VARIATION OF INTERNAL PRESSURE WITH SIZE OF DOMINANT OPENING AND VOLUME

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ABSTRACT

The internal pressure in buildings with a range dominant opening sizes and internal volume sizes are studied using a boundary layer wind tunnel scale model. Ratios of the standard deviation and peak of the internal pressure to external pressure at the opening are related to a non-dimensional opening to volume size $S^*$. Whilst internal pressure fluctuations are attenuated compared to the pressure at the opening for small $S^*$, Helmholtz resonance can amplify internal pressure compared to external pressure for large $S^*$.

KEYWORDS: INTERNAL PRESSURE, HELMHOLTZ RESONANCE, DOMINANT OPENING, VOLUME

Introduction

The internal pressure can contribute a significant proportion to the total design wind loads when there is a dominant opening in the envelope of a building. Holmes (1979), Vickery (1986, 1994), Vickery and Bloxham (1992), Stathopoulos et al (1979) and Ginger et al (1997) have carried out model and full scale studies on internal pressures in nominally sealed buildings and buildings with a range of openings, and showed that results compare favorably with theoretical analysis.

Design internal pressure data specified in the wind load standard AS/NZS 1170.2 (2002) is based on such studies with a limited range of opening sizes and volumes. In this paper, characteristics of internal pressures in buildings, with a range of dominant opening sizes and volumes, are studied using model-scale data to determine their importance when calculating design internal pressures. Results are presented in a non-dimensional format that could be used for revising data in design codes and standards.

Theory

The response of pressure inside a building is related to the external pressures and the air flow in and out of openings in the envelope. The unsteady discharge equation relates the flow, $Q$ through an opening of area, $A$ and the pressure drop, $\Delta p$ across the opening by Eq 1.

$$\Delta p = \frac{1}{2} C_L \rho U_d^2 + C_I \rho \frac{\partial U}{\partial t} \sqrt{A}$$ (1)
Here, \( U_0 = (Q/A) \) is the area averaged velocity through the opening. The first term on the right hand side of Eq. 1 represents the pressure drop due to viscous effects while the second term is that required to accelerate the flow through the opening. The loss coefficient \( C_L \) is equivalent to \( 1/k^2 \), where \( k \) is the discharge coefficient used by Holmes (1979), and \( C_I \) is the inertial coefficient. The effective length of the slug of air accelerated through the opening is, \( l_e = C_I \sqrt{A} \). Vickery and Bloxham (1992) indicated that \( C_L \) and \( C_I \) can only be defined for limited situations such as a sharp edged circular opening connecting two large volumes, where potential flow theory gives \( C_L = \left[ \left( \pi + 2 \right) / \pi \right]^2 = 2.68 \) (i.e. \( k = 0.61 \)) and \( C_I = \sqrt{\pi/4} \).

The external pressures \( (p_e) \) and internal pressures \( (p_i) \) are defined in coefficient form as: \( C_p = p / 2 \rho U_h^2 \), where, \( p, \sigma_p, \bar{p} \) are the mean, standard deviation and maximum pressure, \( \rho \) is the density of air, and \( U_h \) is the mean wind speed at roof height, \( h \). Pressures acting towards a surface is defined positive. The frequency distribution of pressure fluctuations are further studied by analyzing their spectral densities, given by \( S_{C_p}(f) \).

The internal pressure fluctuations are related to the external pressures using the admittance function, \( \left| x_{p_i/p_e} \right|^2 \) shown in Eq. 2, also defined as square of the gain function \( G(f)^2 \).

\[
S_{C_p}(f) = \left| x_{p_i/p_e} \right|^2 S_{C_p}(f) = G(f)^2 S_{C_p}(f) \quad (2)
\]

For a building with a single opening, the mean internal pressure is equal to the mean external pressure at the opening. Furthermore, Vickery (1994) also showed that the internal pressures have negligible variation if the total background leakage is less than about 10% of the dominant opening. In such cases, a valid approach is to study the pressure in a sealed building with a single opening.

