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Technical Note

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Simple Technique for Frequency-Response Enhancement of Miniature Pressure Probes

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I. Introduction

THIS Note deals with the implementation of a simple technique to correct for the pressure measurement error produced in miniature multihole pressure probes caused by the lag in the response of the probe tubing system. As the size of the pressure probe is reduced in order to reduce flow disturbance, the probe's frequency response deteriorates. Reduced frequency response generally causes the wait times in flow-mapping experiments to increase. The wait time is the time that the probe, after it moves to a new measurement location in the flowfield, has to wait before data acquisition can be performed, in order for the pressures at the probe pressure transducers to reach steady state. Moreover, deterioration of probe frequency response limits its capability to resolve temporal information in unsteady flows. In the present work, we introduce a simple algorithm that significantly improves a probe's frequency response. Detailed work in the area was carried out by Whitmore.[1] He developed a mathematical model for a tubing system, derived from the Navier–Stokes and continuity equations. On the basis of this model, he then developed an algorithm to compensate for pneumatic distortion. The technique presented here is simpler and much less computationally intensive and is thus amenable to real-time implementation. The technique presented here is applicable only to critically damped or overdamped tubing systems, as discussed later.

Generally, in pressure-measuring systems such as multihole probes, the pressure at the pressure-measuring instrument (pressure transducer) can be different from the pressure at the source (i.e., the probe tip) because of the time lag and pressure attenuation in the transmission of pressures in the associated tubing. When the pressure at the pressure source is changing rapidly, the pressure at the transducer lags behind that at the source and its amplitude is attenuated because of 1) the time needed for the pressure change to propagate along the tubing (acoustic lag) and 2) the pressure drop associated with the flow though the tubing (pressure lag).[2]

The speed of the pressure propagation along the tubing is the speed of sound. The magnitude of the acoustic lag τ thus depends on only the speed of sound a and the length of the tubing L, as expressed in $\tau = L/a$. Because the speed of sound at standard atmospheric conditions is on the order of 1100 ft/s (340 m/s), errors caused by acoustic lag are of concern only in pressure systems having very long pressure tubing. Errors associated with acoustic lag can be neglected here because the tubing lengths of interest are very short [order of 1 ft (0.3 m)]. Moreover, because of the motion of the air through the pressure tubing between the pressure source and the transducer, the pressure at the transducer is different from the pressure at the source by a pressure drop Δp. The modeling[1–3] of both of these factors and the simplification of the model are briefly discussed next.

II. Modeling of Pressure-Tubing Response

Let us consider a section of pressure tubing of length L and inside diameter d. Let one end of the tubing be connected to a high-frequency-response pressure transducer (transducer T2) and a transient pressure signal $p(t)$ from the pressure source be applied to the other end (Fig. 1). Let the pressure measured by transducer T2 be $p'(t)$. The pressure signal $p(t)$ from the pressure source is measured directly by a second pressure transducer T1 (Fig. 1). The tubing assembly can be modeled as a second-order dynamic system[2]:

$$p(t) = mC\frac{d^2p'(t+\tau)}{dt^2} + RC\frac{dp'(t+\tau)}{dt} + p'(t+\tau) \quad (1)$$

In the preceding expression, m is the equivalent mass of the system. This is the combined mass of the air inside the tubing and the transducer cavity. $1/C$ is the system elastic constant, R is the viscous damping coefficient, and τ is the acoustic lag. If we assume laminar flow in the tubing, then the value of $\lambda = RC$ can be calculated theoretically from the following equation[3]:

$$\lambda = \frac{128\mu LV}{\pi d^4 p_0}$$

where L and d are the length and internal diameter of the tubing, V is the combined volume in the tubing and the transducer cavity, p_0 is a reference pressure in the tubing–transducer system, and μ is the coefficient of viscosity of the fluid medium in the tubing (air in our case). This equation assumes laminar flow in the tubing and applies only to straight tubing of constant diameter. The preceding expression for λ does not hold for a more complex tubing assembly, consisting of tubing sections of different lengths and diameters and/or incorporating bends.

For complicated tubing assemblies, such as those in a probe, theoretical calculation of λ is not practical. As shown later, experimental calculation of λ can yield good results. For small tubing and transducer cavity volumes, one can see that

$$mC \ll RC, \qquad \tau \ll RC \quad (2)$$

Combining Eqs. (1) and (2), we get

$$\lambda\frac{dp'(t)}{dt} + p'(t) = p(t) \quad (3)$$

The preceding equation, because it is first order, holds for any critically damped or overdamped (and not underdamped) tubing assembly regardless of its complex design. The lag constant λ is of course different for different tubing assemblies. If the system lag constant λ is known, the actual pressure signal $p(t)$ applied to

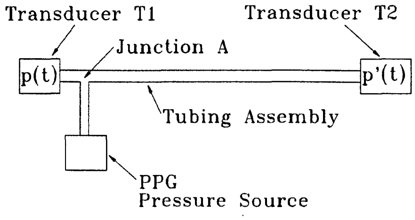

Fig. 1 Schematic of the tubing–transducer assembly.

