Order Number 1335002

Response of stagnation pressure probe systems to a suddenly applied pressure

Pereira, Vernon Cruz Martin, M.S.A.E.

The University of Texas at Arlington, 1988

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

PLEASE NOTE:

In all cases this material has been filmed in the best possible way from the available copy. Problems encountered with this document have been identified here with a check mark __√__.

1. Glossy photographs or pages _____
2. Colored illustrations, paper or print ______
3. Photographs with dark background _____
4. Illustrations are poor copy ______
5. Pages with black marks, not original copy __✓__
6. Print shows through as there is text on both sides of page ______
7. Indistinct, broken or small print on several pages __✓__
8. Print exceeds margin requirements ______
9. Tightly bound copy with print lost in spine _______
10. Computer printout pages with indistinct print ______
11. Page(s) ___________ lacking when material received, and not available from school or author.
12. Page(s) ___________ seem to be missing in numbering only as text follows.
13. Two pages numbered ______. Text follows.
14. Curling and wrinkled pages ______
15. Dissertation contains pages with print at a slant, filmed as received ________
16. Other ____

UMI

RESPONSE OF STAGNATION PRESSURE PROBE SYSTEMS

TO A SUDDENLY APPLIED PRESSURE

The members of the Committee approve the masters thesis of Vernon Cruz Martin Pereira

D D Seath

Donald D. Seath
Supervising Professor

Donald R. Wilson

Constantin Corduneanu

DEDICATION

This Thesis is dedicated to my parents, relatives and friends, who have supported me through out my grduate work.

RESPONSE OF STAGNATION PRESSURE PROBE SYSTEMS TO A SUDDENLY APPLIED PRESSURE

by

VERNON CRUZ MARTIN PEREIRA

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN AEROSPACE ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
August 1988

ACKNOWLEDGEMENT

I would like to extend my thanks to General Dynamics for sponsoring this project and also to Mr. Gene Hull for his professional advice and support.

I would like to express my appreciation to my esteemed advisor Dr. Donald D. Seath, for his guidance and assistance during my thesis program.

Assistance from my committee members Dr. Donald R. Wilson and Dr. Constantin Corduneanu is deeply appreciated.

A debt of gratitude is owed to Mr. Jim H. Holland for his help during the construction and testing of my project.

May 11, 1988

ABSTRACT

RESPONSE OF STAGNATION PRESSURE PROBE SYSTEMS
TO A SUDDENLY APPLIED PRESSURE

Publication No.______

Vernon Cruz Martin Pereira, M.S.
The University of Texas at Arlington, 1988

Supervising Professor: Donald D. Seath

Experimental tests were conducted in the UTA shock tube at applied pressure levels between 1.4-psid and 3.9-psid using stagnation pressure probes of 0.07-, and 0.04-inch diameters and 0.8-, 1.6-, and 2.5-inch lengths. A differential pressure transducer (Entran, EPI - 060, 0.06-inch outside diameter) with a 2.0-psid range and a 15.0-psid overrange was selected to measure the stagnation pressure. A similar theoretical parametric study was done using response time expressions for transducer-probe systems developed for an impulsively applied pressure and unsteady, compressible, fully developed, laminar slip flow in the probe. The theoretical analysis and the experimental results agree within the precision of the experiments.

TABLE OF CONTENTS

		Page
ACKNOWLEDGEMENTS		iv
ABSTRACT		v
LIST OF FIGURES		vii
LIST OF TABLES		ix
NOMENCLATURE		x
Chapter		
I.	INTRODUCTION	1
II.	EXPERIMENTAL TEST PROGRAM	
	2-1 Stagnation Pressure Probe Development	4
	2-2 Shock Tube Description	8
	2-3 Instrumentation	8
	2-4 Shock Tube Operation	12
	2-5 Experimental Test Setup	13
III.	THEORETICAL ANALYSIS	
	3-1 Assumptions	18
	3-2 Theoretical Results	18
IV.	RESULTS AND DISCUSSIONS	25
V.	CONCLUSIONS	32
REFERENCES		33

LIST OF FIGURES

Figure		Page
2-1	Diagram of Stagnation Pressure Probe System with a 2.0-inch length and 0.07-inch diameter probe ..	5
2-2	Diagram of Stagnation Pressure Probe system with a 2.0-inch length and 0.04-inch diameter probe ..	7
2-3	Schematic Diagram of UTA Shock Tube	9
2-4	UTA Shock Tube Diaphragm Section	10
2-5	Block Diagram of Static Pressure Measurement	11
2-6	Typical Static Pressure Transducer Trace	14
2-7	Experimental Test Setup	15
2-8	Block Diagram of Stagnation Pressure Measurement	16
3-1	Assignment of subscripts to regions of the Stagnation Pressure Probe system	20
3-2	Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 1.0-psid Differential Stagnation Pressure	21
3-3	Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 2.0-psid Differential Stagnation Pressure	22
3-4	Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 3.0-psid Differential Stagnation Pressure	23
3-5	Theoretical Response Time Vs. Probe Lenght for a 0.04-inch and a 0.07-inch Diameter Probe at 4.0-psid Differential Stagnation Pressure	24
4-1	Typical Oscilloscope traces for 0.07-inch Diameter Stagnation Pressure Probes	27
4-2	Typical Oscilloscope traces for 0.04-inch Diameter Stagnation Pressure Probes	28

4-3 Method of Determining the Response Time from the Oscilloscope Traces 29

4-4 Theoretical and Experimental Response Time Vs. l/d (Length/Diameter) ratio of the probe for a 1.4-psid to a 3.9-psid differential stagnation pressure range 31

LIST OF TABLES

Table Page

4-1 Theoretical and Experimental Response Time....... 30

NOMENCLATURE

A	Internal cross-sectional area of probe, $inch^2$
d	Internal diameter of probe, inch
K_n	Knudsen number
l	length of probe, inch
ln	logarithm (base e)
P	Pressure, $lb/inch^2$
P_t	Stagnation Pressure, $lb/inch^2$
R	Gas constant, 55.14 ft-lbf/lbm-^oR for nitrogen
T	Temperature, 540^oR
t	Respone Time, seconds
V	Volume, $inch^3$
γ	Ratio of specific heats, 1.40
μ	Viscosity, 2.5×10^{-9} lb-sec/$inch^2$ for nitrogen at room temperature

Subscripts

i	Initial conditions in the transducer-probe system
m	Conditions in the measuring transducer

CHAPTER 1

INTRODUCTION

An experimental approach is necessary to validate Computational Fluid Dynamics (CFD) analysis of the flowfield near the vicinity of a model at hypersonic speeds. Therefore methods and apparatus are needed to obtain data which describe this flowfield with sufficient precision and detail. This paper primarily deals with stagnation pressure measurement using a pressure transducer with a tube extension (probe) attached to it. The physical requirements for the length and diameter of this probe are dictated by two factors. First, in order to maintain minimum flow disturbance in the boundary layer, smaller diameter probes are needed. Finally, since hypersonic tunnels have a short duration run time, measurement sytems must be capable of stabilizing in a time somewhat shorter than the total run time in order that the transducer pressure be very nearly the same as the flowfield pressure. This final requirement controls the length and diameter of the probe. The time required for a system to attain 63 percent of the applied pressure is called its response time.

The specific objective of this program is to experimentally determine the response time for stagnation pressure probes of various diameters and lengths. The University of Texas at Arlington (UTA) Shock Tube facility was used to test these stagnation pressure probe systems. The UTA Shock Tube supplies a step pressure and the output of the stagnation pressure probe system is recorded. By comparing the response times for stagnation pressure probes of various diameters and lengths the relative adequacies of the systems are obtained.

Similar experimental tests were performed by W. E. Smotherman and W. V. Maddox (Ref. 5) and by Henry W. Ball (Ref. 1). Smotherman and Maddox reported experimental results obtained by applying a step pressure to the orifice tube of a small differential pressure transducer. Henry W. Ball used their results to modify the theoretical analysis of Max Kinslow (Ref. 2) for unsteady, compressible, fully developed, laminar continuum flow in a tube. The modification consisted of the inclusion of a velocity-slip boundary condition at the tube wall. Ball also verified his modification experimentally. The theoretical analysis for the response time of pressure probe systems was obtained from Henry W. Ball's paper (Ref. 1).

Smotherman, Maddox and Ball used constant volume wafer-type variable reluctance pressure transducers in their experiments. The pressure transducers consisted of a pressure sensing diaphragm of magnetic material, the deflection of which controls the air gap in each of two magnetic circuits. These gaps change in opposite directions and hence produce corresponding changes in the inductance of two pickoff coils. The magnetic circuits are formed by the outer shell halves, the air gap, and the diaphragm. The flux in these circuits is produced by the 5-v (rms), 20-kc powered coils embedded within the transducer halves. The pressure transducers used in this experiment are silicon diaphragm transducers which use inorganic atomically bonded strain gages in a Wheatstone bridge arrangement. An applied pressure presents a distributed load to the diaphragm, which in turn provides bending stresses and resultant strains to which the strain gages react. This stress creates a strain proportional to the applied pressure which results in a bridge unbalance. With an applied voltage, this unbalance produces a mV (milliVolt) deviation at the bridge output, which is proportional to the net difference in pressure acting upon the diaphragm.

