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A NEW TUBING SYSTEM FOR THE MEASUREMENT OF FLUCTUATING PRESSURES

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Summary

A new technique for the design of pressure tubing systems with lengths up to about 2 m is suggested. The method utilizes a controlled leakage at the transducer end of the tube to avoid resonance in the system. Single tubes as well as systems including manifolds are considered.

For the theoretical verification of the procedure, the electric analogy is applied instead of the direct solution of the fluid dynamic equations of motion used in the conventional design of distortion-free pressure transmission tubes. The electric analogy presented is simpler and gives an easier appreciation of the main parameters affecting the pressure transmission.

The frequency range, as well as the feasible length of the tube, have been considerably improved compared to the characteristics for the usual closed tubing systems. For example, for a tube length of 1 m the transfer function is constant within 1–2% for frequencies less than about 200 Hz and 10% for frequencies less than 350 Hz.

In the authors' opinion the method is superior to the procedures commonly used at wind tunnel laboratories, when mean as well as fluctuating pressures are of importance. However, it should be emphasized that a calibration of the system is necessary, even for mean pressures alone. In this respect the method is more laborious than commonly known procedures.

Nomenclature

A internal area of tube
c speed of sound
c_a acoustic compliancy
C_T acoustic compliancy of the transducer
H transfer function

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i imaginary unit
l tube length
m_a acoustic mass
p pressure
P complex pressure
q flow rate
Q complex flow rate
r_a acoustic resistance
R resistance
U free stream velocity
x coordinate
Z acoustic impedance
Z_L acoustic impedance at the measuring end of the tube
Z_c characteristic impedance of tube

Greek letters
γ propagation factor
ω circular frequency
ρ density of air
ϕ phase

1. Introduction

1.1. Historical background

The first wind tunnel measurements of the pressure distribution on models were made in 1893–94 by the Danish engineer J.O.V. Irminger, Manager of the Copenhagen Gas Works, see ref. 1. The wind tunnel consisted of a rectangular box 40 in. long with a $4\frac{1}{2}\times 9$ in. internal cross-section. The box was inserted in an opening in the side of a 100 ft. high smokestack serving a large number of gas furnaces. The draft of the stack was sufficient to obtain a maximum wind speed in the wind tunnel of 15 m/s. As indicated in Fig. 1, the mean pressures on the model were measured by means of a tubing system connected to a manometer.

Mean pressures on wind tunnel models have been measured extensively ever since Irminger's investigations were carried out. The intense developments in the electronic field in the last two decades have made it possible to measure the pressure fluctuations in excess of the mean pressures. However, it was difficult to design a tubing system with a satisfactory frequency response. So far three different approaches have been undertaken:

(a) Short tubes of lengths up to 10 cm. The short tubes are often impractical or impossible to use in specific investigations.

(b) In order to suppress the resonance in the system dampers are inserted

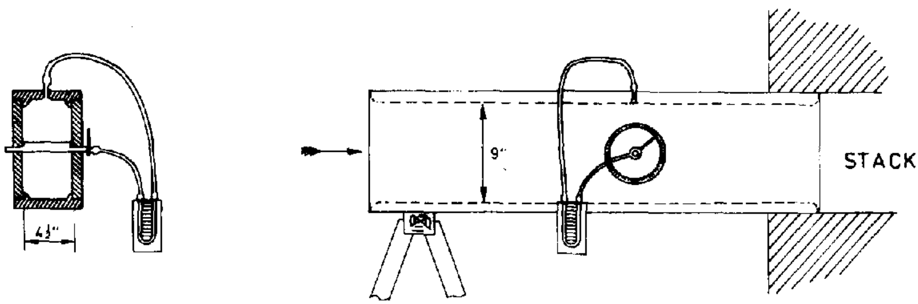

Fig. 1. Wind tunnel measurements of pressures by J.O.V. Irminger in 1893–94.

in the tube. The damper may consist of a small amount of yarn placed near the entrance to the tube, see Durgin [2], or the more usual restrictor as described, e.g., by Surry and Stathopoulos [3]. Typical tube lengths of the restrictor system are about 500 mm and the restrictor is normally located near the centre of the tube. The frequency response of the system is almost flat (within 5%) up to 100 Hz, but at higher frequencies the response is damped out by the tubing system.

(c) As suggested by Irwin et al. [4], a digital correction technique using the known tubing transfer function allows for considerably longer tubes and a higher frequency response to be obtained than is practicable with the tubing-restrictor system. However, due to the extremely large amount of computer calculations involved, this technique is rarely used.

1.2. Required frequency response of pressure transducer–tubing systems

A satisfactory and operational pressure tubing system requires that the transfer function (the ratio between the measured pressure at the transducer and the pressure on the surface of the model) has the following properties:
(a) constant magnitude for all frequencies of interest;
(b) linear phase decay with frequency.

These requirements guarantee a simple and feasible way of computing the pressure on the surface of a model from the recorded pressure. It should be noted that requirement (a) differs from the usual case where the constant magnitude is unity. This opens the way for another method of constructing the tubing system, see Section 1.3. Requirement (b) is mainly of theoretical interest; as long as the magnitude of the transfer function is nearly constant the phase will be essentially linear, see Fig. 7.

