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A THEORETICAL AND EXPERIMENTAL STUDY OF UNSTEADY FLOW PROCESSES IN A LUDWIEG TUBE WIND TUNNEL

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16. Abstract

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DEFINITION OF SYMBOLS

Symbol	Definition
a	speed of sound
A	cross-sectional area
c_p	specific heat at constant pressure
L_0	total length of wind tunnel
M_{TEST}	Mach number in test section during steady-state duration
p	static pressure
p_c	charge pressure
p_t	total pressure
P	right running characteristic variable
Q	left running characteristic variable
R	gas constant
s	specific entropy
S	nondimensional specific entropy $s/c_p(\gamma - 1)$
t	time
t^*	nondimensional time a_0t/L_0
T	temperature
u	velocity
x	axial coordinate
x^*	nondimensional coordinate x/L_0

DEFINITION OF SYMBOLS (Concluded)

Symbol	Definition
γ	ratio of specific heats
ρ	density
Subscripts	
0	reference conditions
Superscripts	
*	nondimensional quantities

A THEORETICAL AND EXPERIMENTAL STUDY OF UNSTEADY FLOW PROCESSES IN A LUDWIEG TUBE WIND TUNNEL

SUMMARY

The application of a numerical procedure generally referred to as the method of characteristics to calculate the nonsteady discharge of compressed air through a Ludwieg tube type of wind tunnel is presented. The mathematical model that underlies the numerical procedure assumes the flow through the wind tunnel to be time-dependent, one-dimensional, and compressible. The theoretical results presented were obtained from a computer program developed for this problem. Diaphragm rupture, variations in cross-sectional areas, contact surfaces, shock waves, and the interaction and reflection of contact surfaces and shock waves are included in the computer program. The theoretical results are compared with static and total pressures measured in a Ludwieg tube wind tunnel that has recently begun preliminary operation at MSFC. Good agreement between theory and experiment is achieved for the cases in which the flow in the test section was subsonic. Only fair agreement between the one-dimensional theory and experiment was achieved in the supersonic test sections. This difference is believed to be attributed to the two-dimensional character of the flow and the extensive flow separation that occurs in the supersonic nozzles during the early development of the flow.

INTRODUCTION

To support present and future missions of our extremely large and fast space vehicles, it is necessary to simulate high Reynolds numbers in our wind tunnel testing programs. Ludwieg [1] first proposed the principle of the pressure tube wind tunnel and supervised the construction of such a wind tunnel [2] at the Aerodynamische Versuchsanstalt in Gottingen, where a facility of this type has been successfully operated [3]. Basically, this type of wind tunnel consists of a long tube filled with high pressure gas, a nozzle, a test section, and an outlet into the atmosphere or some sort of emptying reservoir. The high pressure gas is generally sealed downstream of the test section by a diaphragm. When the diaphragm ruptures, the high pressure gas moves through the test section and establishes, after a certain start time, a period of constant property flow. The attractive characteristic of this type of wind tunnel is the high Reynolds number flows that can be produced in the test section. References 4 and 5 describe the operating principle and report some measurements of a "Ludwieg Tube" wind tunnel constructed at the Royal Armament Research and Development Establishment in England during 1957. Davis [6, 7] presents a feasibility study and some measurements made in a pilot model of a Ludwieg tube wind tunnel that was to be built at Marshall Space Flight Center in 1968.

Analytical methods for solving time-dependent one-dimensional flow through a duct have been available for some time [8, 9]. Because of the complicated wave processes that occur during the early stages of expansion flow through a duct of varying cross section, the automation of the analytical methods has been virtually ignored. References 10 and 11 report recent results from computer programs that solve the transient one-dimensional flow through ducts of varying cross sections by a numerical procedure referred to as the "method of characteristics." Reference 12 presents results based upon an implicit finite difference procedure that solves the compressible gas flow through a duct of constant cross section.

This paper presents a comparison of measured and theoretical results for the flow of air through the high Reynolds number wind tunnel at Marshall Space Flight Center. The method and computer program reported in Reference 10 were used to produce the theoretical results presented. The experimental results are measurements obtained from the pilot model tests and during initial runs of the Ludwieg tube tunnel, which has recently begun shakedown operation at MSFC.

DESCRIPTION OF TEST EQUIPMENT

To obtain data for high Reynolds number flows, MSFC proposed in 1965 the construction of a relatively inexpensive short duration wind tunnel based upon a concept proposed by Ludwieg in 1955. A small pilot model of this type of wind tunnel was constructed in 1967, and results from testing in this model facility were reported by Davis [6]. Construction of the wind tunnel at MSFC was completed in April of 1969, and the operation of this equipment subsequently began. Figure 1 is a pictorial drawing of the major components that make up the wind tunnel. The diaphragm that initially separates the high pressure and low pressure reservoirs is located downstream of the test section. Flow is initiated by cutting the diaphragm, which is composed of sheets of mylar

