDN*MDPT
C CHARGE TUBE MACH NUMBER
SY=MDC/MDCCT
IFL3=6
CALL SOLVER
MC1=XL
NCT=$N
A(1)=(1.*GM102*MC1**2)/(1.*GM102*MC1)**2
TCT0=CT0*A(1)
PCT0=PC*A(1)**S061
ACT0=PCT0*MDR/TCT0**8
PE=OPT
TCT0=TCT0
ACT0=DSRT(GR*TCT0)
A(1)=RTO*ACT0
MDCT0=A(1)*CTA
MDT50=(A1)**8
C N37LE MACH NUMBER AND PRESSURE
SY=MDC/MDC50
IFL3=2
CALL SOLVER
MV=XL
NV=$N
PN=CT0*PO00(MN)
IF(PD.LE.PCT0*PS00)60 TO 241
GO TO 1000
C-----------------------
C SJPERSONIC BRANCH
C-----------------------
500 PT=A17+PO0*(1.30-A17)*PN
IFLG3=1
IFLG12=1
MDP=MDF*PT0(PD+PT)
MDN=MDC-MDPT
MDF=MDF+MDN
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```
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TEO = TCTO
PE0 = MDF*DSORT(TEO)*20/1 AREA(T1)*A3
REQ = PERD*DSORT/TEO*1/2

C DIFFUSE PRESURE AND MACH NUMBER
$ = MDF/MDTS0
IFLS = 2
CALL SOLVER
MD = $X1.
NP = SN.
PD = TCTO*POPQ(MD).

C-------------------------------------
C UPDATE PLNUM CONDITIONS
C-------------------------------------
1000 IF (IFLS2) 1001, 9999, 1002
1001 PT = (1.0 - A17)*PN + A17*PD
GO TO 1003
1002 PT = 0.5*PN + PD.
1003 MDF = ARFAT5(1)*MD + (PD - A16)*A2
RPT = RPT1 + (MD + MDF + MDFE + DT0P)
RP = 5*(RPT + RPT)
IF (IFLS9.EQ.2) GO TO 1108
RPT = RPT1 + (RPT + RPT2)*2
TPT = TPT0 + TPT + A2
PP = RPT1 + (RP/RPT1)*A2
TP = PP * RPT / RP * A2
IF (INSTR(25).EQ.1) GO TO 1020
IF (TPT.EQ.TCTO) GO TO 1020
IFLS = 2.
1010 TP = TCTO
TPT = TCTO
PP = 3*RP + TP/A2
PP = RPT * RPT/A2
1020 MDFE = A1*PP*AREA(T1)/DSORT(T1)*A2
C-------------------------------------
C CONVERGENCE CHECK
C-------------------------------------

IFLS = 2
DO 1050 I = 1, 7
E(1) = 2, DARS(V(I+1) - V(I+3))/V(I+1) + V(I+3)
DO 1100 I = 1, 7
IF (E(I), GT, PESR) GO TO 1200
1100 CONTINUE
C WRITE DATA ON FILE AND PRINT CONVERGED DATA

IFLS = 2
IF (J1H, EQ, 03) GO TO 1115
WRITE(J18P, J16) RSTR, ISTR
FIND(J1R + J16)
1115 CALL PRINT
1116 IF (INSTR(7).EQ.21) GO TO 1180
IF (INSTR(6), NE, 0) WRITE(OUT, 1120) V
1120 FORMAT(15(/ **AR16, A))
C-------------------------------------
C PERFORM EXTRAPOLATION TO NEXT TIME INTERVAL
C-------------------------------------

DO 1170 I = 1, 7
```

92
J=EXTP(I)
C SAVE DATA FOR CURRENT INTERVAL
A(I)=V(J+1)
IF(TIME.EQ.11G0 TO 1160
IF(IFLG4.EQ.1)GO TO 1160
C EXTRAPOLATE
V(J+1)=2.*V(J+1)-V(J+2)
IF(INSTR(6),NE,0)CALL PRINT
C RESET DATA TO BEGINNING OF TIME INTERVAL
V(J+1)=A(I)
IF(IFLG4.EQ.1)IFLG4=2
1170 CONTINUE
C------------------------------------------
C DETERMINE IF ERRORS CUTTING OR DT DOUBLING IS REQUIRED
C------------------------------------------
1180 IF(INSTR(12),EQ,1).AND.INSTR(14),EQ,1)GO TO 1190
DO 1185 I=1,7
IF(IFLG2,NE,1).AND.(1.EQ.I.OR.(1.EQ.6))GO TO 1185
F(I)=2.*DAS(V(I+1)-V(I+2))/(V(I+1)+V(I+2))/INSTR(12)
IF(E(I).GT.PERR)GO TO 1185
IF(INSTR(14),GT.1)GO TO 1184
C ERROR CUTTING
PERR=PERR/INSTR(12)
SEM=SEM/INSTR(12)
WRITE(OUT,183)PERR,SEM
1183 FORMAT(IO)
PERR CUT TO F16.8+ AND SEM CUT TO F16.8
IPAGE=IPAGE+2
GO TO 1190
C DT DOUBLING
1184 DT=3*INSTR(14)
DTPV=DT/PW
ODT=1./DT
ODT2=ODT*2.5
WRITE(OUT,187)DT
1187 FORMAT(IO)
DT RAISED TO F16.8
IPAGE=IPAGE+2
GO TO 1190
1185 CONTINUE
1190 IF(TIME.LE.2)GO TO 1191
C------------------------------------------
C DETERMINE IF NEXT INTERVAL IS PREDICTED TO CHOKE
C------------------------------------------
DMN=MD-MD1
DMN=MN-MN1
IF(MS,MN,LT.DMN1)DMN=DMN1
IF(MS,MN,LT.DMN)DMN=DMN1
IFLG2=SIGN(1.,500*PT-PCT0*PSOP0)
IF(MS,MN,LT.DMN1)OR.(MN,MN,LT.DMN)IFLG2=-1
1191 DM1=MN-MD1
DM1=MN-MD1
IF(IFLG2,LT.0)IFLG10=2
WRITE(OUT,2000)IFLG2,DM1,DMN,MN,MD,MN1
2000 FORMAT(IO)IFLG2=F13.1,DM1,DMN=M2E13.5,MD,MN=M2E13.5
IP=MD,MN1=F13.1
C RESET DATA TO BEGINNING OF TIME INTERVAL
IF(INSTR(23),EQ,0)GO TO 1180
DO 1180 I=1,30
1180 V(I+2)=V(I+1)
      GO TO 150
1190 PPT1=PPT
      IF(INSTR(7, EQ.)=1)GO TO 150
      DO 1195 I=1,7
      J=IFXT(I)
1195 V(J+2)=V(J+1)
      GO TO 150
CRESET CONVERGENCE CONTROL DATA
C------------------------------------
1200 IF(1DF EUG,EQ., OUT)CALL PRINT
1210 DO 1260 I=1,30
1220 IF(I<NE.E1) V(I+1)=A11*V(I+1)+A12*V(I+3)
      V(I+3)=V(I+1)
      GO TO 1260
      V(I+4)=V(I+3)
      V(I+3)=V(I+1)
1260 CONTINUE
      GO TO 240
      END
I$ = W(1)
110 READ(IIN$1201(TV(j+1)+AREA(j+1)+I+1))
120 FORMAT(2E16.8)
   RETURN
200 READ(IIN$50) I1: I2: I3
   IF(I1 = EQ.0) RETURN 1
   GO TO(220, 240, 260): I1
220 READ(IIN$5011STR(I2)
   GO TO 200
240 READ(IIN$1001 RSTR(I2)
   GO TO 200
260 READ(IIN$1001W(I2: I3)
   GO TO 200
END
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100 A3=1

END

200 CONTINUE

C SPRINTS FOR UNSTEADY MASS FLUX FROM MACH NUMBER

A9(R)=MG0GM

A9(0)=GM102

CALL RT004

CALL RFVERT

DO 220 I=1,7

220 RW(I)=A(I)

SA02=ASRTA(R#COH)

IF (VCTI,EQ,7) RETURN

RETURN

END
SUBROUTINE INIT(*)
IMPLICIT REAL*8 (A-H, I-M, O-Z)
COMMON AREA(3,50), AREFATS(3), ANHARM(3), TV(3,50), A1(10), E(7), R(30),
T1F(3), TDELAY(3), HW(7),
COMMON PC, CTIC, IC, MCNTC, FAF, FAPE, FAF, MDTSCTR, MC1N, TCSTGS, GPO2GS,
COMMON GA, G1, GP1, AGP1, A01, TV02, TVG1, TVG2, TVG3,
COMMON T1L, TST, TST02, TSTOP, MDN1, DTPV,
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17,
COMMON PV, PP, PP2, PP3, PPT, PPT2, PPT3, PPT4, PPT5, PPT6, PPT7, PPT8, PPT9,
COMMON PD, PT, PCT0, PCTP, APE, AF, MN, MD,
COMMON AP1, AP2, AP3, AP4, AP5, RDP1, RDP2, RDP3, RDP4, RDP5, RDP6, RDP7, RDP8,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON P0, P01, P02, P03, P04, P05, P06, P07, P08, P09, P10, P11, P12, P13, P14,
COMMON TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17,
COMMON PV, PP, PP2, PP3, PPT, PPT2, PPT3, PPT4, PPT5, PPT6, PPT7, PPT8, PPT9,
COMMON PD, PT, PCT0, PCTP, APE, AF, MN, MD,
COMMON AP1, AP2, AP3, AP4, AP5, RDP1, RDP2, RDP3, RDP4, RDP5, RDP6, RDP7, RDP8,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON P0, P01, P02, P03, P04, P05, P06, P07, P08, P09, P10, P11, P12, P13, P14,
COMMON TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17,
COMMON PV, PP, PP2, PP3, PPT, PPT2, PPT3, PPT4, PPT5, PPT6, PPT7, PPT8, PPT9,
COMMON PD, PT, PCT0, PCTP, APE, AF, MN, MD,
COMMON AP1, AP2, AP3, AP4, AP5, RDP1, RDP2, RDP3, RDP4, RDP5, RDP6, RDP7, RDP8,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON P0, P01, P02, P03, P04, P05, P06, P07, P08, P09, P10, P11, P12, P13, P14,
COMMON TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17,
COMMON PV, PP, PP2, PP3, PPT, PPT2, PPT3, PPT4, PPT5, PPT6, PPT7, PPT8, PPT9,
COMMON PD, PT, PCT0, PCTP, APE, AF, MN, MD,
COMMON AP1, AP2, AP3, AP4, AP5, RDP1, RDP2, RDP3, RDP4, RDP5, RDP6, RDP7, RDP8,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON P0, P01, P02, P03, P04, P05, P06, P07, P08, P09, P10, P11, P12, P13, P14,
COMMON TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9, TP10, TP11, TP12, TP13, TP14,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
COMMON A1, A2, A3, A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, A17,
COMMON PV, PP, PP2, PP3, PPT, PPT2, PPT3, PPT4, PPT5, PPT6, PPT7, PPT8, PPT9,
COMMON PD, PT, PCT0, PCTP, APE, AF, MN, MD,
COMMON AP1, AP2, AP3, AP4, AP5, RDP1, RDP2, RDP3, RDP4, RDP5, RDP6, RDP7, RDP8,
COMMON APE1, APE2, APE3, APN1, APN2, APN3,
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10 V(I,J)=PC
20 V(I,J)=0.
30 V(I,J)=TC
40 V(I,J)=AC

CONTINU

T=0.
T=0.1
.TST=0
.TDS=0.5*DT
.MM=1./DT
.MC=0.
.CO 160 J=1,3
.I=VVT(J)
.DO 140 I=1,11
.TV(J,I)=TV(J+1)*TVF(J)

AREA(J,J)=AREA(J+1)*AREAM(J)

IF(TDIAY(J).EQ.0.).GO TO 160
.I=150 I=1,49
.I=S1+1
AREA(J,J)=AREA(J+1)

TV(J,J)=TV(J+1)*TOFLAY(J)

VVT(J)=VVT(J)*1

CONTINU

DO 170 I=1,3

V(I,25,2)=AREA(I+1)

PSAOA=TOG81*PGA2
TSOR=TSOR
RSOD=TSOR
MSQ0=MSQ0
MSPORT(TSOR)
MST=MSST

CNFTN(I)=70
.A1=..SQRT(TOCG1+GPIGM1+GMOR)
.A4=1./HSG040
.A5=1./HSG070
.A7=2.*GM1/MCTC
.A9=5.+GM0

IF(A10.FQ.0.)A10=TNFTN
IF(A11.FQ.0.)A11=5
IF(A13.FQ.0.)A13=TNFTN
IF(A14.FQ.0.)A14=0.1
IF(A15.FQ.0.)A15=A14

A15=1.+A1
IF(A15.FQ.0.)A15=1,00

100
IF (A16 .EQ. 0.00) A16 = 1.00
IF (A17 .EQ. 0.00) A17 = 1.00
IPASE = 0
NPASE = 90
IP = 0
OKF = 1.0
AWOSW = 1.71*TAUW*TSWA/KW
ITER = 0
IFLS = 0
IFL52 = 1
IFL33 = 0
IFL64 = 0
IFL55 = 0
IFL56 = 0
IFL57 = 0
IFL58 = 0
IFL59 = 0
NO = 0
NV = 0
NCT = 0
11 = 0
12 = 0
13 = 0
14 = 0
15 = 0
DO 200 I = 1, L7
200 E(I) = 0.
IF (VCTL.EQ.6) RETURN 1
RETURN
END
```
**DUMP**

