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The Dynamic Response of Pressure-Measurement Systems

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ABSTRACT

A comparison of theoretical predictions and experimental measurements of the frequency response of dynamic pressure-measurement systems, involving cylindrical connecting tubes is made.

Good agreement is achieved when the flexibility of the pressure transducer diaphragm is incorporated in the theoretical predictions, in the form of an additional 'equivalent volume'. However, when this becomes a large proportion of the total volume exposed to the diaphragm, discrepancies at high frequencies still occur. This is attributed to a frequency dependency of the equivalent volume as the natural frequency of the transducer is approached.

INTRODUCTION

The ability of the fluid mechanics researcher to make dynamic surface pressure measurements has been improved greatly by the recent development of cheap, sensitive and stable solid state pressure sensors of high frequency response (Anon., 1985). However to make use of these devices, and other types of pressure transducer, it is usually necessary to connect them via small diameter tubing to measurement points on wind tunnel models or other exposed surfaces in wind tunnels. Hence there is a need to understand and optimize the dynamic response characteristics of complete pressure measurement systems including pressure tap, connecting tubing and transducer volume. A study to this end has been undertaken at the Division of Building Research (Holmes and Lewis, 1986a and b). This work included a detailed study of the use of restrictor tubes to remove resonant peaks in the response of pressure measurement systems, and of the pneumatic averaging technique now commonly used in wind engineering studies.

The present paper will confine itself to a discussion of the ability of a theoretical model to predict the response of simple tubing systems, and the importance of transducer diaphragm flexibility.

THEORETICAL MODEL

Although the theoretical problem of propagation of sound waves in gases in cylindrical tubing is a classical one, associated with such famous names as Helmholtz, Kirchhoff and Rayleigh, most of the early approximate solutions (for low reduced frequencies) have been superseded by those developed by Iberall (1950) and Bergh and Tijdeman (1965). The motion of the air in a tube of circular cross-section is described by the Navier-Stokes equations of momentum conservation (radial and axial) and continuity. In the tube, and in the transducer volume of a measurement system, the air is required to satisfy the equation of state, and the energy equation.

The following assumptions are made.

(a) The sinusoidal pertubations in pressure, density, temperature and velocity are small in comparison to the mean values.

(b) The length to diameter ratios of the tube sections are assumed large so that end effects are negligible.

(c) The Reynolds Numbers are low enough so that the flow is laminar throughout the system.

(d) The thermal conductivity of the wall of the tubes is assumed to be large, compared to that of air, so that temperature fluctuations at the wall are zero.

(e) The material of the tube walls is assumed to be rigid.

(f) The cross flow velocity at the entrance to the tubes is assumed small.

(g) The pressure expansions in the tubing, and transducer volume are assumed to be polytropic processes.

(h) The reduced frequency $\omega D/a_0$ is much less than unity. Here ω is the circular frequency of pressure fluctuations, D is a tube diameter, and a_0 is the mean speed of sound.

The above conditions are normally adequately satisfied for the pressure measurement systems considered in this paper.

Although not used in the present paper, Iberall (1950) has given first-order corrections to the theory to cover the cases when (a), (b) or (h) are violated.

The recurrence equation derived by Bergh and Tijdeman gives the ratio of the amplitude of sinusoidal pressure fluctuations in volume j to that in volume j-1 for a series of tubes and volumes. The ratio given is a complex number being the ratio of amplitudes of disturbances in the form, $p_j e^{i\omega t}$; thus amplitude and phase changes for real sinusoidal disturbances can be calculated.

MEASUREMENT TECHNIQUES

Experimental response characteristics of pressure measurement systems were measured using dynamic calibration equipment described in detail by Holmes and Lewis (1986a). A fluidic pressure signal generator is used to generate sinusoidal pressure fluctuations in a coupling cavity. These fluctuations were measured by a Bruel and Kjaer type 4147 low frequency microphone. The amplitude of the pressure fluctations was kept approximately constant at around 50 Pascals r.m.s., while the frequency was varied over a range from 1 to 700 Hz by adjusting the supply voltage to the pressure generator. Higher frequencies were achieved by replacing the signal generator by a horn driver from a public address system.

