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Scaling methods for wind tunnel modelling of building internal pressures induced through openings

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Abstract. Appropriate scaling methods for wind tunnel modelling of building internal pressures induced through a dominant opening were investigated. In particular, model cavity volume distortion and geometric scaling of the opening details were studied. It was found that while model volume distortion may be used to scale down buildings for wind tunnel studies on internal pressure, the implementation of the added volume must be done with care so as not to create two cavity resonance systems. Incorrect scaling of opening details was also found to generate incorrect internal pressure characteristics. Furthermore, the effective air slug or jet was found to be longer when the opening was near a floor or sidewall as evidenced by somewhat lower Helmholtz frequencies. It is also shown that tangential flow excitation of Helmholtz resonance for off-centre openings in normal flow is also possible.

Keywords: scaling; volume distortion; internal pressure; Helmholtz resonance.

1. Introduction

It is well known that building internal pressure induced through an opening can have a significant impact on the safety of a building. When combined with external pressure, the internal pressure generated through a windward wall opening for example, such as through a broken window, could almost double the upward lift force on the roof. Over the last three decades, several writers including Holmes (1980), Liu and Saathoff (1981), Stathopoulos and Luchian (1989), Vickery and Bloxham (1992), Vickery (1994), Sharma and Richards (1997a, b, 2003), Oh *et al.* (2007) and Ginger *et al.* (2008) amongst others, have investigated different aspects of this problem.

Whilst most studies on internal pressure in the past have involved model-scale wind tunnel testing, an issue of much importance to scaled model tests highlighted for the first time by Holmes (1980), has largely remained ignored. Holmes showed that if the wind tunnel test velocity was different to the full-scale velocity, then the correct relative position of the Helmholtz resonance frequency in the scaled turbulence spectrum would not be maintained. This would lead to internal pressure measurements that would incorrectly represent the full scale characteristics. Holmes argued that in order to rectify this problem, the building internal cavity volume used at model-scale should be distorted by a factor equalling the square of the ratio of the full-scale to model-scale velocities.

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This matter has been recently discussed again in Holmes (2006).

Since the frequency response characteristics of internal pressure induced through dominant openings is a function of the opening area as well as its thickness (depth), it is presently also argued that large differences in data presented by various authors in the past could also be attributed to the inattention to scaling of the opening details correctly.

This paper firstly seeks to address these issues, and in particular attempts to show the differences in characteristics of internal pressure obtained in model-scale tests with and without volume distortion. The manner in which volume distortion is implemented together with the effects of not scaling the opening details correctly is also investigated. The ill defined parameters of the internal pressure equation, namely the opening loss and inertia coefficients are studied as well.

2. Governing equation

Holmes (1980) used an analogy based on the Helmholtz acoustic resonator to derive for the first time, a second-order non-linear ordinary differential equation

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + \frac{1}{C_d^2}\frac{\rho\forall_o^2 q}{2n^2A_o^2P_a^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \omega_H = 2\pi f_H = \sqrt{\frac{nA_oP_a}{\rho l_e\forall_o}} \tag{1}$$

that governs the dynamics of internal pressure in a building with a dominant opening. In this model, as shown in Fig. 1(a), the oscillatory airflow through the opening is modelled as an air slug of area A_o and length $l_e = \sqrt{(\pi A_o/4)}$ (i.e., of inertia $= \rho\ A_o\ l_e$) that oscillates at the opening, acting