Several authors have considered the frequency interval of interest in wind tunnel investigations concerning the peak pressures on models. As pointed out by Eaton and Mayne [5], the Aylesbury Experiment indicated a need for an upper frequency limit of about 10 Hz full scale for roof pressures on a low-rise building. Assuming typical wind velocity and geometric scaling ratios of 1:3

and 1:100, respectively, the frequency range of interest extends up to about 350 Hz. This result is in reasonable agreement with the frequency requirements mentioned by Holmes [6] for low-rise buildings and Durgin [2] for high-rise buildings.

Other scaling ratios change the frequency interval of interest and consequently the requirements of the pressure transducer–tubing system. Assuming a certain full-scale frequency range of interest, the improved characteristics of the new pressure tubing system facilitate the use of a higher wind tunnel speed causing increased pressure levels. This can be of importance if the fluctuating pressures are very small.

The area of a pressure tube in the model corresponds, in full scale, to the area of a roof tile. Thus, for cladding pressures the whole frequency range is of importance.

Due to the lack of spatial correlation at higher frequencies the requirements can be limited to a lower frequency range for intermediate area loads.

1.3. A new pressure tubing system

The new pressure tubing system utilizes a controlled leakage at the transducer end of the tube. It enables the use of long tubes satisfying the abovementioned requirements up to very high frequencies. In the authors' opinion, the method is superior to the procedures commonly used at wind tunnel laboratories, when mean as well as fluctuating pressures are of importance. A calibration of the system is necessary, even for mean pressures alone. In this respect the method is more laborious than commonly used procedures.

2. Theory: the electrical analogy for tubing systems

The theory of sinusoidal oscillations of a fluid in a tubing system has been described by Bergh and Tijdeman [7,8] and further expanded by Gumley [9,10]. Their expressions for the dynamic pressure and flow in the tube have been used by several authors to analyse tubing systems [7–12]. Due to the complicated nature of the Bergh–Tijdeman equations, others prefer to design their tubing systems by empirical methods, see refs. 3, 4 and 6. At present this is the most common approach in order to obtain satisfactory transfer functions as described in Section 1.2.

The behaviour of pressure tubing systems can more easily be understood by using a consistent electric analogy. This electric analogy is commonly used in acoustic theory [13,14], but in wind engineering the surface has just been scratched by Gumley [9,10].

The electric analogy put forward in this paper is simpler than the direct solution of the fluid dynamic equations of motion. Therefore, only the basic behaviour of the response can be explored through this analogy. It can be extended to the same degree of completeness and number of computational

TABLE 1

The equivalence between the pressure system and the electrical system (from ref. 13)

Acoustic system			Electric system		
Quantity	Symbol	Units	Quantity	Symbol	Units
Pressure	p	Pa	Voltage	U	V
Flow	q	m^3/s	Current	I	A
Acoustic impedance	Z	$Pa/(m^3/s)$	Impedance	Z	Ω
Acoustic resistance	r_a	$Pa/(m^3/s)$	Resistance	R	Ω
Acoustic mass	m_a	$Pa\ s/(m^3/s)$	Inductance	L	H
Acoustic compliance	c_a	m^3/Pa	Conductance	C	F

difficulties as the Bergh–Tijdeman equations. However, this does not seem necessary in describing the main features of the system.

The analogy considers pressures as voltages and flow as current, as shown in Table 1.

For sinusoidal oscillations the pressure, p, and the flow rate, q, can be expressed by the complex notation

$$p = P \exp(i\omega t)$$

$$q = Q \exp(i\omega t) \qquad (1)$$

The relation between pressure and flow is equivalent to Ohm's Law

$$P = ZQ \qquad (2)$$

where Z is the complex impedance. The real part of Z represents the resistance r_a, which is independent of the frequency. The imaginary part of Z is a function of the frequency, the acoustic mass and the acoustic compliance.

The resistance, r_a, is proportional to the loss of energy due to friction or a change in flow conditions. The order of magnitude of the resistance can be estimated through the expressions for energy loss in hydraulic engineering. It can be shown that this resistance is inversely proportional to the radius raised to the power of four. The acoustic mass, m_a, depends upon the mass which can oscillate in the system. The compliance, c_a, represents the compliancy of the system. For an ideal tube the acoustic mass and compliancy are given by [13]

$$m_a = \frac{\rho l}{A} \quad \text{and} \quad c_a = \frac{lA}{\rho c^2} \qquad (3)$$

where l and A are the length and the internal area of the tube, respectively, ρ is the density of air and c is the speed of sound (about 330 m/s). In eqn. (3), the compressibility of air is taken into account.

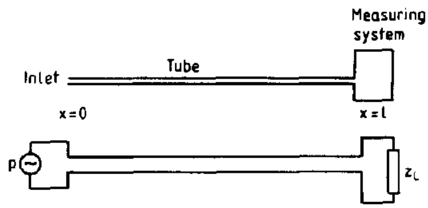

Fig. 2. The tube.

2.1. The impedance of system elements

Changes in the cross section of the tubing system induce a loss of energy. This is, for example, found at the inlet of the tubing system and at the restrictors, and can be modelled by resistance.

The pressure transducer can be modelled as a system of acoustic mass, compliancy and resistances. If the transducer is in parallel with a restrictor, the impedance of the transducer can be treated as infinite (an ideal transducer). If the transducer is in series with a tube, its impedance must be taken into account.