CHAPTER 2

EXPERIMENTAL TEST PROGRAM

The experiments to determine the response time for stagnation pressure probes of various lengths and diameters were performed using the UTA Shock Tube and a Hewlett Packard Digitizing Oscilloscope. The stagnation pressure probe system is described in section 2-1. The UTA Shock Tube is described in section 2-2 and the instrumentation in section 2-3. The operation of the UTA Shock Tube is described in section 2-4. Section 2-5 describes the experimental test setup.

2-1 Stagnation Pressure Probe Development

To test different probe diameters and lengths, an aluminum holder was designed to house the pressure transducer and the probes. The holder has to withstand the aerodynamic forces caused by shock waves of Mach numbers between 1 and 2. In order to achieve this, the front part of the holder was machined into a conical shape and is shown in figure 2-1. The holder was machined out of an aluminum cylinder. A 0.09-inch diameter hole was drilled 0.5-inch deep in the front end of this holder for the probe. Behind the probe lies the transducer in a 0.06-inch diameter by

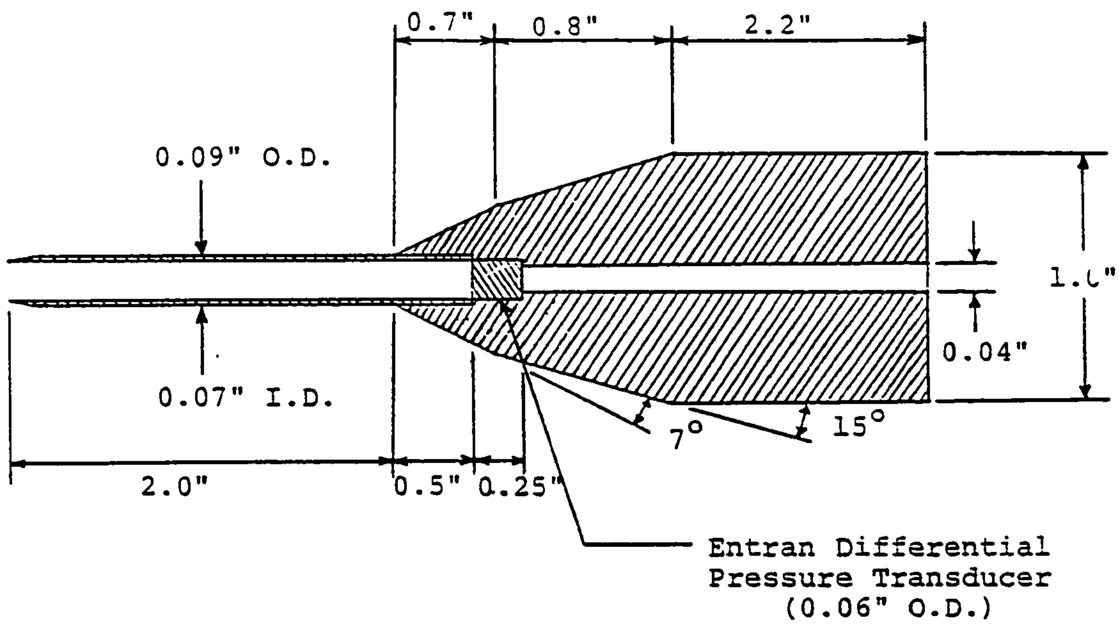


Figure 2-1 Diagram of stagnation pressure probe system with a 2.5-inch length and 0.07-inch diameter probe

0.25-inch length hole. The wires of the pressure transducer are taken out of the aluminum holder through a 0.04-inch diameter hole.

The pressure transducer used in this test is an Entran differential pressure transducer (EPI - 060) with a 0.06-inch outside diameter. It has a 2-psid range and a 15-psid overrange. This transducer has a resonant frequency of 100KHz. The calibration factor for this pressure transducer is 2.205 mv/psid (Calibrated and certified by Entran Devices, Inc.).

The probes were made from stainless steel tubings. The tips of these probes were machined down to a conical shape in order to insure minimum disturbance in the flow in which it was placed. In order to test 0.04-inch inner diameter (I.D.) probes, a smaller length 0.07-inch I.D. probe was used to hold it in place in the aluminum holder. This was accomplished by sliding the smaller I.D. probe into the larger one and soldering the junction of the tip of the larger I.D. probe to the body of the smaller one. The junction was then sanded down to give a smooth transition from the larger I.D. probe to the smaller one. This configuaration can be seen in figure 2-2. This was done for all the three lengths of 0.04-inch I.D. probes.

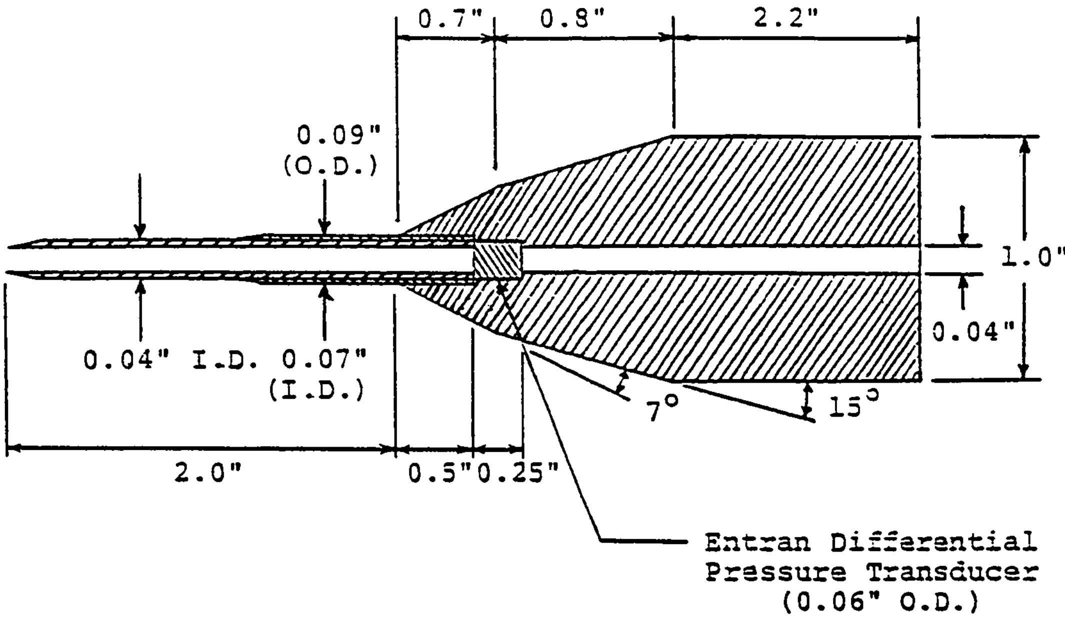


Figure 2-2 Diagram of stagnation pressure probe system with a 2.5-inch length and 0.04-inch diameter probe

2-2 Shock Tube Description

The UTA Shock Tube consists of two tube sections separated by a diaphragm or diaphragms. It is made of stainless steel mechanical tubing, with an overall length of 27 feet. The 4 inch diameter, 6 feet - 10 inch long driver (high pressure) tube contracts to a 2 inch diameter, 20 feet long driven (low pressure) tube. The gas in the driver section is nitrogen and the gas in the driven section is air. The diaphragm(s) used in the shock tube are made of 0.06-inch thick mylar sheets. Figure 2-3 represents the schematic of the shock tube and figure 2-4 shows the diaphragm section.