<table>
<thead>
<tr>
<th>DATE = 75157</th>
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<tbody>
<tr>
<td>11/5/40</td>
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</table>

**TRUE**

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
GO TO (510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650) 1)

C 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
GO TO (510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650) 1)

510 WRITE (OUT, 511) INSTR(1)
511 FORMAT (**, 20X, 'SEND DEBUGGING OUTPUT TO OSRN', I3)
GO TO 1000

520 WRITE (OUT, 521) INSTR(2)
521 FORMAT (**, 20X, 'OBTAIN INPUT FROM OSRN', I3)
GO TO 1000

530 WRITE (OUT, 531) INSTR(3)
531 FORMAT (**, 20X, 'SEND REGULAR OUTPUT TO OSRN', I3)
GO TO 1000

540 WRITE (OUT, 541) INSTR(4)
541 FORMAT (**, 20X, 'PRINTING TIME INTERVAL', I3)
GO TO 1000

550 WRITE (OUT, 551) CHARS(51)
551 FORMAT (**, 20X, 'INPUT AND OUTPUT PRESSURES IN ', A4)
GO TO 1000

560 IF (INSTR(5), EQ, 0) WRITE (OUT, 562)
IF (INSTR(6), NE, 0) WRITE (OUT, 561)
561 FORMAT (**, 20X, 'PRINT DATA AFTER EVERY ITERATION')
562 FORMAT (**, 20X, 'PRINT DATA ONLY WHEN CONVERGED')
GO TO 1000

570 IF (INSTR(7), EQ, 0) WRITE (OUT, 571)
IF (INSTR(7), EQ, 2) WRITE (OUT, 572)
571 FORMAT (**, 20X, 'LINEARLY EXTRAPOLATE TO NEXT TIME INTERVAL AS AN INITIAL GUESS')
572 FORMAT (**, 20X, 'DO NOT EXTRAPOLATE TO NEXT TIME INTERVAL')
GO TO 1000

580 WRITE (OUT, 581) CHAR(5+3-CHARS(8)+J-1+2)
581 FORMAT (**, 20X, 'USE 2nd DEGREE REVERSED SERIES AS INITIAL GUESS')
IS TO MASS FLUX-MACH NUMBER WAVE EQUATION
590 IF (INSTR(9), EQ, 1) WRITE (OUT, 591)
591 FORMAT (**, 20X, 'USING ITERATIVE SOLUTION TO ENERGY AND WAVE EQUATION')
GO TO 1000

590 IF (INSTR(9), EQ, 1) WRITE (OUT, 591)
591 FORMAT (**, 20X, 'USING ITERATIVE SOLUTION TO ENERGY AND WAVE EQUATION')
GO TO 1000

592 FORMAT (**, 20X, 'APPROXIMATE EXPANSIONS FOR ENERGY AND WAVE EQUATIONS')
GO TO 1000

600 IF (INSTR(10), EQ, 0) WRITE (OUT, 601)
IF (INSTR(10), EQ, 1) WRITE (OUT, 602)
601 FORMAT (**, 20X, 'DO NOT INVOLVE AVERAGING OPTION')
602 FORMAT (**, 20X, 'AVERAGE VALUES OF CURRENT ITERATION WITH AVERAGE V VALUES OF PREVIOUS ITERATION')
603 FORMAT (**, 20X, 'AVERAGE VALUES OF CURRENT ITERATION WITH UNAVERAGE 10 VALUES OF PREVIOUS ITERATION')
GO TO 1000

