

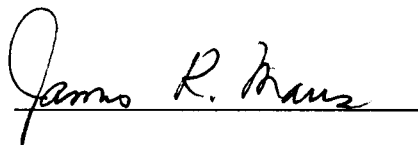
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AN ADVANCED PREDICTION TECHNIQUE
FOR USE IN
WIND TUNNEL PRESSURE MEASUREMENTS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

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ABSTRACT

An algorithm is described which compensates for pneumatic lag effects in wind tunnel pressure measurement systems and thus significantly enhances data productivity. This algorithm is based on the Navier-Stokes equations for flow through a tube, with simplifying assumptions applied to predict orifice pressure from the time-varying transducer output. The validity of the algorithm for various pressure measurement systems is experimentally verified, and guidelines for the use of the technique are documented.

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NOMENCLATURE

A_e	Effective internal cross-sectional area of pressure tube, ft^2
C	Configuration constant, $\frac{1}{\left(\frac{l_2}{l_1}\right)\left(\frac{d_2}{d_1}\right)^4 + 1}$
d	Inside diameter of pressure line, ft
l	Length of pressure line, ft
M	Mass flow in tube, slugs / sec
m	Mass, slugs
P_i	Initial pressure in tube system, psf
P_f	Final pressure at orifice, psf
P_j	Pressure at junction of first and second tubes, psf
P	Pressure at measuring instrument at any time, t , psf
Q	Volume flow, ft^3 / sec
R	Gas constant, $1718 \frac{\text{ft}^2}{\text{sec}^2 \cdot \text{R}}$
r	Distance along tube radius, ft
T	Temperature, $^{\circ} \text{R}$
t	Time, sec
u	Velocity of fluid element, ft / sec
V	Tube volume, ft^3
v	Radial fluid velocity, ft / sec
x	Distance along tube axis, ft
θ	Incremental angle, radians
μ	Absolute viscosity of air, slugs / ft-sec
ρ	Density, slugs / ft^3
τ	Viscous shear stress, psf

SUBSCRIPTS

1	First tube
2	Second tube

1.0 INTRODUCTION

When making pressure measurements as part of wind tunnel testing, it is often necessary to isolate the pressure transducer from the harsh tunnel environment. Thus, the pressure orifice is connected to the transducer by a pressure line which may be several feet in length. Inherent with a measurement system of this type is a response time delay or lag between the time a pressure is applied at the orifice, located in the tunnel, and the time at which the transducer senses this pressure. This phenomenon, referred to as pneumatic lag, can lead to significant measurement errors, especially at extremely low pressures. Therefore it is necessary to allow sufficient time for the transducer output to stabilize at an equilibrium value. In order to increase data gathering rates, efforts have been made to develop data reduction techniques that predict orifice pressures based on transient transducer outputs. One such technique employed by AEDC was developed by D.L. Brown [1]^a and is referred to as the Equilibrium Pressure Prediction Technique. This method models the response of a transducer to a step input at the orifice, fits transient transducer readings by a least squares technique to the transducer data and predicts the orifice pressure. The application of this technique to wind tunnel testing typically involves positioning the pressure orifice at some point in the tunnel flow, obtaining only enough transient reading to allow an accurate curve fit to be performed and then repositioning the orifice at the next measurement location in the flow. By eliminating the need to pause at each point until the transducer reading has completely stabilized at a constant value in time, Brown's technique has resulted in approximately doubling the data collection rates.

Despite the gains in productivity provided by the Equilibrium Pressure Prediction Techniques, recent test requirements have demanded even more efficient pressure measurements at much higher measurement rates. One typical test involved performing

^a Numbers in brackets refer to reference in List of References.

boundary layer pitot pressure surveys over an uncooled cone in hypersonic flow under cold-wall conditions. This required that the surveys be completed within sixty seconds of cone exposure in the wind tunnel. In order to obtain complete surveys within this time, it was necessary to drive the pitot probe continuously through the boundary layer. As a logical extension to the Equilibrium Pressure Prediction Technique, a new model was developed which uses instantaneous pressure measurements rather than curve fitting data. This new model, referred to as the Continuous Sweep Pressure Prediction Technique, makes it possible to predict a time-varying orifice pressure based on instantaneous transducer readings. Accurate pressures can be obtained from a pitot which is driven continuously through the boundary layer. This thesis describes the development, validation and application of the new model which will be called the Continuous Sweep Pressure Prediction Technique.

2.0 DERIVATION OF THE MATHEMATICAL MODEL

In this section, the Navier-Stokes equations will be used to develop the equations of motion for the cylindrical fluid element shown in figure 1. These equations of motion will then be applied to a representative pressure measurement system, and the governing equations developed.

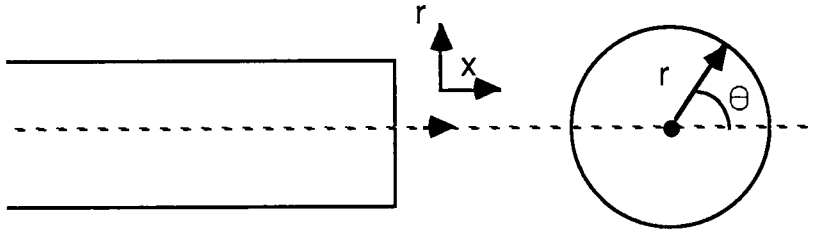


Figure 1. Tube Coordinates

In deriving the basic differential equations, the following initial assumptions are made:

- (1.) Elasticity of the tube walls may be neglected.
- (2.) Temperature variations throughout the tube system are small enough such that constant fluid viscosity can be assumed.
- (3.) Circumferential velocity and circumferential variations in dependent variables (e.g. $\frac{\delta P}{\delta \theta}$) can be neglected.
- (4.) Flow inside the tube is laminar.

These assumption are similar to those made by D'Souza and Oldenburger [2]. As is also stated in [1], and explained in more detail in [3], the Navier-Stokes equation in the axial direction becomes:

$$\rho \left[\frac{\delta u}{\delta t} + u \frac{\delta u}{\delta x} + v \frac{\delta u}{\delta r} \right] = - \frac{\delta P}{\delta x} + \mu \left[\frac{4}{3} \frac{\delta^2 u}{\delta x^2} + \frac{\delta^2 u}{\delta r^2} + \frac{1}{r} \frac{\delta u}{\delta r} + \frac{1}{3} \frac{\delta}{\delta x} \left(\frac{\delta v}{\delta r} + \frac{v}{r} \right) \right] \quad (1.)$$

Where ρ is the fluid density
 u is the axial fluid velocity
 v is the radial fluid velocity
 P is the fluid pressure
 μ is the fluid viscosity

As discussed in Reference [2], the equation of motion in the radial direction can be neglected, since $u \gg v$. This implies that the pressure is constant across the tube cross section and becomes only a function of x and t . Reference [2] also shows that

$\frac{\delta u}{\delta t} \gg u \left(\frac{\delta u}{\delta x} \right)$ and $\frac{\delta u}{\delta t} \gg v \left(\frac{\delta u}{\delta r} \right)$, hence the non-linear terms on the left hand side

of the Equation 1. can be ignored. Also, only the $\frac{\delta^2 u}{\delta r^2}$ and $\frac{1}{r} \frac{\delta u}{\delta r}$ viscous terms on the

right are shown to be important, and the other viscous terms may be neglected. With these simplifications, equation 1 reduces to:

$$\rho \frac{\delta u}{\delta t} = - \frac{\delta P}{\delta x} + \mu \left[\frac{\delta^2 u}{\delta r^2} + \frac{1}{r} \frac{\delta u}{\delta r} \right]$$

This equation can be rewritten as:

$$\frac{\delta}{\delta r} \left(r \frac{\delta u}{\delta r} \right) = \left[\rho \frac{\delta u}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{r}{\mu} \quad (2.)$$

Equation 2 can be expressed in terms of mass flow through the tube, (M) , since $\rho u = \frac{4M}{\pi d^2}$

In addition, Bauer [4] discusses the fact that, for small pressure changes,

$\frac{\delta \rho}{\delta t}$ is small. Therefore, Equation 2 can be rewritten as:

$$\frac{\delta}{\delta r} \left(r \frac{\delta u}{\delta r} \right) = \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{r}{\mu}$$

Integrating,

$$r \frac{\delta u}{\delta r} = \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{r^2}{2\mu} + C_1$$