The measurement system under investigation was connected to the coupling cavity and the output of its pressure transducer was compared to that of the reference microphone, to obtain the amplitude and phase response characteristics. Amplitude characteristics were obtained using a digital voltmeter, and phase differences via a digital phase-meter.

To correlate the theoretical model with the experimental dynamic response data, it will be shown that it is necessary to know the flexibility of the diaphragm of the pressure transducer in the measurement system. A method for the static determination of this was devised.

The procedure used was as follows. A length of clear PVC tubing of known internal diameter, similar to that used in the pressure measurement systems, was connected to a cavity of known volume exposed to the diaphragm of the transducer under test. The tube was kept straight and supported horizontally and a small (5 to 10 mm long) 'slug' of kerosene was inserted into the tube to act as a seal for the air in the cavity volume and part of the tube.

The position of the inner meniscus of the slug was measured using a travelling microscope. A pressure of 500 Pa was applied to the tubing at the opposite end to the transducer. The pressure of the enclosed air was measured using the output of the pressure transducer under test. The new position of the meniscus of the kerosene slug was measured; thus the total volume change of the enclosed air could be determined from the displacement of the slug.

The total volume change was made up of a component due to the compression of the enclosed air, which could be calculated using Boyle's Law, together with the change due to the diaphragm deflection, thus permitting the latter to be estimated. The calculation of volume change due to compression was confirmed by replacing the pressure transducer diaphragm by a rigid surface and repeating the measurement of slug displacement.

The flexibility of the transducer diaphragm is most conveniently expressed as an equivalent additional volume. This can be shown to be given by the product of the volume displacement due to diaphragm deflection per atmosphere of pressure difference, with the polytropic constant for the air expansion in the transducer volume, assumed to be the adiabatic value of 1.4 in the present case.

COMPARISON OF THEORY AND EXPERIMENT

Bergh and Tijdeman (1965) made several comparisons between experimental data for single and two-stage series tubing systems, and their own theoretical model. In most of the examples used, it was found that deviations existed, but that these could be removed if an 'effective tube radius', 2 to 5% lower than the measured radius, was used in the theoretical calculations. They attributed this to inaccurate measurement of the tube radius. In an attempt to resolve this, and to establish a base-line comparison for later studies of more complex systems, a series of comparisons of simple systems were made at CSIRO and are described here.

Figures 1 and 2 show the response characteristics for two nearly identical systems. The main tubes in each case are 430 mm long and are connected by short metal connectors at one end to the coupling cavity in the calibration rig, and at the other end, to identical (Honeywell 163) pressure transducers. The only difference in the two systems is that in Fig. 1, stainless steel tubing of 1.50 mm internal diameter was used, and in Fig. 2, flexible PVC tubing of 1.53 mm internal diameter was used.

The amplitude and phase response characteristics measured in the two cases are shown in each figure, together with the predicted response of the Bergh and Tijdeman theory. The changes in section at the metal connectors at each end were allowed for in the theoretical calculations. In both cases excellent agreement is found in the vicinity of the first resonant peak. The agreement for the steel tubing is near-perfect (Fig. 1); the theory predicts a slightly lower frequency at the peak of the second harmonic in the case of the PVC tube. The theory assumes rigid wall material, and Fig. 2 indicates that the slight wall flexibility of the PVC tubing material has little effect on the response below 400 Hz and can be ignored in theory, with little error.

The agreement of the theory with the experiments has been achieved without the artificial reduction in tube diameter used by Bergh and Tijdeman (1965). However, it should be noted that the pressure transducer used in the systems of Figs 1 and 2, has a stiff silicon diaphragm of small dimensions and, although the small flexibility was incorporated into the theoretical calculations, ignoring the diaphragm flexibility makes little difference in this case. However, the effect of diaphragm flexibility on the response may be more significant for other transducers.

