TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

A RE-EXAMINATION OF THE LEAKED-TUBE DYNAMIC PRESSURE MEASUREMENT SYSTEM

J.D. HOLMES[1] and R.E. LEWIS[2]

[1]CSIRO, Division of Building, Construction and Engineering
P.O. Box 56, Highett, Vic. 3190, AUSTRALIA

[2]Retired from CSIRO, Division of Building, Construction and Engineering

ABSTRACT

The 'leaked-tube' system, proposed by Gerstoft and Hansen (1987), for the measurement of fluctuating pressures, was investigated both experimentally and theoretically. Calculated and measured responses for some practical measurement systems showed frequency response characteristics superior to those obtained with closed measurement systems.

INTRODUCTION

The optimisation of dynamic-pressure-measurement systems, consisting of pressure transducers connected to tapping points by tubing, for use in wind engineering, industrial and aeronautical aerodynamics, and aeroacoustics, has been described in detail by Gumley (1983a), and Holmes and Lewis (1987a, 1987b). Near-constant amplitude response and linear phase response, over a limited range of frequencies, can be obtained by the use of short lengths of small diameter 'restrictor' tubing inserted within the main tubing; these were first introduced by Surry and Isyumov (1975).

However, there are many situations where the constraints of tubing length and transducer characteristics do not allow a sufficiently high frequency response to be obtained with conventional closed measurement systems, especially for single point measurements. Insufficient frequency response causes an attenuation in the peak pressures measured in wind engineering experiments (Holmes 1984).

The 'leaked-tube' system is an innovative system, proposed and investigated recently by Gerstoft and Hansen (1987). It allows a relatively flat amplitude frequency response to a high frequency, to be obtained with a length of connecting tubing much longer than those used with conventional systems (e.g. 500 Hz with 1 m length of main tube). This is achieved by introducing a controlled leak part way down the tube, usually close to the transducer. This has the effect of attenuating the amplitude response to low frequency fluctuations (and to steady pressures), to the level of that of the conventional closed system at higher frequencies. Thus, the leak introduces a high-pass filter into the system. The amplitude ratio at frequencies approaching zero is simply a function of the ratio of the resistance to steady laminar flow of the main flow and the leak tube.

The principle of the leaked-tube system is shown in Fig. 1. The amplitude ratio at zero frequency is equal to the ratio of the pressure drop across the leak tube to the total pressure drop from the entry of the main tube to the exit of the leak tube. The mass flow rates are equal in the main tube and leak tube: assuming laminar flow, for the case shown,

$$H(O) = \frac{(4/1.3^4)}{\left[(1000/1.3^4) + (4/1.3^4)\right]} = 0.585$$

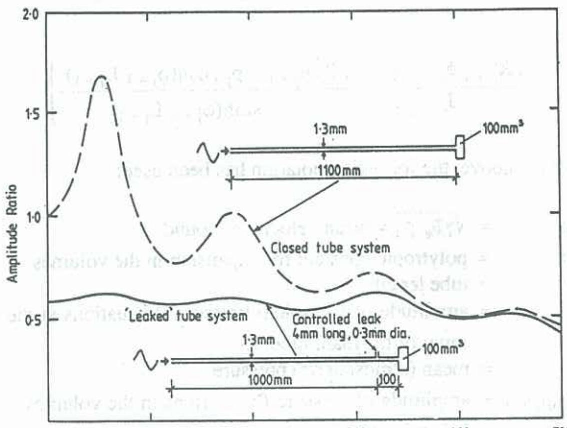

Figure 1 Principle of the 'leaked-tube' system (curves obtained from the theoretical model).

It should be noted that the amplitude frequency response ratio is approximately the same for the leaked-tube system and for the closed system with the same overall length of main tube, at frequencies above about 400 Hz. Thus, the benefit of an improved frequency response is gained at the cost of a lower effective response to steady pressure, equivalent to a reduction in transducer sensitivity.

In this paper, an alternative theoretical model of the leaked-tube system to that used by Gerstoft and Hansen is described. It is validated by a comparison with experimental data for which the geometrical properties are known accurately. Finally some practical realisations, with the inclusion of a 'Scanivalve' pressure scanning device in the system, are described.