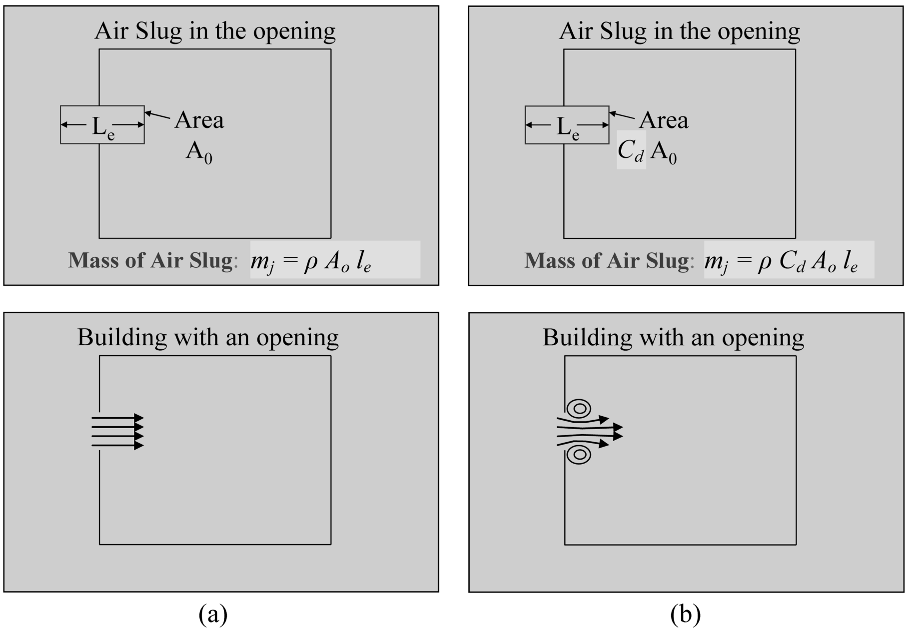


Fig. 1 (a) Holmes (1980) air slug model and un-contracted flow assumption and (b) Liu and Saathoff (1981) contracted air jet model against an air spring consisting of the cavity air. In the equation, A_o = area of the opening, $\forall_o$ = building cavity volume, C_d = opening discharge coefficient, ρ = air density, P_a = ambient pressure, and n = a polytropic exponent. Internal and external pressures are represented by the internal and external pressure coefficients $C_{pi} = p_i / q$ and $C_{pe} = p_e / q$ respectively, where $q = ½\ \rho\ U_h^2$ = reference dynamic pressure, U_h = ridge-height velocity; and f_H = the Helmholtz resonance frequency of the building cavity.

Using numerical solutions to Eq. (1) and parallel experimental testing at model scale, Holmes (1980) showed that wind turbulence could excite the building cavity through the opening causing Helmholtz resonance to occur. This is manifested as intense oscillations in internal pressure about the Helmholtz resonance frequency, as evidenced by resonant peaks in internal pressure spectra. In order to match the Helmholtz frequency as well as the damping (i.e., magnitude of resonant peak) predicted by Eq. (1) to the experimental measurements, Holmes (1980) used a polytropic exponent n = 1.2 and a discharge coefficient C_d = 0.15. Holmes further showed that in order to maintain the correct relative position of the Helmholtz resonance frequency in the wind turbulence spectrum at model-scale, either the model-scale velocity in the wind tunnel needed to match the full-scale velocity, or the model cavity volume needed to be distorted by a factor equalling the square of the ratio of the full-scale to model-scale velocities.

Liu and Saathoff (1981) used the unsteady Bernoulli equation to arrive at an equation very similar to that of Holmes (1980)

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + \frac{1}{C_d^2}\frac{\rho\forall_o^2 q}{2\gamma^2 A_o^2 P_a^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \omega_H = 2\pi f_H = \sqrt{\frac{\gamma C_d A_o P_a}{\rho l_e \forall_o}} \tag{2}$$

The flow through the opening was assumed to be similar to flow through an orifice and that it formed a vena-contracta as shown in Fig. 1(b), hence their model incorporates a discharge coefficient in the inertia term. This implies the cross-sectional area of the air slug assumed in Holmes (1980) resonator model equalled $C_d\ A_o$ instead of A_o. Consequently this appears in the definition of the Helmholtz frequency. The definition of the effective air jet or slug length $l_e = \sqrt{(\pi A_o/4)}$ is the same as that of Holmes (1980), meaning that the inertia of the air jet is $\rho\ C_d\ A_o\ l_e$ as compared with $\rho\ A_o\ l_e$ assumed by Holmes (1980). Furthermore, these writers assumed that the contractions and expansions in the building cavity were fairly rapid and would therefore be isentropic, meaning that the polytropic exponent n in the Holmes (1980) equation should really equal the specific heat ratio γ = 1.4 for air. Later, Liu and Rhee (1986) studied the characteristics of internal pressure at model-scale in a wind tunnel and found that in order to match the measured Helmholtz frequencies, the discharge coefficient should take an average value C_d = 0.88. The damping term was however not examined.

Using the unsteady orifice flow equation with a loss term quantified using an opening loss coefficient C_L, Vickery and Bloxham (1992) derived a governing equation for internal pressure very similar to Eqs. (1) and (2)

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + C_L\frac{\rho\forall_o^2 q}{2\gamma^2 A_o^2 P_a^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \omega_H = 2\pi f_H = \sqrt{\frac{\gamma A_o P_a}{\rho l_e \forall_o}} \tag{3}$$

It was argued that since the orifice flow was highly unsteady, it was not likely to form a vena-contracta, and that a loss coefficient was a more appropriate manner of quantifying losses through the opening which could vary in geometry. Therefore, Eq. (3) does not contain a discharge coefficient, however it contains a loss coefficient C_L in the damping term instead of $1/C_d^2$ that appears in Eqs. (1) and (2). Furthermore, the effective length of the air-slug (or air jet) was determined using an inertia coefficient C_I such that $l_e = C_I\sqrt{A_o}$. Then, $C_I = \sqrt{(\pi/4)}$ was used making $l_e = \sqrt{(\pi A_o/4)}$ the same as those used by Holmes (1980) and Liu and Saathoff (1981). It was also argued that an orifice loss coefficient $C_L = 2.86$ for steady flow yields acceptable results when the response predicted by Eq. (3) was compared with model-scale measurements in the wind tunnel.