2-3 Instrumentation

In order to determine the shock Mach number, static pressure measurements are needed. This is done with Kulite pressure transducers and the data system used is a Hewlett Packard Digitizing Oscilloscope (HP 54201A). Figure 2-5 shows a block diagram of this set up. Two transducers are used, one (Kulite XTS - 1-190 series) to trigger the Hewlett Packard Digitizing Oscilloscope (HP 54201A) and the other (Kulite ITQS - 500 series) to give the pressure trace as the shock wave travels from the diaphragm to the exit. Each of the transducers is driven by a 10-volt D.C. power supply and

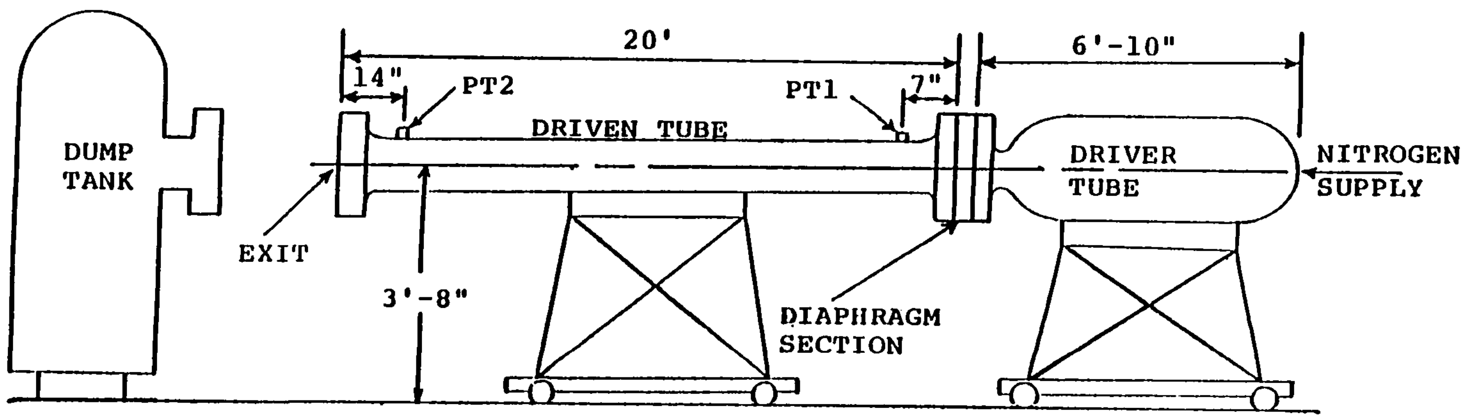


Figure 2-3 Schematic Diagram of UTA Shock Tube

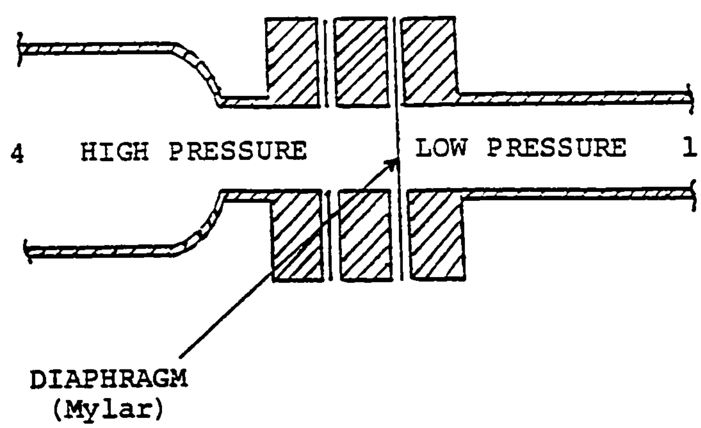


Figure 2-4 UTA Shock Tube Diaphragm Section

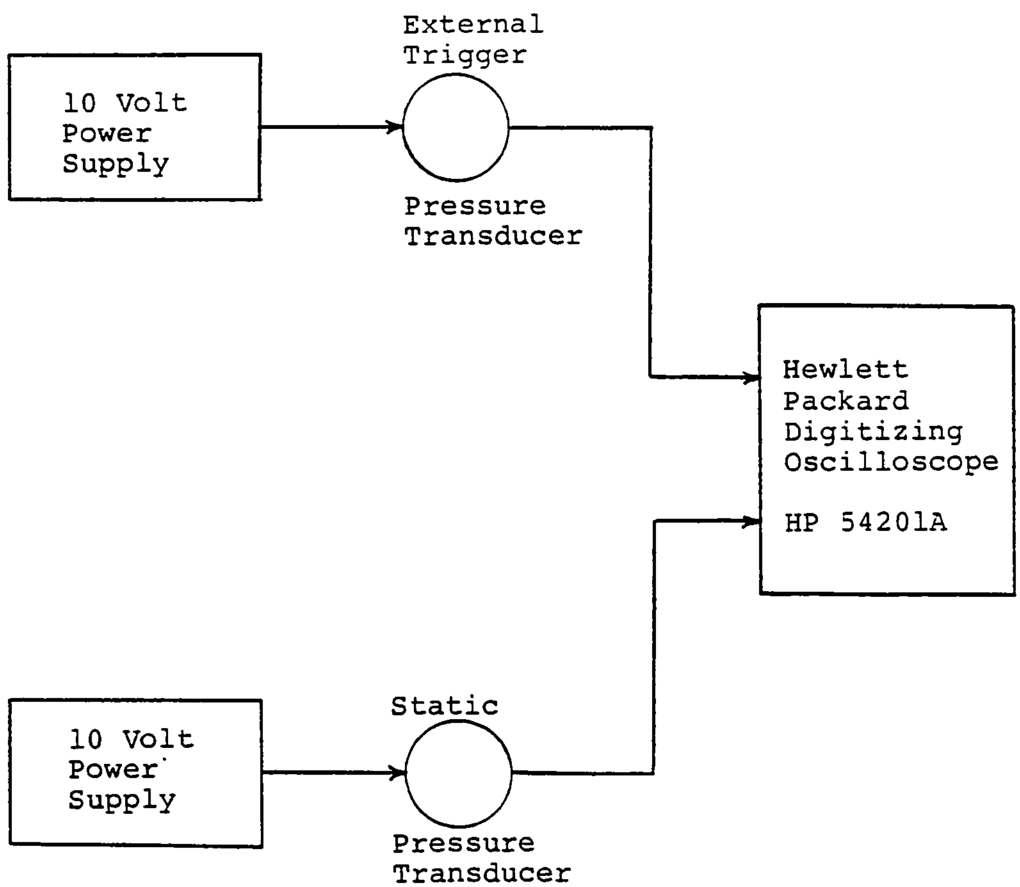


Figure 2-5 Block Diagram of Static Pressure Measurement

its output signal goes to a input terminal on the oscilloscope. The trigger pressure transducer is denoted by PT1 and the other static pressure transducer by PT2. Their locations on the shock tube are shown in figure 2-3.

2-4 Shock Tube Operation

The initial operation runs consisted of determining the pressure at which mylar diaphragms rupture and also to check out the instrumentation. Mylar sheets were found to be the best material for making diaphragms for two reasons. First mylar sheets are easy to work with which means diaphragms can be mass produced in a short time and finally they cost less than manufactured stainless steel diaphragms. The mylar sheets used are 0.06-inch thick and the diaphragms ruptured at 260 psi with a +5 psi or -5 psi change in rupture pressure for repeated tests.

The instrumentation checkout consisted of making sure the trigger mechanism and the pressure trace setup on the scope work properly. One of the main problems was stray line noises that were triggering the scope prematurely. This was corrected by increasing the value of the trigger level sensitivity (in millivolts). Another problem was setting the range of the timebase in order to get the pressure trace on the Oscilloscope. This range had to be greater or equal to the time the shock takes to travel from the pressure transducer (PT1), used as a trigger source, to the end of the shock tube.

The Shock Tube was calibrated to check out the repeatability of the shock speed measurements for a particular driver tube pressure (260 psi). The runs for the nitrogen - air calibration were made with the open end shock tube. The data gathered were pressure rise across the incident shock and shock Mach number. The shock Mach number varied between 1.5 and 1.6.

Figure 2-6 represents a typical open end pressure transducer trace (5 mvolt/div. on vertical scale, 10 msec/div. on horizontal scale). This trace shows a spike or jump (between the symbols X and O) in pressure (voltage) which represents shock passage. From this spike P_2 can be computed using the pressure transducer calibration equation. The ratio P_2/P_1 (ratio of pressure behind shock to pressure ahead of shock) is then calculated from which the shock Mach number, M, can be found from the following Normal Shock relation (Ref. 3) :

$$M = \sqrt{\frac{(\gamma + 1)}{2\gamma} \frac{P_2}{P_1} + \frac{(\gamma - 1)}{2\gamma}}$$

where γ is the ratio of specific heats.