Figures 3 and 4 show experimental response data for constant diameter steel tubes transmitting to instrument cavities of known volume each exposed to a diaphragm of a Setra 237 pressure transducer. The volume change resulting from the diaphragm deflecting under a known constant pressure difference was measured as previously discussed, and found to be significant for this transducer.

The Bergh and Tijdeman theoretical model allows for this effect to be incorporated. Figures 3 and 4 show the computed theoretical responses, with and without the diaphragm flexibility (assumed constant with frequency). It can be seen that incorporation of the diaphragm flexibility greatly improves the agreement between the theory and experiment, especially for the amplitude response. For a given transducer, this effect clearly is more important the smaller the transducer cavity, so that a relatively larger difference between the two theoretical curves is apparent in Fig. 3, compared to Fig. 4.

The Setra 237 (± 700 Pa) transducer used for the results in Figure 3 and 4, had an additional equivalent volume, measured statically as described previously, of 105 mm^3. Although large, this is still less than the actual volume exposed to the transducer diaphragm in both cases. In Figure 5, a much smaller exposed volume of about 20 mm^3 was used with the transducer and the response was measured to a higher frequency. Also shown is the response of a system with nearly identical total volume but using a transducer (Honeywell 163) with a much stiffer diaphragm and hence smaller additional equivalent volume (21 mm^3), but larger actual exposed volume (107 mm^3). The latter system is nearly identical to that previously shown in Figure 2.

The results from the stiff diaphragm transducer matched well with the theoretical predictions (with a constant additional equivalent volume assumed), but the flexible diaphragm data showed lower amplitude response, especially near the second and higher amplitude response peaks. This is caused by the magnitude of the additional equivalent volume increasing with frequency as the natural frequency of the Setra transducer diaphragm is approached. To confirm this, the theory was modified with the diaphragm treated as a single-degree-of freedom system, with an undamped natural frequency, n_o, equal to 1300 Hz, and a critical damping ratio of 0.63. This model matched quite well the measured response of the setra transducer mounted with a flush diaphragm, and compared with a Bruel and Kjaer microphone, as shown in Figure 6.

The modified theoretical response in Figure 5 is seen to better match the experimental response of the system with the setra transducer.

CONCLUSIONS

i) Good agreement between theoretical and experimental dynamic response characteristics for pressure measurement systems with long tubes was achieved for both steel and flexible p.v.c. tubing.

ii) For pressure transducers with flexible diaphragms, it is necessary to incorporate the diaphragm flexibility as an equivalent volume into the theoretical calculations. In some cases, the frequency dependency of the diaphragm flexibility should also be modelled.

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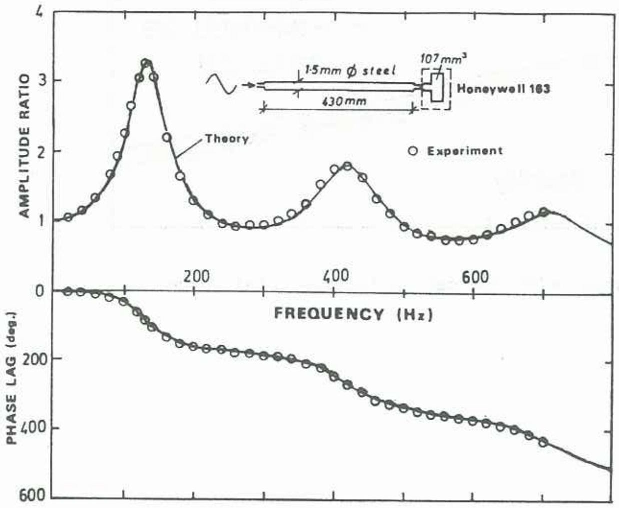