Computational fluid dynamics (CFD) modeling technique was applied for the first time by Sharma and Richards (1997a, b) to study the transient response of building pressure, who using parallel model-scale experimental measurements, argued that the governing equation for internal pressure should take the following form

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + C_L\frac{\rho\forall_o^2 q}{2\gamma^2 A_o^2 P_a^2}|\dot{C}_{pi}|\dot{C}_{pi} + K\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \omega_H = 2\pi f_H = \sqrt{\frac{\gamma C_d A_o P_a}{\rho l_e \forall_o}} \tag{4}$$

CFD flow visualisation was used to show that flow separation and a contracted region was indeed formed past the opening, and therefore it was appropriate to include the discharge coefficient C_d in the inertia term. Furthermore, the decay rate of the transient oscillations in internal pressure revealed that the losses in the system consisted of an additional linear damping component, which was represented by the $K\dot{C}_{pi}$ term in Eq. (4). This was believed to arise from viscous shear stresses around the opening and were shown to be only important at model-scale (Sharma 1996) unless the opening contained a significant neck. The constant K can be quantified from a knowledge of the velocity profile across the plane of the opening. In addition, the effective air jet length l_e was quantified using $l_e = l_o + C_I\sqrt{A_o}$ in which l_o = thickness of the opening was incorporated as in the studies of Stathopoulos and Luchian (1989), and experimental measurements suggested that C_I ranged between 0.66 to 0.98 depending on the location of the opening (Sharma 1996, Sharma and Richards 1997b). It was also shown that the loss coefficient could range between 1.2 and 2.8, and that the discharge coefficient should be C_d = 0.6 for a thin orifice type of opening (when $l_o/d_o \ll 1$); or C_d = 1.0 for a long opening (when $l_o/d_o \approx 1$ or > 1).

In spite of the significance of linear damping at model-scale, the difficulty in trying to estimate its magnitude means that it is practical to lump all the damping effects into an effective loss coefficient C_L and represent all the losses with the non-linear damping term. It is worth noting that even if pipe friction type loss could be assumed for long openings, the flow would hardly ever be fully developed, and therefore assuming a Darcy friction factor formulation would be erroneous. Furthermore, the loss coefficient is also sensitive to the details of the opening, which is not always easy to determine. It therefore remains as one of two ill-defined parameters of the problem. Hence, the following form of the governing equation may be used at both full and model scales

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + C_L\frac{\rho\forall_o^2 q}{2\gamma^2 A_o^2 P_a^2}|\dot{C}_{pi}|\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \omega_H = 2\pi f_H = \sqrt{\frac{\gamma C_d A_o P_a}{\rho l_e \forall_o}} \tag{5}$$

The other poorly defined parameter is the effective air jet length l_e. Some guidance for this can be obtained from the acoustics literature, see for example Kinsler *et al.* (2000), however the building situation for the most part can be a lot different to the Helmholtz resonators studied in acoustics. The proper determination of the effective length therefore requires further investigation at the present time.

3. Scaling

In order to determine the correct scaling methods for internal pressure studies in the wind tunnel, Eq. (5) is first non-dimensionalised and presented in a form

$$\frac{1}{\omega_H^2}\ddot{C}_{pi} + \frac{2}{\omega_H}\left(\frac{C_L M_a^2}{8M_r\omega_H}\left|\dot{C}_{pi}\right|\right)\dot{C}_{pi} + C_{pi} = C_{pe} \qquad \frac{\omega_H}{\omega_e} = \frac{f_H}{f_e} = \sqrt{M_r} \tag{6}$$

that reveals the importance of two non-dimensional parameters to the internal pressure problem, namely the Mach number $M_a = U_h / V_s$ = reference speed / speed of sound, and the inertia ratio $M_r = \rho\, C_d\, A_o\, l_e / \rho\, \forall_o$ = mass of oscillatory air jet / mass of air in building cavity. In Eq. (6)

$$\omega_e = 2\pi f_e = \frac{V_s}{l_e} \quad \text{and} \quad \tau_e = \frac{1}{f_e} \tag{7}$$

which represents the time taken for fluctuations in external pressure to be transmitted (at the speed of sound) to the inside of the building through the opening.