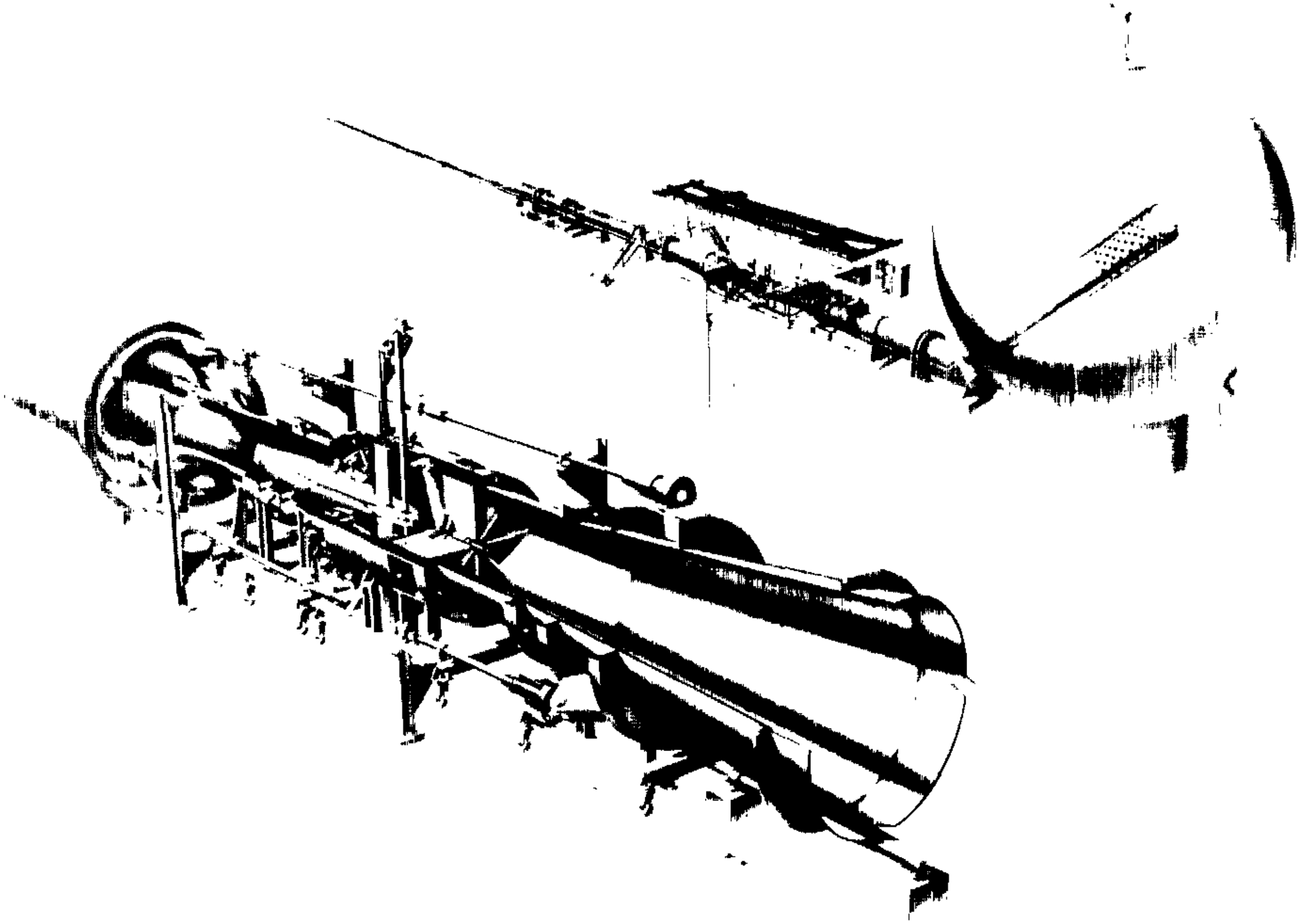

Figure 1. High Reynolds number test equipment.

supported on a cruciform frame. The supply tube is 378 feet long with an inner diameter of 52 inches. A settling chamber separates the supply tube and the nozzle. Its purpose is to reduce the effects of the boundary layer, which grows with time along the supply tube, and to slow the flow before it enters the nozzle, thus tending to improve the quality of the flow before it enters the nozzle and test section. Downstream of the settling chamber is the nozzle section. At present, four nozzles have been designed: a sonic nozzle used in all subsonic test cases, and three supersonic nozzles that produce Mach numbers of 1.4, 1.7, and 2.0 in the test section. For testing at subsonic Mach numbers, a sonic nozzle is installed in the nozzle section, and any particular subsonic Mach number between 0.25 - 0.77 in the test section can be obtained by a proper setting of the choking flaps, which are located immediately downstream of the test section. Each supersonic Mach number in the test section requires insertion of an appropriate nozzle in the nozzle section. The nozzles for the supersonic Mach number cases were designed from the results of a two-dimensional method of characteristics satisfying the condition of uniform flow at the nozzle exit plane. Testing at transonic Mach numbers will be conducted in a special transonic test section now under construction. Immediately downstream of the nozzle is the test section, which has an inner diameter of 32 inches. Reynolds numbers up to approximately 2.0×10^8 per foot for a Mach number of 1.4 in the test section can be attained when the supply tube is charged to its maximum pressure of 700 lb/in.^{2}. Downstream of the test section follow the model support, diaphragm, spool section, diffusers, and an emptying reservoir, which is a large sphere that slowly discharges the high pressure gas into the atmosphere. A large muffler is located at the outlet of this sphere to attenuate the sound of the discharging gas.

Operation of this equipment was begun in April of 1969. Thus far, only shakedown runs at low charge temperatures for subsonic Mach numbers have been conducted. Total pressures and temperatures in the settling chamber and static pressures in the test section have been measured, and are compared with theoretical results in a later section of this report.