Assuming axisymmetric flow, the boundary condition at $r = 0$, $\frac{\delta u}{\delta r} = 0$ can be applied, and C_1 can be shown to be zero. Therefore,

$$r \frac{\delta u}{\delta r} = \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{r^2}{2\mu}$$

Integrating a second time:

$$u = \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{r^2}{4\mu} + C_2$$

Applying the "no-slip" condition at $r = \frac{d}{2}$, $u = 0$:

$$C_2 = - \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \frac{d^2}{16\mu}$$

Substituting :

$$u = - \frac{1}{4\mu} \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \left(\frac{d^2}{4} - r^2 \right)$$

Given this parabolic velocity distribution, the maximum velocity occurs at $r = 0$:

$$u_{\max} = - \frac{d^2}{16\mu} \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right]$$

Since the mean average of a parabola of revolution is one-half the maximum value, the volume flow at any section of the tube is:

$$Q = \frac{\pi d^2}{4} \left(\frac{u_{\max}}{2} \right) = - \frac{d^4 \pi}{128\mu} \left[\frac{4}{\pi d^2} \frac{\delta M}{\delta t} + \frac{\delta P}{\delta x} \right] \quad (3.)$$

We will now apply these equations to the representative 2-tube pressure system shown in figure 2:

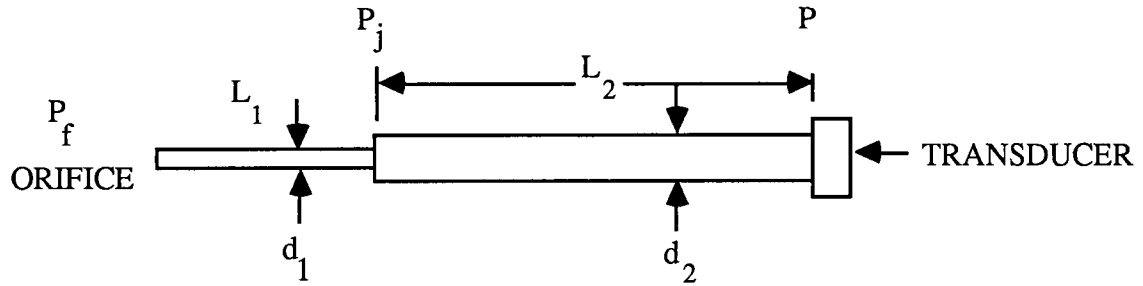


Figure 2. Representative Pressure System

In applying the equations of motion to the pressure measurement system shown in Figure 2, the transducer volume will be assumed to be negligible. This is because of the extremely small internal volumes of the transducers used in the experiments described in this thesis (e.g. 0.0004 in³ Druck ® transducer). However, Reference [4] presents derivations of the math model which consider transducer volume. The mass of air in the system at any time is:

$$m = V_1 \rho_1 + V_2 \rho_2 \quad (4.)$$

Where:

V_1 is the volume of the first tube,

V_2 is the volume of the second tube,

and ρ_1, ρ_2 is the density for the respective tubes.

Since the densities ρ_1 and ρ_2 vary along the tube in an unknown manner, it is necessary to select an average value for each. Bauer [4] uses the approximation that the average density is the arithmetic average of the two end densities. Using this approximation,

and employing the equation of state and assuming isothermal conditions,

$$\rho_1 = \frac{P_f + P_j}{2RT}$$

$$\rho_2 = \frac{P_j + P}{2RT}$$

Substituting into (Equation 4.):

$$m = V_1 \frac{P_f + P_j}{2RT} + V_2 \frac{P_j + P}{2RT} \quad (5.)$$

The rate of change of mass within the system with respect to time is:

$$\frac{dm}{dt} = \frac{1}{RT} \left[\frac{(V_1 + V_2)}{2} \frac{dP_j}{dt} + \left(\frac{V_2}{2}\right) \frac{dP}{dt} \right] \quad (6.)$$

The mass flow into or out of the system is determined by multiplying Equation 3. by the average density in the first tube:

$$M = - \frac{d_1^2 (P_f + P_j)}{64 \mu RT} \frac{\delta M}{\delta t} - \frac{d_1^4 \pi (P_f + P_j)}{256 \mu RT} \frac{\delta P}{\delta x} \quad (7.)$$

Since the mass flow into or out of the tube is equal to the rate of change of mass within the tube,

$$M = \frac{dm}{dt}, \quad \frac{\delta M}{\delta t} = \frac{d^2 m}{dt^2},$$

Equation 6. and the first derivative of Equation 6.:

$$\frac{d^2 m}{dt^2} = \frac{1}{RT} \left[\frac{(V_1 + V_2)}{2} \frac{d^2 P_j}{dt^2} + \left(\frac{V_2}{2}\right) \frac{d^2 P}{dt^2} \right]$$

can be substituted into equation 7:

$$\begin{aligned} \frac{(V_1 + V_2)}{2} \frac{dP_j}{dt} + \left(\frac{V_2}{2}\right) \frac{dP}{dt} = & - \frac{d_1^2 (P_f + P_j) (V_1 + V_2)}{128 \mu RT} \frac{d^2 P_j}{dt^2} \\ & - \frac{d_1^2 (P_f + P_j)}{64 \mu RT} \left(\frac{V_2}{2}\right) \frac{d^2 P}{dt^2} - \frac{d_1^4 \pi (P_f + P_j)}{256 \mu} \frac{\delta P}{\delta x} \end{aligned} \quad (8.)$$

Although Equation 8. is the general expression for flow through the system, further assumptions must be made to develop an approximate solution. The assumption that is made is that the acceleration terms are small compared to the steady flow terms, so that the acceleration terms can be neglected. Bauer [4] develops the following condition for this assumption to be valid, based on the ratio of the acceleration terms to the steady flow terms:

$$\frac{V_1 d_1^4 C P_f^2}{1024 \mu^2 RT L_1^2 \left[\frac{(V_1 + V_2) C + V_2}{2} \right]} \ll 1 \quad (9.)$$

where:

$$C = \frac{1}{\left(\frac{L_2}{L_1}\right) \left(\frac{d_1}{d_2}\right)^4 + 1}$$

The validity of this assumption for various systems tested will be examined in subsequent sections. Neglecting the acceleration terms, the volume flow into or out of the tube can be represented by Poiseuille's equation for flow through the tube:

$$Q = - \frac{d^4 \pi}{128 \mu} \frac{\delta P}{\delta x}$$

The pressure at the junction between the first and second tubes can now be determined by equating the mass flow through the first tube with the mass flow through the second tube. As shown in Reference [5], the pressure at any station in the first tube is:

$$P_x = \sqrt{(P_j^2 - P_f^2) \frac{x}{L_1} + P_f^2}$$

Differentiating with respect to x gives:

$$\frac{\delta P_x}{\delta x} = \frac{(P_j^2 - P_f^2)}{2L_1 \sqrt{(P_j^2 - P_f^2) \frac{x}{L_1} + P_f^2}}$$

The mean value of $\frac{\delta P}{\delta x}$ is :

$$\left(\frac{\delta P}{\delta x} \right)_{\text{mean}} = - \frac{(P_f - P_j)}{L_1}$$

The density is:

$$\rho_x = \frac{1}{RT} \sqrt{(P_j^2 - P_f^2) \frac{x}{L_1} + P_f^2}$$

The mean density for small pressure differences is:

$$\rho_{x \text{ mean}} = \frac{(P_j + P_f)}{2RT}$$

Substituting into Poiseuille's equation yields:

$$M_1 = - \frac{d_2^4 \pi}{256 \mu RT L_2} (P_j^2 - P_f^2)$$

Similarly, the mass flow through the second tube is:

$$M_2 = - \frac{d_2^4 \pi}{256 \mu RT L_2} (P^2 - P_j^2)$$

Equating M_1 and M_2 and solving for P_j yields

$$P_j = \sqrt{(1-C) P_f^2 + C P^2}$$

Where C, as stated previously, is:

$$C = \frac{1}{\left(\frac{L_2}{L_1}\right) \left(\frac{d_1}{d_2}\right)^4 + 1}$$