THEORETICAL MODEL

In their paper, Gerstoft and Hansen (1987) used an electrical-acoustic analogy in a theoretical model of the leaked-tube system. The leak tube was not necessarily considered to be a length of tubing of constant diameter, and was modelled as a resistance with a single parameter. However, a direct comparison of their theoretical model with experimental data, was not given. Presumably to do this would require an independent experimental measurement of the resistance of the leak tube. In the work described in the present paper, the leak tube is always assumed to be a length of capillary tubing of circular cross-section with constant diameter.

The Bergh and Tijdeman (1965) theoretical model has been shown to be very accurate for the prediction of the response of conventional single-tube systems (Holmes and Lewis 1987a). It has also been extended to allow the inclusion of parallel tubes and averaging manifolds (Gumley 1983b).

The leaked-tube system can be represented as a system with two unequal tubes leading into an averaging manifold, as shown in Fig. 2. Then the equation derived by Gumley (1983b, Equation 24), for the mass balance within an averaging manifold with unequal input tubes can be applied:

$$\frac{-\omega^4 \gamma V_j p_j}{a_o^2 k} = \frac{\pi R_G^2 \phi_G J_2\langle\alpha_G\rangle}{J_o\langle\alpha_G\rangle}\left[\frac{p_j \cosh(\phi_G L_G) - p_o}{\sinh(\phi_G L_G)}\right]$$

$$+ \frac{\pi R_H^2 \phi_H J_2\langle\alpha_H\rangle}{J_o\langle\alpha_H\rangle}\left[\frac{p_j \cosh(\phi_H L_H)}{\sinh(\phi_H L_H)}\right] \qquad (1)$$

$$- \frac{\pi R_{j+1}^2 \phi_{j+1} J_2\langle\alpha_{j+1}\rangle}{J_o\langle\alpha_{j+1}\rangle}\left[\frac{p_{j+1} - p_j \cosh(\phi_{j+1} L_{j+1})}{\sinh(\phi_{j+1} L_{j+1})}\right]$$

In the above, the following notation has been used:

a_o = $\sqrt{\gamma P_s/\rho_s}$ = mean velocity of sound
k = polytropic constant for expansion in the volumes
L = tube length
p_o = amplitude of sinusoidal pressure fluctuations at the input of the main tube, G
p_s = mean (atmospheric) pressure
p_j, p_j+1 = amplitude of pressure fluctuations in the volumes j, j+1, respectively
R = tube radius
V_j = volume of 'manifold' (set to zero)
α = $i^{3/2} R \sqrt{(\rho_s \omega/\mu)}$ = shear wave number
γ = ratio of specific heats
μ = air viscosity
ω = circular frequency
ρ_s = mean density
ϕ = $(\omega/a_o)\sqrt{(J_o\langle\alpha\rangle \gamma / J_2\langle\alpha\rangle n)}$
n = $\left[1 + \frac{\gamma - 1}{\gamma}\frac{J_2\langle\alpha\sqrt{Pr}\rangle}{J_o\langle\alpha\sqrt{Pr}\rangle}\right]^{-1}$

Pr denotes the Prandtl Number (the ratio of kinematic viscosity to thermal conductivity), and $J_o\langle\,\rangle$ and $J_2\langle\,\rangle$ denote Bessel Functions of the zeroth and second order, respectively.

It should be noted that the amplitude of sinusoidal fluctuating pressure, at the free end of the leak tube, is assumed to be zero. The volume of the 'manifold' can be assumed to be negligible, making the term on the left-hand side of Equation (1) zero.

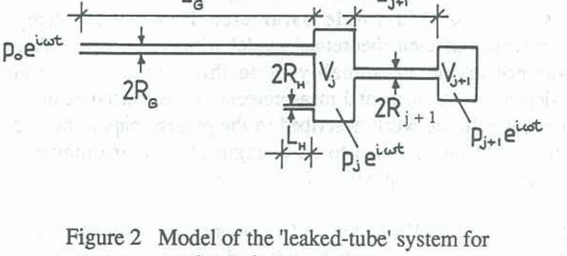

Figure 2 Model of the 'leaked-tube' system for theoretical analysis.