2-5 Experimental Test Setup

The experimental test setup can be seen in figure 2-7 and the block diagram of the stagnation pressure measurement in figure 2-8. The probe holder is bolted on the dump tank

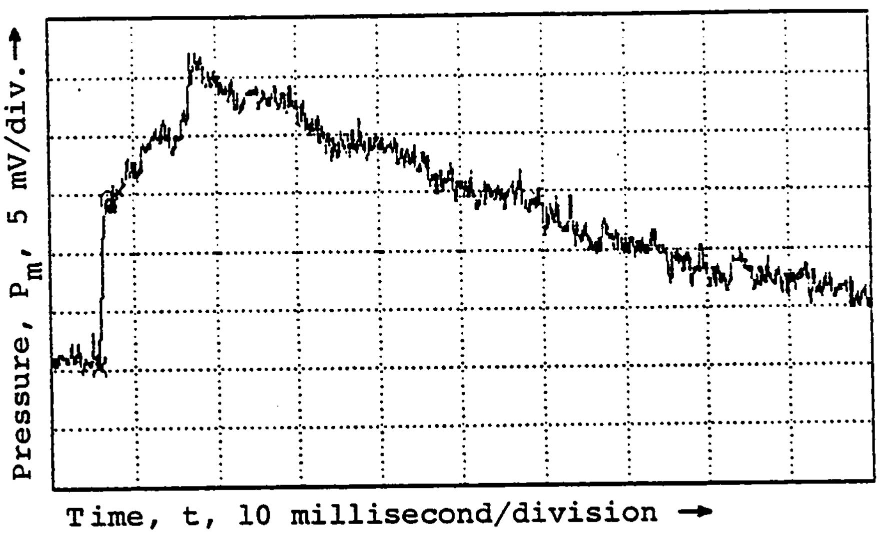


Figure 2-6 Typical Static Pressure Transducer Trace

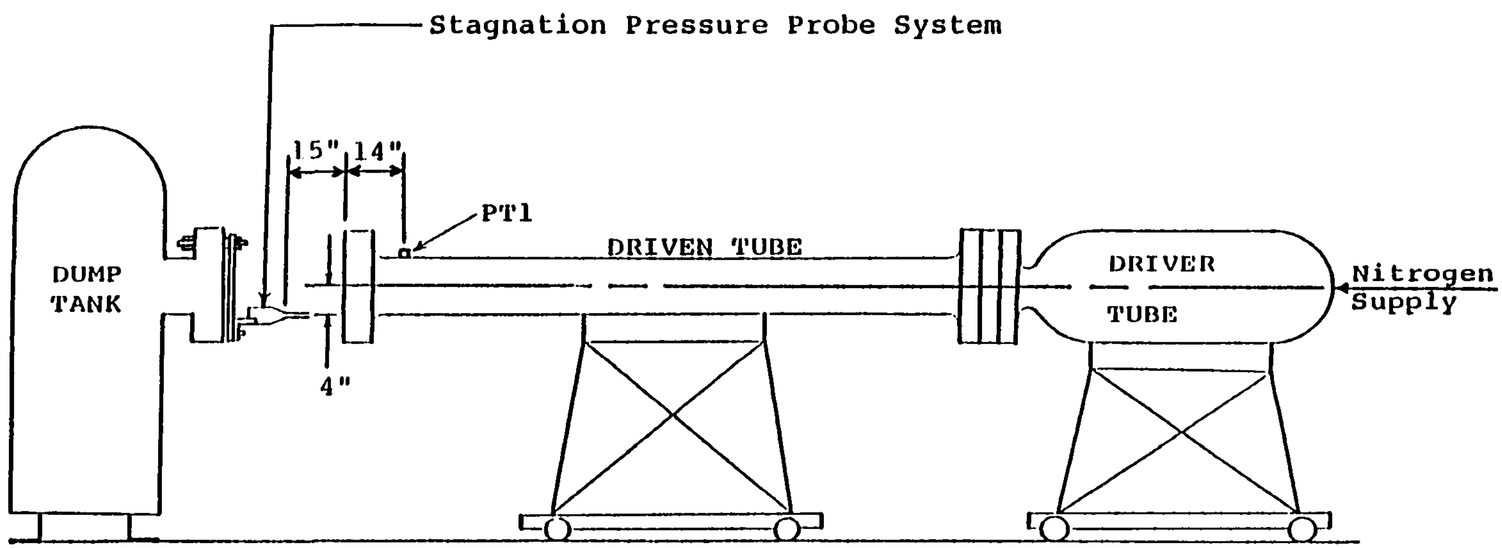


Figure 2-7 Experimental Test Setup

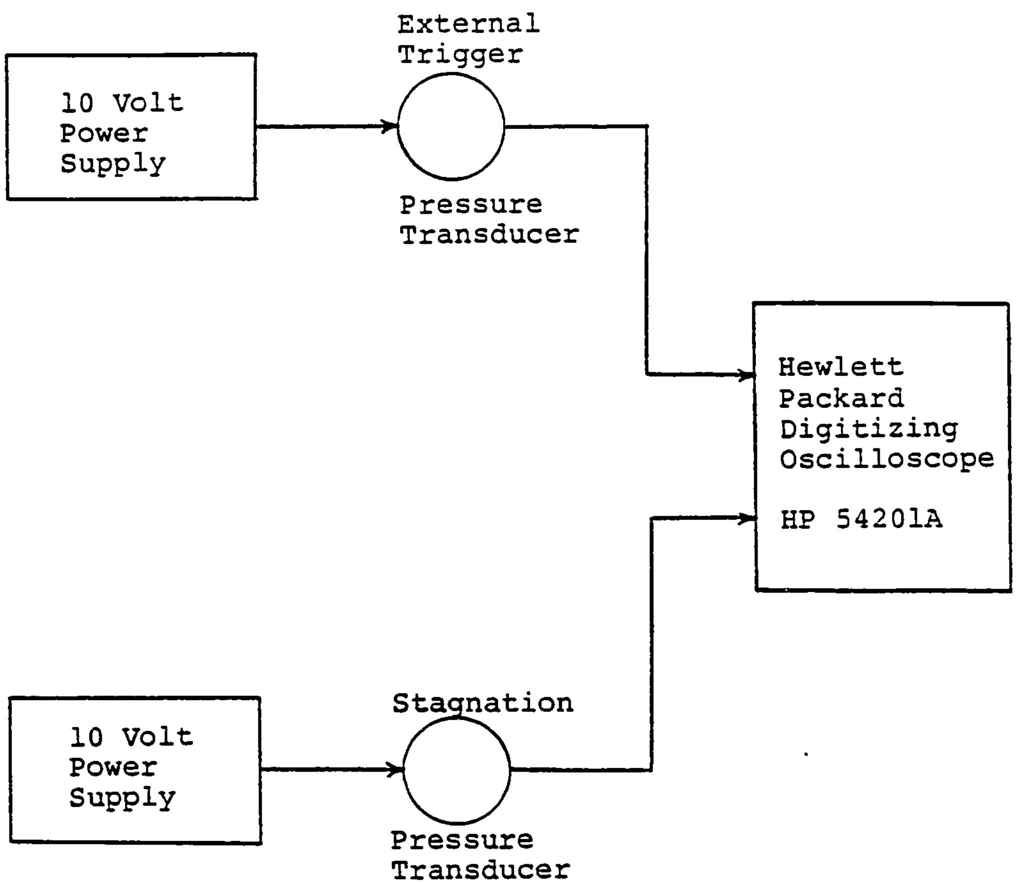


Figure 2-8 Block Diagram of Stagnation Pressure Measurement

in line with the shock tube exit. For all the tests the holder was 15 inches away from the exit and 4 inches below the shock tube centerline. Preliminary test runs were made to find this position where the pressure did not exceed the pressure range of the Entran transducer that was used in the stagnation pressure probe system. The preliminary test runs were performed using a 500 psi Kulite pressure transducer, PT3 (ITQS - 500 series). In order to obtain data in microseconds the timebase range setting on the oscilloscope had to be reduced to 200 microseconds. It takes the shock wave more than 200 microseconds to travel from the diaphragm section to the stagnation pressure probe system located downstream. Therefore a delay time had to be found where data acquisition would begin before the shock wave passed the stagnation pressure probe system. This was particularly difficult because of the variation in shock speed. Runs had to be made in order to determine the shock speed and from this the delay time can be computed.

CHAPTER 3

THEORETICAL ANALYSIS

The method of analysis chosen to determine the response time of a stagnation pressure probe system was obtained from reference 1.

3-1 Assumptions

The theoretical analysis obtained from reference 1 is based on the following assumptions:

1. The gas obeys the ideal gas equation of state.
2. The temperature of the fluid is constant and thus the viscosity is also constant.
3. The flow in the tube is fully developed laminar flow.
4. The inertial forces are negligible relative to the pressure and viscous forces.

3-2 Theoretical Results

The analysis is based upon a step-type of pressure change at the orifice of the tube system. Defining the response time, T, as the time for P_m (pressure measured by the transducer) to attain a value of $p_i + 0.63 \; (p_t - p_i)$, which is equivalent to the time when $\frac{P_m}{P_t} = 0.63 + 0.37\frac{P_i}{P_t}$, results in

$$T = \frac{16\pi\mu\ell\left(V_m + \frac{A\ell}{3}\right)}{A^2 p_t(2 + 16K_n)} \ln\left[\frac{\left(1 - \frac{p_i}{p_t}\right)\left(1.63 + 0.37\frac{p_i}{p_t} + 16K_n\right)}{\left(1 + \frac{p_i}{p_t} + 16K_n\right)\left(0.37 - 0.37\frac{p_i}{p_t}\right)}\right]$$

where

$$K_n = \sqrt{\frac{\pi RT}{2}}\ \frac{\mu}{p_t d}$$

Assignment of the nomenclature and subscripts to regions of the stagnation pressure probe system is shown in figure 3-1. The Volume of the transducer, V_m, is zero since it measures the change in pressure with a strain gage either bonded to a thin circular diaphragm or atomically diffused into a silicon diaphragm. The initial pressure, p_i, is the atmospheric pressure.

