The ill-defined parameters of the building internal pressure dynamics problem

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Abstract

A review of literature is carried out on the building internal pressure dynamics problem to show that a wide range for the opening parameters, namely the loss and inertia coefficients, $C_L$ and $C_I$, are in use. An analysis in the present study shows the fluctuating and peak internal pressure coefficients can vary over the range of these ill-defined parameters by as much as 40%. This is not satisfactory and further studies into these ill-defined parameters of the internal pressure problem are recommended.

Introduction

The safety of a building during the passage of windstorms depends on the characteristics of both internal as well as external pressures, since these can combine to produce extreme loads on elements of the building envelope. Traditionally, building designers and wind engineers focussed largely on the characteristics of building external pressure, hence a large body of literature exists in this area. Internal pressure on the other hand has received relatively less attention even though its importance has continually been highlighted during the aftermath of severe windstorms around the globe [1].

Non-neutral internal pressure in buildings may be induced by the wind through leakage’s or permeability of the envelope; through dominant openings; and through the flexibility of the envelope. Of particular interest under windstorm conditions is the generation of internal pressure fluctuations through dominant openings. Such openings may be created by impact of wind-borne debris. Sudden breakage of windows and doors in this manner is not uncommon in severe windstorms. Similarly, intentional opening of doors for escape during windstorms is also common.

There are two issues of concern once a dominant opening has been created. First is the internal pressure overshoot, if any, in the ensuing transient response to a suddenly created opening that presents a sudden change in pressure at the opening. Second is the subsequent response including any resonant response of the building cavity to the turbulent wind via the fluctuations in external pressure at the opening. Both these mechanisms could produce peak internal pressure values that could combine with envelope (e.g. roof) external pressure to generate extreme loading on the envelope. Similarly, the so-called steady-state response, or the subsequent response after the transients if any, have died down, could involve Helmholtz resonance effects, that could produce (a) peak internal pressures that are higher than the peak values for external pressure at the opening; and (b) significant fluctuations in internal pressure thus enhancing fatigue loading on the components of the building.

The characteristics of internal pressure will depend upon the characteristics of the driving external pressure at the opening, as well as the frequency response characteristics of the building cavity determined by the opening area, internal volume, background leakage, secondary openings, partitioning, and the flexibility of the envelope, if any. Since a large body of literature already exists as far as external pressures are concerned, and that wind loading codes have comprehensive provisions for them, the characteristics of external pressure required for the prediction of internal pressure characteristics are readily available. On the other hand, following a novel treatment of the internal pressure problem by Holmes [2], several researchers [3-10] amongst others, have since greatly increased the understanding of the frequency response characteristics of building cavities and the characteristics of internal pressure induced through dominant openings. Whilst this may be the case, however, even for the apparently simplest case of a rigid, non-porous, single compartment building with a dominant opening, there still remains a number of aspects of the problem that require further investigation.

Firstly, there are a number of variations of the governing equation for internal pressure that are in use at present. Secondly, the coefficients used in the governing equation also vary quite significantly from one study to another. The internal pressure response computed using the governing equations are strongly dependent on these coefficients. Thirdly, a number of different methodologies are in use to predict the RMS response of and gust factors for internal pressure, and not all are in agreement with each other.

It is therefore the purpose of this paper to (a) review the governing equations for internal pressure, for the case of a rigid, non-porous, and single compartment building with a dominant opening, (b) collate data and present discussions on the ill-defined parameters of the flow through dominant openings in buildings, and (d) conduct numerical modelling of internal pressure fluctuations to establish its sensitivity to the ill-defined parameters of the internal pressure problem.

Governing equation for building internal pressure

The four different formulations for the governing equation in use today have been summarised previously by Sharma et al [11]. The problem to be considered is that of a building cavity with a dominant opening, as shown in Figure 1.

Figure 1. Building with a dominant opening

Wind speed $\vec{U}_w$

External pressure $P_e(t)$

Opening Area $A_o$

Internal volume $V_i$

Internal pressure $P_i(t)$

$h$

This is not satisfactory and further studies into these ill-defined parameters of the internal pressure problem are recommended.
In the Holmes [2] analogy of the Helmholtz acoustic resonator, the oscillatory airflow through the opening is modelled as an oscillatory airflow through the building cavity were assumed to be fairly rapid and therefore isentropic, hence the specific heat ratio \( \gamma \) equalling the square of the ratio of the full-scale to model-scale velocities. The flow through the opening was assumed to form a vena-contracta, and the contraction or discharge coefficient \( C_a \) was set to be 0.88 in order to match the measured Helmholtz frequencies. The damping term was however not examined.