Then solving for the ratio of pressure amplitudes, p_o/p_j, we obtain:

$$\frac{p_o}{p_j} = \cosh(\phi_G L_G)$$

$$+ \frac{R_H^2 \phi_H \sinh(\phi_G L_G) J_2\langle\alpha_H\rangle J_o\langle\alpha_G\rangle \cosh(\phi_H L_H)}{R_G^2 \phi_G J_o\langle\alpha_H\rangle J_2\langle\alpha_G\rangle \sinh(\phi_H L_H)} \qquad (2)$$

$$+ \frac{R_{j+1}^2 \phi_{j+1} J_o\langle\alpha_G\rangle J_2\langle\alpha_{j+1}\rangle \sinh(\phi_G L_G)}{R_G^2 \phi_G J_o\langle\alpha_{j+1}\rangle J_2\langle\alpha_G\rangle \sinh\langle\phi_{j+1} L_{j+1}\rangle}$$

The effect of the leak tube appears in the second term on the right-hand side of Equation (2). The other two terms are, in fact, identical to those in the basic recurrence equation for a tube element derived by Bergh and Tijdeman (1965) (see also Holmes and Lewis 1987a, Equation 1).

It was relatively simple to incorporate the additional term into a BASIC computer program used to compute the response of a series of tubes of various lengths and diameters in previous studies, (Holmes and Lewis 1987a).

COMPARISON OF THEORY AND EXPERIMENT

Figure 3 shows the experimental and calculated response characteristics of a system developed for use with a Honeywell 163 pressure transducer, connected to a pressure tapping with approximately 1 m of tubing. The computer program based on the theory described in the previous section requires the main input tubing up to the leak to have a constant diameter. Thus, for the lines marked 'Theory' in Fig. 3, the pressure tapping was assumed to have the same internal diameter as the main tube, i.e. 1.3 mm. In fact, the diameter of the pressure tapping was 1.0 mm. However, the dimensions of the leak tube, and of the main tubing between the leak and the transducer were modelled accurately. The experimental data were obtained using the calibration equipment described by Holmes and Lewis (1987a).

The slight difference between the main tube geometry in the experiment, and that assumed for the theoretical response calculations, may explain the small differences between the measured and calculated amplitude and phase response curves. However, the agreement is comparable with that achieved previously for closed systems, when tubing lengths and diameters, and transducer characteristics, are accurately modelled (Holmes and Lewis 1986,1987a).

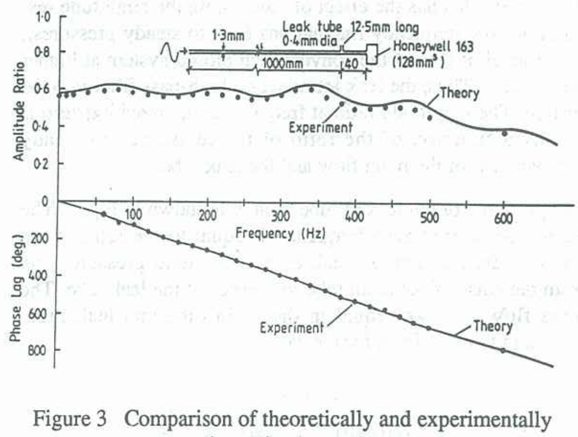

Figure 3 Comparison of theoretically and experimentally determined system responses.

SOME PRACTICAL SYSTEMS

The system shown in Fig. 3 is a practical system developed for use with the Honeywell 163 piezo-resistive pressure sensor with silicon diaphragm. Even though about 1 m of main tubing was used, the system gives an amplitude response ratio within 10% of the zero frequency value up to 400 Hz and within 20% up to 500 Hz. The upper frequency limit achieved exceeds by 100 to 150 Hz that achieved using a closed system with one-quarter of the main tube length (see Holmes and Lewis 1987a, Fig. 18). The system in Fig. 3 appears to be similar to those tested experimentally by Gerstoft and Hansen, and confirms the results obtained by those authors. The main tube internal diameter of 1.3 mm seems to be important to obtain good response characteristics, as inferior results were obtained with larger diameters. The effect of this dimension on the optimum response achieved for a given length is under investigation, and will be reported later.

