The effect of background leakage on wind induced internal pressure fluctuations in low rise buildings with dominant openings

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Keywords: background leakage; internal pressure; low rise building; dominant opening.

ABSTRACT

Numerical investigations of the effect of background leakage on wind induced internal pressure fluctuations in low-rise buildings with windward dominant openings have been carried out. The assumptions involved in the deduction of the analytical model are lumping of leakages on the leeward side with suction pressure, ignoring the effect of inertia and pipe friction losses in the discharge equation for leakages, using a representative average leakage loss coefficient and a time and area averaged value of leeward wall pressure coefficient. The assumptions are considered to be adequate compared to the uncertainties associated with the distribution of leakage paths, lack of knowledge regarding their loss coefficients and effective air slug lengths as well as limitations posed in procuring actual data. The presence of background leakage generates an additional linear damping term in the governing equation of internal pressure response. The results show that background leakages damp out the turbulence induced internal pressure fluctuations caused by the presence of windward dominant opening with the internal pressure variance being reduced by more than 50% with increase in porosity ratio (ratio of the area of background leakage to that of dominant opening) from zero to 0.50.

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1. Introduction

The importance of wind induced internal pressures on the net loading of low-rise buildings have long been recognized with notable contributions from Holmes (1979), Liu and Saathoff (1982), Vickery & Bloxham (1992), Sharma & Richards (1997) among others. Past research has indicated that internal pressure in a building is nominally induced by the wind through the external pressure field via three mechanisms: transmission through leakages in buildings, transmission through dominant openings like doors and windows and through flexibility of building envelope, with the most significant effects occurring in the presence of dominant openings. Complicating this further and the subject of discussion in this paper is the presence of background leakages on the building surfaces caused by normal construction tolerances and small openings for ventilation purpose, the effect of which is to mitigate the wind induced internal pressure fluctuations transmitted through the dominant opening. The biggest problem however, challenging a designer in real life is the uncertainty associated with the distribution of leakage paths and value of loss coefficients and effective air slug lengths associated with such leakage paths.

While theoretical advancement coupled with experimental observations (both wind tunnel and full scale) have greatly led to the understanding of internal pressure response in presence of a dominant opening (both transient and steady state effects) as well as the effect of building “skin” flexibility, a closed form solution to the effect of background leakage as noted by Vickery (1994) is yet to be developed. However, certain simplifications which are reasonable yet conservative can be made to the problem and numerical solutions to such problems should nevertheless provide us with valuable insights of the effect of background leakage into the internal pressure dynamics of buildings with a windward dominant opening. Studies on the effect of background leakage on internal pressure variance are few by far and needs further theoretical treatment as well as detailed full scale and wind tunnel studies.

In their model scale studies with dominant opening, Vickery & Bloxham (1992) found that background leakage attenuated Helmholtz resonance, and with a background leakage of 10% of that of the dominant opening, the resonance contribution to internal pressure variance is halved.

From their wind tunnel studies of buildings with a range of dominant opening (orifices) sizes and background leakage (porous opposite wall), Woods & Blackmore (1995) reported mean internal pressure values in close agreement with area averaged opening pressures for all azimuths for area ratios (ratio of opening to that of wall area) greater than 4%. They concluded that the effect of an opening is dominant when its area is about 2.5 times the equivalent area of the leakages in the spirit of Cook (1985).

Fahrtash & Liu (1990) carried out full scale internal pressure measurements on three full scale building configurations with and without dominant windward openings. They concluded that large building leakage and flexible walls/roof of the buildings provide sufficient damping to prevent Helmholtz resonance from happening though the internal pressure fluctuations were much higher when large openings existed on buildings.