2.2. The impedance of the tube

For the qualitative description of the behaviour of the tube a simple model is chosen. It gives a reasonable agreement with reality, see Section 3.3. The primary assumptions are: compressible air, plane waves in the tube, inextensible walls of the tube and no heat conduction through the walls. The tube has the acoustic resistance r_a, the acoustic mass $m_a = \rho/A$ and the compliancy $c_a = A/\rho c^2$ per unit length (Fig. 2).

The equations of motion of the air in the tube are given by:

(A) The decrease in pressure per unit length of the tube is used for the acceleration of the acoustic mass, m_a, and to pass the resistance, r_a (equation of momentum).

(B) The difference between the incoming and outgoing airflow is used to change the density (conservation of mass).

This implies the following equations, valid for sinusoidal flow

$$\frac{dP}{dx} = -(r_a + i\omega m_a)Q$$
$$\frac{dQ}{dx} = -i\omega c_a P \tag{4}$$

Equations (4) are similar to those for current and voltage in a transmission line. The solution of eqns. (4) can be written as the sum of two linearly independent solutions, which represent progressing waves, running in opposite directions. Thus

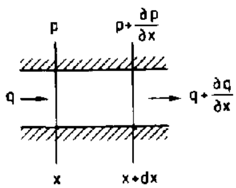

Fig. 3. The pressure tubing system and the electric analogy.

$$P(x)=P_1\exp(-\gamma x)+P_2\exp(\gamma x)$$
$$Q(x)=\frac{P_1}{Z}\exp(-\gamma x)-\frac{P_2}{Z}\exp(\gamma x) \tag{5}$$

where Z is a frequency-dependent impedance and γ the propagation factor. P_1 and P_2 are complex constants determined by the boundary conditions at $x=0$ and $x=l$. Putting these expressions into eqns. (4) implies

$$Z=\sqrt{\frac{r_a+i\omega m_a}{i\omega c_a}} \qquad Re(Z)\geq 0 \tag{6}$$

$$\gamma=\sqrt{i\omega c_a(r_a+i\omega m_a)} \qquad Re(\gamma)\geq 0 \tag{7}$$

For an ideal tube $(r_a=0)$

$$Z_c=Z(r_a=0)=\sqrt{\frac{m_a}{c_a}}=\frac{\rho c}{A} \qquad \gamma=i\omega\sqrt{c_a m_a}=i\omega/c \tag{8}$$

where Z_c is the characteristic impedance of the tube. It can be shown that the impedance of an infinitely long tube is equal to the characteristic impedance.

2.3. Transfer function of a tube

The pressure transducer–tubing system and the electric analogy shown in Fig. 3 are considered. The resistance of the inlet has been neglected, because it has been found to be of minor importance from the experiment.

The transfer function, $H(\omega)$, defined as the ratio between the pressure at the entrance and that at the end of the tube, can be found from eqn. (5) as

$$H(\omega)=\frac{P(x=l)}{P(x=0)}=\frac{2Z_L}{(Z_L+Z)+(Z_L-Z)\exp(-2\gamma l)}\exp(-\gamma l) \tag{9}$$

where

$$Z_L=\frac{P(x=l)}{Q(x=l)}=\frac{P_1\exp(-\gamma l)+P_2\exp(\gamma l)}{P_1\exp(-\gamma l)-P_2\exp(\gamma l)}Z \tag{10}$$

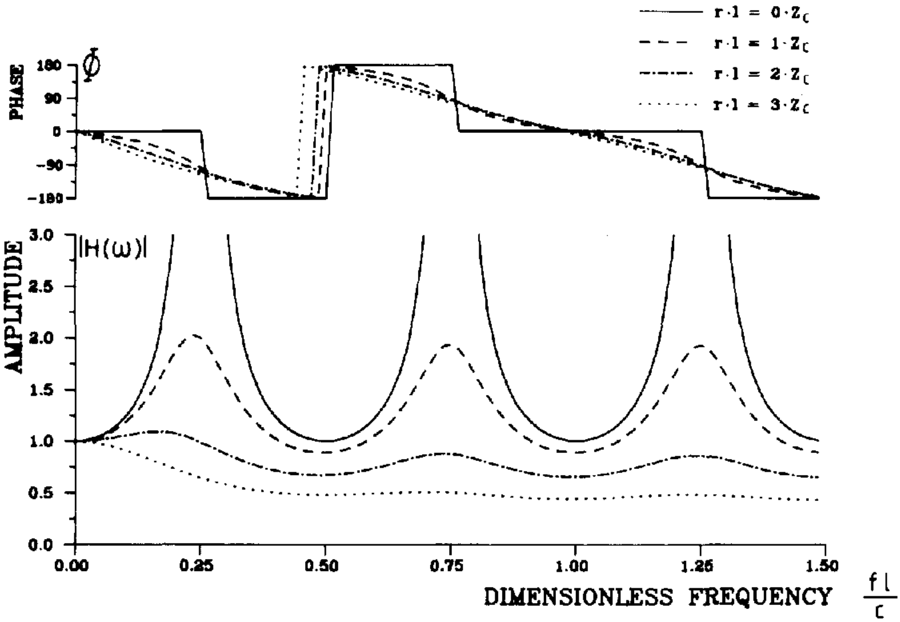

Fig. 4. Computed transfer functions $H(\omega) = |H(\omega)|\exp(i\phi)$. The measuring end is closed ($Z_L = \infty$). The parameters are $l = 1$ m, $A = 1.3$ mm^2, and thus $Z = 3.2 \times 10^8$ Pa/(m/s^3).

is the impedance at the measuring end of the tube. Z and γ are given by eqns. (6) and (7). For convenience the following notation is used

$$H(\omega) = |H(\omega)| \exp(i\phi) \tag{11}$$

As both the impedance Z and the transmission coefficient γ are dependent on the frequency, the magnitude of the transfer function, H, will generally vary in a complicated way.