From the above equation of the response time it can be seen that it is a function of diameter, d, and length ,l, of the probe, stagnation pressure, P_t, atmospheric (initial) pressure, P_i, temperature, T, and viscosity, μ. The three parameters, diameter, length and stagnation pressure are varied and the corresponding values of response time are calculated and plotted in figures 3-2 through 3-5. From these plots it can be seen that for a particular stagnation pressure an increase in probe diameter decreases the value of the reponse time and an increase in the length of a particular diameter probe increases the value of the response time.

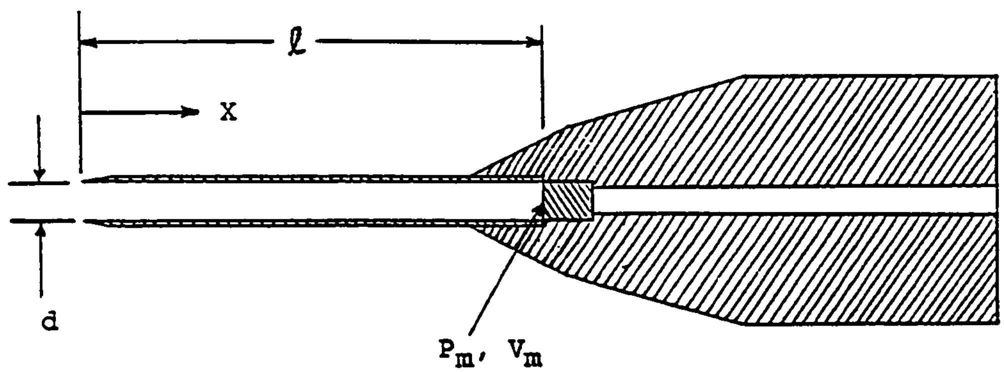


Figure 3-1 Assignment of nomenclature and subscripts to regions of the stagnation pressure probe system

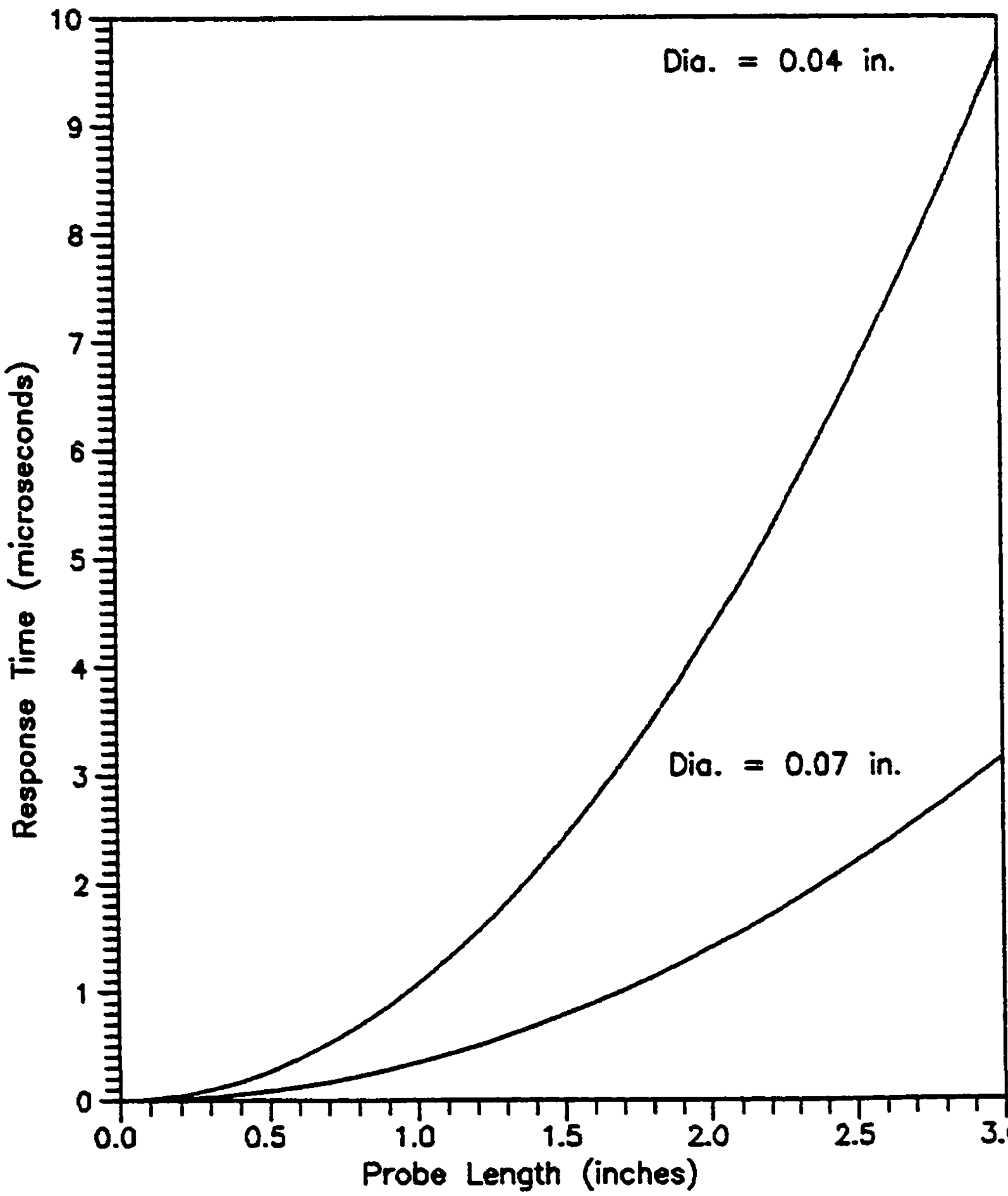


Figure 3-2 Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 1.0-psid Differential Stagnation Pressure.