Baur further simplifies the equation for P_j by expanding P_j into a Taylor series about P_f and assuming that :

$$\frac{(P - P_f)}{2 P_f} \ll 1$$

Resulting in:

$$P_j = (1-C) P_f + CP$$

and, assuming constant P_f ,

$$\frac{dP_j}{dt} = C \frac{dP}{dt}$$

These assumptions and simplifications enable Equation 8. to be rewritten as:

$$\left[\frac{(V_1 + V_2)C + V_2}{2} \right] \frac{dP}{dt} = \frac{d_1^4 \pi C}{256 \mu L_1} (P_f^2 - P^2)$$

This equation can be further modified to express the orifice pressure (P_f) as a function of transducer pressure (P) and the time rate of change of transducer pressure:

$$P_f = \sqrt{P^2 + \frac{1}{K} \frac{dP}{dt}} \quad (10.)$$

Where:

$$K = \frac{d_1^4 \pi C}{256 \mu L_1 \left[\frac{(V_1 + V_2)C + V_2}{2} \right]}$$

Brown [1] developed a similar form of Equation 10, but modified it with corrections for the slip and free-molecular flow regimes developed in Reference [6]. The modified equation is thus:

$$P_f = -\frac{A}{2} + \sqrt{\left(\frac{A}{2}\right)^2 + \left(P^2 + AP + \frac{1}{K} \frac{dP}{dt}\right)} \quad (11.)$$

Where:

$$A = \frac{16}{d_1} \left(\frac{2}{f} - 1 \right) \frac{R^* T}{2^{1/2} \pi N \sigma^2} \quad (12.)$$

Where:

d_1 is the tube diameter for the first tube

f is the fraction of molecules diffusely reflected from the tube walls = 0.8

R^* is the universal gas constant = 1545.31 ft lb/lb-mole ° R

N is Avagadro's number = 2.73179×10^{26} /lb-mole

σ is the effective collision diameter of mean air molecule 1.1975×10^{-9} ft.

The value of A is estimated based on the minimum tube radius and average tube temperature. It should be noted that the predicted orifice pressure P_f is generally insensitive to changes in A for typical pressure levels and tube sizes. Brown presented an example that showed only a ten percent error in the predicted pressure for a case in which the value of A was increased by a factor of three for the computation; in that example the orifice pressure was 0.02 psia.

Kinslow [7] developed a formula for K which can be applied to systems with more than 2 tubes:

$$K = \frac{A e^2}{16 \pi \mu L e V} \quad (13.)$$

Where:

$$\frac{A_e^2}{L_e} = \left(\frac{1}{\frac{L_1}{A_1^2} + \frac{L_2}{A_2^2} + \dots + \frac{L_n}{A_n^2}} \right)$$

$$\text{and } V = V_1 + V_2 + \dots + V_n$$

The values of K and A, and Equation 9 will be evaluated for typical pressure measurement systems in subsequent sections. The relationship presented in Equation 11 is used in the continuous sweep pressure prediction routine to predict orifice pressure (P_f) based on the transducer pressure (P) and its time rate of change. The assumptions made in the derivation of this relationship certainly would not apply to all measurement systems or to all measured pressure-time histories. Those assumptions which particularly restrict the range of application of the technique are restated below:

- (1.) The flow within the pressure measurement system is laminar.
- (2.) Temperature variations throughout the measurement system are small.
- (3.) The change in orifice pressure with respect to time is small
- (4.) Acceleration effects are small relative to viscous effects (i.e. steady flow is assumed)

In the following chapters, experiments will be described which verify the use of the technique for certain wind tunnel test scenarios, and guidelines for the use of the technique will be presented.

3.0 VERIFICATION OF THE MATHEMATICAL MODEL

3.1 LABORATORY EXPERIMENT

In order to experimentally assess the applicability of Equation 11 to pressure measurement systems, a small vacuum tank was instrumented with both a close-coupled transducer which directly measured tank pressure, and a transducer which was isolated from the tank by a series of small-diameter pressure tubes.

The vacuum tank employed was a 4-inch diameter, 44 -inch long cylinder to which a vacuum pump was attached as shown in figure 3. The top of the cylinder was fitted with the close-coupled transducer, the isolated transducer, and a solenoid-activated bleed valve (see figure 3). The close-coupled transducer was a Druck 15 psid transducer, referenced to near vacuum , which was mounted directly on top of the cylinder. The other transducer was also a 15 psid Druck transducer , referenced to near vacuum, but was connected to the cylinder by means of a .5 inch long, .005 inch I.D. tube; a 7 inch long , .024 inch I.D. tube ; and an 11 inch long, .063 inch I.D. tube in series (see figure 4). This arrangement was chosen because it closely matched the pressure system employed when making boundary layer pitot probe measurements in the wind tunnel.

The pressure tank was evacuated to a pressure of approximately 0.5 psia and the tank pressure was increased by opening the bleed valve. The output data from the two transducers was recorded using a DEC-10 computer at a data rate of 10 scans /second. The output data of the two transducers are shown in figure 5. As can be seen from this data, the output of the isolated transducer considerably lags the direct measurement, and does not approach equilibrium for more than six seconds after the tank pressure has stabilized.