THEORETICAL ANALYSIS

The theoretical results presented in this report are based upon the assumption that the flow of gas through the duct is time-dependent, one-dimensional, and compressible. The differential equations in Eulerian form, which describe the flow based upon these assumptions, are as follows:

Continuity

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho u A)}{\partial x} = 0 \quad (1)$$

Momentum

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \quad (2)$$

State

$$a^2 = \gamma\frac{p}{\rho} = \gamma RT \quad (3)$$

First law of thermodynamics

$$s - s_0 = c_p \ln\frac{T}{T_0} - c_p\frac{\gamma - 1}{\gamma} \ln\frac{p}{p_0} \quad . \quad (4)$$

Since the results appearing in this report do not include wall friction effects or mass removal from the duct, for example, in a transonic section with porous walls, the terms that account for these effects are not included in the above equations. The partial differential equations (1) through (4) are of the hyperbolic type and can readily be solved by a numerical procedure referred to as the method of characteristics. For a detailed derivation of the characteristic equations from the partial differential equations and a description of the method in which the characteristic equations are then solved, the reader should refer to Reference 10. Briefly, the method consists of deriving finite difference equations from the partial differential equations so that certain parameters, usually called Riemann or characteristic variables, can be solved by a step-by-step procedure along particular charactersitic curves in the plane of the independent variables. For the problem at hand, the parameters are referred to as P (the right running characteristic), Q (the left running characteristic), and S (the entropy), which follows the particle path in the x, t plane. In regions where the Q characteristics travel toward the left, the flow is subsonic; vertically, the flow is sonic; and toward the right, the flow is supersonic. Whenever two curves of the same family (either P or Q) meet, a discontinuity in the pressure exists at this point. A boundary in the flow is thus established, and this boundary is defined as a normal shock wave. Two types of shock waves can therefore occur, either a P shock (converging of the P characteristics) or a Q shock (converging of the Q characteristics).

Since it is assumed that changes of the flow variables across a shock wave take place instantaneously, the steady-state relationship between flow variables on each side of the shock can be used. The equations that relate the flow variables upstream and downstream of a stationary normal shock are generally referred to as the Rankine-Hugoniot equations. The mathematical process at a shock point is to match the normal shock solution with the characteristic solution. Details of the matching procedure and the normal shock equations are published in Reference 10.

Another discontinuity that can occur is referred to as a "contact surface." A contact surface is defined as a boundary through which no flux of matter can pass. It is an interface or boundary in the x, t plane in which the conditions of equal velocity and pressure on each side are satisfied, with, however, other properties being discontinuous. An example of this type of discontinuity is the path of the interface separating two different gases that are flowing through a duct or the path of the interface between the same gas at different entropy levels in the x, t plane. At a contact surface point, the mathematical process is to match the characteristic solution with the boundary conditions on each side of the point.

It can easily be seen that possibilities exist for discontinuities to intersect with one another. Such possibilities are shocks of like families intersecting, shocks of unlike families intersecting, and shock and contact-surface intersecting. Although the general methods for handling these interactions are similar, each case requires somewhat different calculation procedures.

A computer program to calculate the complete flow field for the Ludwieg tube problem with time was constructed. The calculation begins at diaphragm rupture and automatically solves the flow phenomenon that occurs for time-dependent, one-dimensional, compressible flow of gas through the duct.

Figure 2 shows a wave diagram of the calculated results for the Ludwieg tube wind tunnel with a Mach 2 nozzle mounted upstream of the test section. When the diaphragm is ruptured, the high pressure gas on the left expands and compresses the low pressure gas on the right, creating a P shock wave that travels downstream through the undisturbed gas. Proceeding downstream behind the P shock is a contact surface, which is the interface between the gas particles that were initially in contact with each side of the diaphragm. Also created at diaphragm rupture is an expansion fan that is bounded on the left by the headwave and on the right by a tailwave. The waves shown in the expansion fan belong to the family of left running or Q characteristic waves.