Using the unsteady orifice flow equation with a loss term quantified using an opening loss coefficient \( C_l \) being equivalent to \( 1/C_a^2 \), Vickery and Bloxham [6] derived Equation (3),

\[
\frac{1}{\omega_{inh}} \ddot{C}_{pi} + C_l \frac{\rho \gamma q q}{2 \gamma A_c P_c} \ddot{C}_{pi} + C_{pe} \ddot{C}_{pi} + C_{mu} = 0
\]

Using numerical solutions to Equation (1) and parallel experimental testing at model scale, Holmes [2] showed that wind turbulence could excite the building cavity through the opening causing Helmholtz resonance to occur. This manifests as intense oscillations in internal pressure about the Helmholtz resonance frequency, as was evidenced by resonant peaks in internal pressure spectra. Having fixed the effective slug length with \( l_e = \sqrt{\pi A_o/4} \), Holmes [2] had to use a polytropic exponent \( n = 1.2 \) and a discharge coefficient \( C_d = 0.15 \) in order to match the Helmholtz frequency and the damping (i.e. magnitude of resonant peak) predicted by Equation (1) respectively, to experimental measurements. Equally importantly, 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 increased (distorted) by a factor equalling the square of the ratio of the full-scale to model-scale velocities.

Liu and Saathoff [3] used the unsteady Bernoulli equation to arrive at an equation very similar to that of Holmes [2], Equation (3),

\[
\frac{1}{\omega_{inh}} \ddot{C}_{pi} + \frac{1}{C_d} \frac{\rho \gamma q q}{2 \gamma A_c P_c} \frac{1}{n} \ddot{C}_{pi} + C_{pe} \ddot{C}_{pi} = 0
\]

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\]

Equation (7). As such, there is some uncertainty regarding the exact formulation to use for the internal pressure equation, however, as long as the parameters have been defined properly, others, for example Sharma and co-workers [7-8, 11], have tended to use a combination of the former as described by Equation (7). As such, there is some uncertainty regarding the exact formulation to use for the internal pressure equation, however, as long as the parameters have been defined properly,
the choice of the equation would probably not matter a great deal, say, in the prediction of peak internal pressures.

An even greater uncertainty appears to exist with regards the values for the loss and inertia coefficients to be utilised, as summarised in Table 1. While loss coefficients \( C_l \) (some assuming this equals \( 1/C_p^2 \)) can range between 2.5 and 6 (up to 18 x the lowest value), the inertia coefficient \( C_i \) appears to have much smaller variability, ranging 0.89 to 1.55 (up to 2 x lowest value). To understand the significance of these large variations of the poorly defined parameters, the sensitivity of the standard deviation and peak internal pressure coefficients predicted using the governing equation(s) to these parameters is examined next.

Table 1. Parameters of the internal pressure equation for buildings / building models with a dominant opening, from experimental studies

<table>
<thead>
<tr>
<th>Location</th>
<th>Opening type</th>
<th>Opening area (m²)</th>
<th>Wall thickness (mm)</th>
<th>Wall area (m²)</th>
<th>Wall location</th>
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**Building**

A typical low rise building having the following characteristics was considered for the numerical analysis:

- **Building:** \( v_o = 500 \text{m}^3 \), Wall height \( h = 4 \text{m} \), Width \( w = 9 \text{m} \)
- **Opening:** \( A_o = 2 \text{m}^2 \), \( l_p = 0.1 \text{m} \), \( l_p = l_p + C_{pe}/A_o \), \( C_e = 0.6 \)

At wall centre, centred at \( x = w/2 \), \( y = h/2 \)

**Wind characteristics**

- **Air properties:** \( \rho_d = 1.2 \text{kg/m}^3 \), \( P_o = 101,300 \text{Pa} \), \( y = 1.4 \)
- **Wind / terrain:** \( U_h = 25.6 \text{m/s} \), \( U_p/h = 2.5 \text{ln}(z/z_o) \)
- **Turbulence:** \( l_{ux} = 1/\ln(z/z_o) \)

**External pressure**

- **Mean:** \( C_{pe} = 0.68 \) (mean pressure coefficient)
- **Spectrum:** \( S_{Cpe}(f) = (2C_{pe}/U_h)^2|S_u(f)|^2 \)
- **Admittance:** \( |X_{Cpe}|^2 = (1 + 8(n_1\sqrt{fY})^{-0.8}(1 + 15n_2)^{-0.9}) \)
  - \( n_1 = f\sqrt{Wh}/U_h \), \( n_2 = f\sqrt{A_o}/U_h \)
  - \( \hat{x} = x/(w/2) \), \( \hat{y} = y/h \)