Holmes (1979) derived Eq. 3, to describe the time dependent internal pressure in a building with a dominant opening of area \( A \), in terms of internal pressure coefficient, \( C_{p_i} \) and external pressure coefficient at the opening, \( C_{p_e} \). Here, \( p_0 \) is the atmospheric pressure, \( n \) is the ratio of specific heats of air, and \( V_{le} \) is the effective internal volume of the building which also accounts for flexibility of the building. The speed of sound \( a_s = (n \times p_0 / \rho)^{1/2} \), where \( n = 1.4 \) for an adiabatic process. The undamped Helmholtz frequency is \( f_H = 1 / 2 \pi \sqrt{a_s^2 \sqrt{A} / C_{p_e} V_{le}} = \alpha_H / 2 \pi \). Vickery and Bloxham (1992) defined \( \beta \approx \frac{1}{2} \sqrt{C_{p_i} U_h / a_s} \sqrt{V_{le} / A^2} \) and presented Eq. 3 in the form of Eq. 4.

\[
\frac{C_{p_i} V_{le}}{A a_s} \dot{C}_{p_i} + \left[ \frac{V_{le} U_h}{2kAa_s^2} \right]^2 \dot{C}_{p_i} \left| \dot{C}_{p_i} \right| + C_{p_e} = C_{p_i} \quad (3)
\]

\[
\frac{1}{\omega_H^2} \dot{C}_{p_i} + \left[ \frac{\beta}{\omega_H} \right]^2 \dot{C}_{p_i} \left| \dot{C}_{p_i} \right| + C_{p_e} = C_{p_i} \quad (4)
\]

Holmes (1979) also showed that the internal pressure fluctuations can be represented as a function of the five non-dimensional parameters: \( \Phi_1 = A^{1/2} / V_{le} \), \( \Phi_2 = a_s / U_h \), \( \Phi_3 = \rho U_h \sqrt{A} / \mu \), \( \Phi_4 = \sigma_u / U \) and \( \Phi_5 = \lambda_u / \sqrt{A} \), where, \( \mu \) is the viscosity of air, \( U \) and \( \sigma_u \) are the mean
velocity and turbulence intensity respectively of the flow at a given elevation, and \( \lambda_U \) is the integral length scale of turbulence. Eq. 3 can be written in the non-dimensional form of Eq. 5, by introducing these non-dimensional parameters, and by defining a non-dimensional time, \( t^* = \frac{t U_h}{\lambda_U} \). The first term in Eq. 3 describes the “inertia” of the air flow in and out of the opening, while the second term represents the damping of the flow through the opening.

\[
C_I \frac{1}{\Phi_1 \Phi_2^2 \Phi_5^2} \frac{d^2 C_{p_i}}{dt^*^2} = \left( \frac{1}{4k^2} \right) \left[ \frac{1}{\Phi_1 \Phi_2^2 \Phi_5^2} \right] \frac{dC_{p_i}}{dt^*} \frac{dC_{p_i}}{dt^*} + C_{p_i} = C_{p_i}
\]

The product \( \Phi_1 \Phi_2^2 \) in Eq. 5, can be replaced by a single non-dimensional variable and defined as the non-dimensional opening to volume parameter, \( S^* = \left( \frac{a_s}{U_h} \right)^2 \left( \frac{A^2}{V_{le}} \right) \). Eq. 5 shows that the variation of internal pressure for given external pressure fluctuations is dependent on \( S^*, A, C_I \) and \( k \), and that there is a unique solution for \( C_{pi} \) with \( S^* \), for a given \( A, C_I \) and \( k \). Therefore, given the values \( C_I \) and \( k \), the ratio of internal pressure fluctuations to external pressure fluctuations at the opening, can be presented by a family of curves, with variables of \( S^* \) and \( \Phi_5 \). Eq. 5 also shows similarity is maintained by keeping \( S^* \) constant, giving the same volume distortion requirements recommended by Holmes (1979), for model tests.