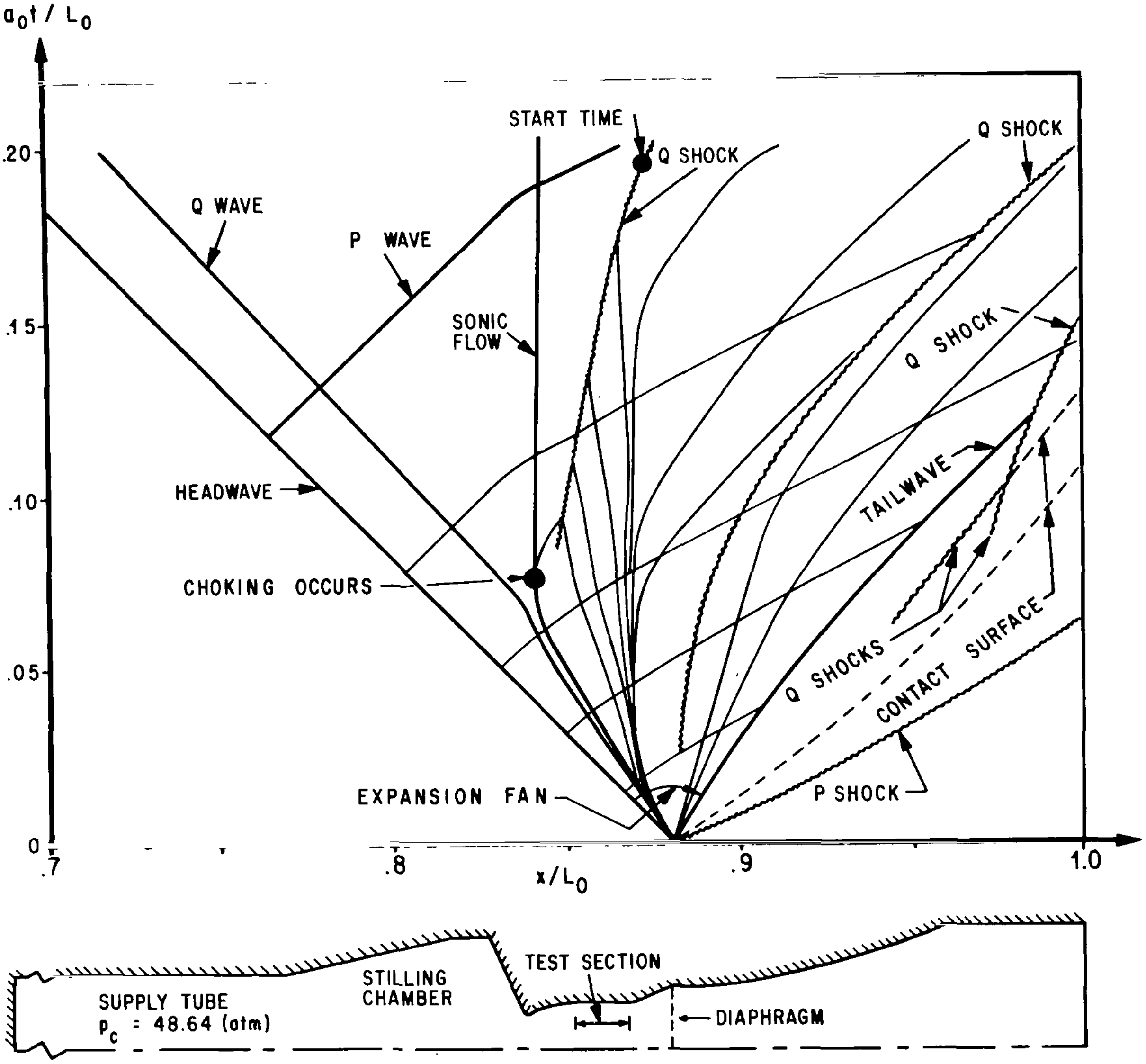

Figure 2. Wave diagram for a Mach 2 nozzle.

In Figure 2 can be seen that part of the fan which travels upstream through the nozzle and into the supply tube before choking at the nozzle throat occurs. After the throat chokes, no more expansion or Q characteristic waves can pass through the throat position. Subsequently, sonic flow is established at the nozzle throat, as illustrated by the vertically running Q characteristic curve in the wave diagram. Immediately after choking, a Q shock is formed downstream of the nozzle throat. This shock wave, which becomes stronger as it travels through the expanding portion of the nozzle, is eventually swept through the test section, leaving behind it a period of steady flow. Along with the P shock that was created at diaphragm rupture, a total of four Q shocks were formed within the duct during the time under consideration. A few selected P characteristics are shown in the diagram to illustrate the grid of characteristics on the x, t plane. No physical significance is rendered by the direction of the P characteristics, whereas, the direction of the Q characteristics illustrates the local flow regimes.

The method developed to calculate the time-dependent solution of the gas flow properties in the Ludwieg tube wind tunnel employs a step-by-step procedure that marches at a constant time interval of Δt in the time direction. For the reader to gain some insight into the practicality of this procedure, let us return to Figure 2. The non-dimensional time interval used in calculating this wave diagram was 0.001. There was approximately a total of 20 000 points that were calculated, consuming 27 minutes of CDC 3200 computer time.

COMPARISON OF THEORETICAL WITH EXPERIMENTAL RESULTS

Figure 3 presents the time-dependent behavior of the static pressure at a location in the test section that was calculated from the one-dimensional analysis for the 18.75-percent pilot model of the Ludwieg tube wind tunnel. The pilot model did not include a settling chamber. The experimental data were obtained from tests conducted in the pilot facility at MSFC. For this case, a supersonic nozzle is mounted upstream of the test section so that flow of gas at a Mach number of 2 is established during the steady-state period. First, the behavior of the static pressure in the test section that results from the theoretical analysis will be discussed. Since the settling chamber has very little effect on the flow properties in the supersonic test section, the wave diagram shown in Figure 2 will be referred to when explaining the results shown in Figure 3. Following the time dependence of the flow at $x^* = 0.86$ in the wave diagram shown in Figure 2, it is seen that flow will begin at $t^* = 0.02$ upon arrival of the expansion fan. The pressure immediately