610 WRITE (OUT, 611) INSTR(11)
611 FORMAT (**, 20X, 'CURENT WIGHT IS HALVED BEYOND *IT* ITERATIONS')
GO TO 1000

620 IF (INSTR(12), EQ, 1) WRITE (OUT, 621)
IF (INSTR(12), NE, 1) WRITE (OUT, 622) (INSTR(12), J=1+2)
GO TO 1000

700 IF(NSTR(11) .NE.0) AND (NSTR(20),NE.0) WRITE(TOUT,701) INSTR(2)
    IF((INSTR(11),0.0).AND.(INSTR(20),NE.0)) WRITE(TOUT,702)
701 FORMAT('***,20X,*INCREMENT INSTR(11) BY *13,1 WHENEVER WEIGHT IS H
ALVED')
702 FORMAT('***,20X,*DO NOT MODIFY INSTR(11)')
    GO TO 1000
710 IF(NSTR(21),EQ.0) WRITE(TOUT,711)
    IF(NSTR(21),NE.0) WRITE(TOUT,712)
711 FORMAT('***,20X,*DO NOT CHANGE EXTRAPOLATION OPTION (INSTR(21))')
712 FORMAT('***,20X,*INVOKING EXTRAPOLATION OPTION (SET INSTR(7)=2 WHEN
WEIGHT IS HALVED')
    GO TO 1000
720 WRITE(TOUT,721) INSTR(22)
721 FORMAT('***,20X,*SET INSTR(23)=2 WHEN ITER > *17')
    GO TO 1000
730 IF(NSTR(23),EQ.0) WRITE(TOUT,731)
    IF(NSTR(23),NE.0) WRITE(TOUT,732)
731 FORMAT('***,20X,*DO NOT USE SMALL PERTURBATION EXPANSIONS')
732 FORMAT('***,20X,*USF SMALL PERTURBATION EXPANSIONS AS INITIAL GUESS
1 FOR NEXT TIME INTERVAL')
733 FORMAT('***20X***USE SMALL PERTURBATION EXPANSION AS SOLUTION')
GO TO 1000
740 IF (INSTR(24),EQ,0) PRINT (IOUT,741)
IF (INSTR(24),NE,0) PRINT (IOUT,742)
741 FORMAT('***20X***RESULTS FROM SMART NOT PRINTED')
742 FORMAT('***20X***RESULTS FROM SMART PRINTED')
GO TO 1000
750 IF (INSTR(25),EQ,1) PRINT (IOUT,751)
IF (INSTR(25),EQ,2) PRINT (IOUT,752)
751 FORMAT('***20X***ASSUME PLENUM IS (SENTROPIC!)
752 FORMAT('***20X***SET TP AND TPT = MAX(ISPN TP,ICTO)')
GO TO 1000
760 PRINT (IOUT,761) INSTR(26)
761 FORMAT('***20X***RESTART TO EXACT SUPERSOIC SOLUTION ***17***TIME IN INCREMENTS AFTER CHOKE')
GO TO 1000
1000 CONTINUE
PRINT (IOUT,1110) (J=1,126) +10
1110 FORMAT('***26*** J,12) + 132 (J=4) + 2615)
11=0
DO 1020 I=1,13
IF (VT(I).GT.11) I=VT(I)
1020 CONTINUE
PRINT (IOUT,1040) (J=1,12) + 133 (J=TV(J,1)) + SFA(J,1), J=1,1)
1 =1)
1040 FORMAT('FLOW AREAS VERSUS TIME/40.133 (5X4,TV(J,1),133)
1 AX+ARFA(J,1), 3J) +SFA(J,1), SFA(J,1)+ 50+1+13,616, 41)
IF (VT(1,1,4) = 1 RETURN 1
RETURN
END
SURROUTINE: SOLVER(*)

IMPLICIT REAL*8(A-H,M-O,Z-*).

COMMON AREE(3*50)+ARETS(3)+AREAM(3)+TV(3*50)+E(10)+F(7)*8(30).

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C ELLIPTIC ENERGY EQUATION GIVING PRESSURSF FROM MASS FLUX
GUES51(D1)=PSQR+IFLAG*4*DSORT(1.*(A5*D1)*2).

C ELLIPTIC ENERGY EQUATION GIVING MACH NUMBER FROM MASS FLUX
GUES52(D1)=DSORT(GUES51(D1)**A8 = 1.*TOGQ).

C ELLIPTIC ENERY/CONTINUITY EQUATION GIVING MACH NUMBER FROM AREA RATIO
GUES53(D1)=GUES52(1./D1).

C APPROXIMATE UNSTEADY HAYE EQUATION GIVING MACH NUMBER FROM MASS FLUX
GUES54(D1)=GUES52(1./D1)**A2=D1=0.

SDX=0.01

GO TO 10,20,30,40.*IFLAG

10 SX1=GUES51(SY)

GO TO 50

20 IF(SY<4.*DSQRMO)GO TO 25

GO TO 50

25 SX1=1.D0

RETURN

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SOLVER

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30 $X1=GUESS3($Y*45)
   GO TO 60
40 IF(INSTR(9),EQ.1)GO TO 45
   $X1=GUESS4($Y)
   GO TO 50
45 $X1=0.
   GO 46  T=1.7
   $X1=$X1+NW(1)*$Y*1
50 IF(INSTR(9),EQ.2)RETURN
   WRITE(1DEBUG/100)SY,$DX,$EMAX
   100 FORMAT(* SOLVER/1*OSY=1,F16.8,1*SDX=1,F16.8,1*SEMAX=1,F16.8,1*N%=$X% 
   *9X$=1,F16.8,1*8X?Y1=1,F16.8,1*9X$F(N)=1,F16.8)
   $Y=0
   120 GO TO(1100,1200,1300,1400,1FLG
   130 $E1=($Y-SY1)/$Y
   140 $E2=$E1
       $Y2=$SY2
   150 $N=NN+1
       GO TO 120
   160 $SEP=$E1*$F
       $SDF=DARS($F1)-DARS($F2)
       WRITE(1DEBUG/200)SN,$X1,$SY1,$X2,$SY2,$E1,$E2,$SDF,$SEP,$DX
   200 FORMAT(* 13,9F14.6,1*ABS($F1),LE.$EMAX)RETURN
   160 IF($SEP,LT.0.)GO TO 220
   $DX=5*$DX
   210 $X1=$X2*$SY2
       GO TO 160
   220 IF($DX,LT.0.)GO TO 140
   $DX=-$DX
       GO TO 210
C ENERGY EQUATION GIVING MASS FLUX FROM PRESSURE
   1100 $Y1=$X1**T06-$X1**GPGM1
       $Y1=090($Y1)
       GO TO 130
C ENERGY EQUATION GIVING MASS FLUX FROM MACH NUMBER
   1200 $Y1=$X1**T07-$X1**GPGM2
       GO TO 130
C AREA RATIO VERSUS MACH NUMBER
   1300 $Y1=17G0P111.*G4102*$X1**21)*GPGM12/$X1
       GO TO 130
C UNSTAFY MASS FLUX FROM MACH NUMBER
   1400 $Y1=$X1**T08-$X1**GPGM4
       GO TO 130
END
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140 WRITE (10, 160) T, TSTR, X, PT, PP, PD, PN, PPT, ND, PCT0, PE0, NCT, ND, NN, MDCT, NMDT, MDN, NMD, MDPE, NMDPE, MDTSO, TMDCTO, TP, TPT, TP0, NCT, NCTO, RP, PPT, REN, NCT0, 4RT, MITS, TET, E, DT, 11

150 FORMAT (5(/**.E16.6+4))

IPAGE=IPAGE+1
RETURN

300 IF (IPAGE .EQ. 0) GO TO 320
   IF (IPAGE .LT. NPAGE) GO TO 360

320 WRITE (10, 340)

340 FORMAT (11X, PPT, 10X, TSTR, 10X, PT, 11X, PP, 11X, PD, 10X, PN, 10X, PPE0, 10X, PCT0+)
   IPAGE=IPAGE+1
   IF (NCTL .EQ. 10) RETURN
   RETURN

END.
SURROUN O: RINOM(*)
IMPLICIT REAL(*)
COMMON ARF*(3,50),ARFATS(3),AREAM(3),TV(3,50),A(10),E(7),B(30),
1 TVF(3),TDELAY(3),RT(7).
COMMON PC,RC,TC,AC,MDC,TCF,RTCF,RFH,MH,MRT,TRRTF,TRRT,MC,ACF,
1 SQGR
COMMON GM1,GP1,N0G,GP1O2,GM1O2,GM1O6,GM1O6,0G1P1,0G1M1,
1 2GM1,003P1,003M1,GM1O2,10GM1,10GPM2,10GP1,0GP412,
2 QG0G4,M00G1M1,AR,OR,AP,SR,PR,AR,DR,PR,DPR,ANGK,ODA1,00KF,KF,K3
COMMON TSL,TST,TSTP,TSV,TSTAP,TSTV,CTA,PPV,VPDTSY,TAUW
COMMON TSI1,DTSTR,DT02,TST02,000T,0TOPV
COMMON A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,A17
COMMON P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,PCT05,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
COMMON P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,PCT01,PCT02,PCT03,PCT04,
1 MD,MDP,MDCT,MDTP,MDTPS,MDCT0,FD0,TF0,TP0,
2 APE,AF,N,MD
A(1)=1.
10 IF(I.GT.6)GO TO 20.
14=1
A(1)=A(1) *(A(9)-IM1)/I
WRITE(TDEBUG,151)A1(1)
15 FORMAT(* I=*,I7,1I1=*,I7,1I1=*,I7)
GO TO 16
20 WRITE(TDEBUG,301)
30 FORMAT(10000000/10013,6,5)
DO 40 T=1,7
40 A(1)=A(1) *(A(9)**(1-1))
WRITE(TDEBUG,901)A
RET JAN
END
SUBROUTINE REVERT(*)
IMPLICIT REAL*4(A-H,M-N,Z-S)
COMMON AREA(3,50),AREATS(3),AREAM(3),TV(3,50),A(10),E(7),B(30),
       TVC(3),TDELAY(3),PM(7)
COMMON PCRC,TCAC,MCMT,EAE,EAPE,FAF,MDSTR,INFIN,TMS05G,GP025G,
       1 SG0R
COMMON G,GMP,GP1+MP2,GM12+GM10+G1++GMP1+G1M12,
       1 GM12,GP25,PGM2+PGP1+GM12,
COMMON TSO,TSG,TSP,TSM,TSN,TSV,CTG,CTA,PSIS,TRANS,TAUW
COMMON T,ITN,TTP,TN02,TSTOP,TUN,DTDVP
COMMON A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,A17
COMMON PN,PP,PP1,PP2,PT1,PT2,PT3,PT,PT0,PTC0,PF0,MDE,
       MD0,MW,MDPT,MDCT,MDPE,MDTSO,MDCTO,TE0,TP,
       TPT,TCT0,AP,AP1,RPT,RED,RCT0,ACT0,MCT,AE,
       APE,AF,MN,MD
COMMON PN1,PP1,PP2,PP3,PT1,PT2,PT3,PTC0,PF01,MDE1,
       MD01,MW1,MDPT1,MDCT1,MDPE1,MDTS01,MDCT01,TE01,TP1,
       TPT1,TCT01,AP1,RPT1,RED1,RCT01,ACT01,MCT1,AE1,
       APE1,AF1,MN1,MD1
COMMON PN2,PP2,PP3,PP4,PT2,PT3,PT2C0,PF2,MDE2,
       MD02,MW2,MDPT2,MDCT2,MDPE2,MDTS02,MDCT02,TE02,TP2,
       TPT2,TCT02,AP2,AP3,RED2,RCT02,ACT02,MCT2,AE2,
       APE2,AF2,MN2,MD2
COMMON PN3,PP3,PP4,PP5,PT3,PT3C0,PF3,MDE3,
       MD03,MW3,MDPT3,MDCT3,MDPE3,MDTS03,MDCT03,TE03,TP3,
       TPT3,TCT03,AP3,RED3,RCT03,ACT03,MCT3,AE3,
       APE3,AF3,MN3,MD3
COMMON S,SY,SY1,SY2,SY3,SHA,SHA1,SA2,SHMAX,SEP,SDF
COMMON INSTR(26),INERUS,TN,TOUT,NP,IP,ITER,NVT(3),ITNT,ITPAE,
       INPAE,INP1,ITNP1,TIMPNP1,TPN2,TPD1,TPD2,TPD3,TPD4,
       TPI1,TPI2,TPI3,TPI4,TPI5,TPI6,TPI7,TPI8
COMMON J1,J2,J3,J4,J5,J6,J7,J8,J9,J10,J11,J12,J13,J14,J15,J16,J17
COMMON JCTL
INTEGER N
REAL A,INF14,XF,KW
R(1)=1./A(1)
R(2)=A(2)/A(1)**3
R(3)=(2.*A(2)**2-A(1)**2)/A(1)**6
R(4)=A(4)**2*(A(1)**2-A(3)**2)/A(3)**2
R(5)=(4.*A(1)**2*A(4)**2-3.*A(1)**2*A(3)**2)/A(3)**2
R(6)=A(6)**2/21.*A(1)**2*A(3)**2
R(7)=A(7)**2/21.*A(1)**2*A(3)**2
R(8)=A(8)**2/21.*A(1)**2*A(3)**2
R(9)=A(9)**2/21.*A(1)**2*A(3)**2
R(10)=A(10)**2/21.*A(1)**2*A(3)**2
R(11)=A(11)**2/21.*A(1)**2*A(3)**2
R(12)=A(12)**2/21.*A(1)**2*A(3)**2
R(13)=A(13)**2/21.*A(1)**2*A(3)**2
R(14)=A(14)**2/21.*A(1)**2*A(3)**2
R(15)=A(15)**2/21.*A(1)**2*A(3)**2
R(16)=A(16)**2/21.*A(1)**2*A(3)**2
R(17)=A(17)**2/21.*A(1)**2*A(3)**2
R(18)=A(18)**2/21.*A(1)**2*A(3)**2
R(19)=A(19)**2/21.*A(1)**2*A(3)**2
R(20)=A(20)**2/21.*A(1)**2*A(3)**2
A(1)=1./A(1)
WRITE(10,E34,418)
FORMAT(10,F20.10,10E13.5)
RETURN
END
CC1 = PFO1 * A(1)
CC1 = 0.570 * PFO1 * A(1) * AE1 / TR01