**Numerical analysis**

Internal pressures can be simulated for a range of internal volumes, \( V_{le} \) and dominant opening areas, \( A \) using the measured external pressure fluctuations at the opening by applying a first order explicit finite difference scheme to solve Eq. 3. The time derivatives of internal pressures are calculated at each time step \( j \), based on \( C_{pi} \) values at the preceding two time steps, as shown in Eq. 6, where \( \Delta t \) is the time step. In these simulations, the measured mean wind speeds are used, along with the external pressure coefficient \( C_{pe} \) values measured at each time step as the driving function.

\[
\frac{\dot{C}_{p_i}(j)}{\Delta t} = \frac{C_{p_i}(j) - C_{p_i}(j-1)}{\Delta t}
\quad \text{and} \quad
\frac{\ddot{C}_{p_i}(j)}{\Delta t^2} = \frac{C_{p_i}(j) - 2C_{p_i}(j-1) + C_{p_i}(j-2)}{\Delta t^2}
\]

**Experimental Set-Up, Results and Discussion**

External and internal pressures were measured on a 200 \times 400 \times 100 mm model building shown in Fig 1, in a boundary layer flow simulated to terrain category 2 (as per AS/NZS 1170.2 (2002)) at a length scale of 1/200, in the wind tunnel at James Cook University. The 200 \times 400 \times 600 mm volume located below floor level in the wind tunnel is available for varying the internal volume of the building. External pressures were measured at 30 taps on a panel centered on the 400 mm long windward wall of the nominally sealed model building, for \( \theta = 0^\circ \) winds approach, as shown in Fig 1. Pressure measurements on selected taps are combined to give area-averaged external, mean, standard deviation and maximum \( C_{ps} \) on Areas A1, A2, A3 and A4 representative of potential dominant openings on the building defined in Table 1. Internal pressures measured inside the model with a dominant opening of A1, A2, A3 or A4 on the 400mm long wall, and internal volumes V1, V3, V5 or V7, for approach wind direction, \( \theta = 0^\circ \), and the Helmholtz frequencies, \( f_H \) calculated for these combinations of opening sizes \( A \) and volumes \( V_{le} \) are also given in Table 1. Tests were carried out at mean approach wind speeds at roof height, \( U_h \) of about 10 m/s. The pressure
signals were sampled at 1250 Hz for a single run of 30 s duration, and averaged over five runs. The results indicate that the mean internal pressure closely follows the mean external pressure for each dominant opening size.

![Fig 1: 200 x 400 x 100 mm model with 200 x 400 x 600 mm volume below floor](image)

**Table 1: Measured external and internal pressure coefficients for dominant opening sizes (A1, A2, A3 and A4), internal volume sizes (V1, V3, V5 and V7) $\overline{U}_h \sim 10$ m/s**