For a tube closed off at one end, equivalent to an ideal transducer ($Z_L = \infty$), the transfer function, eqn. (9), is shown in Fig. 4 as a function of the resistance in the tube. It is seen that the magnitude of the transfer function varies considerably.

2.4. Transfer function of a usual restrictor-tubing system

The simplicity and accuracy of the electric analogy will be demonstrated by an example.

Consider the tubing system in Fig. 5. From eqn. (3), the acoustic mass and the compliancy per unit length can be established and from eqn. (8) the characteristic impedance is found

$$m_a = \frac{\rho}{A} = 9.6 \times 10^5 \ \ (\text{kg/m}^4)/\text{m}$$

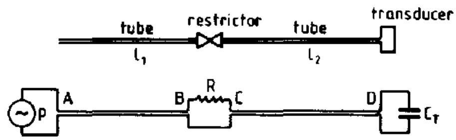

Fig. 5. Usual restrictor-tubing system and its electric analogy. $A=1.3$ mm^2, $l_1=0.25$ m, $l_2=0.35$ m, $R=3\times10^8$ Pa/(m^3/s).

$$c_a=\frac{A}{\rho c^2}=9.6\times10^{-12}\ \text{m}^3/\text{Pa}$$

$$Z_c=\frac{\rho c}{A}=3.2\times10^8\ \text{Pa}/(\text{m}^3/\text{s}) \tag{12}$$

The resistance of the tube varies in a complicated way with the tube characteristics. However, the resistance at lower frequencies can be measured using the method given in Section 2.7. For the tube used in this experiment the resistance per unit length was

$$r_a=3.3\times10^8\ [\text{Pa}/(\text{m}^3/\text{s})]/\text{m} \tag{13}$$

The impedance Z and the propagation factor γ of the tube can now be established as a function of frequency (eqns. 6 and 7). The volume of the transducer ($V\approx100$ mm^3) can be treated as an acoustic compliancy with the magnitude

$$C_T=\frac{V}{\rho c^2}=7.4\times10^{-13}\ \text{m}^3/\text{Pa} \tag{14}$$

The relation between the inlet pressure and the transducer pressure can be found by usual electrical network theory and eqns. (3), (5) and (6). This is easiest done by starting at the transducer end of the tube. The transfer function is found to be

$$H^{-1}(\omega)=\frac{0.5}{1+K}\times\left\{e^{-\gamma(l_2-l_1)}\left[2K\,e^{2\gamma l_2}+\frac{R}{Z}(K\,e^{2\gamma l_2}-1)\right]+e^{-\gamma(l_2+l_1)}\left[2+\frac{R}{Z}(K\,e^{2\gamma l_2}-1)\right]\right\} \tag{15}$$

where

$$K=\frac{(1/i\omega C_T)+Z}{(1/i\omega C_T)-Z} \tag{16}$$

The transfer function is depicted in Fig. 6. Comparison with Fig. 10 reveals that the analogy explains the main features of the system. Compared to the

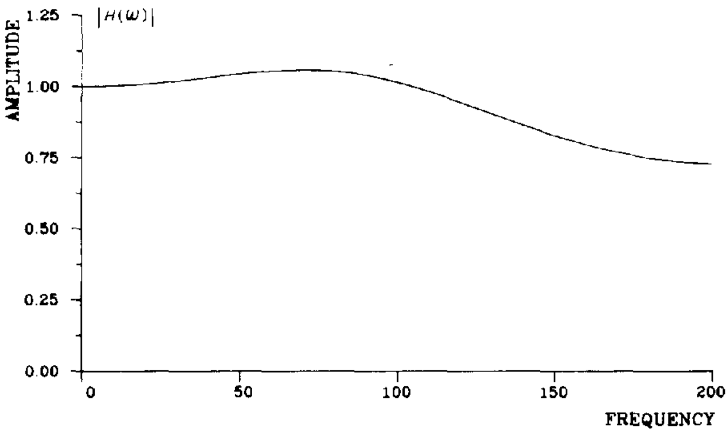

Fig. 6. Calculated transfer function for the usual restrictor–tubing system in Fig. 5.

calculated transfer function, the measured one has lower values at higher frequencies. This is due to an underestimate of the resistance at higher frequencies.

2.5. Matching

When the impedance at the measuring end of the tube, Z_L, is chosen to be equal to the characteristic impedance, Z_c, the transfer function (9) is nearly constant with frequency as computed in Fig. 7. This choice of Z_L is termed Impedance Matching.