C EQUATION 2
90 CA9 = -1.70
A(9) = A1 / HSORT(TP1) * A2
CA9 = -AF1 * A(2)
CC9 = -PP1 * A(2)
CD9 = 0.000 * PPI * A(2) * AF1 / TP1

C EQUATION 3
CA3 = -1.70
CA3 = (PPI - P1 / A(16) + NOKF * A2
CC3 = -af1 * NOKF * A2
CD3 = -CC3 * A(4)

C EQUATION 4
CA4 = -1.70
CA4 = AWOKW * A2
CC4 = -CB4 * A15

C EQUATION 5
CA4 = -1.70
CA4 = MQTPW
CC5 = CTB
CD5 = CTB
CF5 = (CTB * CTPF + MDF + MDPT)

C EQUATION 6
CA7 = 1.00
CA7 = 1.00
CC7 = -1.70
IF(IFLAG2,VE,1)GO TO 91

C EQUATION 7
CA7 = 1.00
CA7 = 1.00
CC7 = -1.70

C EQUATION 8
CA8 = -1.70
A(3) = 1.70 -CTI
A(4) = 1.70 + GM102 * MCT1
CA8 = MCTC * A(3) / A(4) ** (GM1 * 2.00)

C EQUATION 9
CA9 = -1.70
A(9) = 1.70 + GM102 * MCT1 ** 2
CA9 = -A(3) * PFR1 / A(4) / A(5)

C EQUATION 10
CA10 = -1.00
CA10 = -GM1 * A(7) * TE01 / A(4) / A(5)

C EQUATION 11
91 CA11 = -1.00
IF(IFLAG2,99,9999,1000
100 CA11 = 0.570
CC11 = CA11
GO TO 101
99 CA11 = 1.70 -A17
CC11 = A17

C EQUATION 12
101 A(9) = -GM1 / MDTS01 ** 2
A(10) = GM1 / MDTS01 ** 3
CA12 = A(9) * MDT01

114
<table>
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<tr>
<th>SUPPORT</th>
<th>DATE = 75/157</th>
<th>11/58/40</th>
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```
C912 = A(10) * M01 **2
IF(I6L62, EQ, 1) A(14) == P01/PE01
IF(I6L62, NE, 1) A(14) == P01/PC01
A(7) = A(5) ** TO6
A(8) = A(5) ** G6106
NU13 = TO6 * A(7) - G8106 * A(R)
NU23 = TM80G * A(7) - G802G * A(R)
IF(I6L62) 94, 99999, 93
93 CC12 = NU13 / P01 / PE01
CC12 = NU23 / (P01 * PE01) ** 2
GO TO 94
94 CC12 = NU13 / P01 / PC01
CC12 = NU23 / (P01 * PC01) ** 2
95 IF(I6L62, NE, 1) GO TO 92
```

C EQUATION 13

```
CA13 = A(9) * M0111
CA13 = A(10) * M0111 ** 2
B(1) = PNL / PE01
B(2) = R(1) ** TO6
B(3) = S(1) ** G6106
NU14 = T0684(2) - G806G * A(3)
NU24 = TM80G * A(2) - G802G * A(3)
CC13 = NU14 / PNL / PE01
CC13 = NU24 / (PNL * PE01) ** 2
```

C EQUATION 14

```
CA14 = -1.0D0
CA14 = TS6 / SQRT(T80) * A2
CC14 = -0.500 / PE01 / CA14 / T601
```

C EQUATION 17

```
92 GO TO(96, 98) I6L69
98 CA17 = 0.62
CA17 = RCT01
GO TO 97
96 CA17 = RPT1
CA17 = -1 * RPT1
97 CA17 = -1.70
CA19 = 0.500
CC19 = RPT1 - RPT1
```

C EQUATION 18