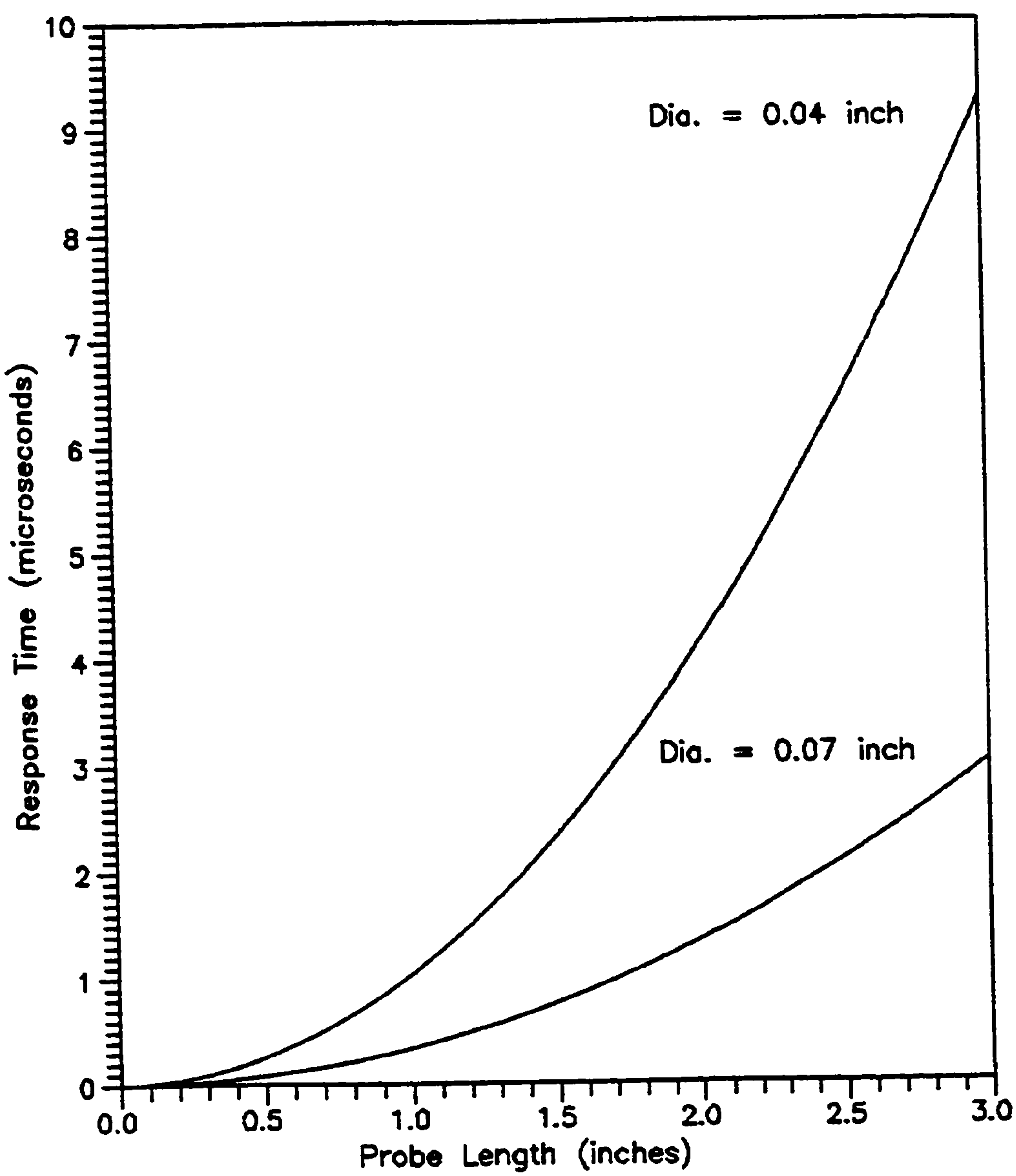


Figure 3-3 Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 2.0-psid Differential Stagnation Pressure.

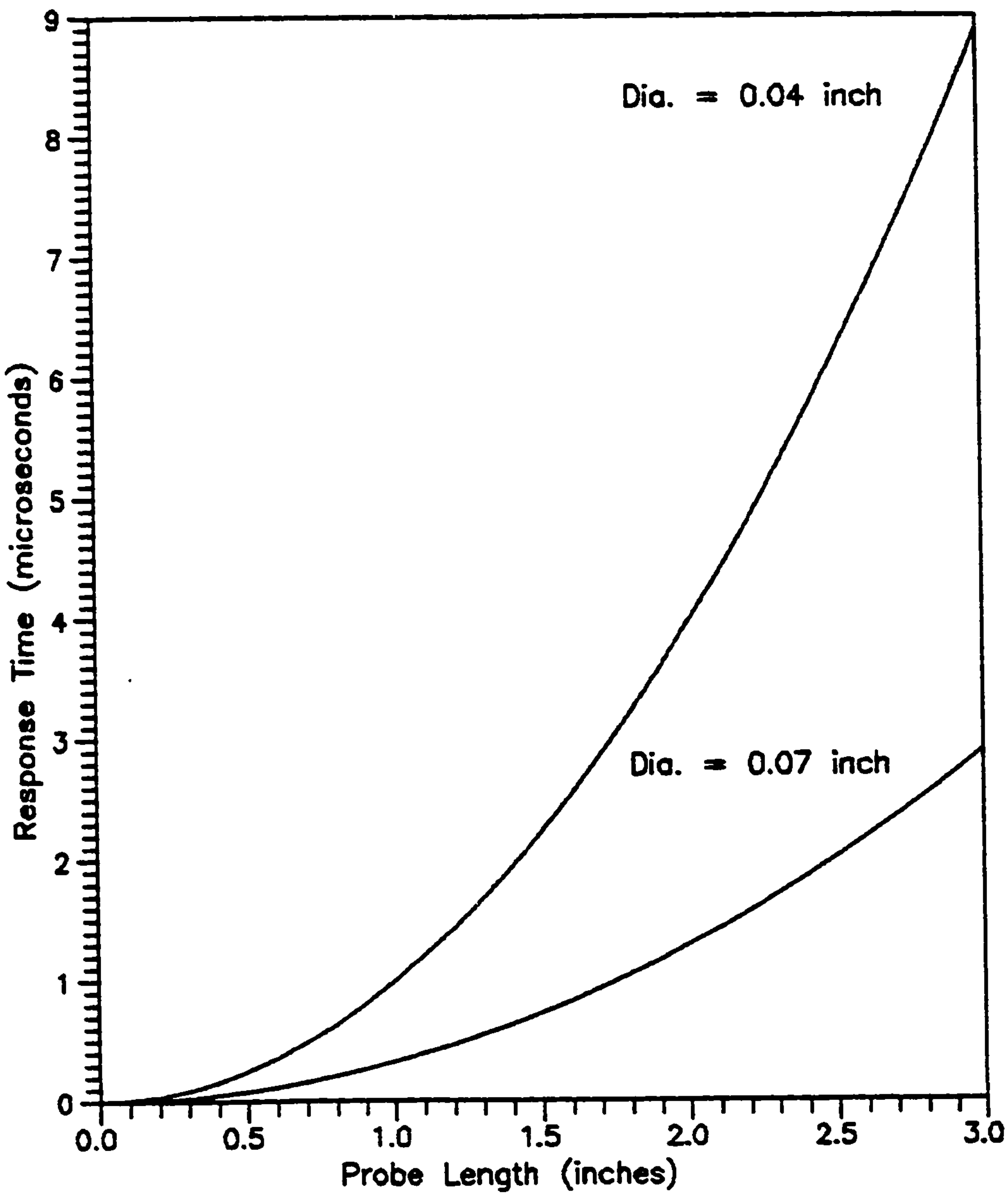


Figure 3-4 Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 3.0-psid Differential Stagnation Pressure.

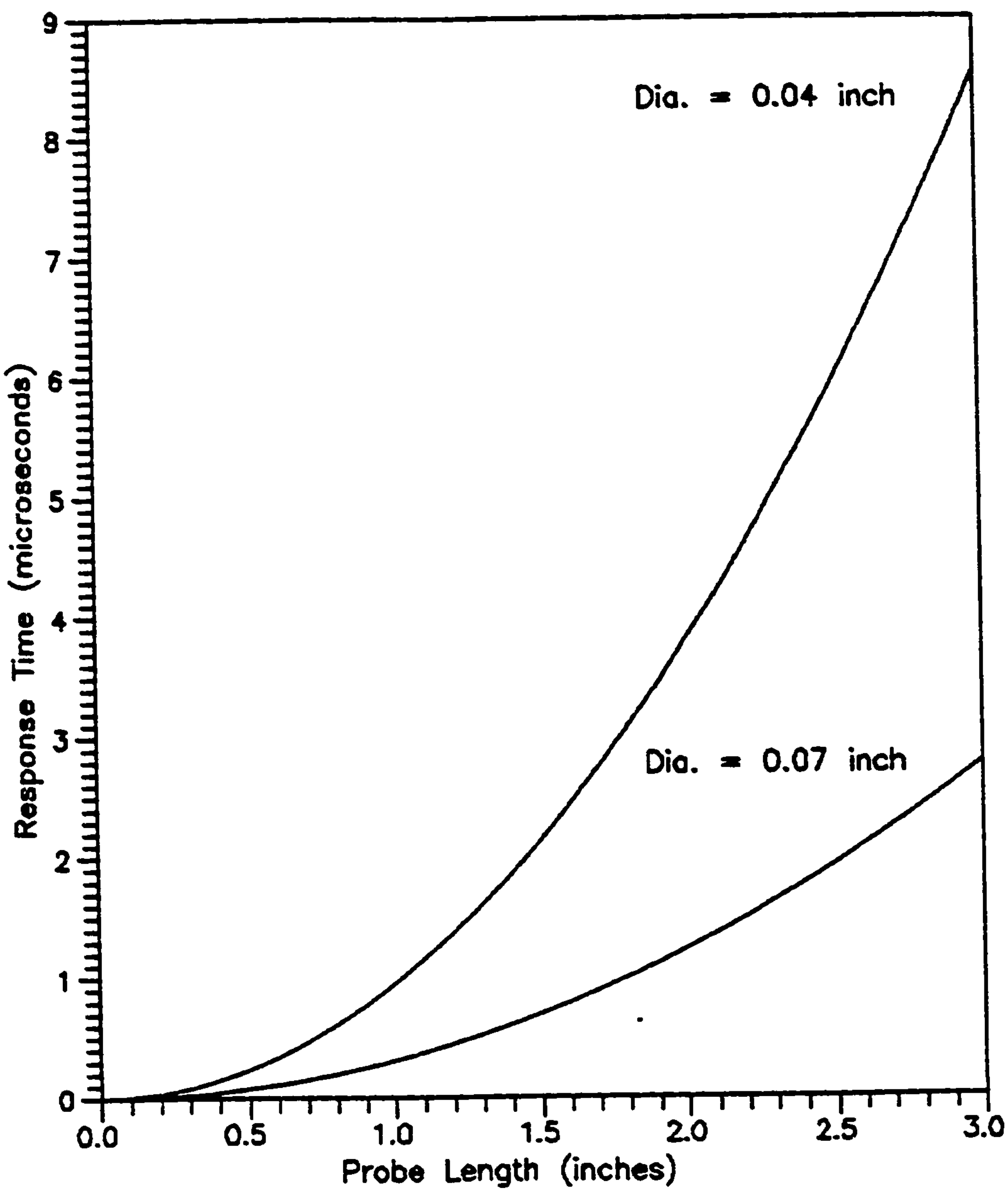


Figure 3-5 Theoretical Response Time Vs. Probe Length for a 0.04-inch and a 0.07-inch Diameter Probe at 4.0-psid Differential Stagnation Pressure.