Physically, the matching can be explained by the amplitude of the incoming and reflected wave. From eqn. (10) it is seen that a closed end ($Z_L = \infty$) causes a symmetric reflection, whereas an open end ($Z_L = 0$) causes an antisymmetric reflection. For an ideal tube which is neither closed nor open, the opening is such that the reflected wave will be cancelled, in which case matching occurs.

For an ideal tube coupled with a matching resistance, the magnitude of the transfer function will be unity (Fig. 7). For a non-ideal tube the resistance in the tube will cause a minor reflected wave. Thus, the transfer function will vary with frequency (Fig. 7). For high and low frequencies the following amplitudes can be found.

High frequencies

For matching and high frequencies, it is found from eqn. (9) and a Taylor expansion of eqns. (6) and (7), that the magnitude of the transfer function will approach the constant value

$$H(\omega) = \exp\left(-\frac{r_a l}{2Z_c}\right) \tag{17}$$

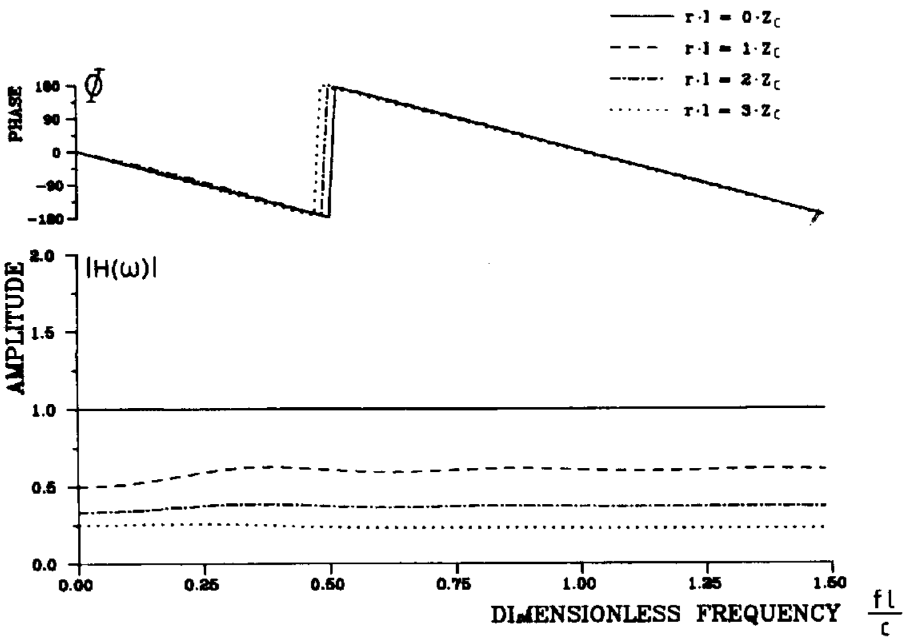

Fig. 7. Computed transfer function $H(\omega) = |H(\omega)|\exp(i\phi)$ at impedance matching $(Z_L = Z_c)$. The parameters are $l = 1$ m, $A = 1.3$ mm^2 and thus $Z_c = 3.2 \times 10^8$ Pa/(m/s^3).

Low frequencies

For matching and low frequencies, the magnitude of the transfer function can be calculated from the resistance $r_L = Re(Z_L)$ and the resistance $r_a l$ in the tube

$$H_s = |H(\omega = 0)| = \frac{r_L}{(r_a l) + r_L} \tag{18}$$

For long tubes (greater than 2–3 m) the difference between the high-frequency value (17) and the low-frequency value (18) is too large and it becomes impossible to obtain a constant transfer function.

2.6. *The adjustment of the impedance* Z_L

The adjustment of the impedance Z_L can only be done by connecting a resistance parallel to the transducer with the magnitude (assuming the transducer has an infinite impedance)

$$r_L = Z_c = \frac{\rho c}{A} \tag{19}$$

This can be accomplished by connecting a restrictor at the end of the tube to the reference pressure, which will work as a shunt, letting some of the air leak out past the transducer. The resistance cannot be obtained by connecting a new tube or a volume parallel to the transducer, as these would introduce an imaginary part of the impedance due to their acoustic mass or compliance.

As eqn. (19) is independent of the tube length, the same restrictor can be used for different tube lengths. This means a considerable saving in time compared with designing a usual restrictor–tubing system.

2.7. Additional considerations

As air is leaking out through the shunt-restrictor, the pressure measured by the transducer will not equal the pressure at the surface of the model. Nevertheless, it can be obtained by dividing the measured pressure with the value H_s formula (18). H_s can be obtained in two ways.

(a) Dynamic method: the transfer function is found by connecting a white noise vibrator to the entrance of the tubing system. The value at low frequencies equals H_s.

(b) Static method: a continuous air supply keeps the pressure at the entrance constant. The ratio between the transducer pressure and the entrance pressure is the value H_s.

Both methods were used, and it was found that the agreement was within 1%. Hence two methods for calibrating the system are possible. The constant flow rate through the tube system is

$$q=\frac{p}{r_L+r_a l} \tag{20}$$

where p is the pressure at the surface of the model. The resistance of the restrictor, r_L, is found from eqn. (19) to be 3×10^8 Pa/(m^3/s). Neglecting the resistance in the tube, $r_a=0$, and assuming $p=300$ Pa (maximum) implies $q=10^{-6}$ m^3/s. This is equivalent to a Reynolds number of about 100 indicating a laminar flow in the tube (A is about 1 mm^2).