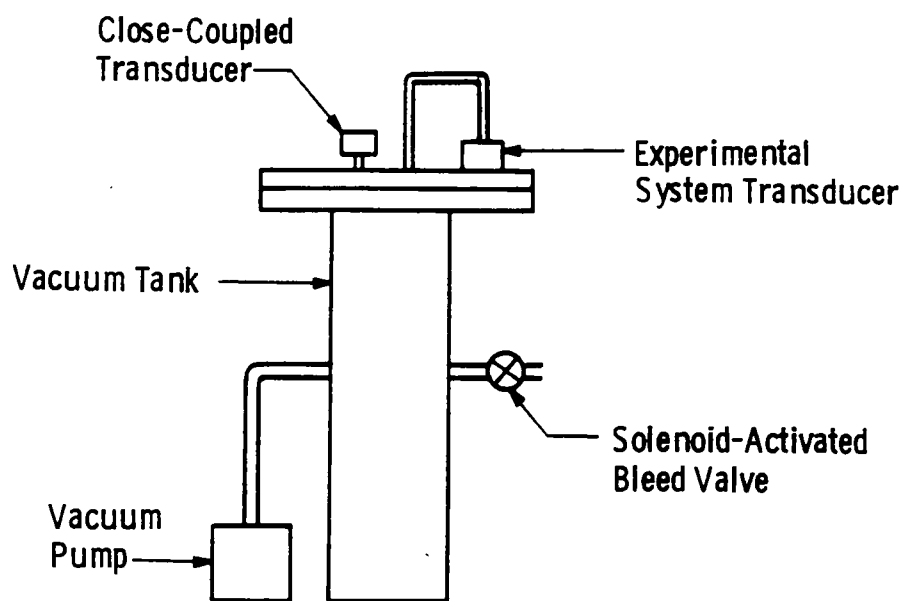


Figure 3. Experimental Apparatus

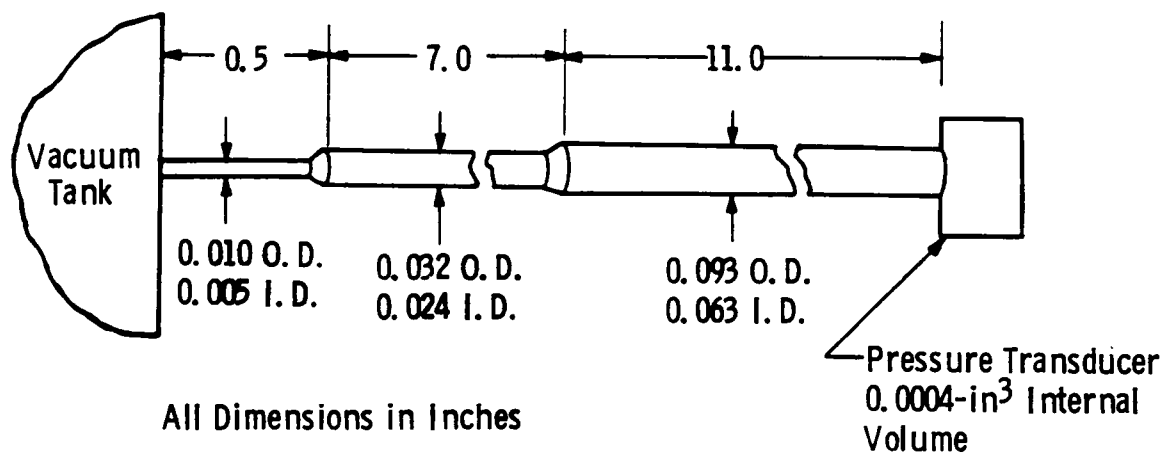


Figure 4. Experimental Measurement System Tubing Arrangement

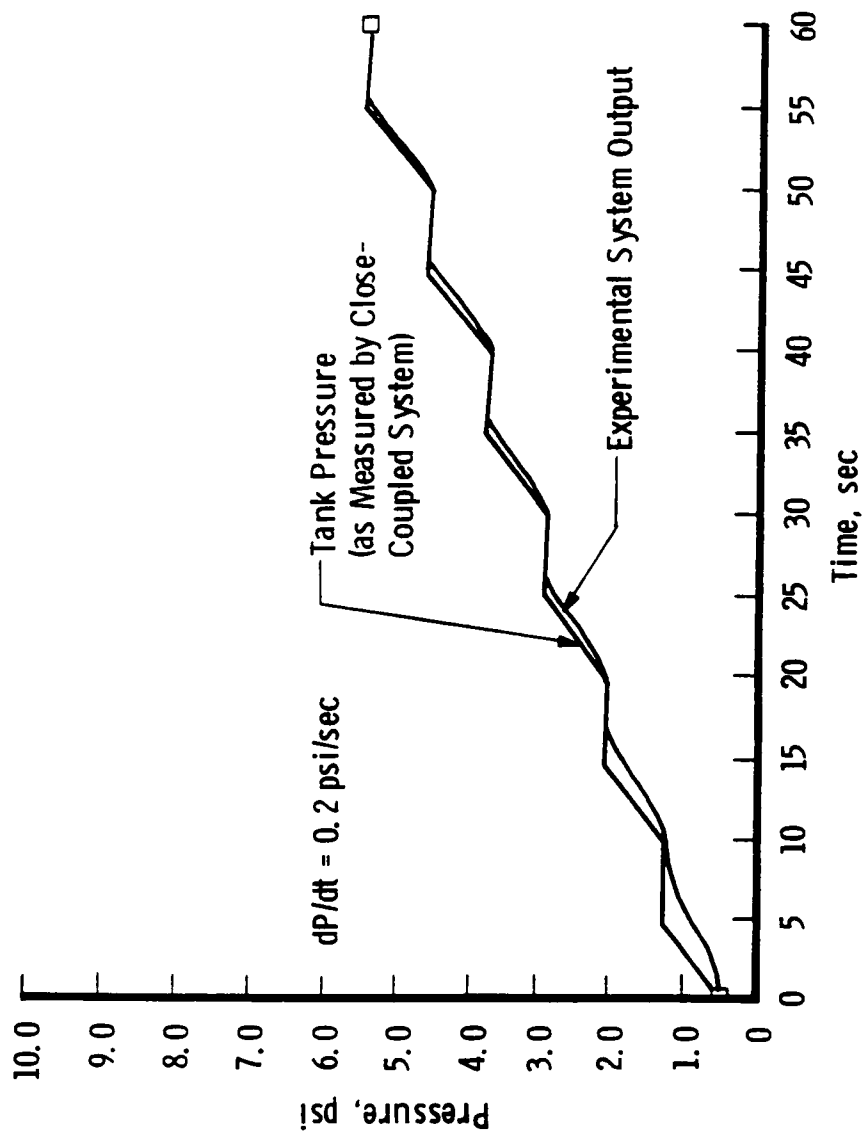


Figure 5. Experimental System Output

3.2 COMPARISON OF RESULTS

In order to produce a time history of the predicted output of the lagging transducer, Equation 11 was used in a CSMP program with input ramp functions employed to simulate the pressure applied at the orifice. The program used Equation 13 to formulate an effective K value.

Figure 6 presents plotted values for the tank pressure as measured by the close-coupled transducer, the pressure as measured by the lagging transducer, and the timewise predictions of the lagging transducer output produced by the CSMP program. As is evident, the values predicted from Equation 11 show excellent agreement with the experimental results. This agreement indicates that the assumptions involved in the mathematical model are essentially valid, at least for the system tested.

4.0 VERIFICATION OF THE PREDICTION TECHNIQUE

The next logical step in the effort to validate the prediction technique is to apply the model to predict the output of the lagging transducer and to compare the predicted values with the closely-coupled transducer measurement of tank pressure. In order to do this, the equations and were programmed to be solved on the DEC-10 computer and allowed to predict the tank pressure from the lagging transducer measurements.

In the implementation of Equation 11, the following equation was used to determine $\frac{dP}{dt}$ from the timewise pressure measurements:

$$\frac{dP}{dt}(i) = \frac{P(i+m) - P(i-m)}{2m\Delta t} \quad (14.)$$

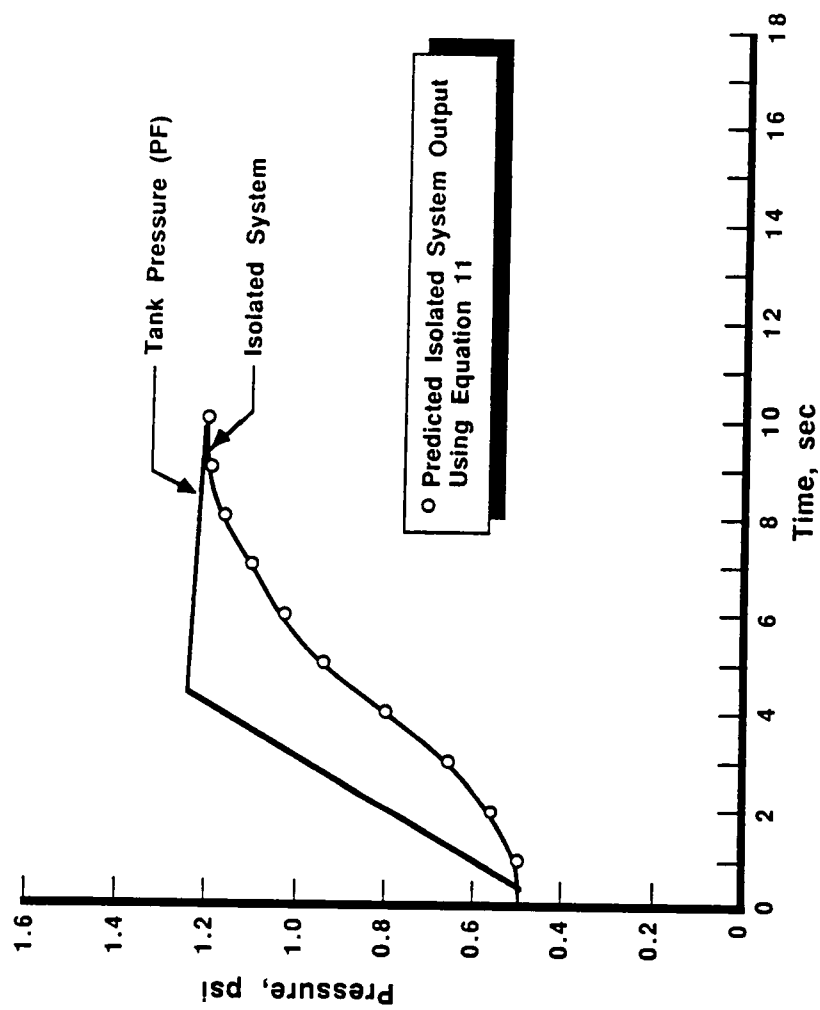


Figure 6. Output of Isolated System: Theoretical and Measured Values

Where Δt is the time between measured data points and m is a smoothing integer used to minimize the effects of transducer noise. This simple relationship was used to minimize the complexity of the data reduction equations and thus reduce computational time. However, for future applications, the implementation of a sliding curve fitting technique should be considered. Figure 7 presents the orifice (tank) pressure predicted by the technique compared with the measured pressure. As would be expected from the previous comparison, the predicted orifice pressures show good agreement with the experimental values. Presented in this figure are predictions using smoothing integers of $m = 1.0$ and $m = 2.0$ in Equation 14. As is indicated, predictions using $m = 2.0$ show slightly better agreement with measured values. The experiment was repeated for various bleed rates and the results are presented in Figures 8 and 9. Comparison of these results indicates the technique is valid up to bleed rate of $dP/dt = 0.6$ psi/sec, although the prediction is not quite as accurate at $dP/dt = 0.6$ as it was for $dP/dt = 0.2$ and 0.4 .