Even though the internal pressure system is non-linear, an equivalent linear damping ratio for the internal pressure system can now be identified from Eq. (6), and which is given by

$$\varsigma = \frac{C_L M_a^2}{8M_r\omega_H}\left|\dot{C}_{pi}\right| \tag{8}$$

Since Vickery and Bloxham (1992) have postulated that $\left|\dot{C}_{pi}\right|$ is proportional to $\omega_H C_{pi(\mathrm{RMS})}$, and as the objective of wind tunnel modelling is to maintain $C_{pi(\mathrm{RMS})}$ the same at model scale (MS) and full scale (FS), then to maintain similarity in damping between model and full scale, it is required that

$$\left(\frac{C_L M_a^2}{M_r}\right)_{MS} = \left(\frac{C_L M_a^2}{M_r}\right)_{FS} \tag{9}$$

Geometric scaling is given by a length scale factor $SF = h_{FS} / h_{MS}$ = the ratio of full scale building height h_{FS} to model height h_{MS}. Similarly, the velocity scale factor $VF = U_{FS} / U_{MS}$ is the ratio of full scale velocity U_{FS} to model scale velocity U_{MS}. Boundary layer scaling means that the frequencies in the turbulence spectrum scale to a frequency scaling factor $FF = f_{FS} / f_{MS} = VF / SF$. For the model, the areas scale to SF^2, while the volume to SF^3. If all geometrical details are scaled accurately, the Helmholtz resonance frequency scales as $f_{H,FS} / f_{H,MS} = 1 / SF$. In order that the relative position of the Helmholtz frequency in the turbulence spectrum is retained at model scale, it must however scale to the $FF = VF / SF$. This is only possible if $VF = 1$ i.e., when the wind tunnel and full scale velocities are matched, which is not usually possible. Typically, the model scale velocities are a lot smaller than the full scale velocities, and a remedy to the problem is to increase the model cavity volume by a factor equal to VF^2 such that

$$\forall_{o,\,MS} = \frac{\forall_{o,\,FS}}{SF^3} \times VF^2 \tag{10}$$

which was first suggested by Holmes (1980, 2006). This approach not only maintains the relative position of f_H in the turbulence spectrum at model scale, but it leads to similarity in damping as well if the loss coefficient at model scale is similar to that at full scale - see Eq. (9). As an example, if SF = 60 and U_{MS} = 6 m/s, then for this test to represent internal pressure characteristics at U_{FS} = 30 m/s, VF = 30/6 = 5 means that the model cavity volume has to be increased by a factor of VF^2 = 5^2 = 25. This might present challenges especially if the space under the test section in the wind tunnel is limited.

4. Experimental details

A 1:60 scale model of the Texas Tech University (TTU) test building (Levitan and Mehta 1992a, b) was tested in the de Bray boundary layer wind tunnel at the University of Auckland. A rural (Terrain Category 2 in AS/NZS1170.2 – Standards Australia/Standards New Zealand 2002) boundary-layer simulation was developed, and the characteristics of this are compared with generally-accepted profiles of velocity and turbulence intensity in Figs. 2 and 3. The mean velocity profile was consistent with the accepted profile to a full scale equivalent height of about 16 m, being four times the full scale height of the TTU test building. On the other hand, the turbulence levels were somewhat smaller than the theoretical levels.

The experimental procedure was initially validated through external pressure measurements against benchmarking data available in the literature. The pressures were sensed using Honeywell XSCL04DC differential pressure transducers with short restricted tubing having a flat frequency response up to 200 Hz.

The overall external dimensions of the nearly rectangular 1:60 scale model of the TTU building were 230 mm long × 153 mm wide × 67 mm high, and its internal dimensions were 218 mm long × 141 mm wide × 61 mm high. This meant that the internal model cavity volume was 1.875 × 10^{-3}

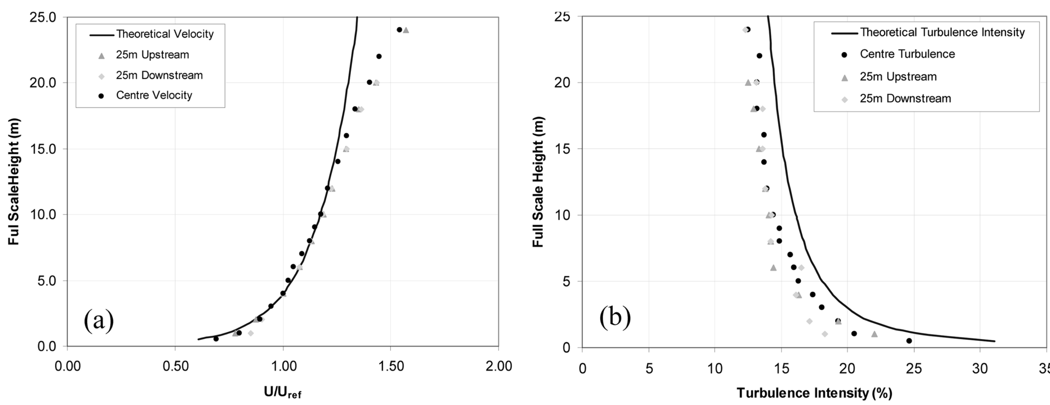


Fig. 2 (a) Normalised velocity profile and (b) turbulence profile in the wind tunnel