Pressure distortion due to leakage

The leakage at the transducer end of the tube and the pressure difference between the tube ends causes a small airflow through the tube. This flow will disturb the main flow past the model and consequently affect the measured pressure. The pressure at a specific location on the model is influenced in two ways:

(A) By the induced airflow in the corresponding tube.

(B) By the induced airflows at adjoining taps. The same phenomenon is present in the manifold system, where the airflow in the tubes can be much larger and yet insignificant.

Since the flow rate in the tubes is small, distortion effects are not likely to be significant, as confirmed by the tests described in Section 4.2.

Item (A) has been examined by Tijdeman and Bergh [8]. They found that the largest additional pressure, Δp, due to the speed, V, of the air in the tube is given by

$$p = K\rho UV \qquad K \approx 0.9 \tag{21}$$

U is the free stream velocity. Using eqns. (19) and (20) gives

$$\Delta p/p = kU/c \qquad k \approx 0.4\text{–}0.9 \tag{22}$$

where p is the pressure at the surface of the model and c is the speed of sound. The maximum error due to this effect is about 3% which is within the uncertainty range.

3. Measurement of the tubing system transfer function

This section describes the testing of the new tubing system with regard to fluctuating pressures.

3.1. Calibration procedure

A Brüel and Kjær high-pressure microphone calibrator (type 4221) is used for obtaining the transfer function of the tubing system. The generating signal to the microphone, including the pressure fluctuations, is chosen to be white noise.

As seen from Fig. 8, the transducer will only give a constant value for low frequencies. Therefore, the signal from the generator is used as a reference pressure at high frequencies, where the resonance of the transducer becomes significant. The pressure at the end of the tubing system is measured by another transducer. The two signals are analysed by a Nicolet Scientific Corporation 660A dual-channel FFT analyser enabling the determination of the transfer function of the tubing system.

To find the characteristic impedance of the tube, the resistance in one restrictor was varied until a nearly constant transfer function was obtained. For this value of the resistance, impedance matching occurs. The resistance can now be used for all tube lengths.

3.2. Pressure transducers

The performance of the new pressure tubing system has been tested with two types of transducer:

(a) The capacitive, Setra 237 type transducer. At present, this is probably the most widely used instrument in wind engineering. It can be used without any additional amplification and it fits the Scanivalve pressure scanning switch.

(b) Some newly developed, low-cost piezoresistive silicon pressure transducers manufactured by Siemens were found convenient for wind tunnel use. They are capable of measuring the response within approximately the same frequency range as practicable with the Setra transducer, see Fig. 8. The signal

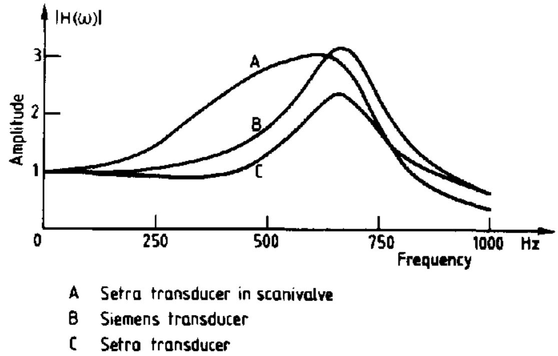

Fig. 8. The frequency response of transducers.

from the Siemens transducers was amplified by standard signal conditioners from the Institute.

The resistance can be varied by changing the internal diameter of the tube by for example bending the restrictor. This is a very sensitive method as the resistance varies with the radius raised to the power of minus four.

3.3. Test results

The theory put forward in Section 2 has been used to develop constant-value transfer functions. The test results indicate that the transfer functions are independent of the pressure levels within ± 300 Pa.

Single tubes

Figures 9 and 10 reveal the efficiency of the new method. From the figures it can be concluded that the phase of the transfer function always varies linearly with frequency. The system has a constant transfer function up to about 200 Hz for tubes less than 2 m in length (Figs . 9 and 10). When the length of the tube is 1 m the transfer function is constant within 1–2% for frequencies less than 200 Hz and 10% for frequencies below 350 Hz. However, it should be noted that for tubes longer than 3 m the method will not work, as the "dynamic" value of the transfer function is very quickly approached (see Section 2.5). For shorter tubes, the decay towards the high-frequency asymptote can be delayed by inserting a tube between the shunt-restrictor and the transducer, see Fig. 9.

For comparison, the transfer function of a commonly used 60 cm long tubing–restrictor system is included in Fig. 10. The transfer function for this system starts to decay at frequencies above approximately 50 Hz. It should be emphasized that the resistance of the restrictor in this system is different from the magnitude of the shunt-restrictor.