CHAPTER 4

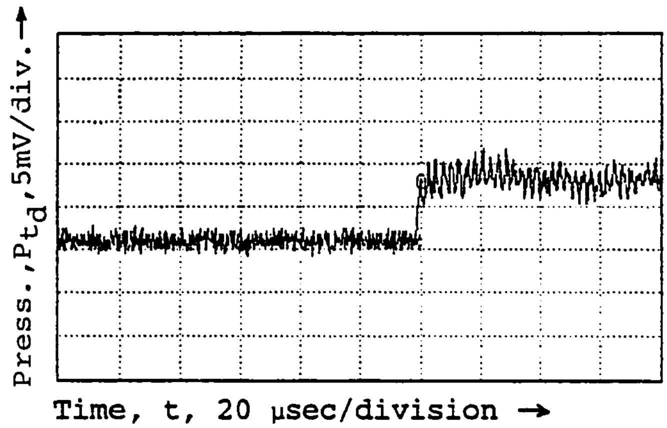
RESULTS AND DISCUSSIONS

A typical printout of an Oscilloscope trace for 0.04-inch and 0.07-inch probe diameters can be seen in figures 4-1 and 4-2. The experimental response time was calculated from these traces. The method used to obtain a value of the response time from each of these traces is illustrated in figure 4-3. From this figure it can be seen that a line was drawn connecting the midpoints of the peaks. These experimental values and the theoretical values are listed in table 4-1 for 0.04-inch and 0.07-inch diameter probes. It can be seen that the experimental results agree with the theoretical results. Each of the theoretical response times was computed using the stagnation pressure measured during the particular experimental test. The experimental response time values are plotted versus length/diameter (l/d) ratio of the probe in figure 4-4 for a 1.4-psid to 3.9-psid differential stagnation pressure range. From this figure it can be noted that the response time is independent of small changes in differential stagnation pressure. The possible errors in the experimental tests are:

1. The vibration of the stagnation pressure probe system as the shock passed it might have changed

the pressure measured.

2. The output signal recorded had a lot of noise in it due to the electrical disturbance encountered during the tests.

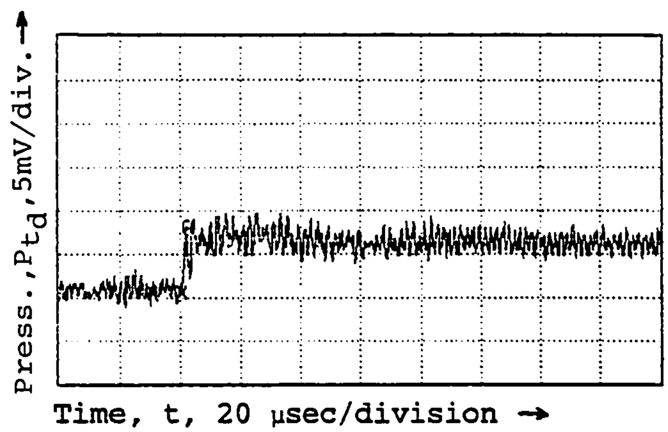


Stagnation Pressure
Probe Dimensions:

d = 0.07 inch
l = 2.50 inch

Response Time,

T = 2.17 microseconds

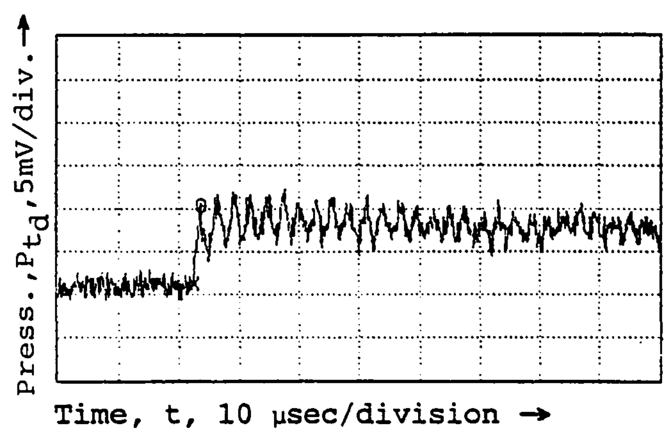


Stagnation Pressure
Probe Dimensions:

d = 0.07 inch
l = 1.60 inch

Response Time,

T = 0.87 microseconds



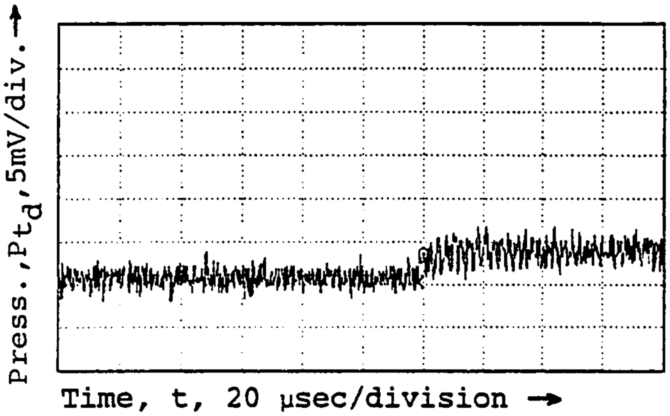
Stagnation Pressure
Probe Dimensions:

d = 0.07 inch
l = 0.80 inch

Response Time,

T = 0.22 microseconds

Figure 4-1 Typical Oscilloscope Traces for a 0.07-inch Probe Diameter

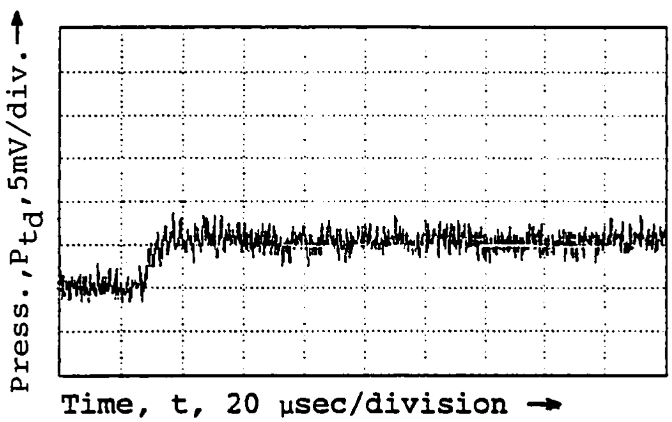


Stagnation Pressure
Probe Dimensions:

d = 0.04 inch
l = 2.50 inch

Response Time,

T = 6.96 microseconds

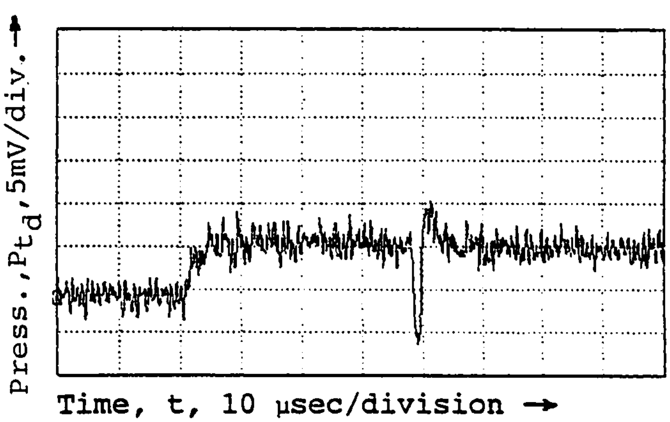


Stagnation Pressure
Probe Dimensions:

d = 0.04 inch
l = 1.60 inch

Response Time,

T = 2.61 microseconds



Stagnation Pressure
Probe Dimensions:

d = 0.04 inch
l = 0.80 inch

Response Time,

T = 0.70 microseconds

Figure 4-2 Typical Oscilloscope Traces for a 0.04-inch Probe Diameter

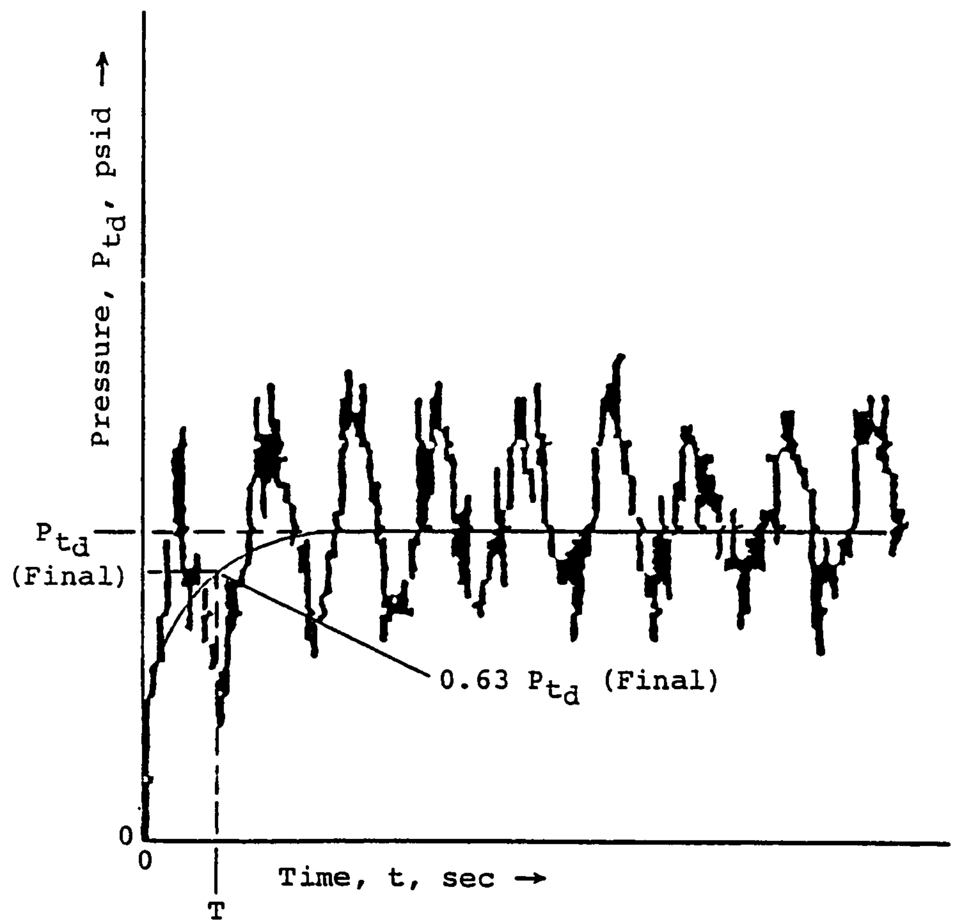


Figure 4-3 Method of Determining the Response Time from the Oscilloscope Traces

TABLE 4-1

THEORETICAL AND EXPERIMENTAL RESPONSE TIME

Probe Length (inch)	Differential Stagnation Pressure (psid)	Probe Diameter = 0.07 inch Response Time (microseconds)	
		Theoretical	Experimental
2.5	3.83	1.95	2.17
1.6	2.83	0.83	0.87
0.8	3.68	0.20	0.22

Probe Length (inch)	Differential Stagnation Pressure (psid)	Probe Diameter = 0.04 inch Response Time (microseconds)	
		Theoretical	Experimental
2.5	1.42	6.65	6.96
1.6	2.62	2.57	2.61
0.8	1.98	0.66	0.70

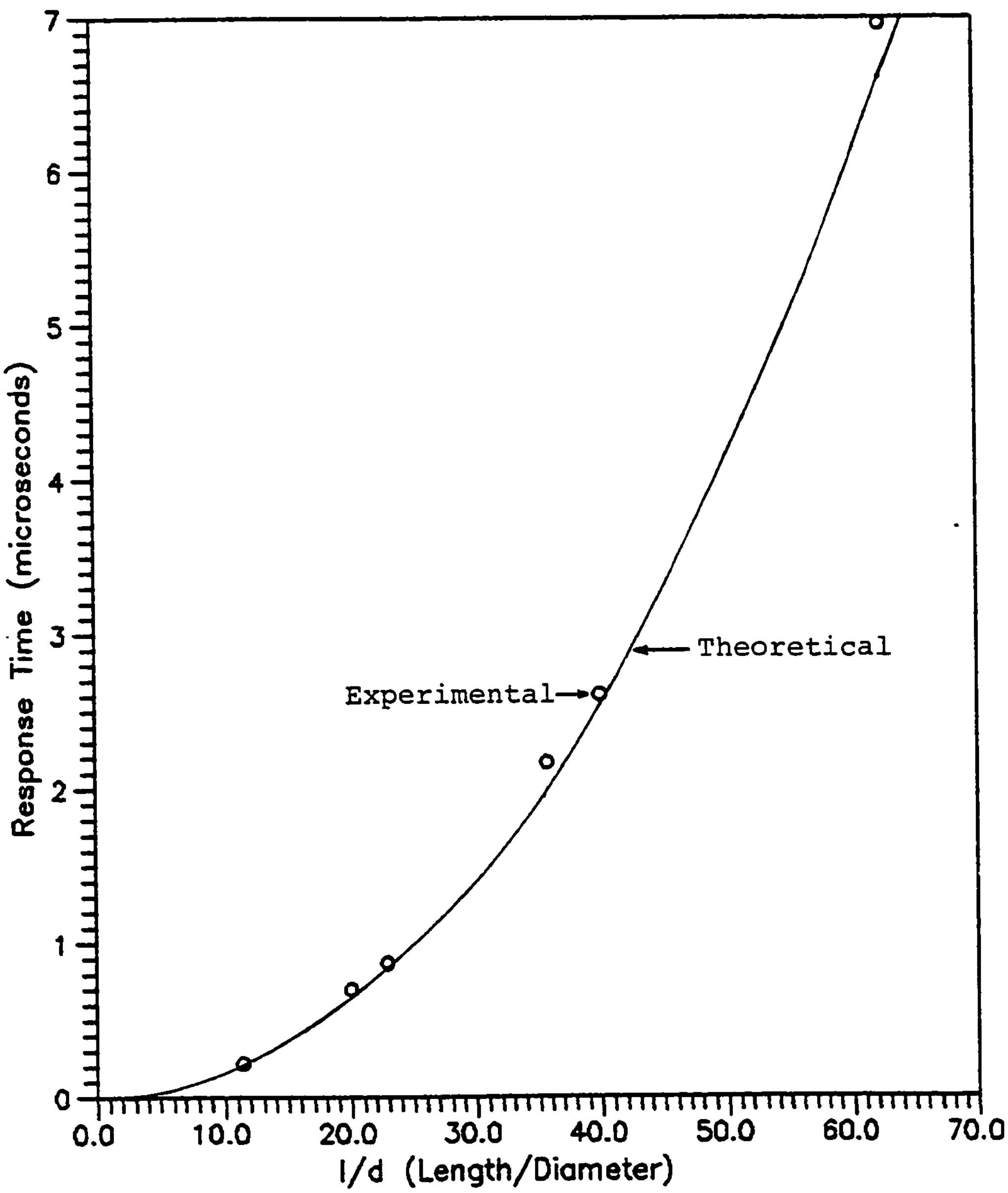


Figure 4-4 Theoretical and Experimental Response Time Vs. l/d (Length/Diameter) ratio of the probe for a 1.4-psid to a 3.9-psid differential stagnation pressure range

CHAPTER 5

CONCLUSIONS

Experimental tests have been conducted with the UTA shock tube on stagnation pressure probes of 0.04- and 0.07-inch diameter and 0.8-, 1.6-, and 2.5-inch lengths at applied pressure levels between 1.4-psid and 3.9-psid. Within this range of variables the following conclusions can be made:

1. The theoretical and experimental results agree within the precision of the experiments.
2. From the experimental results obtained it shows that the theoretical analysis is valid, within the limits of the assumptions clearly indicated in Chapter 3, to design a stagnation pressure probe.
3. The shock tube is an excellent test facility for providing a step change in pressure.

REFERENCES

1. Ball, Henry W., "Response of Hotshot Tunnel Pressure Measuring Systems to a Suddenly Applied Pressure." ARO, Inc., AEDC-TR-65-238, December 1965.
2. Kinslow, Max. "Correction for Lag Time in Pressure Measuring Systems." AEDC-TR-58-8 (AD 161040), August 1958.
3. Zucker, Robert D., Fundamentals of Gas Dynamics, Matrix Publishers, Inc., Oregon, 1977.
4. White, Frank M., Fluid Mechanics, McGraw-Hill Book Company, New York, 1979.
5. Smotherman, W. E., and Maddox, W. V. "Variable Reluctance Pressure Transducer Development." AEDC-TDR-63-135 (AD 410171), July 1963.