For many applications, including multi-tap pressure measurements on model buildings in wind engineering studies, a pressure scanning device, such as a 'Scanivalve', is usually required. Figure 4 shows the response of a system with about 1 m of main tube supplying a Type J 'Scanivalve', obtained experimentally. The leak tube has been inserted between the 'Scanivalve' and the externally-mounted Honeywell 163 pressure sensor, so that only one leak tube is required for all the input tubes to the 'Scanivalve'. Although the amplitude ratio has maxima nearly 20% above the zero frequency value, the response from 0 to 300 Hz does not exceed ± 10% limits from the average over this frequency range. This system is being used for commercial wind-tunnel tests on tall building models.

Figure 5 shows a response curve for a system developed with constraints on the main tube length and diameter of 1750 mm and 1.8 mm, respectively. The slight peak in the amplitude response, at about 40 Hz, could not be eliminated, and a rather low value of steady state response was obtained. However, a near-flat amplitude response from 60 to 300 Hz compensated somewhat for these disadvantages.

An important requirement, when using these systems in actual experimental situations, is to ensure that the outlet of the leak tube is exposed to an environment with a negligible level of pressure fluctuations. It is clear, from Fig. 2, that the system will try to average any pressure fluctuations there, with those being measured at the inlet to the main tube. The steady pressure at the outlet to the leak tube should be the same as the reference pressure to which the rear face of the transducer diaphragm is connected.

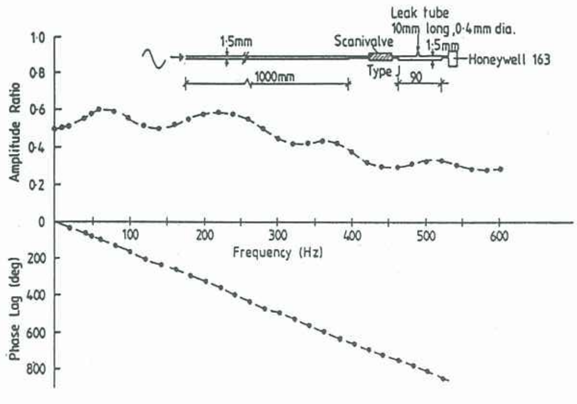

Figure 4 A practical system with Scanivalve, (a) (lines are drawn through experimental points, and are not theoretical curves)

CONCLUSIONS

A re-examination of the leaked-tube pressure measurement system has been carried out, using a theoretical model based on previous work by Bergh and Tijdeman (1965) and Gumley (1983b), together with new experimental measurements. The agreement between theory and experiment was good, and the results confirmed those of Gerstoft and Hansen (1987). Further investigations of the geometrical parameters affecting the response of these systems are being pursued, using the theoretical model.

Some practical measurement systems, based on the leaked-tube principle, have been produced and are being used successfully, for single-point measurements. Near-flat amplitude response characteristics to frequencies much greater than those obtained from closed systems with shorter connecting tubes and restrictors, have been obtained, although the characteristics achieved for systems with a 'Scanivalve' included are not as good as those without one.

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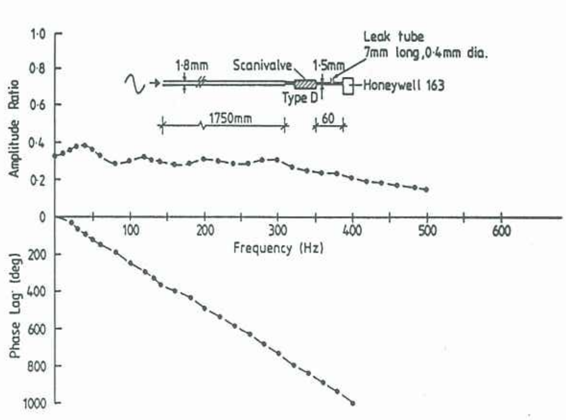

Figure 5 A practical system with 'Scanivalve', (b) (lines are drawn through experimental points, and are not theoretical curves)

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