**Internal pressure**

Internal pressure coefficients were obtained from the equation,

\[
\frac{1}{\sigma_{lin}^2} \overline{C_{pi}} + C_L \frac{\rho \sigma^2 \hat{y}^2 \hat{x}}{2} A_o \frac{C_{pi}}{\pi^2} \overline{C_{pi}} + C_{pi} = C_{pe} \quad (9)
\]

\[
f_{int} = \frac{1}{2\pi} \sigma_{int} = \frac{1}{2\pi} \sqrt{\frac{1}{\rho_d \nu_{w_o}}} \frac{\gamma C_{pe} A_o P_o}{\rho_d l_{v_o}} \quad (10)
\]

for the following ranges of the loss and inertia coefficients:

- **Loss coefficient:** \( C_L = 2.5, 5, 10, 20, 45 \)
- **Inertia coefficient:** \( C_I = 0.7, 0.9, 1.0, 1.25, 1.55 \)

**Simulated wind and pressure characteristics**

A simulated wind speed, and external and internal pressure coefficient \( (C_{pe} \text{ and } C_{pi}) \) time series are shown in Figures 2 and 3.

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**Numerical modelling details**

The governing equation for internal pressure, Equation (6) without the linear damping term was solved using a 4th order Runge-Kutta scheme for a typical building cavity – opening combination, under strong wind conditions. The required external pressure forcing function was derived using an inverse FFT technique utilising a spectrum for wind turbulence and external pressure admittance function of Sharma and Richards [12].
respectively. Figure 3, which is for \( C_L = 10 \) and \( C_I = 0.7 \) demonstrates the enhancement of fluctuations in internal pressure due to Helmholtz resonance, as the excursions away from the mean level and the peaks in \( C_{pi} \) are higher than those in \( C_{pe} \).

**Sensitivity of peak and fluctuating internal pressure to loss and inertia coefficients**

The sensitivity of internal pressure on the opening loss and inertia coefficients, \( C_L \) and \( C_I \), for the building cavity with the fixed opening area, are shown in Figures 4 and 5 below.

Plots of the ratio of the rms internal pressure coefficient to rms external pressure coefficient \( C_{pi}/C_{pe} \) in Figure 4 reveal a very strong correlation between internal pressure fluctuations and \( C_L \). The governing equation shows that increasing the loss coefficient \( C_L \) increases the damping of the internal pressure system, hence decreases the cavity response, resulting in decreased internal pressure fluctuations. Since internal pressure fluctuations are driven through the opening by the external pressure fluctuations, a decreased response means the ratio \( C_{pi}/C_{pe} \) decreases as well. As \( C_L \) is increased from 2.5 to 45, the \( C_{pi}/C_{pe} \) ratio decreases by between 30-40% depending on the inertia coefficient \( C_I \). Plots of the ratio of the peak internal pressure coefficient to peak external pressure coefficient \( C_{pi}/C_{pe} \) in Figure 5 reveal very similar sensitivity to \( C_L \). As \( C_L \) is increased from 2.5 to 45, the peak pressure coefficient ratio \( C_{pi}/C_{pe} \) decreases by approximately 20% except when \( C_L = 0.7 \), when the decrease is less than 10%.

On the other hand, the sensitivity of internal pressure on the inertia coefficient \( C_I \) is not as pronounced. This is due to the independence of the damping term on \( C_I \). The inertia term is however dependent on \( C_I \) and it influences the resonance frequency \( f_{HH} \). Over the range of possible values for \( C_I \), the \( f_{HH} \) varies between 2.6 to 1.8Hz. As \( f_{HH} \) decreases with \( C_I \), the energy available in the onset wind turbulence at the resonance frequency for excitation increases only slightly, hence the increase in \( C_{pi}/C_{pe} \) with \( C_I \) is not as significant as that observed with the decrease in \( C_L \). Over the \( C_I \) range 0.7-1.55, the increase in \( C_{pi}/C_{pe} \) is about 10%. Figure 5 shows that the sensitivity of peak internal pressure to \( C_I \) is even less significant, except at the lowest values of \( C_L \).

**Conclusions**

The wind resistant design of a building relies on our ability to accurately predict the characteristics of internal pressure, especially which is induced through dominant openings. This ability is limited at the present time largely because of the little attention that internal pressure has received. As a result, the literature shows a wide range for the opening parameters, namely the loss and inertia coefficients, \( C_L \) and \( C_I \), in use. The analysis in the present study shows the rms and peak internal pressure coefficients can vary by as much as 40%. Clearly, this is not satisfactory, and further studies into these ill-defined parameters of the internal pressure problem are recommended.

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**References**