```
CA19 = 0.7 * RPT1
CA19 = 0.5 * RPT1
CC19 = A2
IF(I6L62) 94, 99999, 93
```

C SUPPORT ARMS

```
? IF(TDE6UG, E0, 03) GO TO 70
CA1 = TNFIN
CA1 = TNFIN
CC1 = TNFIN
CC1 = TNFIN
CA7 = TNFIN
CA7 = TNFIN
CC7 = TNFIN
CA9 = TNFIN
```

115
C EQUATION 1

70 SALP11 = -CC11 / CA11

C EQUATION 1a

SALP12 = -CA10 / CA1A
SALF12 = -CC1A / CA1A

C EQUATION 1b

A(1) = -1.00 / CA10
SALP19 = CA19 * SALP18 * A(1)
SALF19 = CC19 * A(1)
SAG419 = CA19 * SALF18 * A(1)

C EQUATION 2

A(2) = -1.00 / CA?
SALP2 = (CA19 * CA2 * SFET19) * A(2)
SALP2 = CA2 * SALP19 * A(2)
SAG42 = (CC2 * FAPF + CA2 * SAG419) * A(2)

C EQUATION 3

A(3) = -1.00 / CA3
SALP3 = CA3 * A(3)
SAL13 = CA3 * A(3)
SAG43 = CA3 * EAP * A(3)

C EQUATION 4

A(4) = -CA17 / CA17
SALP17 = SALP19 * A(4)
SALF17 = SFET18 * A(4)

C EQUATION 4 CONTINUED

SALP4 = CA4 * SALP11

C EQUATION 5

SALP5 = CA5 * CA5 * SFET2
SALP5 = CA5 * SALP2 + CC5 * SALP3
SAG45 = CC5 * SFET2
SAG45 = CA5 * SALP2 + CC5 * SFET2
SAG45 = CA5 * SFET2

C EQUATION 5 CONTINUED

SALP5 = SALP5 * SALP17 + SFET5
A(5) = -1.00 / S105
S105 = SAG45 * A(5)
SAG45 = CA5 * A(5)
SAG45 = SAG45 * SFET17 + SAG45

C EQUATION 4 CONTINUED
SMPRT  DATE = 75157  11/58/40

SETA6 = CA6 + SRETA6 - SF6
SEPS6 = - (SEFT6 - SZE16 + SALP6) / SETA6
SEFT6 = - (SEFT4 * SKAP6 + SGAM4) / SETA6

C EQUATION 6
A(6) = CA6 / CA6
SALP6 = SEPS6 * A(6)

SREFT6 = SZE16 * A(6)

C EQUATION 12
SGAM12 = CD12 * PCT01 ** 2
SALP12 = (CA12 * PCT01 + CA12 * SALP6) / SGAM12

SEFT12 = CA12 * SREFT6 / SGAM12

IF (DEBUG.EQ.0) GO TO 60
SEPS3 = INFIN
SGAM6 = INFIN
SEPS6 = INFIN
SZE16 = INFIN
SETA6 = INFIN
SIOT6 = INFIN
SLAM6 = INFIN
SAUR = INFIN
SNU6 = INFIN
SALP7 = INFIN
SEFT7 = INFIN
SGAM7 = INFIN
SEPS7 = INFIN
SZE17 = INFIN
SETA7 = INFIN
SIOT7 = INFIN
SKAP7 = INFIN
SALP8 = INFIN
SALP9 = INFIN
SALP10 = INFIN
SGAM9 = INFIN
SALP11 = INFIN
SALP13 = INFIN
SALP13 = INFIN
SGAM13 = INFIN

SALP14 = INFIN
SALP14 = INFIN
SALP14 = INFIN
SGAM14 = INFIN
SEPS14 = INFIN
SZE14 = INFIN
SETA14 = INFIN
SIOT14 = INFIN
SGAM17 = INFIN
SEPS17 = INFIN

90 A(7) = 0.5 * SGAM12
Y(2) = 0.5 * SQRT(A(7) ** 2 - SEFT12)
Y(1) = -A(7) + Y(2)
Y(2) = -A(7) + Y(2)

C SORT_ROOTS
C I=0
SMPERT  DATE = 75157  11/58/60

DO 200 K = 1,2
IF (ABS(DIMAG(Y(K))) .GT. 1.D-12) GO TO 200
I(15) = DREAL(Y(K))/PO1
WRITE(10,E8) Y(K),X(K),Y(2),Z(14)+R(15)
IF (ABS(R(15))) .GT. DABS(A14) GO TO 200
I = I + 1
EPS(12) = Y(K)
200 CONTINUE

IF IF(I-EQ.1) GO TO 205
IF (DIMAG(Y(2)) .LT. DABS(DREAL(Y(1)))) Y(1) = Y(2)
EPS(12) = Y(1)
I = 1
205 IF(L38 = 0
K = 1
IF (K .GT. 1) GO TO 230
WRITE(10,I) 2101
210 FORMAT(*$MPERT (SUPERSONIC) 1,2,13,1, SOLUTIONS FOUND!)
IDF3UG = 06
IFL39 = 1
K = 0
220 K*K = K
IF (K .GT. 2) GO TO 40
EPS(12) = Y(K)
C------------------------
C COMPUTE INCREMENTS
C--------------------
230 EPS(6) = SALP6 * EPS(12) + SBET6
EPS(4) = SEPS4 * EPS(12) + SEET4
EPS(5) = SEPS5 * EPS(12) + SETA5 * EPS(4) * SKAPS
EPS(17) = SALP17 * EPS(5) + SBET17
EPS(3) = SALP3 * EPS(17) + SBET3 * EPS(12) + SGAM3
EPS(2) = SALP2 * EPS(17) + SBET2 * EPS(5) + SGAM2
EPS(19) = SALP19 * EPS(5) + SBET19 * EPS(17) + SGAM19
EPS(18) = SALP18 * EPS(5) + SBET18
EPS(11) = SALP11 * EPS(12)
EPS(1) = 0,00
EPS(7) = 0,00
EPS(8) = 0,00
EPS(9) = 0,00
EPS(10) = 0,00
EPS(13) = 0,00
EPS(14) = 0,00
WRITE(10,I) (EPS(12),I = 1,241)
C------------------------
C COMPUTE PROPERTY VALUES
C------------------------
DO 240 I = 1,19
J = IEXP(I)
IF (J .EQ. 0) GO TO 240
V(J+1) = V(1+2) * FPS(I)
240 CONTINUE
TEN = TCT0
MDF = MDF = MDF
PEN = MNE = MPSRT(TFN) / (A1 * A2 * AE)
GO TO (P39,P38)+IFLG9
SMFPERT

DATE = 75157  11/58/40

239 PPT = PPT1 * (RPT / RPT1) ** 0
PPT = PPT + A2 * AOR / RPT
GO TO 237
238 PTP = TCT
PPT = RPT * R = TPT / A2
237 REN = PEO = A2 * AOR / TEO
MOD = MACH*(PD)
IF((INSTR(23) = .NE.2) .AND. (INSTR(24) = .EQ. 0)) GO TO 241
J16 = J16 + 1
CALL PRINT
J16 = J16 - 1
WRITE(OUT,242)
242 FORMAT(*24*)
241 IF((IFLG, .EQ. 0) .AND. (TDFUG, .EQ. 0)) RETURN
WRITE(TDFUG+32, V)

C---------------------------------------
C SMALL PERTURBATION RESIDUALS
C---------------------------------------

DO 250 I = 1,19
250 Q(I) = INFIN
Q(2) = CA2 * EPS(2) + CB2 * EPS(17) + CC2 * FAPE + CD2 * EPS(19)
Q(3) = CA3 * EPS(3) + CB3 * FAE + CC3 * EPS(17) + CD3 * EPS(12)
Q(4) = CA4 * EPS(4) + CB4 * EPS(17) + CC4 * EPS(11)
Q(5) = CA5 * EPS(5) + CB5 * EPS(2) + CC5 * EPS(3) + CD5 * EPS(11)
# + CC5
Q(6) = CA6 * EPS(6) + CB6 * EPS(4)
Q(7) = INFIN
Q(8) = INFIN
Q(9) = INFIN
Q(10) = INFIN
Q(11) = CA11 * EPS(11) + CC11 * EPS(12)
Q(12) = CA12 * EPS(13) + CC12 * PCT01 * EPS(12) + CD12 * PCT01 ** 2
# * EPS(12) ** 2
Q(13) = INFIN
Q(14) = INFIN
Q(17) = CA17 * EPS(17) + CB17 * EPS(18)
Q(18) = CA18 * EPS(19) + CB18 * EPS(1) + CC18
Q(19) = CA19 * EPS(19) + CB19 * EPS(18) + CC19 * EPS(17)
WRITE(TDFUG+13) (1I11=1*I+20)*0

C---------------------------------------
C EXACT RESIDUALS
C---------------------------------------

DO 60 T = 1,19
60 Q(I1) = 1.070
Q(2) = MPE*DPE*AP2*AP2*DSRT(TPT)*A2
Q(3) = MPE*AP2*DSRT(PP = PD*AP2)*A2
Q(4) = MPE*AP2*AP2*AP2*DSRT(PP = PD*AP2)*A2
Q(5) = MPE*AP2*AP2*AP2*DSRT(PP = PD*AP2)*A2
Q(6) = MPE*AP2*AP2*AP2*DSRT(PP = PD*AP2)*A2
IF(IFLG2, 254, 9999) 255
254 Q(11) = PT - (1.00 - A17)*P + A17*PD
GO TO 256
255 Q(11) = PT - 0.60*AP2*P + PD
256 Q(I1) = 1.00*PCT0
Q(13) = TOWG*MOD*PS*2
Q(I2) = MOD**2*9(13)*1(PP*AP2(12)**2)*TOP-(PD*AP2(12)**2)*AP100
<table>
<thead>
<tr>
<th>SMPERT</th>
<th>DATE = 75157</th>
<th>11/58/40</th>
</tr>
</thead>
<tbody>
<tr>
<td>GO TO (251+252)*IFLAG9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>251 Q(17)=PP<em>PPT1</em>(RP/RPT1)**6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GO TO 253</td>
<td></td>
<td></td>