Recently, Oh et al. (2007) carried out wind tunnel simulations using models with two different opening sizes and uniformly distributed background leakage. Parallel numerical and spectral investigations showed that while it is sufficient to use a Single Discharge Equation (SDE) approach for the opening with porosity ratio of 7%, a MDE approach is necessary to accurately predict the internal pressure response for the case of the opening with a porosity ratio of 70%. It was also found that the MDE approach out-performed the continuity equation (based on simple mass balance) in predicting the internal pressure response of a nominally sealed but leaky building due to consideration of compressibility effects. Their observations were further supported by Kopp et al. (2008) who using wind tunnel studies of a typical north American dwelling model reported peak attic internal pressures of 80% of that of the leaving space (internal volume of rooms) with a windward dominant opening for an internal opening of area just 0.4% of the false ceiling separating the leaving area from the attic in presence of uniformly distributed wall background leakage of porosity ratio 11%.
This paper seeks to reinforce the findings of past researchers by numerically investigating the effect of background leakages on internal pressure fluctuations. A non-linear model following the work of Yu et al. (2008) is proposed wherein the uncertainties described before were overcome by using simplifications such as lumping of the leakages on the leeward side (with suction pressure) and ignoring the effect of inertia and pipe-friction losses through leakage openings. The determination of external pressure at individual leakage opening is impossible in real life; hence the area and time averaged leeward suction pressure coefficient had been used in derivation of the governing equation. These simplifications partly arise out of the practical limitations involved in procuring data and partly due to reasoning. Vickery (1994) and Harris (1990) for example, had shown using sample calculations that for nominally sealed but leaky buildings, the effect of damping through leakage holes is around $10^7$ orders of magnitude greater than the effect of inertia; hence the inertial term in the discharge equations for leakage holes were safely neglected. The lack of knowledge of the individual leakage geometry in real life i.e. effective length and diameter restricted the possibility of taking into consideration the effect of pipe-friction losses and uncertainties regarding their distribution as well as lack of knowledge of their loss coefficients forced the usage of area and time averaged leeward wall external pressure coefficient and a representative loss coefficient respectively. As shown by past research [Selvam (1992)], the leeward wall external pressure fluctuations are much less as compared to sidewall and roof external pressure fluctuations (influenced by flow separation and reattachment) and hence using a time averaged value (easily available from wind tunnel tests) was not totally unjustified in the derivation of the governing differential equation. Numerical solutions to the proposed analytical model shows the presence of additional damping caused by the background leakage with the internal pressure fluctuations being reduced by more than 50% due to an increase in leakage area from zero to 0.50.

2. NON-LINEAR MODEL: GOVERNING EQUATION

A schematic of the building model with a windward opening and leakages lumped on the leeward side is presented in figure 1.

![Figure 1: Windward dominant opening with background leakages on the leeward side](image)

Assuming, the instantaneous area averaged windward external pressure coefficient at the opening $C_{peW} = p_{eW}/q$ to be greater than the instantaneous internal pressure coefficient $C_{pi} = p_i/q$ i.e. ($C_{peW} > C_{pi}$), the equation of motion of the oscillatory air slug through the windward dominant opening can be represented by the unsteady orifice discharge equation for an incompressible flow as follows:
\[ \rho l_v \dot{v} = q \left( C_{pw} - C_{pl} \right) - C_L \frac{\rho}{2} v |v| \]  

(1)

where \( \rho \) is the density of air inside the building cavity, \( l_v \) is the effective length of the oscillatory air slug at the windward opening, \( v \) and \( \dot{v} \) are the velocity and acceleration of flow through the opening respectively, \( C_L \left( \frac{1}{1 - (A_W/A_{WW})^4} \right) \approx 1/c^2, A_W \ll A_{WWL} \) is the thin orifice-plate loss coefficient [White (1999)]; \( A_W, A_{WWL} \) and \( c \) being the windward opening area, windward wall area and orifice discharge coefficient respectively and \( q = 0.5 \rho U_h^2 \) is the reference dynamic pressure; \( U_h \) being the ridge height velocity.

For the leakages lumped on the leeward side with effective thickness of openings comparable to their diameters (\( l_e = d \)), the pipe-friction losses become significant and the equation of motion through an individual leakage path assuming instantaneous internal pressure coefficient \( C_{pi} = \bar{p}/q \) to be greater than the instantaneous area averaged leeward pressure coefficient \( C_{peL} = \bar{peL}/q \) i.e. \( C_{pi} > C_{peL} \) is given by Oh et al. (2007):

\[ \rho l_v \dot{v}_n = q \left( C_{pi} - C_{peL} \right) - C_L \frac{\rho}{2} v_n |v_n| - \frac{32 \mu l_v d_n}{\rho} v_n \]  

(2)

where subscript \( n = 1, 2, 3 \ldots \) represents individual leakage openings. As explained previously, simplification to equation (2) can be made by ignoring the inertial as well as pipe-friction loss terms of individual leakage openings and replacing individual opening pressure and loss coefficients \( C_{peL} \) and \( C_L \) and by an area and time averaged leeward wall external pressure coefficient \( C_{peL} \) and representative loss coefficient \( C_L' \) respectively in terms of a lumped leakage discharge equation as:

\[ C_L' \frac{\rho}{2} v_L |v_L| = q \left( C_{pi} - C_{peL} \right) \]  

(3)

where \( v_L \) is the velocity of flow through the representative lumped leeward leakage.