5.0 MODIFICATION OF THE TECHNIQUE TO INCLUDE SECOND - ORDER EFFECTS

As is indicated in the previous section, the assumption of negligible second-order effects was shown to be valid for a typical pitot-pressure measurement system. However, as part of a recent wind-tunnel test, the technique was used with a nontypical measurement system. This system, shown in figure 10, contained an extremely long, small diameter tube and orifice. The experimental method previously discussed was used to evaluate the lag characteristics of the measurement system. As is indicated in Figure 11, the predicted pressure varies noticeably from the tank pressure during certain portions of the pressure-time history. Investigation of this phenomenon revealed that the error in predicted pressure was

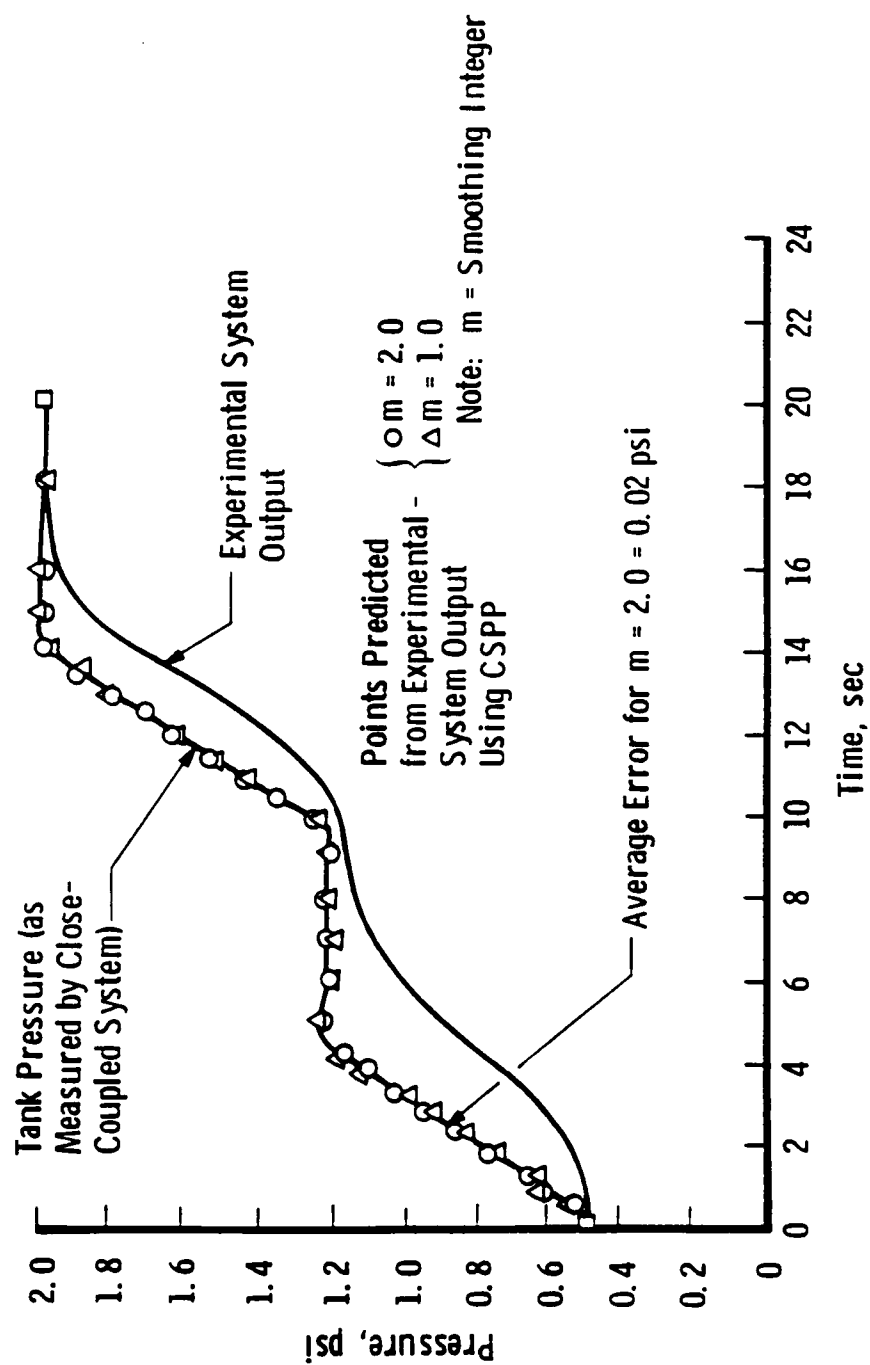


Figure 7. Predicted Pressures $dP/dt = 0.2$ psi/sec

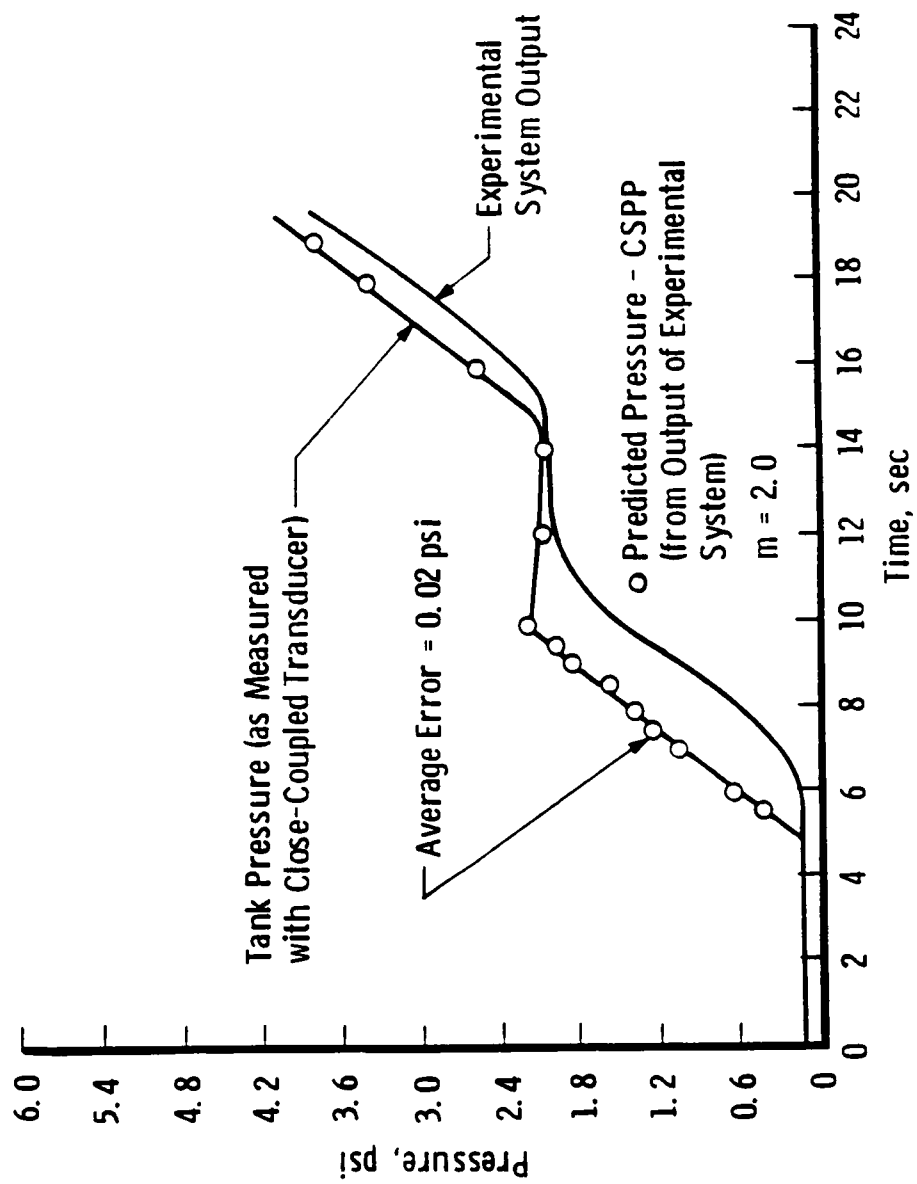


Figure 8. Predicted Pressures $dP/dt = 0.4$ psi/sec

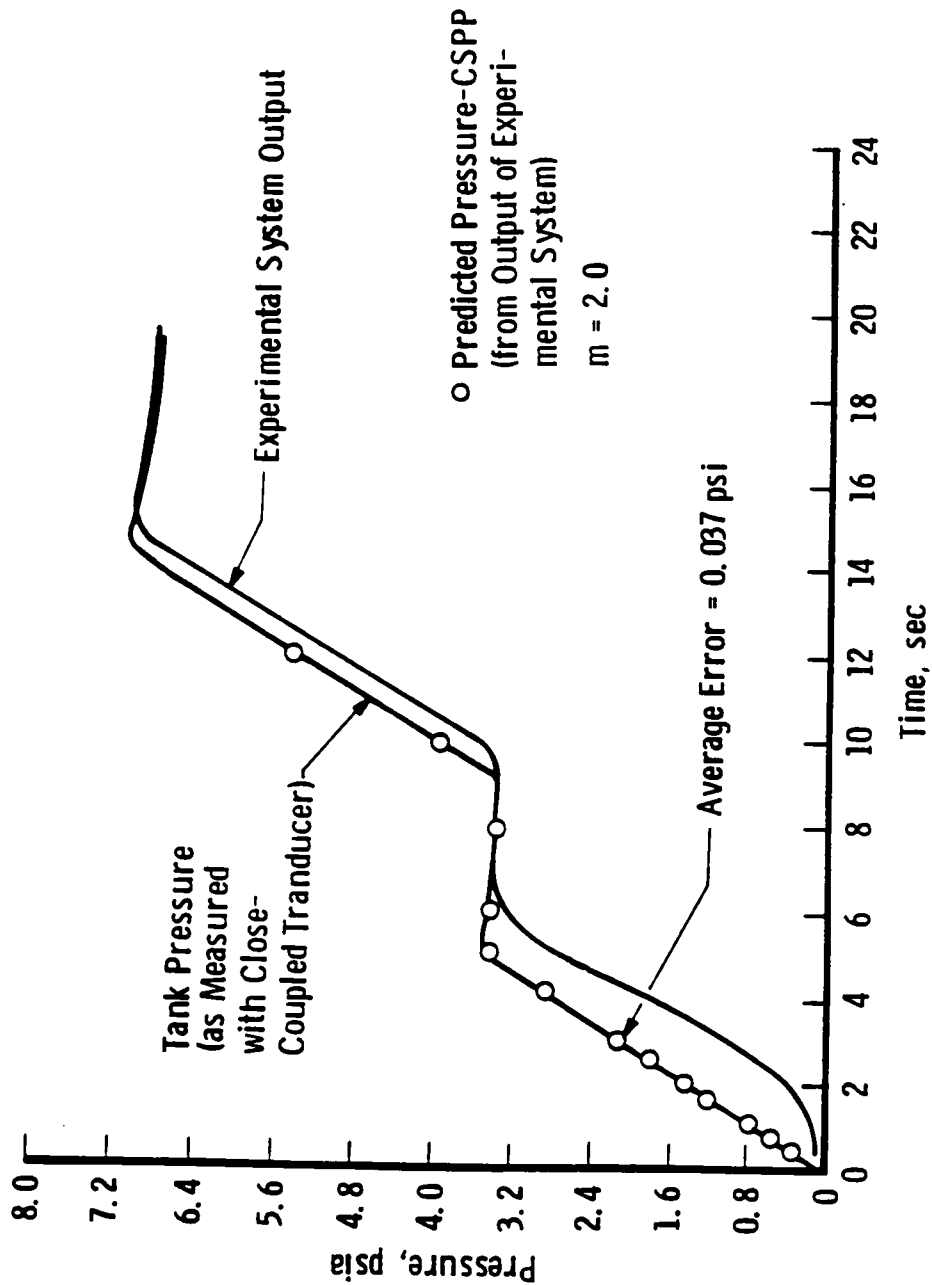


Figure 9. Predicted Pressures $dP/dt = 0.7$ psi/sec