Fig 1: Comparison between theory and experiment - steel tubing

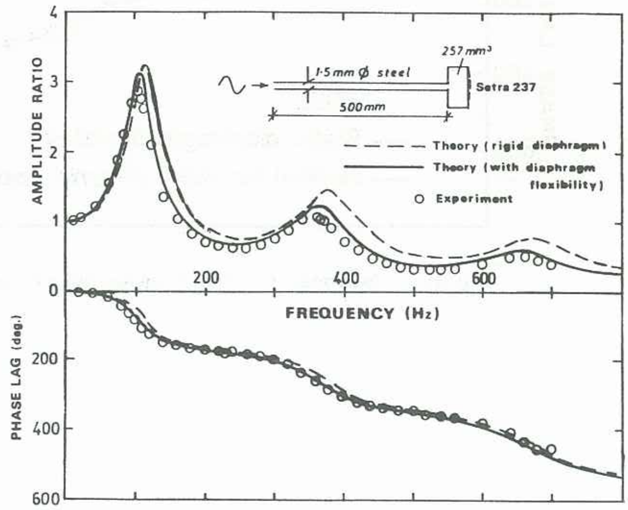

Fig 3: Effect of diaphragm flexibility (i)

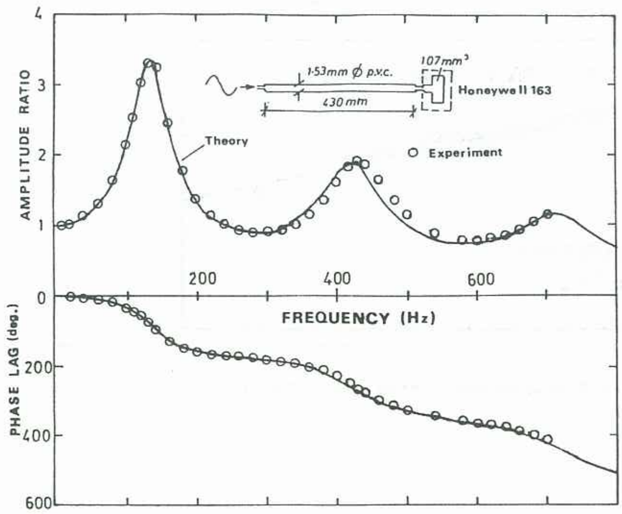

Fig 2: Comparison between theory and experiment - p.v.c. tubing

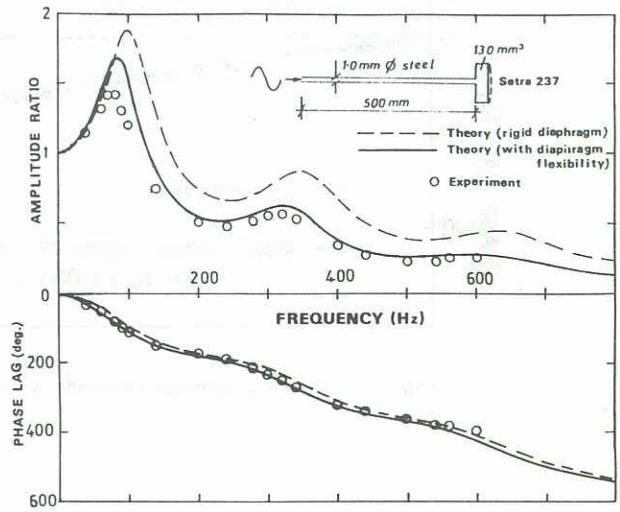

Fig 4: Effect of diaphragm flexibility (ii)