</tr>
<tr>
<td>252 Q(17)=PP<em>SR</em>TP/A2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>253 Q(18)=PP<em>0.5</em>0*(RPT*RPT1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q(19)=TP-PD<em>QDR/RP</em>A2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GO TO 259</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**C.SUPERSONIC BRANCH**

**C. COMPUTE CONSTANTS FOR SOLUTION**

**C.EQUATION 19**

\[
3 \text{SALP19} = -\text{CB19} / \text{CA19}
\]
\[
\text{SFBT19} = -\text{CC19} / \text{CA19}
\]

**C.EQUATION 2**

\[
B(4) = -1.00 / \text{CA2}
\]
\[
\text{SALP2} = (\text{CA2} + \text{CD2} * \text{SFBT19}) * B(4)
\]
\[
\text{SFBT2} = \text{CS2} + \text{SALP19} * B(4)
\]
\[
\text{SGAM2} = \text{CC2} + \text{EAE} * B(4)
\]

**C.EQUATION 5**

\[
\text{SALP5} = \text{CS5} * \text{SALP2}
\]
\[
\text{SFBT5} = \text{CS5} * \text{SFBT2}
\]
\[
\text{SGAM5} = \text{CS5} * \text{SGAM2} * C5
\]

**C.EQUATION 8**

\[
\text{SALP8} = -\text{CA8} / \text{CB8}
\]

**C.EQUATION 10**

\[
\text{SALP10} = -\text{CA10} / \text{CB10}
\]
\[
\text{SFBT10} = -\text{CC10} / \text{CB10}
\]

**C.EQUATION 5 CONTINUE**

\[
\text{SKAPS} = \text{CS5} + \text{SFBT10} + \text{SFBT5}
\]
\[
B(5) = 1.00 / \text{SKAPS}
\]
\[
\text{SEP55} = \text{SALP5} * B(5)
\]
\[
\text{SZFT5} = \text{CC5} * B(5)
\]
\[
\text{SETA5} = -\text{CD5} * B(5)
\]
\[
\text{SIT5} = -\text{CA5} * \text{SFBT10} + \text{SGAM5} * B(5)
\]

**C.EQUATION 10**

\[
\text{SALP10} = -\text{CB10} * \text{SALP8} / \text{CA10}
\]

**C.EQUATION 11**

\[
\text{SALP11} = -\text{CB11} / \text{CA11}
\]
\[
\text{SFBT11} = -\text{CC11} / \text{CA11}
\]

**C.EQUATION 17**

\[
\text{SEP57} = \text{CA17} + \text{CB17} * \text{SEP55}
\]
\[
B(6) = -\text{CB17} / \text{SEP57}
\]
\[
\text{SALP17} = \text{SZFT5} * B(6)
\]
\[
\text{SFBT17} = \text{SETA5} * B(6)
\]
\[
\text{SGAM17} = \text{SIT5} * B(6)
\]

**C.EQUATION 1**

\[
B(7) = -1.00 / \text{CA1}
\]
\[
\text{SALP1} = \text{CS1} * B(7)
\]
\[
\text{SFBT1} = \text{CS1} + \text{SALP10} * B(7)
\]
\[
\text{SGAM1} = \text{CC1} + \text{EAE} * B(7)
\]

**C.EQUATION 3**

\[
\text{SEP53} = \text{CS3} + \text{CC3} * \text{SALP17}
\]
\[
B(8) = -1.00 / \text{SEP53}
\]
SMPERT

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C EQUATION 4

SALP3 = CC3 \* SRET17 \* B(0)
SRET3 = C93 \* B(0)
SGAM3 = (CC3 \* SGAM17 + CR3 \* EAF) \* R(0)

C EQUATION 5

SEP54 = CR4 \* CR4 \* (SRET17 + SALP17 \* SALP3)
B(9) = - 1.00 \* SEPS4
SALP4 = (CR4 \* SALT17 \* SRET3 \* CC4 \* SBFT11) \* B(9)
SRET4 = C94 \* SALT11 \* B(9)
SGAM4 = CR4 \* (SALT17 \* SGAM3 \* SGAM17) \* R(9)

C EQUATION 6

B(10) = - CR4 \* CR4
SALP6 = SALT17 \* B(10)
SRET6 = SRET4 \* B(10)
SGAM6 = - CC6 \* CR6
SEPS6 = SGAM6 \* B(10)

C EQUATION 7

SZE7 = CA7 \* SGAM6 \* CC7 \* SBFT1
B(11) = - 1.00 \* SZE7
SALP7 = (CA7 \* SALP6 \* CR7 \* (SRET3 \* SALP3 \* SALP4)) \* B(11)
SRET7 = (CA7 \* SRET6 \* CR7 \* SALP3 \* SBFT4) \* B(11)
SGAM7 = CC7 \* SALT1 \* B(11)
SEPS7 = (CA7 \* SEPS6 \* CR7 \* SGAM3 \* CC7 \* SGAM1 \* C97 \* SALP3 \* SGAM4) \* B(11)

C EQUATION 6 CONTINUED

SZE7 = SALP6 \* SGAM6 \* SALT7
SETA6 = SRET6 \* SGAM6 \* SRET7
SIO76 = SGAM6 \* SGAM7
SKAP6 = SEPS6 \* SGAM6 \* SEPS7

C EQUATION 14

B(12) = CC14 \* SALP10
SALP14 = CR14 \* B(12) \* SGAM7
SRET14 = 3(12) \* SALP7
SGAM14 = B(12) \* SRET7
SEPS14 = 3(12) \* SEPS7

C EQUATION 9

B(13) = CR9 \* SALP8
SZE7 = CA9 \* B(13) \* SGAM7
SGAM9 = B(13) \* SZE7
SALP9 = SGAM9 \* SALP7
SRET9 = SGAM9 \* SRET7
SGAM9 = SGAM9 \* SEPS7

C EQUATION 14 CONTINUED

B(14) = - 1.00 \* CA14
SZE14 = (SALP14 \* SALP9 \* SRET14) \* B(14)
SETA14 = (SALP14 \* SRET9 \* SGAM14) \* B(14)
SIO14 = (SALP14 \* SGAM9 \* SEPS14) \* B(14)

C EQUATION 6 CONTINUED

SALM6 = SZE7 \* SIO76 \* SALP9
SIO6 = SRET6 \* SIO76 \* SRET9
SM6 = SKAP6 + SIO76 \* SGAM9

C EQUATION 7 CONTINUED

SRET7 = SALP7 \* SGAM7 \* SALP9
SIO77 = SRET7 \* SGAM7 \* SRET9
SKAP7 = SEPS7 \* SGAM7 \* SGAM9

C EQUATION 12

SALP12 = PE01 \* PD1 \* SALP9
I2=J
B(15)=Y(J)
320 CONTINUE
   IF(I1 .NE. 12) GO TO 340
   I=1
   EPS(12)=X(I1)
   EPS(13)=Y(I2)
340 IFILG8=0
   IF(I.EQ.11) GO TO 17
   WRITE(TOUT,16) T
16 FORMAT(6SMPERT,14X,13X,1 SOLUTIONS FOUND)
10 IFILG8=06
   IFILG8=1
   K=0
18 IF(K.GT.4) GO TO 60
   EPS(12)=X(K)
   EPS(13)=Y(K)
C-----------------------------------------
C COMPUTE INCREMENTS
C-----------------------------------------
17 EPS(6) = SLAM6 * EPS(12) + SNU6 * EPS(13) + SNU6
   EPS(7) = SETA7 * EPS(12) + SIOT7 * EPS(13) + SKAPT
   EPS(9) = SALP9 * EPS(12) + SRET9 * EPS(13) + SGM9
   EPS(10A) = SZET16 * EPS(12) + SETA16 * EPS(13) + SIOT16
   EPS(4) = SALP4 * EPS(12) + SRET4 * EPS(13) + SGM4
   EPS(3) = SALP3 * EPS(4) + SRET3 * EPS(12) + SGM3
   EPS(1) = SALP1 * EPS(9) + SRET1 * EPS(7) + SGM1
   EPS(17) = SALP17 * EPS(3) + SRET17 * EPS(4) + SGM17
   EPS(11) = SALP11 * EPS(13) + SRET11 * EPS(12)
   EPS(10) = SALP10 * EPS(7)
   EPS(1A) = SEPS5 * EPS(17) + SZET5 * EPS(3) + SETA5 * EPS(4) +
   SIOT5
   EPS(5) = SALP18 * EPS(18) + SRET18
   EPS(8) = SALP8 * EPS(7)
   EPS(2) = SALP2 * EPS(17) + SRET2 * EPS(18) + SGM2
   EPS(19) = SALP19 * EPS(18) + SRET19 * EPS(17)
   WRITE(TOUT,20) (T(I)=1.24) * EPS
20 FORMAT(3(1X,6(5X,EPS(11),14X),I1),3/I,14X,EPS(18))
C-----------------------------------------
C COMPUTE SMALL PERTURBATION PROPERTY VALUES
C-----------------------------------------
C DO, 30 J=1,19
25 J=IXTP(I)
   IF(J.EQ.0) GO TO 30
   V(J,1)=V(J,2)+EPS(1)
30 CONTINUE
   GO TO(341,342,4)IFILG9
341 PPT=PPT+A (RPT/RPT) ** G
   TPT=PPT*0GR/RPT**A2
   GO TO 363
342 TPT=TPT
   PPT=PPT*RPT/TPT/A2
343 PCT0=PE0
   TCT0=TE0

123
# AEDC-TR-76-39

**DATE = 75157  11/5/84**