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one end of the pressure tubing can be calculated from the measured signal $p'(t)$, using Eq. (3), even before steady state has been reached.

III. Experimental Calculation of the Lag Constant λ

The lag constant λ can be experimentally determined in several ways, based on the solution of Eq. (3) for different initial conditions. The method used in the experiments conducted here is described next. Equation (3) provides the basis for determining λ:

$$\lambda = \frac{p(t) - p'(t)}{dp'(t)/dt} \tag{4}$$

This technique can be used to significantly accelerate the mapping of a flowfield, through on-the-fly data acquisition. The actual pressure $p(t)$ can be measured as the probe sweeps through the area of interest. In other words, the probe need not stop at a point and wait for pressure $p'(t)$ to reach steady state. Through this technique, one can also measure the actual pressure $p(t)$ in a unsteady flowfield since one can calculate $p(t)$ from $p'(t)$ if the lag constant λ of the particular tubing assembly in use is known. However, the bandwidth that can be resolved through the technique is limited. Following the work of Whitmore and Moes,[4] one can see that a rigorous criterion that must be satisfied for the first-order model [Eq. (3)] to be valid is given (for moderate or short tubing lengths) by

$$\omega \ll 32\mu \big/ d^2 \rho_0 \tag{5}$$

where ω is the radian frequency of the flow unsteadiness and ρ_0 is the density. Let us consider an example involving the miniature multihole probes for which the algorithm was developed. The size of these probes is small for minimum intrusiveness, especially in intrusion-sensitive flows. In these probes, tubing i.d. of 0.25 mm are typical. For such diameters and typical density and viscosity values, we get, from Eq. (5), $\omega \ll 7500$ rad/s. So, if we take ω to be one order of magnitude smaller than 7500 rad/s, this translates to a frequency of 120 Hz. This is sufficient for many unsteady-flow-measurement applications and can yield very small wait times in flow surveys.

IV. Experimental Setup

Figure 1 shows the schematic of the experimental setup used. A pressure pulse generator (PPG) is used to apply the transient pressure signal $p(t)$ to one end of the pressure tubing. This pressure is measured directly by pressure transducer T1, and the other end of the pressure tubing is connected to the pressure transducer T2.

The pressure source (PPG) represents a flowfield. The pressure sensed by transducer T1 simulates the pressure at the tip of the probe, and that measured by transducer T2 simulates the pressure measured by the pressure transducer the probe is connected to. Any tubing assembly of interest can be inserted between junction A and transducer T2, and its equivalent lag constant λ can be determined. The operation principle of the PPG is described in Ref. 5.

Data acquisition was performed by a DAS-16 Jr A/D board (Computer Boards). The outputs from transducers T1 and T2 (Validyne) were fed into two channels of the board, and data acquisition was performed sequentially and not simultaneously. To minimize the error caused by this, the data were acquired at a sampling rate of 40,000 samples/s. Only the samples taken at every millisecond (for example, samples 1 and 2, then samples 41 and 42, then 81 and 82, and so forth) were retained and used for further analysis. The pressure transducers were regularly calibrated. A five-point calibration was performed, which accounted for transducer nonlinearities and thermal drifts. The reference manometer used for calibration had an uncertainty of 0.005 torr for the range of pressures used here (± 6 torr). The preceding calibration, along with a one-count A/D conversion uncertainty, yielded a pressure measurement uncertainty of 0.010 torr. To render the pressure applied at junction A, a smoother function of time, a damper tube was introduced between the PPG outlet and junction A (Fig. 1). Moreover, to reduce the noise in the calculation of the pressure time derivative, a digital filter (running average) was first applied to the acquired data. The lag constant λ for the tubing system was then determined from Eq. (4).

V. Results

Typical pressure signals $p(t)$ and $p'(t)$ are shown in Fig. 2 for a single actuation of the PPG. These data correspond to a simple tubing assembly, consisting of a single straight tube 18.5 in. (0.47 m) long with constant inside diameter of 0.010 in. (0.25 mm). Equation (4) was used to calculate a λ value of 0.862. As stated earlier, there is a time lag between $p'(t)$ and $p(t)$. In other words, the pressure at transducer T2 takes some time Δt to reach the 99% of the steady-state pressure value. For the particular tubing used, the time lag was $\Delta t = 3.877$ s, which would be a significant wait time in flow-mapping experiments.