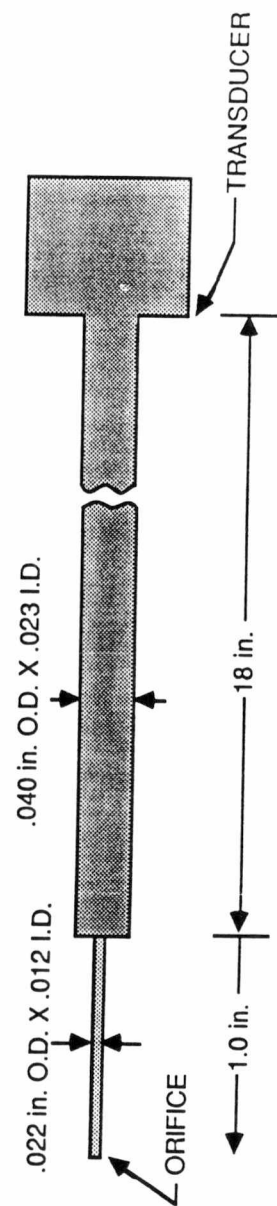


Figure 10. Non-Typical Measurement System

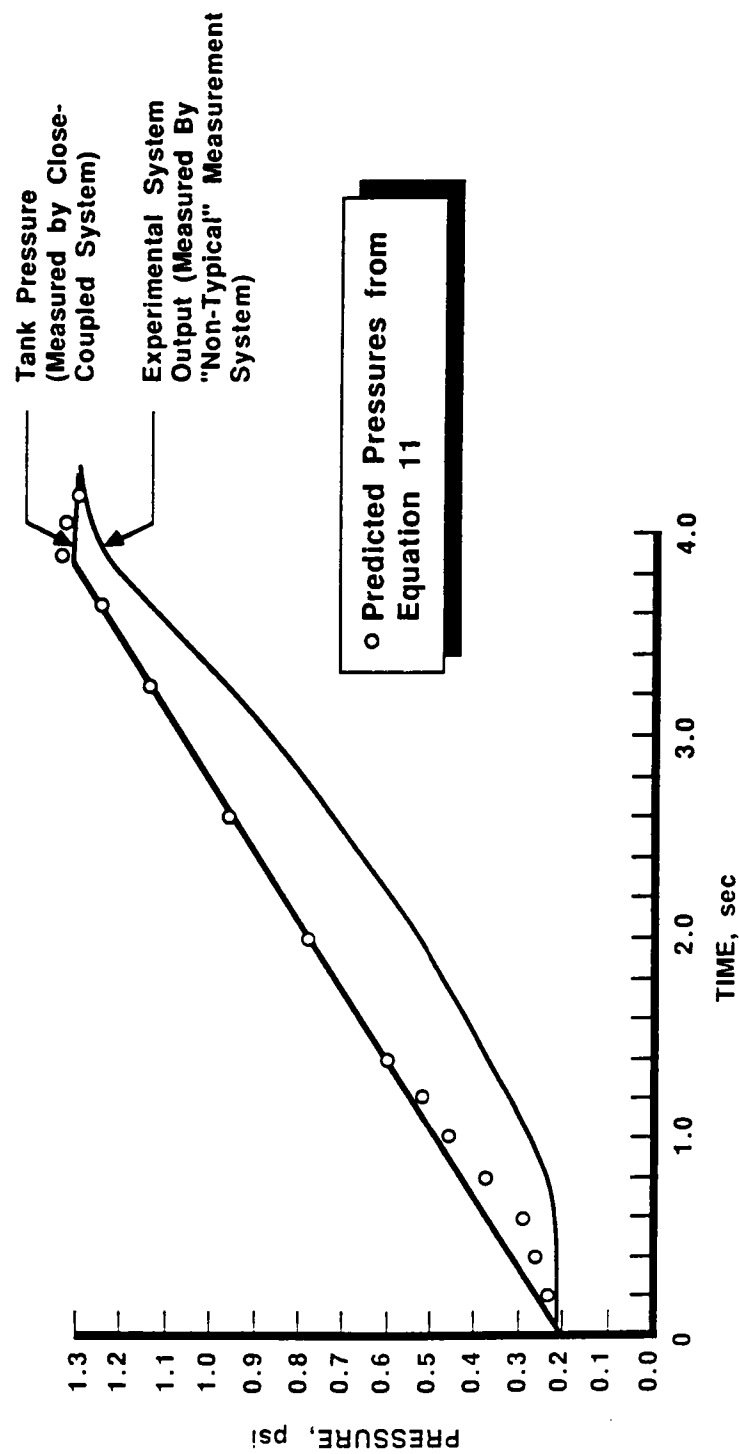


Figure 11. Output of "Non-Typical" System with Predicted Points

proportional to the second derivation of pressure with respect to time (d^2P/dt^2). While the value of d^2P/dt^2 quickly approached zero for the typical measurement system, the value was substantial for a greater time with the nontypical system. Brown in Reference [1] reported similar findings with certain pressure systems and suggested the modification of Equation 11 as shown:

$$P_o = -\frac{A}{2} + \sqrt{P^2 + AP + \left(\frac{A^2}{2}\right) + \frac{1}{K} \frac{dP}{dt} + \left(\frac{B}{K}\right) \frac{d^2P}{dt^2}} \quad (15.)$$

while Brown was able to experimentally determine a value of B which gave an acceptable prediction, he was unable to analytically evaluate this value. He did, however, speculate that B would be a function of measured pressure. In order to apply Equation 15 to the system shown in figure 10, it was first necessary to evaluate values of B and K. Values of