```fortran
RE0 = PEO / DDR / TEO * 67
ACT0 = REO
ACT0 = NSORT(GR * TCT0)
MOD0 = ACT0 * ACT0 * CIA
M0 = MACHPD0
MN = MACHPN
IF((INSTR(23,%OE%2),AND,(INSTR(24,%OE%0))GO TO 28
J16=J16+1
CALL PRINT
J16,J16-1;
WRITE(TOUT,29)
29 IF((IFIA,G04)3,AND,(IDEAUG,E03))RETURN
WRITE(IDEBUG,32)
32 FORMAT(*SMALL* PERTURBATION PROPERTIES,*13/* ,8E16.8))
C*******************************
C SMALL PERTURBATION RESIDUALS
C*******************************
DO 35 I=1,19
35 Q(I)=1.070
Q(1) = CA1 * EPS(1) + CB1 * EPS(9) + CC1 * EAF + CD1 * EPS(8)
Q(2) = CA2 * EPS(2) + CB2 * EPS(17) + CC2 * EAF + CD2 * EPS(9)
Q(3) = CA3 * EPS(3) + CB3 * EAF + CC3 * EPS(17) + CD3 * EPS(12)
Q(4) = CA4 * EPS(4) + CB4 * EPS(17) + CC4 * EPS(11)
Q(5) = CA5 * EPS(5) + CB5 * EPS(2) + CC5 * EPS(3) + CD5 * EPS(4) +
Q(6) = CA5 * EPS(6) + CB6 * EPS(4) + CC6 * EPS(7)
Q(7) = CA7*EPS(6) + CB7 * EPS(3) + CC7 * EPS(1)
Q(8) = CA8 * EPS(7) + CB8 * EPS(8)
Q(9) = CA9 * EPS(8) + CB9 * EPS(8)
Q(10) = CA10 * EPS(10) + CB10 * EPS(8)
Q(11) = CA11 * EPS(11) + CB11 * EPS(13) + CC11 * EPS(12)
Q(12) = CA12 * EPS(14) + CB12 * EPS(14) + CC12 * B(15) + CD12 * B(15)
B(16) = PP01 * EPS(13) - PN * EPS(9)
Q(13) = CA13 * EPS(7) + CB13 * EPS(14) + CC13 * B(16) + CD13 * B(16)
Q(14) = CA14 * EPS(14) + CB14 * EPS(9) + CC14 * EPS(10)
Q(15) = CA17 * EPS(17) + CB17 * EPS(18)
Q(16) = CA18 * EPS(18) + CB18 * EPS(5) + CC18
Q(17) = CA19 * EPS(19) + CB19 * EPS(18) + CC19 * EPS(17)
WRITE(IDEBUG,13)(I=1,20)
13 FORMAT(*RESIDUALS FROM SMALL PERTURBATION EQUATIONS*,
1 2/* ,10(6X,12.5X),12// ,10E13,5))
C*******************************
C EXACT RESIDUALS
C*******************************
DO 140 I=1,19
140 Q(I)=1.070
Q(1) = MPEP*AE*PEO/DSORT(TE0)A2
Q(2) = MPEP*AE*PEP/EPE/DSORT(TPT)A2
Q(3) = MPEP*AE*PEO/PP-PD*16A2
Q(4) = MPEP*AE*PEP/PP-PPT*15A2
Q(5) = RPT-RPT1 = (MDPEP+MDF*MDPT)DTPV
```

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SMPF

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Q(6) = MNO + MDF = MCT
Q(7) = MDO + MDF = MDE
B(9) = 1.00 * GM102 * MCT
B(10) = 1.00 * GM102 * MCT**2
Q(11) = MCT - MDC + G10(9) ** MOPGM
B(11) = B(10) / B(9) ** 2
Q(9) = PF - PC * B(11) ** GOM1
Q(10) = TD - CB(11)

IF (IFLG2) = 144, 9999, 145
144 Q(11) = PI - (1.00 - A17) * PN - A17 * PD
GO TO 146

145 Q(11) = PT - 0.500 * (PN * PD)
146 R(12) = 1.00 / PD
B(13) = TOW * MT50 ** 2
Q(12) = MNO ** 2 - B(11) ** ((PD * R(12)) ** T06 - (PD * R(12)) ** G106)
Q(13) = MCT ** 2 - B(11) ** ((PT * R(12)) ** T06 - (PD * R(12)) ** G106)
Q(14) = MT50 * 500 * PD * TS50 * NSRT * (TE0) ** 2
GO TO 141, 142, IFLG09

141 Q(17) = PP - OPT1 * (RP/RPT1) ** G
GO TO 143

142 Q(17) = PP - RP * RPT1 / A2
143 Q(18) = RP - 0.500 * (RPT1 * A2)
Q(19) = TP - PP * 0.500 / RP * A2

C----------------------------------_uL
CAPPED TO PERCENTAGES
C----------------------------------_uL

39 DO 49 J = 1, 119
J = I * EXP(I)
IF (J > EQ.0) GO TO 49
IF (J > EQ.0.6) GO TO 45
IF (J > EQ.0.6) GO TO 41
IF (J > EQ.0.4) GO TO 42
IF (J > EQ.0.12) GO TO 43
IF (J > EQ.0.13) GO TO 42
GO TO 46
41 J = 10
GO TO 46
42 J = 12
GO TO 46
43 J = 9
GO TO 46
45 J = 11
46 IF (V(J, 2) .NE. 0.001) GO TO 47
Q(J) = 1
GO TO 49
47 Q(J) = 0.1 / V(J, 2)
48 CONTINUE
WRITE (TOFESUG, 21) (I, I = 1, 120) * 0
21 FORMAT (10 RESIDUALS FROM EXACT EQUATIONS)
GO TO 48
AEDC-TR-76-39

OSIMUL

SURROUN Hit OSIMUL(A, R2, F2, N2, F2, A3, R3, C3, O3, F3, F3, 1NTERUG, XX, Y)


COMPLEX*16 X(2, 2), Y(4)

SIGMA = UPSLON + PHI + PSI + OMEGA + ZERO + A1 + B1 + C1

C = 1

DATA ZERO/(10, 0, 0, 0, 0)/O/OMEG/(1, 0, 0, 0)/X/(1, 0, 0, 0)

C COMPUTE QUARTIC COEFFICIENTS

C--------------------------------------------

C = 1

ALPHA = A2 + ALPHA + B2 + C2 + DELTA + F2 + B1SQ

UPSLO = 2, 0, 0 + A2 + ALPHA + B1AT + R2 + DELTA + C2 + FSLII +

* 2, 0, 0 + E2*AT2 + N2 + B1SQ

P = 2, 0, 0 + ( BETA ** 2 + 2, 0, 0 + ALPHI + GAMMA ** 2 + A2 + EPSLII +

* C2 + ZERII + F2 + ATISQ + F2 + B1SQ + 2, 0, 0 + D2 + B1R1

PSI = 2, 0, 0 + BETA + GAMMA ** 2 + A2 + R2 + ZERII + C2 + ETA1 +

* 2, 0, 0 + F2 + 1N1 + D2 + ATISQ

OMEGA = A2 + GAMMA ** 2 + 2, 0, 0 + ETA1 + F2 + ATISQ

SIGMA = UPSLO + PSI + PSI + PSI + PSI

PHTI = OMEGA

IF(1NTERUG.EQ.0, 0, 0) GO TO 0

C--------------------------------------------

C PRINT COEFFICIENTS

C--------------------------------------------

WRITE(0, 1) 1, AP, R2, C2, N2 + F2, A3 + B3 + C3 + O3 + F3

0, 0, 0, 0 + ALPHI + BETA1

- GAMMA + BETA1 + DELTA + FSLII + ZERII + BETA1 + ATISQ + ATII + ATISQ

1 FORMAT(132, 1) + O1, 0 + O1, X, + A1, 0 + 1A + 1A + 1A + 1A

1 = 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1

2 + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A + 1A

3 = 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1

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OSIWUL

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4 10X*FPSL+11Y**+7E15.8/0*5X*ZFTA11**11X*ETAIL**11X*

5 INT*11X*INT**112X*INT**115E16.8)

WRITE (1)E8U+2)SIGMA+UPSLO+PHI+PSI+OMEGA+ZERO

2 FORMAT(9*0*13X*SIGMA+27X*UPSLON+29X*PHI+29X*PHI/I+1*)

1BE15.8/0*14X*OMEGA+27X*ZERO/I+1*+E16.8)

C-------------------------C
C FIND ROOTS TO QUARTIC
C-------------------------C

9 N=4

IF(REAL(SIGMA),NE.0,DO)GO TO 40

N=3

IF(REAL(UPSLON),NE.0,DO)GO TO 30

N=2

IF(REAL(PSI),NE.0,DO)GO TO 20

C LINPAR

N=1

10 OMEGAPSI=OMEGA/PSI

PSI=ONF

CALL QANDC(N,OMEGA,OMEGA+ZERO,PSI,PSI+ZERO,1,Y1*2,Y3*4)

GO TO 45

C QUADRATIC

20 PSI=PSI/PHI

OMEGA=OMEGA/PHI

PHI=ONF

CALL QANDC(N,PSI+OMEGA+ZERO+PHI+Y1*2,Y3*4)

GO TO 45

C CURIC

30 PHI=PHI/UPSLON

PSI=PSI/UPSLON

UPSLON=ONE

CALL QANDC(N,PHI+PSI+OMEGA+ZERO+PSI+Y1*2,Y3*4)

GO TO 45

C QUARTIC

40 UPSLON=UPSLON/SIGMA

PHI=PHI/SIGMA

PSI=PSI/SIGMA

OMEGA=OMEGA/SIGMA

SIGMA=ONE

CALL QANDC(N,UPSLON+PHI+PSI+OMEGA+Y1*2,Y3*4)

GO TO 45

C FIND ALL X VALUES FOR EACH Y ROOT

C-------------------------C

45 Y(1)=Y1

Y(2)=Y2

Y(3)=Y3

Y(4)=Y4

DO 100 I=1,4

IF(1+BT,N)GO TO 100

B1=-5*1(B2+2*Y(I))**/A2

C=COSORT(RI*T)*2-(N2*Y(I)+F2*Y(I)**2)/(A2)

X(I+1)=31+C

X(2+I)=31+C

B1=-5*1(3*Y(I))**/A3

C=COSORT(RI*T)*2-(N3*Y(I)+F3*Y(I)**2)/(A3)

X(1+2+I)=31+C

100 CONTINUE

128
C WRITE(10,95) SIGMA,UPSLON,PHI,PSI,OMEGA,ZERO