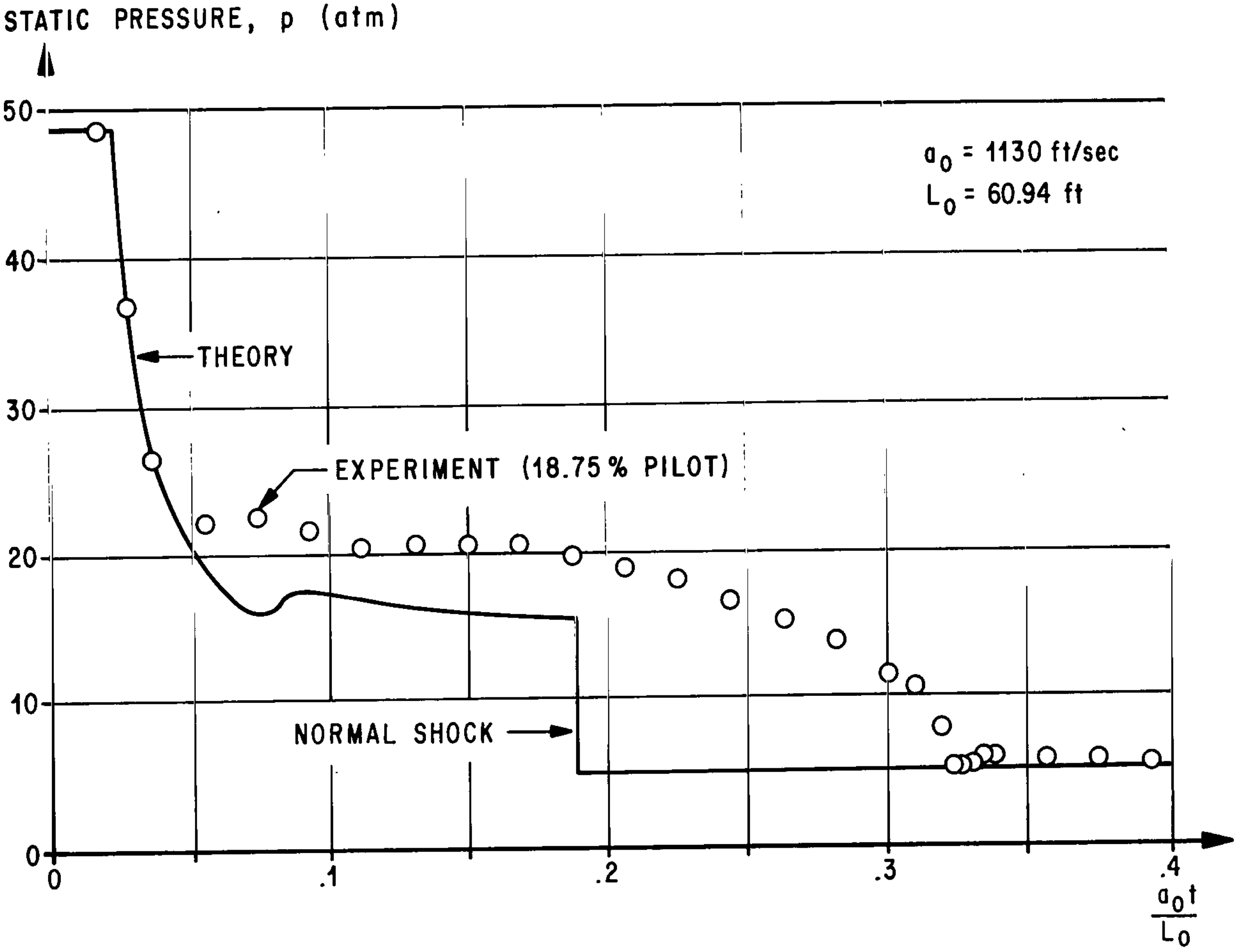

Figure 3. Time dependence of test section static pressure for $M_{TEST} = 2.0$.

decreases as the velocity increases, as shown in Figure 3. The flow chokes at the nozzle throat, which is located upstream of the test section at $t^* = 0.076$, and a normal shock (Q shock) forms just downstream of the throat because of an overexpansion. The flow is supersonic behind and subsonic ahead of this shock as it moves through the nozzle and test section. Figure 3 shows the sudden drop in the theoretical static pressure curve as the normal shock passes the location in the test section where the pressures are being tabulated. A steady flow is left behind the shock as it passes through the test section.

Figure 3 shows a considerable deviation in the theoretical and experimental results between the non-dimensional times 0.05 to 0.35. Based upon some observations reported by Bull [13], the following arguments are assumed to account for this difference between theory and experiment for a supersonic nozzle. The wave diagram in Figure 2 shows that the head of the rarefaction fan passes through the throat at approximately $t^* = 0.04$, and gas flow is initiated there at this time. At approximately $t^* = 0.05$, the flow separates at the narrowest cross section, and the flow just downstream acts as a jet of gas issuing from the throat with a separation region lying between the jet boundaries and the tunnel wall. Shortly afterwards, sonic velocity is reached at the throat and a curved normal shock forms just downstream of the throat with the separated region and the free jet effect immediately downstream of the shock wave. The curved normal shock develops into a crossed-shock pattern with the free streamlines of the jet boundaries parallel to the velocity vector behind the shock waves. This complete system moves through the nozzle and test section, leaving behind it a flow that is approximately one-dimensional and steady. The difference in theory and experiment is therefore attributed to the flow behavior being two-dimensional rather than one-dimensional downstream of the supersonic nozzle during the early development of the flow, as postulated above.

Figure 4 presents theoretical and experimental static pressures as a function of time in a subsonic $(M_{TEST} = 0.7)$ test section of the 18.75 percent pilot model of the wind tunnel. As mentioned earlier, the flow is choked downstream of the test section by choking flaps to obtain subsonic Mach numbers in the test section. Upstream of this sonic throat, the flow is always subsonic, and no shocks are developed upstream of this position. For the example presented in Figure 4, the flow was choked at approximately 2 milliseconds. Steady flow in the test section is established when the transient effects on the flow properties caused by the area changes between the supply tube and the sonic throat die out with time. This period of steady flow is ended when the expansion fan headwave, which has reflected off the closed end of the supply