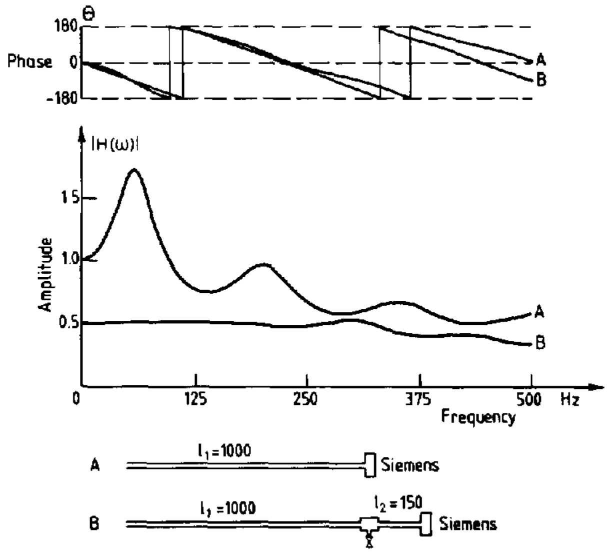

Fig. 9. The frequency response of a 1000 mm long tube with or without shunt.

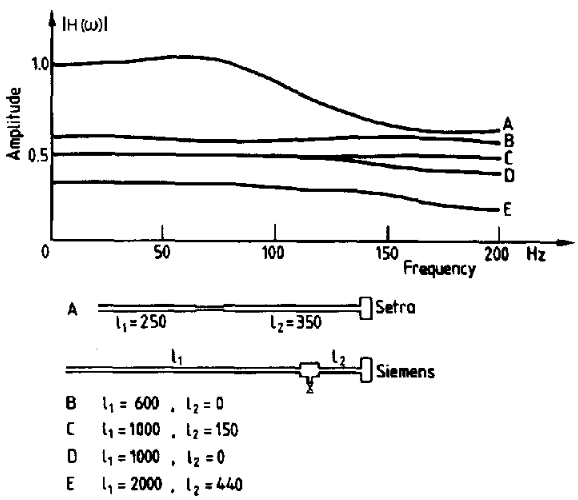

Fig. 10. The frequency response of tubes of length 600, 1000 and 2000 mm. The response of a "standard restrictor system" is included. The restrictor in this system has a resistance different from the resistance of the shunt restrictor.

Manifold system

In a measuring system with a manifold (six inlets) the transfer function decays above 100 Hz (curve A, Fig. 11) when the transducer is located close to the shunt. This behaviour can be improved by connecting a tube between the shunt and the transducer (curve B, Fig. 11). The Scanivalve system has

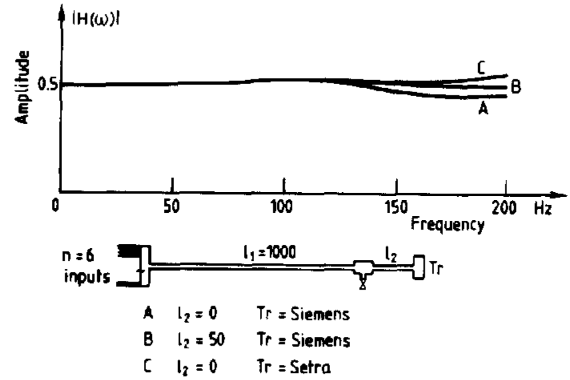

Fig. 11. The frequency response of the manifold-tube-shunt system.

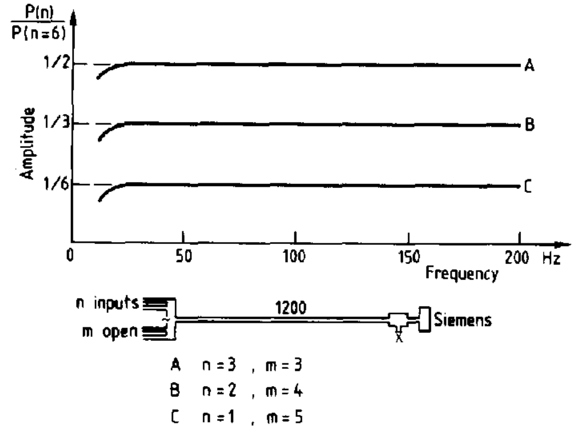

Fig. 12. The efficiency of the manifold. Some of the input channels are disconnected from the vibrator. The signal will be an average of the m open tubes and the n connected to the vibrator.

the same effect (curve C). As seen from Fig. 12, the averaging by the manifold is very accurate.

For low frequencies the microphone cannot give a constant signal when air is leaking out at the open ends of the manifold. This explains the inaccuracy at low frequencies (Fig. 12).

3.4. Comments on the impedance-matched system

The resistance of a restrictor can be changed by bending it. In this way, the resistance causing the optimum transfer function was obtained. The resistance of the restrictor is now given by eqn. (19).

Additional restrictors can easily be produced by varying the resistance until the static value of the transfer function for this system equals H_s (eqn. 18).

The restrictor can also be mass-produced. Just as for usual restrictor systems, see Holmes and Lewis [12], it requires careful construction in order to