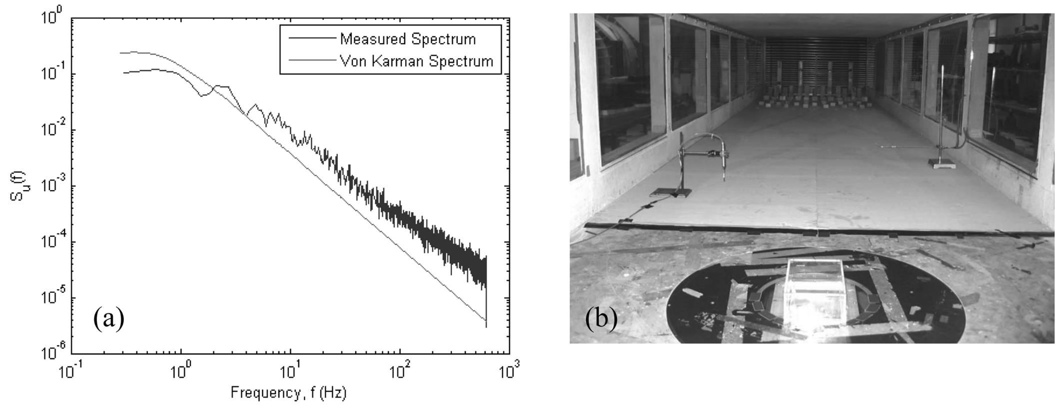


Fig. 3 (a) Longitudinal turbulence spectrum S_u(f) [m^2/s] at full scale equivalent 10 m height in the (b) wind tunnel

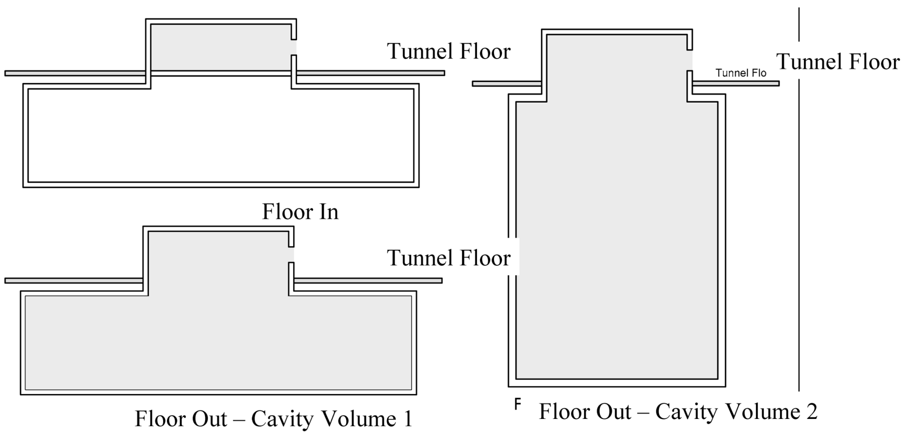


Fig. 4 Added cavities to effect volume distortion

m^3. As discussed in section 3, to maintain Strouhal number similarity when the model scale velocity is not matched to full scale, the model cavity volume has to be increased according to Eq. (10). As the wind tunnel tests were conducted at an equivalent 10 m height wind speed of 6 m/s, then for the results to correctly represent full scale condition at a stormy wind speed of 30 m/s (VF = 30/6 = 5), meant that the model cavity volume had to be increased by a factor of $VF^2 = 5^2 = 25$, such that the total cavity volume was $25 \times 1.875 \times 10^{-3}$ m^3 = 46.875×10^{-3} m^3. As there was sufficient space underneath the test section, a supplementary cavity was able to be added. In order to investigate the influence of the nature of additional cavity to effect volume distortion, two types of cavities were tested. As illustrated in Fig. 4, the first was a fairly shallow but wide rectangular box underneath the model, whilst the second was a deep cavity having a rectangular cross section of similar dimensions to the floor of the model.

A number of 25 mm square openings representing 1.5 m square windows at full scale, at a number of locations as shown in Fig. 5, and two different opening thicknesses, 6 mm and 2 mm (i.e., 360 mm and 120 mm at full scale), were investigated in order to examine the influence on loss and inertia coefficients, and on the characteristics of internal pressure.