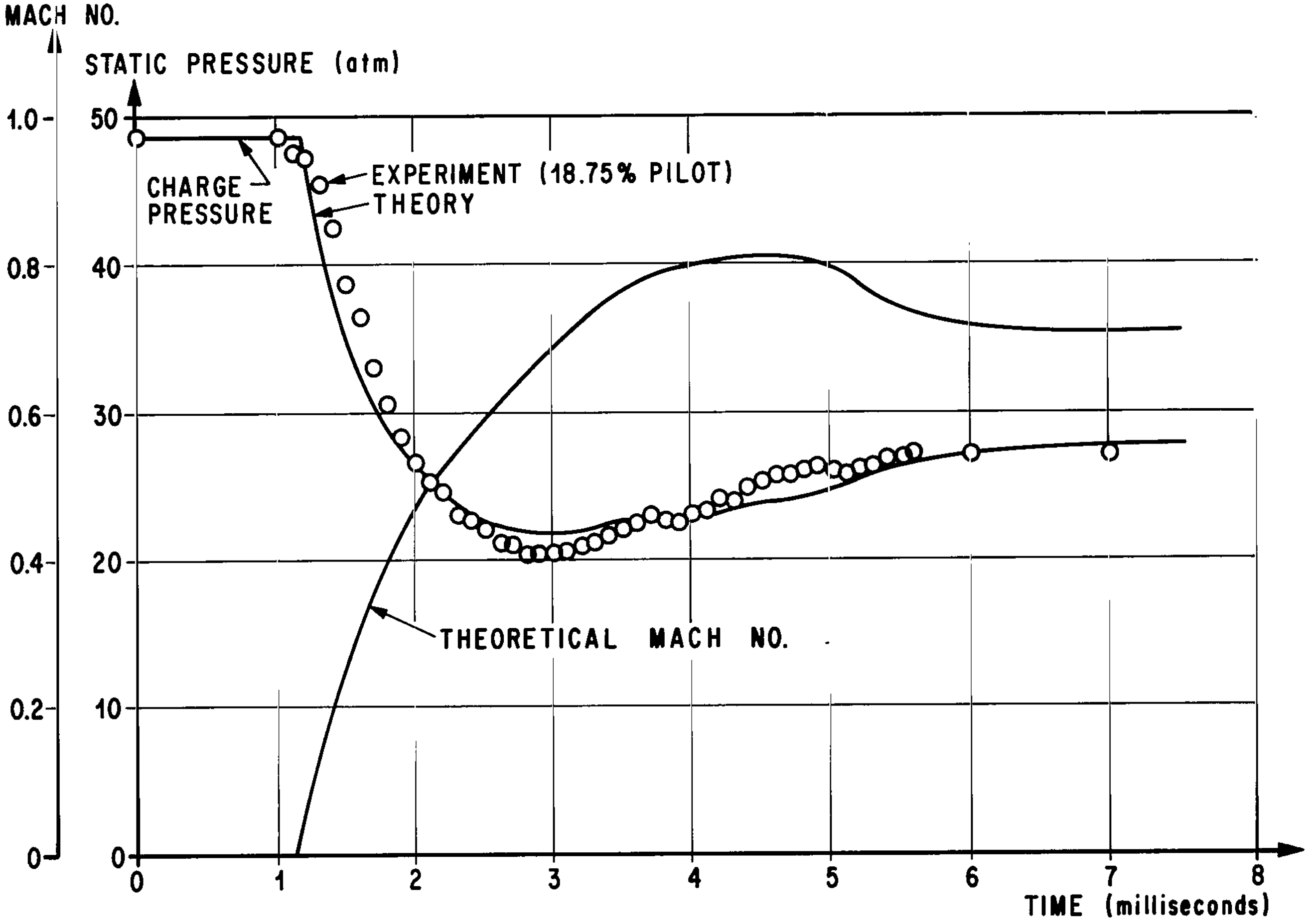

Figure 4. Time dependence of static pressure and Mach number in the subsonic ($M_{TEST} = 0.7$) test section of a Ludwieg tube pilot facility.

tube, returns to the test section. Thus, a long supply tube is essential for a long testing time. Figure 4 shows that the theoretical results agree extremely well with the measured data for the subsonic test section.

Figure 5 presents a wave diagram for the Ludwieg tube wind tunnel for a subsonic test case ($M_{TEST} = 0.47$) . Only shock waves, contact surfaces, and selected Q characteristics are shown in the diagram. Figure 6 shows the theoretical and experimental static pressures that were measured and calculated at $x^* = 0.891$ in the test section for this case. The measured data were obtained during initial runs of the wind tunnel, which has recently begun preliminary operation. As in the case for the pilot model (Fig. 4), the results from the one-dimensional theory agree quite well with the static pressure measurements made in the test section of the large tunnel.

Since energy is not conserved in an unsteady expansion, the stagnation conditions through the nozzle decrease with time from the storage conditions until a steady state is reached. Figure 7 presents both calculated and measured total pressures that were made in the middle of the settling chamber. The hump in the total pressure curve is caused by the cross-sectional area changes of the settling chamber. This figure also shows good agreement between theory and experiment.

CONCLUSIONS

The application of a numerical procedure reported in Reference 10 for calculating the nonsteady discharge of compressed air through a Ludwieg tube type of wind tunnel has been presented. The mathematical model that underlies the numerical procedure, generally referred to as the method of characteristics, assumes the flow through the wind tunnel to be time-dependent, one-dimensional, and compressible. The theoretical results presented were obtained from a computer program that was developed for this problem. Diaphragm rupture, variations in cross sectional areas, contact surfaces, shock waves, and the interaction and reflection of contact surfaces and shock waves are included in the computer program. The theoretical results are compared with static and total pressures measured in a Ludwieg tube wind tunnel that has recently begun preliminary operation at MSFC. As Figures 4 and 6 show, good agreement between theory and experiment is achieved for the cases in which the flow in the test section was subsonic. Only fair agreement between the one-dimensional