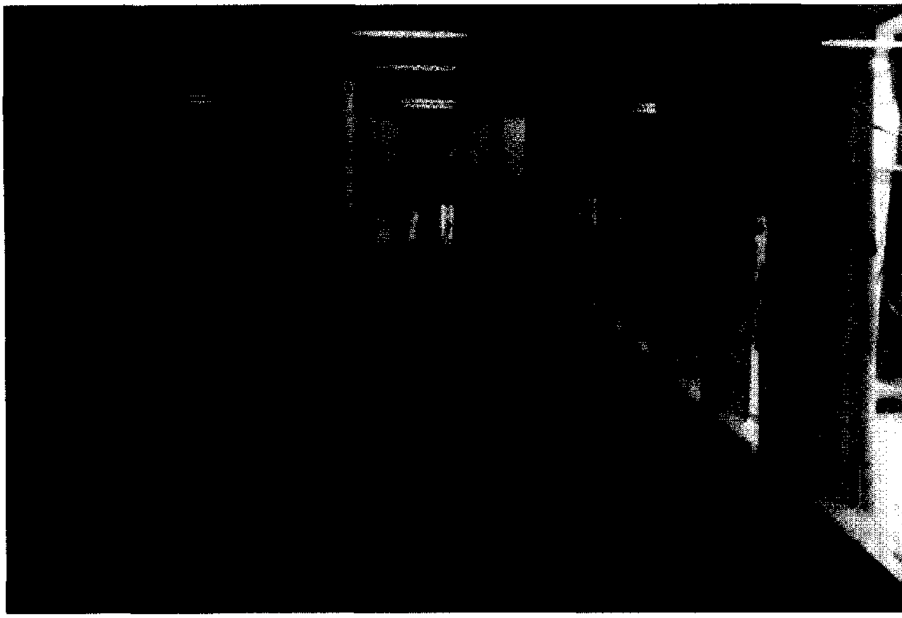

Fig. 13. The triangular model situated in the wind tunnel.

assure a constant and reproducible transfer function. The resistance can be varied by varying the internal diameter and the length of the restrictor.

4. Wind tunnel measurements

In order to prove that the new tubing system is also suitable for the measurement of mean pressures it has been tested in the boundary layer wind tunnel at the Danish Maritime Institute. Mean values of the pressures were determined by means of the new system as well as by the commonly used closed tubes.

4.1. The wind tunnel

The wind tunnel has been described in detail by Hansen and Sørensen [15].

The boundary layer wind tunnel has a working section of principal dimensions: length 20.8 m, width 2.6 m and height 1.8 m (adjustable from 1.8 to 2.3 m). The fan is positioned in the downstream end, which means that the static pressure in the working section is below atmospheric pressure. An airtight box beneath the tunnel floor at the downstream positioned turntable ensures that approximately the same static pressure is available at the transducer location just below the wind tunnel floor. However, a small but constant difference between the static pressure in the tunnel and that at the transducer location was observed. This difference was measured by a separate transducer to facil-

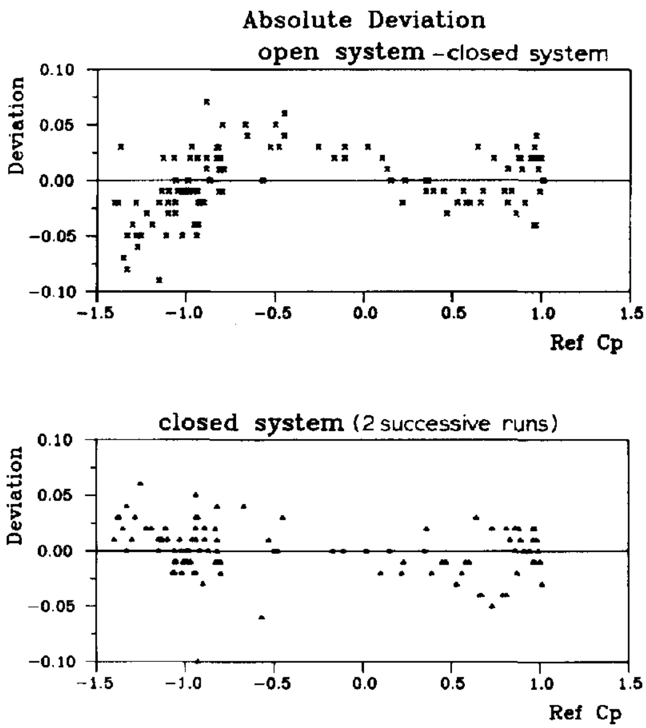

Fig. 14. The absolute deviation of mean pressure coefficients. Wind velocity about 20 m/s.

itate a correction of the pressures determined by the open tubing system. A correction is not necessary when the closed system is in use.

4.2. The experimental set-up and test results

A 1.20 m high, equilateral triangular model was used for testing. The pressures at ten taps located at a height of 40 cm were measured for different wind directions by means of the newly designed system and a commonly closed system. The distance between the ten taps was approximately 3–5 mm.

The standard Scanivalve system equipped with a Setra 237 transducer was used for the pressure measurements. By using only one transducer, the uncertainties inherent in the comparison were kept to a minimum. The model situated in the wind tunnel is shown in Fig. 13.

Figure 14 shows the absolute deviation between the mean pressures measured by the newly designed open system and those from the commonly used closed system. For comparison, the absolute difference between two successive runs with the closed system is included.

The new design is as precise as the commonly used closed system in measuring mean pressures. The differences are negligible compared with the uncertainties inherent in measurements in wind tunnels, as found in the Aylesbury Experiment, see ref. 16.

5. Conclusion

The proposed technique, utilizing a controlled leakage at the transducer end of the tube, has been tested and verified for tube lengths up to 2 m.

A theoretical model of the pressure fluctuations has been developed from the electric analogy. This model strongly supports the experimental results.

The method seems to be superior to the procedures commonly in use at wind tunnel laboratories, when both mean and fluctuating pressures are of importance.

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