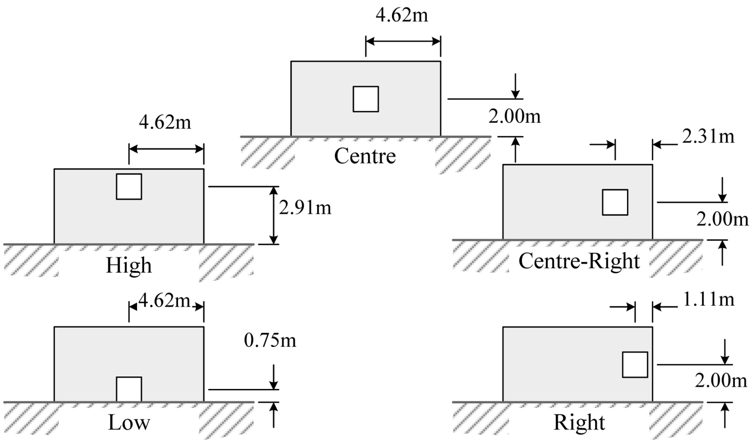


Fig. 5 Wall opening locations - full scale dimensions are shown

5. Results and discussions

Figs. 6(a) and (b) show the internal pressure spectra obtained for the opening 'Centre' with 6 mm and 2 mm thick openings respectively, and for the three cavity volumes tested. For the 6 mm thick opening, with the floor in i.e., without volume distortion, a Helmholtz resonance peak was obtained at 170 Hz. When a shallow rectangular cavity, cavity 1 was used, two resonant peaks were observed. This interesting phenomenon seen throughout for all other openings with cavity 1, as in all the internal pressure spectra presented in Fig. 6, is believed to be due to the added cavity acting as another Helmholtz resonator in series with the resonator formed by the window opening and the model cavity above the floor-line. Such a situation exists when buildings have partitioned compartments with connecting doors as discussed by Sharma (2003). The arrangement of the model with cavity 1 presents such a situation, which is not desired as the frequency response characteristics are altered significantly that will lead to incorrect predictions of the fluctuating internal pressures. Clearly then, this is not satisfactory for the modelling of building internal pressure dynamics in wind tunnel studies.

As shown also in Figs. 6(a) and (b), the influence of the deep cavity, cavity volume 2, is significantly different to that obtained with cavity volume 1. In this case, a single resonant peak is observed at a frequency of 35 Hz for the 6 mm thick opening, and 33 Hz for the 2 mm thick opening. These are very close to the Helmholtz resonance frequencies calculated using Eq. (5). Very similar comparisons were obtained for all the openings investigated in the present study as shown in Fig. 6. Consequently, the use of a deep cavity, such as cavity 2, is deemed to be more appropriate than a shallow but wide cavity. Furthermore, the frequency response characteristics of the model with the increased volume (in this case cavity 2) is quite different to that without the added cavity, in particular, the Helmholtz resonance frequencies are very different (35 Hz versus 170 Hz). This means that the internal pressure responses for these two cases are driven by different sections of the onset turbulence spectrum which will inevitably lead to significantly different fluctuating internal pressures being measured. It highlights the need to consider the frequency scaling in model scale testing, so that the Helmholtz resonance frequency scales according to the frequency scaling of the boundary layer turbulence.