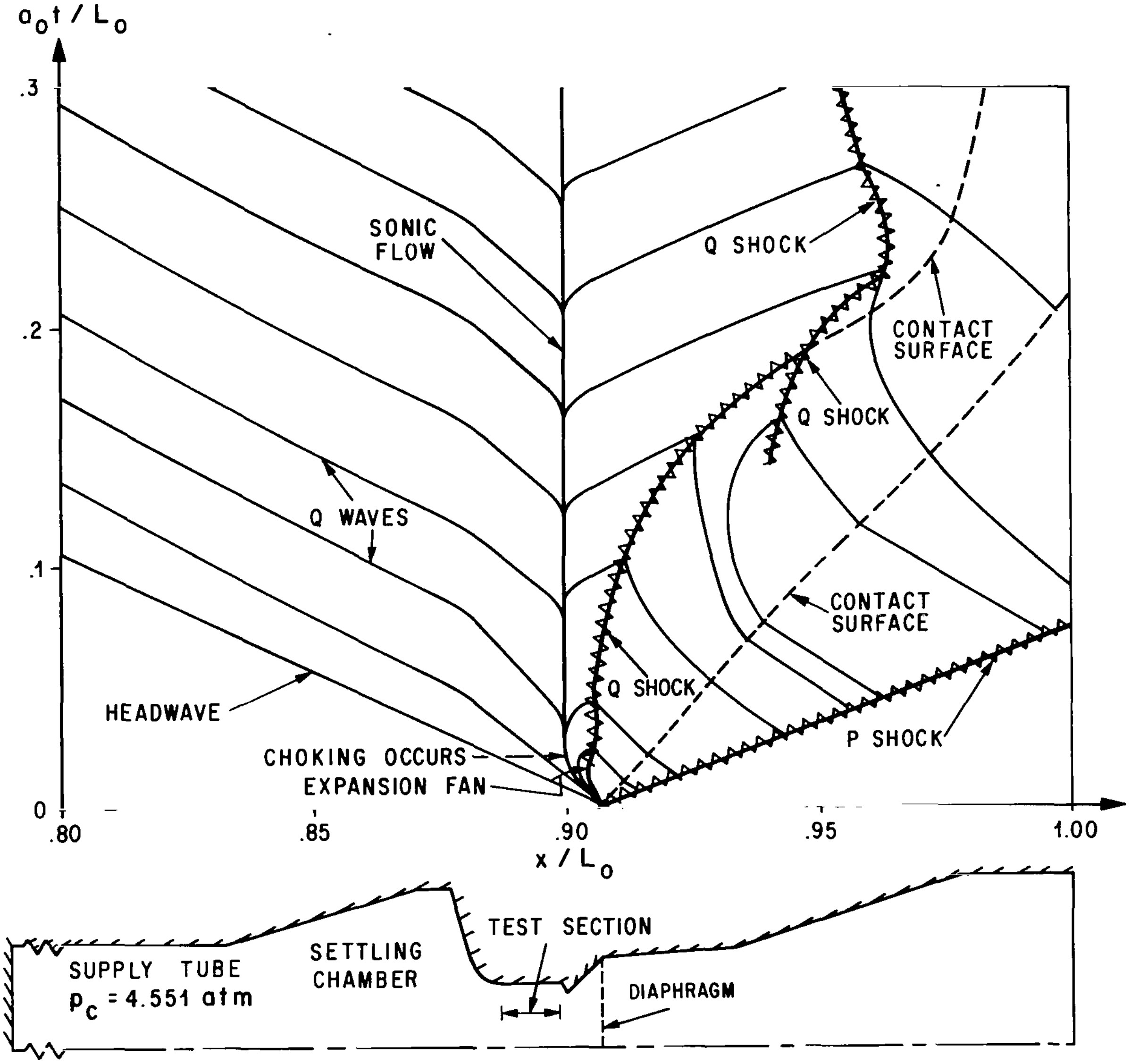

Figure 5. Wave diagram for $M_{TEST} = 0.47$.