Now conservation of mass requires that difference between the rate of mass influx at the windward opening and the mass flux out of the leeward leakage should be equal to the rate of change of mass of air inside the building volume as shown in figure 1. This can be written as:

\[ \rho \left( A_W \dot{v} - A_L \dot{v}_L \right) = V_0 \frac{dp}{dt} \]  

(4)

where \( A_L \) is the area of the lumped leakage on the leeward side and \( V_0 \) is the internal volume of the building. Assuming small air density changes between the immediate external region and an internal point within the convergent flow region along a streamline as well as ignoring the effect of flexibility of the building envelope, the isentropic gas law yields:

\[ \frac{dp}{\gamma} = \frac{q}{\gamma} \frac{dC_{pi}}{dt} \]  

(5)

where \( \gamma = 1.4 \) is the ratio of specific heat capacities of air for an isentropic process and \( P_a \) is the ambient pressure of air. Thus equation (5) can be used to modify equation (4) as:

\[ c A_W \dot{v} - A_L \dot{v}_L = q V_0 \frac{dp}{dt} \]  

(6)

Replacing \( v_L \) from equation (3) in equation (6), the velocity of flow (\( v \)) and its derivative (\( \dot{v} \)) through the dominant windward opening can be expressed as:
Finally, replacing $\nu$ and $\dot{\nu}$ from equations (7) and (8) in equation (1), the governing differential equation of internal pressure response through the windward dominant opening considering the effect of background leakage can be worked out as:

$$
\rho l V_0 \frac{d^2 C_{pi}}{dt^2} + \frac{A_L U_h}{2 A_W \sqrt{C_L (C_{pi} - C_{pel})}} \frac{d C_{pi}}{dt} = 0
$$

(9)

As can be seen from equation (9), consideration of the effect of background leakage results in an additional linear damping term whose magnitude is directly proportional to the total leakage area ($A_L$). Putting $A_L = 0$ in equation (9) yields the governing equation of internal pressure response for a single windward dominant opening as derived by Sharma & Richards (1997).

The Helmholtz frequency of resonance ($f_{HH}$) can be seen to be given by equation (9) as:

$$
f_{HH} = \frac{1}{2\pi} \sqrt{\frac{\rho P_0 A_W}{l V_0}}
$$

(10)

It can be seen that equation (9) is essentially non-linear and numerical methods are needed to be employed to obtain the time history of internal pressure response under forcing by windward and leeward external pressure coefficients.

### 3. RESULTS AND DISCUSSION

Numerical solutions to the proposed non-linear model were obtained using the second-order Runga-Kutta method for a range of porosities ($A_L/A_W$) varying from 0 to 50%. A 10 seconds time history of internal pressure response of a building representative of the TTU test setup [15] following a step change of the windward opening area averaged pressure coefficient ($C_{peW} = 0.7$) is presented in figure 2. A synthetically generated 10 seconds external pressure time history from Kaimal spectrum [VDI 3783-Part 12 (2000)] using appropriate aerodynamic admittance as proposed by Vickery (1965) was also used to force the internal pressure response of the same building configuration and presented in figure 3. A building internal volume ($V_0$) of 497 m$^3$ and a windward opening area ($A_W$) of 1.94 m$^2$ were used for computations. A discharge coefficient ($c$) of 0.6 and an opening loss coefficient ($C_L$) of 1.2 were used following the work of Sharma & Richards (1997). A representative loss coefficient ($C_L' \approx 1/c^2$) of 2.68 was considered for the lumped leeward leakage opening. The area and time averaged leeward wall external pressure coefficient ($C_{pel}$) of -0.3 and a design wind speed ($U_h$) of 30 m/s was used for the simulation purpose.
The effect of additive damping of internal pressure response with increase in background leakage is evident from both figures 2 and 3. There is a reduction in the amplitude of fluctuation of internal pressure by around 40\% with increase in porosity ratio from 0 to 50\%.