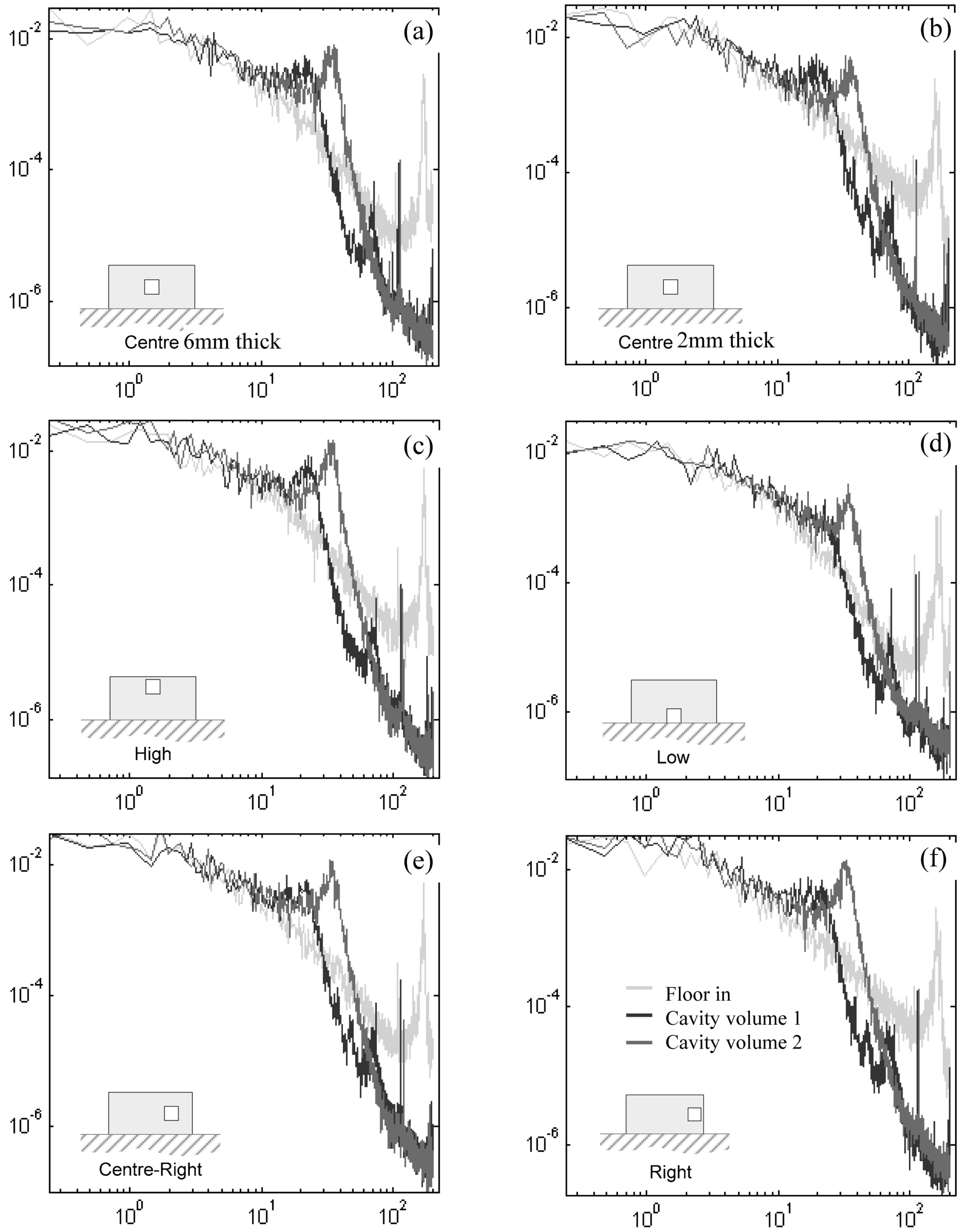


Fig. 6 Internal pressure spectra S_{pi}(f) [Pa^{2}s] versus frequency f [Hz] for all the openings tested

On the other hand, the differences between the internal pressure spectra for the two different opening thicknesses are relatively small in terms of the Helmholtz frequency, being 35 Hz versus 33 Hz for the 6 mm and 2 mm thick openings respectively. For these, the peak spectral energy density values, 7.86×10^{-3} Pa^{2}s against 5.33×10^{-3} Pa^{2}s, are however different. A clearer picture as to the differences emerges when one considers the statistical ratios of internal pressure.

Table 1 compares the RMS to mean internal pressure coefficient and peak to mean internal

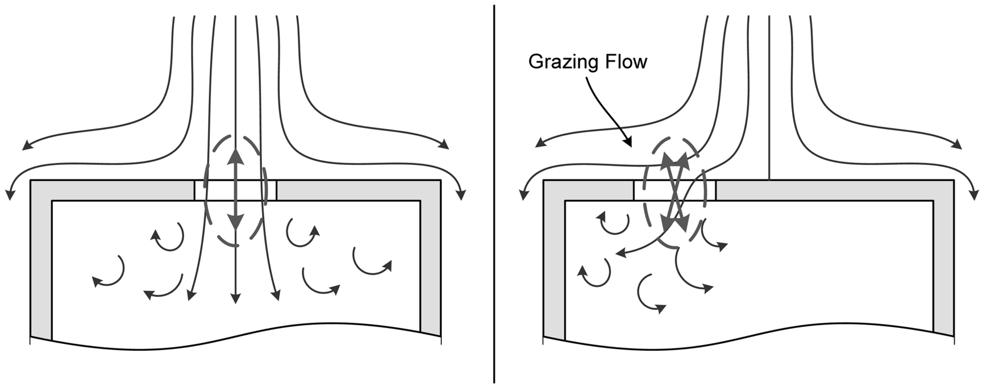
Table 1 Internal pressure characteristics and parameters