3 FORMAT(101,15X,Y(1+1=1)*X
1 2(+1)=11(+1)=1
2 *POSITIVE+11(-1)+111(-1)+111111(PHIF)=111
3/4X ROOTS BASED ON Y1/1=1/1=1/1=1
4 1/4X ROOTS BASED ON Y1/1=1/1=1/1
5 1/4X ROOTS BASED ON Y1/1=1/1=1/1
C CHECK ALL X AND Y VALUES IN ORIGINAL SYSTEM OF CONICS
C
DO 130 L=1,2
DO 120 I=1,4
DO 114 J=1,2
DO 118 K=1,2
IF(DPVAL(Y(1)),GT,1.093)GO TO 115
GO TO (101+110)+L
100 R(J,K+1)=APX(J,K+1)+B2*APX(J+1,K)+C2*X(J,K+1)+D2*Y(1)
1 E2*Y(1)**2+F2
GO TO 115
110 R(J+1,K)=APX(J+1,K)+B3*APX(J+1,K)+C3*X(J+1,K)+D3*Y(1)
1 E3*Y(1)**2+F3
115 CONTINUE
114 CONTINUE
120 CONTINUE
130 CONTINUE
C WRITE(10,101)R
4 FORMAT(103,RUG,3/R
C SORT OUT EXTRANEOUS ROOTS
C
135 L=0
DO 160 J=1,4
DO 180 I=1,2
DO 140 K=1,2
IF(DCARAS(R(1+1,J+1),LT,1.093)GO TO 140
GO TO 180
160 CONTINUE
L=L+1
IF(L.LT.4)GO TO 150
WRITE(IOUT,145)
145 FORMAT(105,STYL: MORE THAN FOUR ROOTS FOUND)
STOP
150 IIT(L)=I
JJJ(L)=J
180 CONTINUE
160 CONTINUE
L=L+1
DO 200 L=1,4
XX(L)=CNFIN
IF(L.GT.LLL)GO TO 190
XX(L)=X(IIT(L)+1+JJJ(L))
GO TO 200
190 Y(L)=CNFIN
200 CONTINUE
WRITE(IOUT,220)XX,Y
220 FORMAT(110,STYL: MORE THAN FOUR ROOTS FOUND)
STOP
C WRITE(10,240)
240 FORMAT(105,STYL: MORE THAN FOUR ROOTS FOUND)
STOP

129
SUBROUTINE QANOC (N, R, Q, F, X1, X2, X3, X4)
IMPLICIT COMPLEX*16 (A, B, C, D)
COMPLEX*14 T
DATA T /1.000, 1.000/ + CINFIN(1, 0.70, 1.070)/
GO TO (30, 20, 10, 51, 14, 30)
C QARITIC
5 A = ((4.000 - 3.000) - 3.000)/2.000
A1 = (C*R*F - 4.000)/6.000
A2 = (C*R*F)/2.000
A = A1 + A2
A3 = CDSORT ((A3) + ((A3) + (A3) + (C*F)/3.000))/2.000
R = A6
CALL CHRT (A/3.000)
PRINTASTAR = 0.000 - C*C/3.000
R1 = PSTAR/(1.000 + R)
R2 = (R + 1.000 + 1.000 - C)*R1
PRINT = CDSORT (R2/4.000 - C*C)
R3 = CDSORT (0.0000 - 0.000 + C*R)
P = CDSORT (C25000/000 + 6.000)
A4 = 5.000 + A2
P00 = 2.000 + P00
IF (CDAH5 (A2 + P00)) AT, CDAH5 (A3 + P00) P00 = P00
P = (CDAH5 (A3))
C CALCULATING THE F/005
A1 = (1.000 + 0.000)
A2 = (A/2.000 + D)
C3 = (A/2.000 + P)
X1 = (1.000 + 2.000 - 4.000*A1*C11)/(2.000 + A1)
X2 = (1.000 + 2.000 - 4.000*A1*C11)/(2.000 + A1)
R1 = (R/2.000 + P)
C4 = (A/2.000 + P)
X3 = (1.000 + 2.000 - 4.000*A1*C11)/(2.000 + A1)
X4 = (1.000 + 2.000 - 4.000*A1*C11)/(2.000 + A1)
DST JKH
C CJRF
1n CONTINUE
P = (C**2/3.000)
Q = (C/3.000 + C/3.000)/2.000
Z1 = (1.000 + 0.000) + CDSORT ((C**2/4.000) + (C**3/27.000))
Z2 = (1.000 + 0.000) + CDSORT ((C**2/4.000) + (C**3/27.000))
IF (CDAH5 (Z1), C/DH5 (Z1)) Z2 = Z1
IF (CDAH5 (Z2), C/DH5 (Z1)) Z2 = Z2
IF (CDAH5 (Z2), C/DH5 (Z2)) Z2 = Z2
IF (CDAH5 (Z1), C/DH5 (Z2)) Z2 = Z2
Z1 = (1.000 + 0.000)/2.000 + R*F
IF (CDAH5 (Z1), C/DH5 (Z1)) R*F = Z1
C4 = (A/3.000)
W2 = (1.000 + 2.000 + 4.000 + 5.000 + 2.000)
X2 = (1.000 + 2.000 + 4.000 + 5.000 + 2.000)/2.000
X1 = (1.000 + 2.000 + 4.000 + 5.000 + 2.000)/2.000
X4 = CINFIN
RFT JKH
C QARITIC
20 A1 = 5.000
A2 = CDSORT (A1**2 - C)
X1 = 1.000
X2 = 6.000
X3 = CINFIN
X4 = CINFIN
RFT JKH
C LINRF
30 X1 = H
X2 = CINFIN
X3 = CINFIN
X4 = CINFIN
RFT JKH
FV0
SUBROUTINE CUBRT(AA,RR,RA)
IMPLICIT COMPLEX*16(A-G,Z)
REAL*8,H1,H13,H1H
REAL*8,PT,SSSS
COMPLEX*16
CONTINUE
I=0.11
II=1
Z1=AA+RR
Z2=AA-RR
IF(COARS(Z2),GF,COARS(Z1)) A=Z2
IF(COARS(Z1),GF,COARS(Z2)) A=Z1
R=CONJG(A)
HIA=(A+B)/2.00
H1B=-I*(A-B)/2.00
H1H=DATAN2(H13+H1A)
H=(H1A**2+H1B**2)**.500
P1=3.14159265358979300
SSSS=3.00
RR=(H**1*(1.00/3.00)) + DCOS((H1H+(II-1)*2.00*PT)/SSSS)*I* DSIN((H1H
IIH=(II-1)*2.00*PT)/SSSS))
RETURN
END

FUNCTION DREAL(CC)
COMPLEX*16 CC
REAL*8 D(CC)
EQUIVALENCE (C(2),D(1))
D(CC)=D(1)
RETURN
END

FUNCTION DIMAG(II)
COMPLEX*16 II
REAL*8 D(II)
EQUIVALENCE (I(2),D(1))
I(2)=DIMAG(2)
RETURN
END
NOMENCLATURE

A

Area

$A_{11}$

Solution weighting parameter, Eq. (25)

$A_{15}$

Momentum correction coefficient in wall crossflow model, Eq. (7)

$A_{16}$

Flap correction coefficient in the flap flow model, Eq. (8)

$A_{17}$

Weight used in computing test section pressure, Eq. (10)

$A_i, B_i, C_i, D_i, E_i$

Arrays of coefficients in the small perturbation equations

E

Computational error

F

Function

k

Flow coefficient, as in $k_f$ and $k_w$

M

Mach number

$M_\infty$

Steady, asymptotic test section Mach number

$m$

Mass flow rate

$m_0$

Convenient quantity with units of mass flow rate defined as

$$
m_0 = \sqrt{\frac{\gamma}{\gamma - 1}} \frac{P_{ct_0}}{R \sqrt{T_{ct_0}}} A_{ts}
$$

$m$

Nondimensional mass flow rate defined as $\sqrt{\frac{\gamma - 1}{2}} \frac{m}{m_0}$, Eq. (B-3)

$m_c$

Nondimensional mass flow rate defined as $\frac{m}{m_c}$, Eq. (B-1)

$m_c$

Convenient quantity with units of mass flow rate defined as

$$
m_c = \sqrt{\frac{\gamma}{\gamma - 1}} \frac{P_c}{R \sqrt{T_c}} A_{ct}
$$

n

Iteration number

P

Pressure

$\tilde{P}$

Nondimensional pressure, $P/P_0$
R  Perfect gas constant
T  Temperature
$t$  Time
$t^*$  Midpoint of a time interval
$t_F$  Final time in an area time curve
V  Volume, as in $V_p$ or $V_{ts}$
$v_i$  Scratch variable used to develop small perturbation expansion, Eq. (27)
X,Y  Variables in numerical reversion procedure (Fig. 10)
$a$  Constant defined as $\sqrt{\left(\frac{\gamma+1}{\gamma-1}\right)^{\gamma-1} \frac{\gamma}{R}}$, Eqs. (4) and (5)
$\gamma$  Ratio of specific heats
$\delta_f$  Flap gap
$\epsilon_i$  Array of small perturbations of the variables from the exact solution (Table A-1)
$\epsilon_{A_c}$  Perturbation in the main valve area
$\epsilon_{A_f}$  Perturbation in the flap area
$\epsilon_{A_{pe}}$  Perturbation in the plenum exhaust valve area
$\rho$  Density
$\tau$  Porosity, percent of test section wall area drilled out to allow crossflow

**SUBSCRIPTS**
c  Charge condition
c_t  Charge tube (or supply tube)
d  Diffuser end of test section
e  Main tunnel exit, main valves
f  Flaps
i  Array index
max  Maximum value as in $A_{p_{e\text{\_max}}}$
n  Nozzle end of test section
p  Plenum
pe  Plenum exhaust
pt  Plenum - Test Section
t, ts  Test section, as in $P_t$ or $A_{ts}$
tsw  Test section wall, as in $A_{tsw}$, the total wall area
w  Test section wall, as in $A_w$, the effective flow area
0  Stagnation condition
1  Test value in numerical reversion (Fig. 10)

**SUPERSCRIP****

*  Sonic conditions