The gain function of internal pressure over the windward external pressure fluctuations were carried out by forcing the internal pressure response using a sinusoidally varying external pressure coefficient given by $0.6 + \sin(2\pi f - \pi/2)$ over a range of excitation frequencies $f$ from 0 to 10 Hz. The mean external pressure coefficient of 0.6 corresponds to the area averaged value over the extent of the windward dominant opening while amplitude of 0.14 corresponds to a root-mean square pressure coefficient of 0.14. Solutions were obtained up to 10 seconds in order to estimate the steady state amplitude ratios for obtaining the gain functions presented in figure 4.
Figure 4 shows that the magnitude of Helmholtz frequency ($\approx 2.5$ Hz) of the building setup remains unchanged with change in porosity ratio. This is expected as the theoretical value of Helmholtz frequency as given by equation (10) is independent of the magnitude of porosity of the building. However the gain of internal pressure fluctuations steadily decreases with increase in porosity ratio due to the additional damping provided by the linear damping term in the governing equation (9).

The effect of background leakage on internal pressure fluctuations is estimated as the ratio of root-mean square value of internal pressure in presence of background leakage to that of the root-mean square value without background leakage as function of porosity ratio for a range of non-dimensional opening area-building internal volume ($V_0$) and presented in figure 5. The results which qualitatively match to those reported by Yu et al. (2008) shows a reduction in internal pressure fluctuations with increase in porosity ratio for all values of the non-dimensional opening area-building internal volume ratio. The most interesting observation, however, is that for a porosity ratio of 10%, the internal pressure fluctuations are within 90% of the no leakage configuration for $A_{V_0}^{3/2}/V_0 = 0.001, 0.002$ and 0.003 respectively. This is in agreement with the observations of Vickery & Bloxham (1992) and a conservative estimate is to neglect the mitigating effect of background leakage for design purposes. However, for values of $A_{V_0}^{3/2}/V_0$ beyond 0.003, the internal pressure fluctuations decrease rapidly with a 20% decrease in internal pressure fluctuations for $A_{V_0}^{3/2}/V_0 = 0.01$. The system, thus gradually proceeds to behave like a two opening system with openings located on opposite (windward and leeward) faces and some reduction in internal pressure gust factor may be permitted provided sufficient damping is being provided for by the cavity air and envelope flexibility.
Figure 5: Influence of background leakage and non-dimensional area-volume ratio on fluctuating internal pressure variance

Power spectral density (psd) plots of the internal pressure response of a building representative of the TTU test setup following a step change in area averaged windward external pressure coefficient over a range of porosity ratios varying from zero to 50% in figure 6 confirm the presence of Helmholtz resonance at around a frequency of 2.5 Hz as shown in figure 4 earlier.

Figure 6: Power spectral density of internal pressures for different porosity ratios

Numerical integration of the psd plots over the entire frequency band carried out using equation (11) gives the fluctuating (RMS) internal pressure for each porosity ratio.

\[ \widetilde{C}_{pi}(f, A_l/A_w) = \int_0^\infty S_{C_p}(f, A_l/A_w) df \]  

(11)

The RMS internal pressure coefficients calculated using equation (11) is summarized in table 1 for porosity ratios varying from 0 to 0.50.

<table>
<thead>
<tr>
<th>$A_l/A_w$</th>
<th>0</th>
<th>0.10</th>
<th>0.20</th>
<th>0.30</th>
<th>0.40</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{pi}$ (RMS)</td>
<td>0.1366</td>
<td>0.0997</td>
<td>0.0780</td>
<td>0.0648</td>
<td>0.0564</td>
<td>0.0501</td>
</tr>
</tbody>
</table>

Table 1: Calculated RMS internal pressure coefficients for different porosity ratios
It shows that background leakage decreases the RMS values thus confirming the idea to date that background leakage has a generally damping effect on internal pressure fluctuations. Infact, a decrease in internal pressure variance by more than half is caused by an increase in leakage from zero to 50%.

5. CONCLUSIONS

The effect of background leakage on wind induced internal pressure fluctuations through a dominant opening is investigated. The governing equation has been suitably modified using relevant simplifications including lumping of the leakage holes on the leeward side, ignoring the effect of inertia as well as pipe-friction losses in the discharge equation for leakages, using an averaged representative loss coefficient for lumped leakage paths and a time and area averaged value of leeward wall pressure coefficient in the forcing term for discharge through leakages. The mitigating effects of background leakages are quantified using an additive linear damping term in the governing equation. The results indicate that background leakages do damp out the internal pressure fluctuations and increase in background leakage gradually shifts the system behavior from that with a single dominant opening to a two opening system with openings located on opposite (windward and leeward) faces. Numerical simulations show a decrease in RMS internal pressure value by around 63% with increase in porosity ratio from zero to 50%.

REFERENCES