$\frac{d^2P}{dt^2}$ were determined for several points in the pressure-time history using the equation

$$\frac{d^2P}{dt^2} = \frac{\frac{dP}{dt} (i+m) - \frac{dP}{dt} (i-m)}{(2)(m)(\Delta t)} \quad (16.)$$

At a point where $d^2P/dt^2 = 0$, the values of measured pressure and tank pressure were used to solve for a value of K using Equation 15. Then, at a point where $d^2P/dt^2 \neq 0$, this value of K, along with the measured pressure and the tank pressure, was used to solve Equation 15 for B. Evaluation of B at various pressures led to the formulation of B as a linear function of measured pressure. As shown in figure 12, the modification of the technique in this manner greatly improved the accuracy of the predicted pressures.

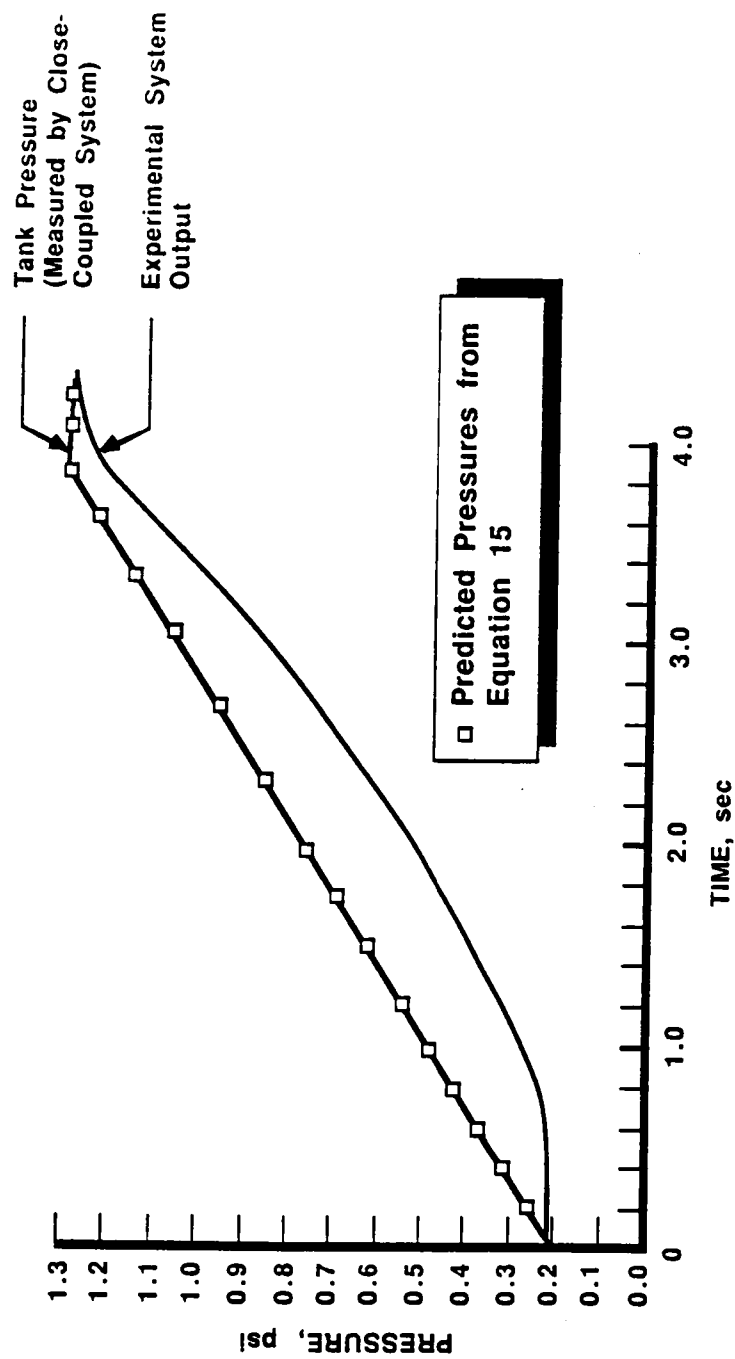


Figure 12. Predicted Points Using Second-Order Prediction Technique

6.0 APPLICATION TO WIND TUNNEL TESTING

6.1. PRE-TEST EXPERIMENTAL VERIFICATION

The first step in applying the prediction technique to wind tunnel pressure measurements is to calculate values for K and A using Equations 12 and 13. The experimental method described in Chapter 3.0 should then be repeated with the measurement system to be used. This experimental procedure is vital to determine the range of applicability of the governing equations. In addition, the procedure serves to verify the analytical value for K , and provides an indication of expected transducer noise. If the transducer noise is found to be high, the value of M used in Equation 14 can be increased. Out of this experimental verification should come following:

- (1.) Confidence in the applicability of Equation 11 to the measurement system, or an indication of the need to use the second-order form, Equation 15.
- (2.) The highest level of change in orifice pressure with respect to time for which the technique is valid.
- (3.) An experimentally - validated value for K .
- (4.) Values for expected transducer noise, and optimum values for m .

6.2 WIND TUNNEL TEST PROCEDURES

As has been discussed previously, the continuous sweep pressure prediction technique uses the relationship presented in Equation 11 to predict a time-varying orifice pressure based on the transducer pressure time history. As part of wind tunnel tests, the technique involves driving a pitot probe continuously through a boundary layer or flow field, and using Equation 11 to determine the pressure profile. In addition, if model pressures are

being measured, the model angle-of-attack can be continuously varied. However, the use of the technique in wind tunnel measurements requires that verification procedures be followed as part of the test sequence, in addition to the pre-test verification described in the previous section. The primary reasons for performing these additional tests are:

- (1.) Crimping or partial obstruction of the measurement tubing may occur during test installation, which would drastically alter the pressure lag characteristics.
- (2.) The pressure profile that is measured during the wind tunnel test might be substantially different than was expected, and resulting pressure levels and pressure variations with time might be different than the tested in those pre-test verification.

Two test procedures that should be followed are outlined below.

The first procedure takes place following installation of the measurement system, but prior to the acquisition of the wind tunnel data. In this test, a vacuum source is applied to the pressure orifice, and the pressure tubing evacuated. The vacuum source is then removed, and the resulting transducer pressure time history obtained. This pressure time history is then used with the curve fitting technique presented in Reference [1] to verify the value of K used. This provides an indication of possible tube obstruction or crimping during installation.

The second verification procedures takes place as part of the wind tunnel data acquisition process. In this verification, pauses are incorporated into the drive or sweep sequence. These pauses should be long enough to allow the measured pressure to completely settle. Post-test, the response of the measuring transducer during a pause can be curve fitted using the method set forth in Reference [1] to further verify the value of K used.

In addition to these verification procedures, the data produced by the technique

should be carefully examined during the course of the wind tunnel test, to determine if the change in orifice pressure with respect to time that is encountered significantly exceeds the time-wise change that was used in the pre-test verification. If this is found to be the case, the probe drive speed or model sweep speed can be adjusted accordingly.