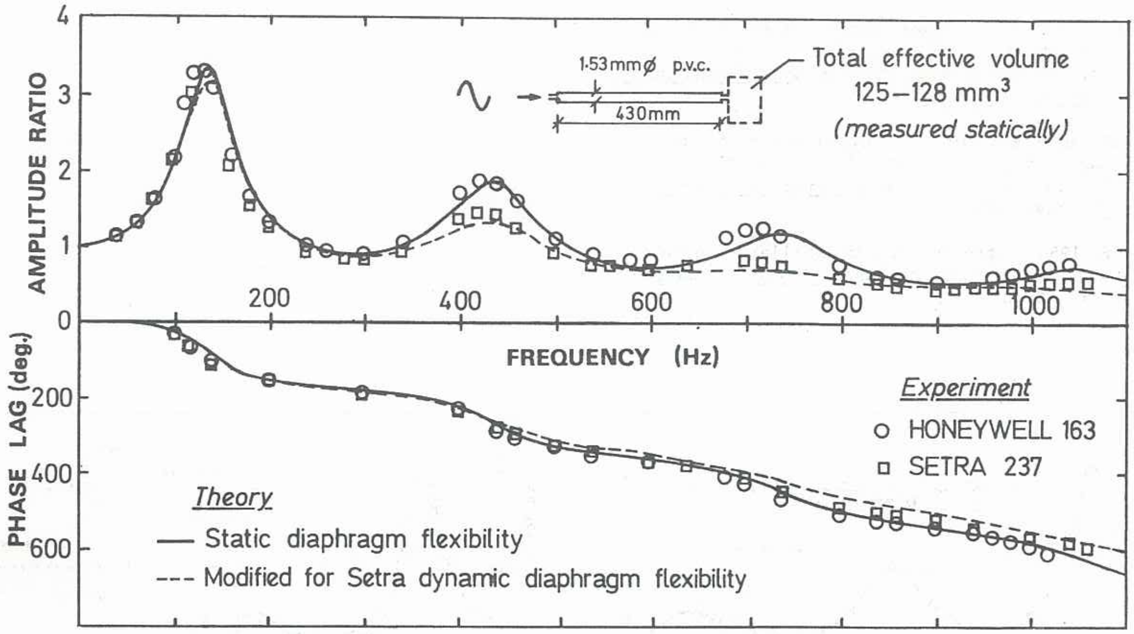

Fig 5: Response to high frequencies of two systems with the same effective total volume

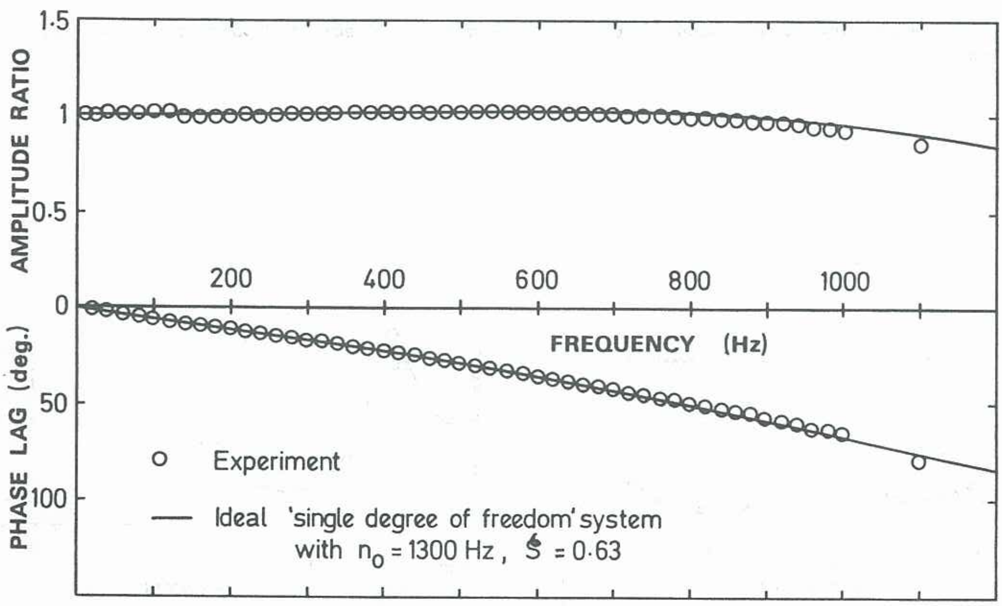

Fig 6: Flush diaphragm response of Setra 237 transducer (Serial No. 57416)