	Cavity	Opening Location					
		Low	High	Centre-Right	Right	Centre 6 mm	Centre 2 mm
$\frac{C_{pi}(\mathrm{RMS})}{C_{pi}(\mathrm{MEAN})}$	Floor In	0.31	0.36	0.41	0.44	0.37	0.44
	Cavity 1	0.33	0.38	0.37	0.45	0.34	0.35
	Cavity 2	0.35	0.41	0.37	0.53	0.39	0.40
$\frac{C_{pi}(\mathrm{MAX})}{C_{pi}(\mathrm{MEAN})}$	Floor In	2.32	2.46	2.73	2.90	2.56	2.89
	Cavity 1	2.20	2.39	2.32	2.55	2.23	2.29
	Cavity 2	2.46	2.61	2.62	2.96	2.53	2.78
f_H (Hz)	Floor In	168.5	171.4	171.4	158.9	170.4	158.9
	Cavity 2	34.2	34.4	33.5	32.7	35.4	33.2
l_e (mm)	Floor In	21.31	20.58	20.58	23.93	20.82	23.93
	Cavity 2	20.68	20.39	21.6	22.58	19.28	21.92
C_I	Floor In	0.61	0.58	0.58	0.72	0.59	0.88
	Cavity 2	0.59	0.58	0.62	0.66	0.53	0.80

pressure coefficient ratios ($C_{pi(RMS)}$ / $C_{pi(MEAN)}$ and $C_{pi(MAX)}$ / $C_{pi(MEAN)}$) for the different cavity and opening configurations that were tested. The differences in these ratios between the different cavities illustrate the significant influence of the nature of the cavity on the characteristics of internal pressure, and highlights the need for correct modelling procedures to be applied to model scale studies on building internal pressure. Table 1 also shows that these characteristics vary quite considerably with opening location, and that a 2 mm thick window leads to somewhat different characteristics of internal pressure when compared with a 6 mm thick window. Hence, modelling the opening thickness accurately is important as well, but has remained largely ignored in previous studies.

Table 1 also includes the Helmholtz resonance frequencies that were obtained from experimentation and the effective air slug lengths l_e and inertia coefficients C_I that were computed using Eq. (5), with C_d =0.6 as suggested by Sharma and Richards (1997b). These show dependence of the slug length and the inertia coefficient and thus the Helmholtz frequency on opening location as found previously by Sharma and Richards (1997b). The longest slug length of approximately 24 mm occurs for the 2 mm thick centre opening, being significantly different to the 6 mm centre opening. This is possibly due to the sharpness of the thinner opening leading to pronounced contracted flow and therefore a higher momentum air jet extending to a longer distance than with the thicker opening. When all the 6 mm thick openings are compared, those that are in the vicinity of the floor ('low') or sidewalls ('right') present the longest slug length. This is possibly due to the presence of the walls extending the jet flow during in-flow in much the same way the phenomenon of 'coanda effect' aids air jets issuing from diffusers into rooms to adhere to ceilings and have an extended 'throw'.

Of all the 6 mm thick openings, the largest values for RMS and peak to mean C_{pi} ratios were found for the 'right' and 'centre right' openings (see Table 1). The phenomenon of tangential flow excitation of Helmholtz resonance as discussed previously by Sharma and Richards (2003) is believed to have contributed here. The manner in which this is possible is illustrated in Fig. 7. The off-centre openings are presented with tangential flow as the onset wind tries to negotiate around the building passing tangentially across such openings.



(a) Centre opening (b) Off-centre opening

Fig. 7 The possibility of tangential or grazing flow excitation with off-centre openings in normal flow

Lastly, some idea of the opening loss coefficient C_L may be gained by considering the peak internal pressure spectral values at resonance. Unfortunately however, this needs to be done relative to the characteristics of external area pressure averaged over the extents of the opening, which was not a part of this experimental investigation.

6. Conclusions

Appropriate scaling methods for wind tunnel modelling of building internal pressures were investigated. In particular, model cavity volume distortion and geometric scaling of the opening details were studied. It was found that volume distortion alters the fluctuating characteristics of internal pressure quite significantly. Furthermore, the manner in which volume distortion is implemented was found to have a profound influence on the dynamics of internal pressure. With a shallow but wide added volume underneath the model, the system was found to behave as two Helmholtz resonators connected in series, which is not desirable. The use of a deep but narrow cavity remedied this situation and resulted in a single resonance. Significant differences in the characteristics of internal pressure were also observed between models with correctly scaled opening thickness and those without which is typical of most studies found in the literature. Furthermore, the effective air slug or jet was found to be longer when the opening was near a floor or sidewall as evidenced by somewhat lower Helmholtz frequencies. Evidence for the phenomenon of tangential flow excitation of Helmholtz resonance was also found for off-centre openings.

It is concluded that while model volume distortion may be used to appropriately scale down buildings for wind tunnel studies on internal pressure, proper care must be taken to implement the added volume in such a manner, as to not create two cavity resonance systems. Furthermore, the details of the opening and in particular its thickness should also be correctly scaled.

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