In order to illustrate these recommended practices, a typical application of the technique will be described. In this instance, the system described in Chapter 3.0 was used to obtain cold-wall boundary layer pitot pressure profiles for a conical model in hypersonic flow. The measuring transducer, as well as the probe drive mechanism were mounted inside the model and the probe drive sequence was controlled using a programmable controller. Prior to each data run, the probe was positioned on the model surface. Upon injection of the model into the wind tunnel, the probe was driven continuously through the boundary layer, with four pauses included as part of the drive sequence. Presented in figure 13 are the measured pressures from the transducer vs. probe position. The "flat spots" in the pressure plot indicate the change in transducer output during each pause. If the prediction technique is being properly applied, the pressures measured during a pause will produce a single predicted pressure at each probe location. Figure 14 indicates that this is indeed the case. The "flat spots" have collapsed into a single point at each pause, so that the measured and predicted data are verified as to being the same value.

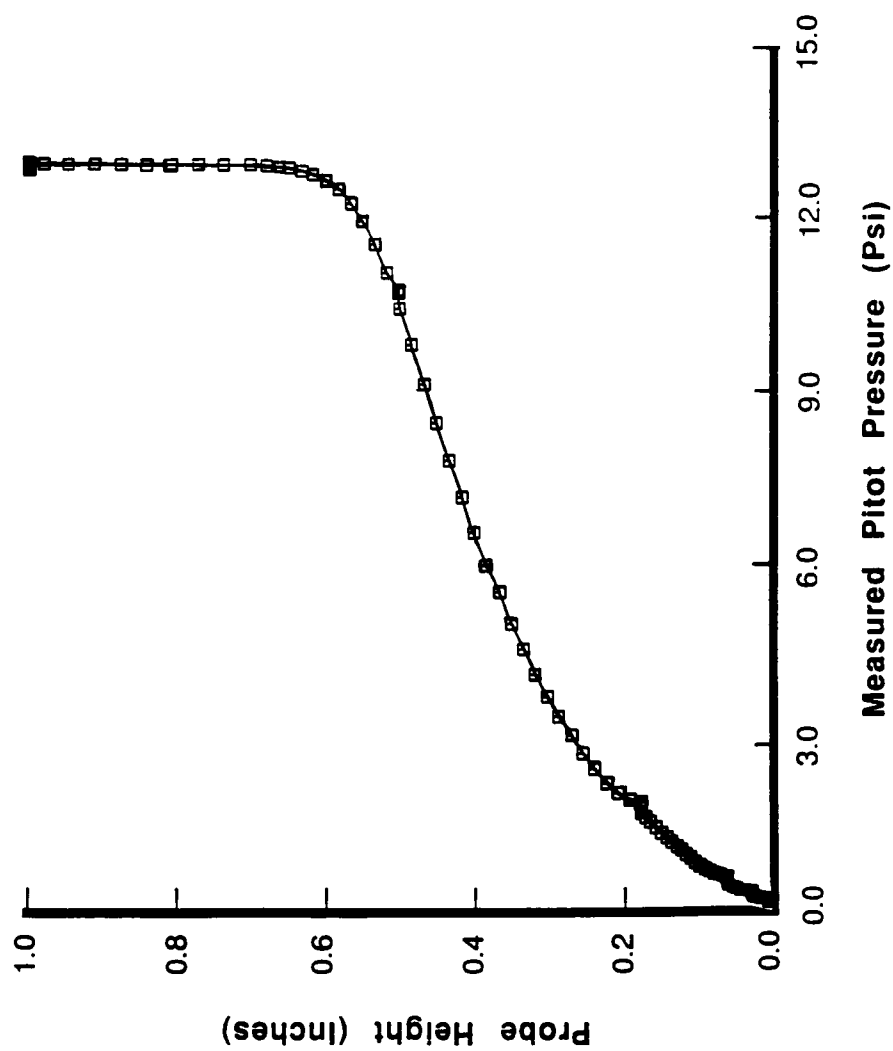


Figure 13. Measured Pitot Pressure - Mach 8

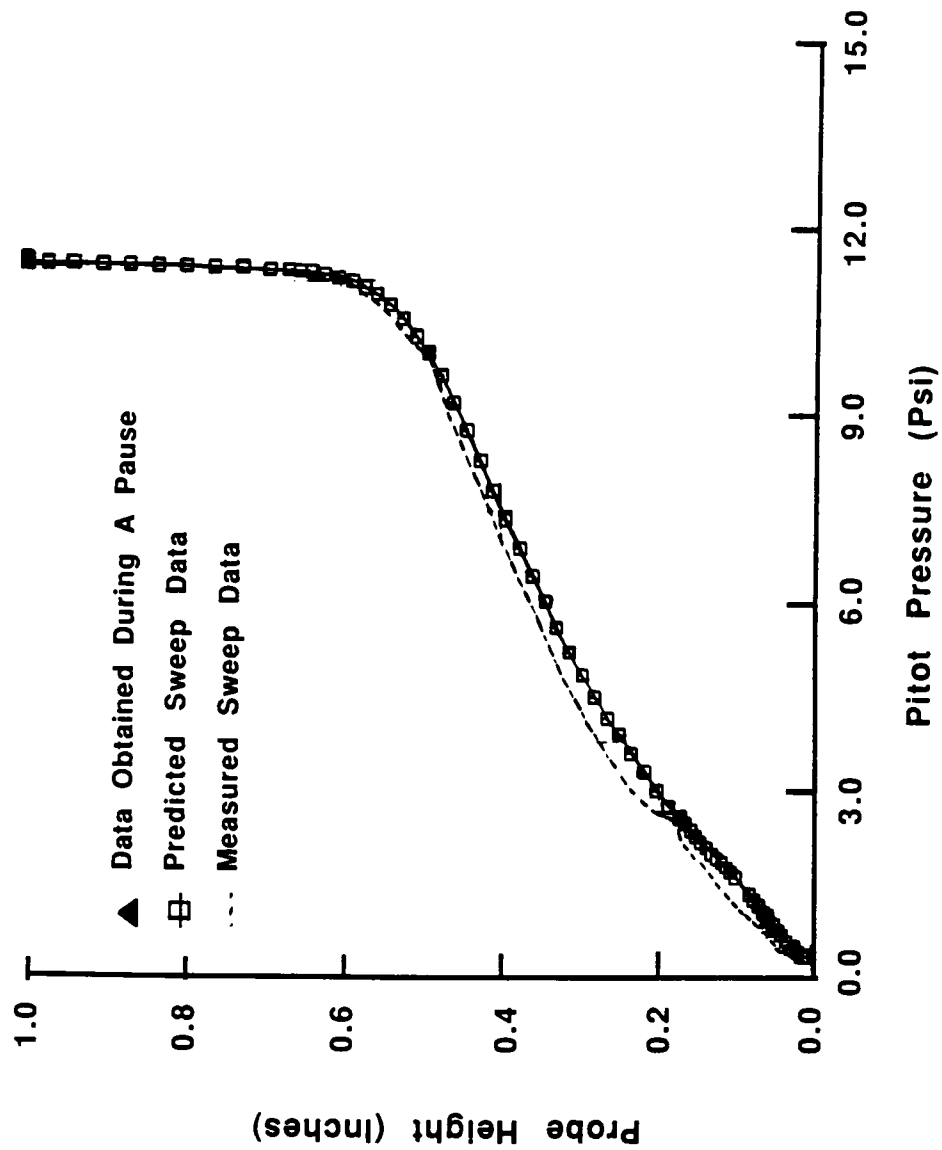


Figure 14. Predicted Pitot Pressure - Mach 8

7.0 SUMMARY AND RECOMMENDATIONS

In summary, an advanced pressure prediction technique has been derived which predicts a time-varying orifice pressure based in the transducer pressure time history. The technique has been shown to provide accurate results for one commonly used pressure measurement system. For another type of system, the technique was shown to provide insufficient accuracy, and a modified version, using experimentally-derived empirical values, was developed. Both versions of the technique have been used in wind tunnel experiments and have been found to produce accurate results with significant increases in data productivity. The recommendations that have been made regarding the use of the technique are:

- (1.) Pre-test laboratory verification of the technique should be made with the pressure measurement system that is to be used in the wind tunnel.
- (2.) Following installation in the wind-tunnel, further checkouts should be should be made to identify changes to the system lag characteristics that may have occurred as part of the installation process.
- (3.) During the wind tunnel tests, pauses should be incorporated into the data acquisition sequence to allow the pressure measurement to settle, and to provide data to be used to further verify the technique.

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VITA

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