<table>
<thead>
<tr>
<th>Area of opening</th>
<th>$V_{le} \ (mm^3)$</th>
<th>$f_{ij} \ (Hz)$</th>
<th>$C_{\overline{pe}}$</th>
<th>$C_{\overline{pE}}$</th>
<th>$C_{\overline{pI}}$</th>
<th>$C_{\overline{opl}}$</th>
<th>$C_{\overline{p\beta I}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 = 20×20 $mm^2$</td>
<td>$V1 = 200×400×100$</td>
<td>91</td>
<td>0.52</td>
<td>0.21</td>
<td>2.10</td>
<td>0.56</td>
<td>0.23</td>
</tr>
<tr>
<td>$\phi_5 = 15.0$</td>
<td>$V3 = 200×400×300$</td>
<td>53</td>
<td>0.46</td>
<td>0.20</td>
<td>1.42</td>
<td>0.48</td>
<td>0.19</td>
</tr>
<tr>
<td>$\phi_5 = 15.0$</td>
<td>$V5 = 200×400×500$</td>
<td>41</td>
<td>0.46</td>
<td>0.19</td>
<td>1.24</td>
<td>0.48</td>
<td>0.19</td>
</tr>
<tr>
<td>$\phi_5 = 15.0$</td>
<td>$V7 = 200×400×700$</td>
<td>34</td>
<td>0.48</td>
<td>0.19</td>
<td>1.54</td>
<td>0.48</td>
<td>0.19</td>
</tr>
<tr>
<td>A2 = 50×25 $mm^2$</td>
<td>$V1 = 200×400×100$</td>
<td>121</td>
<td>0.53</td>
<td>0.21</td>
<td>2.04</td>
<td>0.57</td>
<td>0.20</td>
</tr>
<tr>
<td>$\phi_5 = 8.5$</td>
<td>$V3 = 200×400×300$</td>
<td>70</td>
<td>0.50</td>
<td>0.22</td>
<td>1.52</td>
<td>0.53</td>
<td>0.22</td>
</tr>
<tr>
<td>$\phi_5 = 8.5$</td>
<td>$V5 = 200×400×500$</td>
<td>54</td>
<td>0.50</td>
<td>0.22</td>
<td>1.52</td>
<td>0.53</td>
<td>0.22</td>
</tr>
<tr>
<td>$\phi_5 = 8.5$</td>
<td>$V7 = 200×400×700$</td>
<td>46</td>
<td>0.53</td>
<td>0.22</td>
<td>1.63</td>
<td>0.53</td>
<td>0.22</td>
</tr>
<tr>
<td>A3 = 50×50 $mm^2$</td>
<td>$V1 = 200×400×100$</td>
<td>144</td>
<td>0.55</td>
<td>0.22</td>
<td>1.98</td>
<td>0.59</td>
<td>0.23</td>
</tr>
<tr>
<td>$\phi_5 = 6.0$</td>
<td>$V3 = 200×400×300$</td>
<td>83</td>
<td>0.57</td>
<td>0.23</td>
<td>1.81</td>
<td>0.59</td>
<td>0.26</td>
</tr>
<tr>
<td>$\phi_5 = 6.0$</td>
<td>$V5 = 200×400×500$</td>
<td>64</td>
<td>0.59</td>
<td>0.26</td>
<td>1.89</td>
<td>0.55</td>
<td>0.23</td>
</tr>
<tr>
<td>$\phi_5 = 6.0$</td>
<td>$V7 = 200×400×700$</td>
<td>54</td>
<td>0.55</td>
<td>0.23</td>
<td>1.77</td>
<td>0.55</td>
<td>0.23</td>
</tr>
<tr>
<td>A4 = 50×80 $mm^2$</td>
<td>$V1 = 200×400×100$</td>
<td>162</td>
<td>0.52</td>
<td>0.20</td>
<td>1.89</td>
<td>0.54</td>
<td>0.20</td>
</tr>
<tr>
<td>$\phi_5 = 4.7$</td>
<td>$V3 = 200×400×300$</td>
<td>94</td>
<td>0.52</td>
<td>0.20</td>
<td>1.62</td>
<td>0.52</td>
<td>0.20</td>
</tr>
<tr>
<td>$\phi_5 = 4.7$</td>
<td>$V5 = 200×400×500$</td>
<td>73</td>
<td>0.53</td>
<td>0.22</td>
<td>1.68</td>
<td>0.53</td>
<td>0.22</td>
</tr>
<tr>
<td>$\phi_5 = 4.7$</td>
<td>$V7 = 200×400×700$</td>
<td>61</td>
<td>0.53</td>
<td>0.21</td>
<td>1.69</td>
<td>0.53</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The pressure spectra, $S_{cp}(f)$ and admittance functions, $G(f)^2$ obtained from measured windward wall external pressure and measured and simulated (using $k = 0.15, 0.3$) internal pressures for A2, and V1 and V7 are shown in Figs. 2a and 2b, respectively. The figures show that internal pressure resonance occurs close to the Helmholtz frequency (which decreases with increase in volume), and that $k = 0.15$ and 0.3 give satisfactory simulations of internal pressures. In accordance with Eq. 3, although a reduction in $S^*$ (increase in $V_{le}$) results in increased damping of internal pressure, an increase in $k$ gives comparable peaks in $G(f)^2$ near the Helmholtz frequency. The magnitude of internal pressure fluctuations also
depends on the position of Helmholtz frequency in relation to the energy containing range of frequencies in the external pressure fluctuations, notwithstanding an increase in damping.