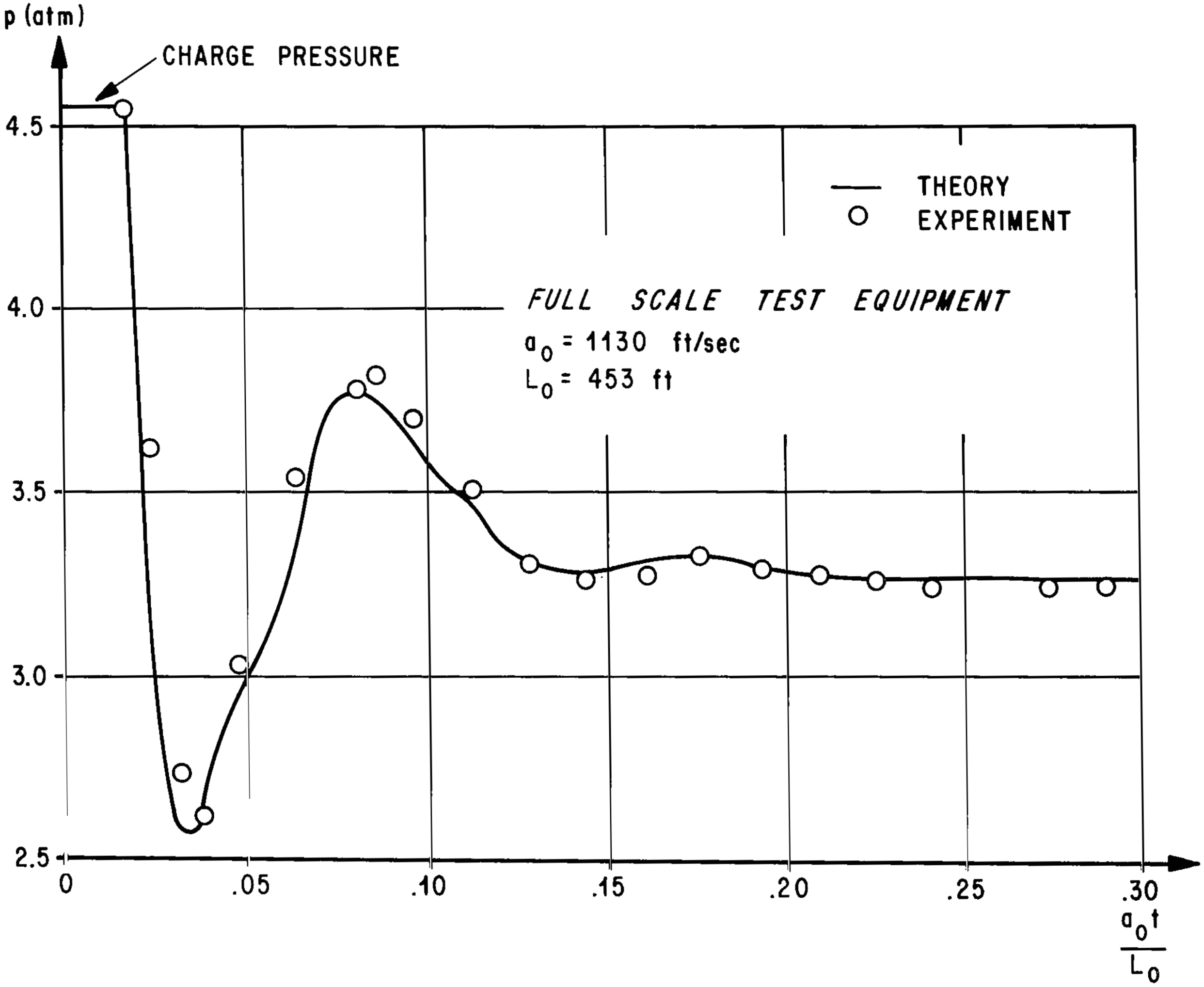

Figure 6. Time dependence of static pressure in the subsonic ($M_{TEST} = 0.47$) test section of Ludwieg tube.

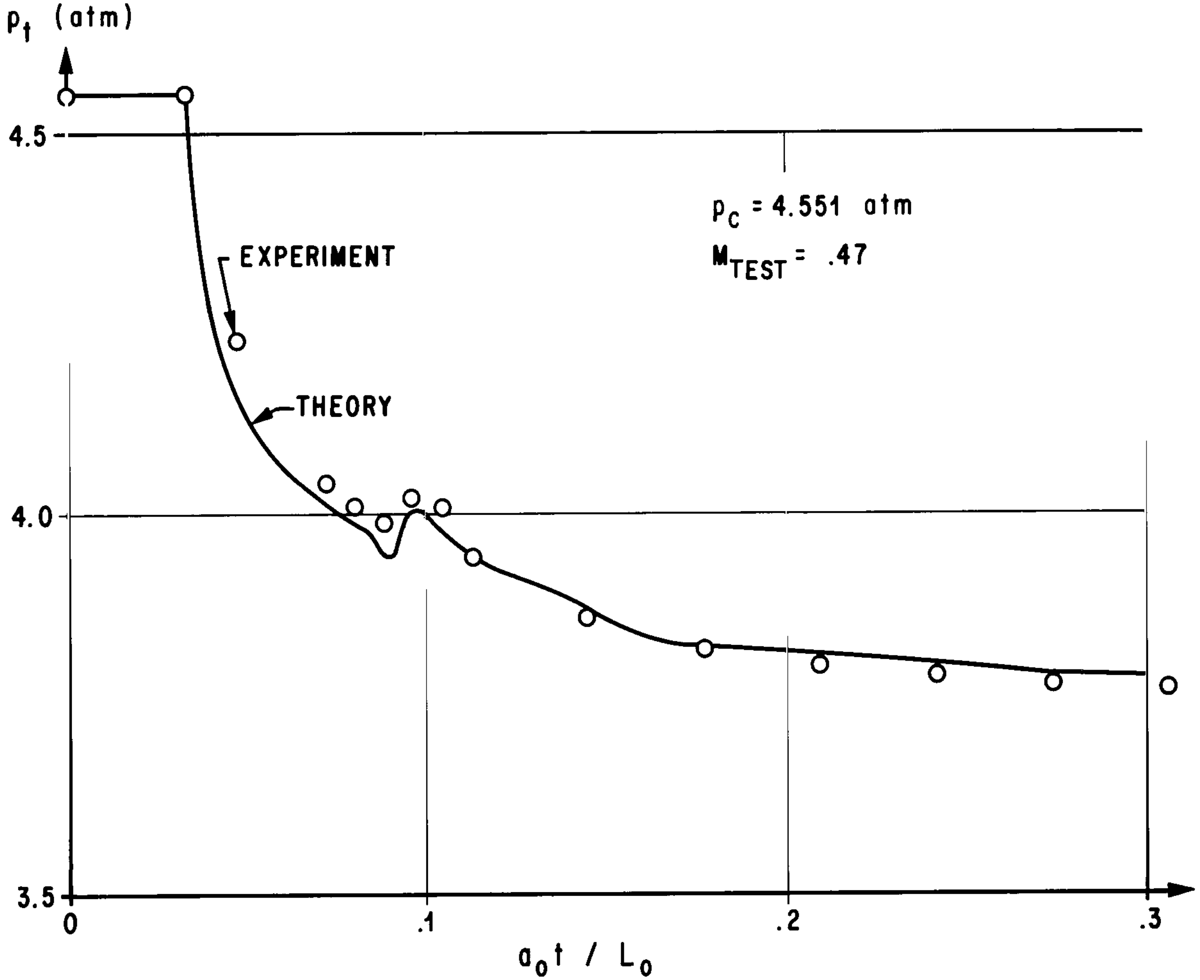

Figure 7. Time dependence of total pressure in the settling chamber.

theory and experiment was achieved in the supersonic test section, as illustrated in Figure 3. This difference is believed to be attributed to the two-dimensional character of the flow and the extensive flow separation that occurs in the supersonic nozzle during the early development of the flow.

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