Once the value of λ is calculated, we can calculate the corrected pressure $P_{\text{corr}}(t)$ from the measured pressure $p'(t)$ from the equation

$$P_{\text{corr}}(t) = p'(t) + \lambda \frac{dp'(t)}{dt} \tag{6}$$

This should be equal to the applied pressure $p(t)$. Figure 2 shows good agreement between $P_{\text{corr}}(t)$ and $p(t)$. The average error was 0.007 torr. Subsequently, and for validation purposes, an arbitrary pressure signal $p(t)$ was generated by repeated random actuations of the PPG. The two pressure signals $p(t)$ and $p'(t)$ were measured and

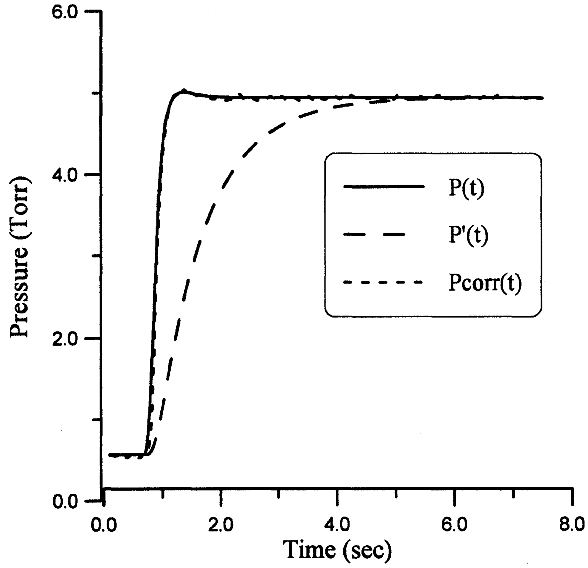

Fig. 2 Response of transducers T1 and T2 for a tubing of length 18.5 in. (0.47 m) and inner diameter of 0.010 in. (0.25 mm) for a single PPG actuation and corrected pressure $P_{\text{corr}}(t)$.

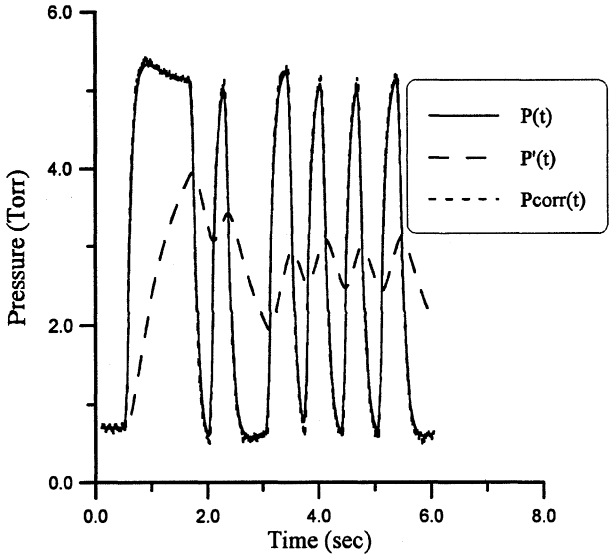

Fig. 3 Response of transducers T1 and T2 for the tubing corresponding to Fig. 2 for a series of random PPG actuations and corrected pressure $P_{\text{corr}}(t)$.

are shown in Fig. 3. From the already calculated value of λ (=0.862) and pressure signal $p'(t)$ measured by transducer T2, the corrected pressure P_{corr} was calculated and should reconstruct $p(t)$. As seen in Fig. 3, the agreement is excellent. For application of the technique to actual real-time flow measurements, the reader is referred to Ref. 5.

VI. Conclusion

A simple technique was developed for pressure measurements in unsteady flows and on-the-fly data acquisition in steady flows using conventional pressure-sensing methods. This technique provides a means of compensating for the errors caused by pressure lag and attenuation in the pressure tubing, is computationally very inexpensive, and is implemented in real time. It is, however, limited to critically damped or overdamped tubing systems. The agreement of predicted and actual pressures validates the simple mathematical model for the tubing and the algorithm used to predict the actual applied pressure. This technique will help to bridge the gap until new pressure-sensing techniques are developed based on the incorporation of microelectromechanical systems pressure transducers on or near the surface of the probe tip. This development is currently undertaken by our group.

Acknowledgments

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