![Graph with frequency (f), Hz vs. G(f) and S_p(f)^2](image)

(a) A2 and V1 & simulated k = 0.15

![Graph with frequency (f), Hz vs. G(f) and S_p(f)^2](image)

(b) A2 and V7 & simulated k = 0.3

Figure 2: External (+++) and internal (measured (___) and simulated (._._.) S_p(f)^2 and G(f),

Standard deviation and peak (i.e. maximum), simulated (k = 0.3) internal to windward wall external pressure ratios are shown for A1, A2, A3 and A4, as a function S*, in Figs. 3a and 3b respectively. The measured internal to windward wall external, standard deviation pressure ratios shown in these figures are in good agreement with the simulations, but the peak internal pressures are generally overestimated by these simulations. Nevertheless, this analysis shows that the size of the opening and volume play an important part in internal pressure fluctuations, and that its magnitude increases with increasing S*. 
Figure 3. Pressure ratios vs $S^*$ simulations (symbols with lines) with $k = 0.3$ and measured values (symbols only) $\Phi_5 = 15, 8.5, 6$ and 4.7.

The magnitude of the simulated internal pressure fluctuations is greatly influenced by the value of $k$. As shown in Eq 5, an increase in $k$ will reduce the level of damping and hence increase the resonant response. Other studies Vickery (1986, 1994), Saathoff and Liu (1982), Liu and Saathof (1983) and Oh et al (2007) on internal pressures in a building with a dominant opening have measured or estimated the discharge coefficients ($k$) up to about 0.6, in turbulent flow conditions. Ginger et al (2009) showed that $k$ can vary between 0.1 and 0.4.
as $S^\star$ is varied. Therefore, $k = 0.15$ to 0.3 may be used for determining internal pressure fluctuations in codes and standards. Standard deviation and peak (i.e. maximum), simulated (with $k = 0.15$) internal to windward wall external pressure ratios are shown for A1, A2, A3 and A4 (i.e. $\Phi_5 = 15, 8.5, 6$ and 4.7), as a function of $S^\star$, in Figs 4a and 4b respectively.

Figure 4. Pressure ratios vs $S^\star$ simulations (symbols with lines) with $k = 0.15$ and measured values (symbols only) $\Phi_5 = 15, 8.5, 6$ and 4.7
Conclusions

This study found that the characteristics of the internal pressure fluctuations are influenced by the size of the dominant opening and the size of the volume, and by the approach wind speed. The relationship between the internal pressure fluctuations and the external pressure at the dominant opening can be provided in terms of the standard deviation and peak pressure ratios versus $S^* = (a_s/U_0)^2 (A^{3/2}/V_{in})$, for a range of opening sizes. The internal pressure fluctuations (standard deviation and peak) are amplified as $S^*$ increases. Internal pressures simulated with $k = 0.1$ to 0.4 provide satisfactory comparisons with measured internal pressures and internal to external pressure ratios, for a range $S^*$. These relationships are similar to that found with limited full-scale data by Ginger et al (2008) and also presented in Holmes and Ginger (2009). Higher values of $k$ produce larger internal pressure fluctuations for a given $S^*$.

References