The effect of background leakage on wind induced internal pressure fluctuations in a low rise building with a dominant opening

GUHA T.K. ¹, SHARMA R.N. ², RICHARDS P.J. ³

¹Ph.D. Candidate, University of Auckland, Auckland, New Zealand, tguh001@aucklanduni.ac.nz
²Senior Lecturer, University of Auckland, Auckland, New Zealand, r.sharma@auckland.ac.nz
³Associate Professor, University of Auckland, Auckland, New Zealand, pj.richards@auckland.ac.nz

ABSTRACT

The objective of this paper is to numerically investigate the effect of background leakage on wind induced internal pressure fluctuations in a low-rise building with a windward dominant opening. The leakages were lumped on the leeward side for simplicity and the governing differential equation of internal pressure response was further simplified by ignoring the effect of inertia and pipe-friction losses in the discharge equation for leakages. The loss coefficients of individual leakages were replaced by a representative average loss coefficient and a time and area averaged value of leeward wall pressure coefficient was used in the forcing term. The simplifications adopted 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. A linear analogue presented offers a reasonably good simplification of the non-linear model.

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 [1], Liu and Saathoff [2], Vickery and Bloxham [3], Sharma and Richards [4] 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. Since the flow field developed past a bluff body such as a building is highly anisotropic, geometry and location of the dominant openings with respect to the prevailing wind directions, internal volume and compartmentalization of the building, turbulence in the upstream flow all affect the internal pressure response significantly. 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 [5] 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.

Vickery and Bloxham [3] conducted wind tunnel experiments using a model scale building for a range of dominant openings and back face (leeward) leakages in both smooth uniform and turbulent shear flow. The resonant component of fluctuating internal pressure decreased with increase in leeward background leakage area causing them to conclude that the presence of background leakage increases damping and attenuates the resonant response. They reported that the Helmholtz resonance contribution to the internal pressure variance is roughly halved with a background leakage area more than 10% of the dominant opening area.

Woods and Blackmore [6] conducted wind tunnel studies using 1:200 scale cube model with a range of dominant windward and leeward opening size (area ratio of 25%, 16%, 9%, 4% and 1%) and background leakage (porous opposite wall). The measured values of mean internal pressure were similar to the average pressure at the dominant opening for all azimuths for area ratios 25%, 16%, 9% and 4%. However, for the case of opening with area ratio of 1%, the opening size was comparable to the size of pours (area ratio of 1.5%) and the measured internal pressure was an arithmetic average of the opening pressures on the windward and leeward wall like a two opening case. They concluded that the effect of the opening is dominant when its area is about 2.5 times the equivalent area of the leakages which is in close agreement with the definition of dominant opening provided by Cook [7]. Cook defined a dominant opening as an opening with area at least twice the size of the total area of distributed leakages in a building.

Fahrtash and Liu [8] 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. [9] as part of UWO, TTU and NIST initiative to develop an aerodynamic database of internal pressure for low rise buildings, carried out wind tunnel simulations on a 1:100 scale building model with openings of two types: a) Uniform background leakage consisting of 80 holes distributed uniformly on the walls and b) Dominant openings of two sizes with porosity ratios (ratio of background leakage to the dominant opening area) 7% and 70% respectively. They conducted parallel numerical investigations using single unsteady discharge equation (corresponding to the dominant opening), multiple unsteady discharge equation (corresponding to the dominant opening as well as each of the leakage holes) and continuity equation (based on mass balance) to predict the time history and spectra of internal pressure fluctuations for nominally sealed (no dominant opening) configuration and for dominant openings with background leakages. For the case of dominant opening with porosity ratio 7%, the numerically simulated time history fluctuations and spectra of internal pressure using unsteady single and multiple discharge equations were in close agreement to the measured data indicating the insignificance of the effect of background leakage on internal pressure response. Thus, the internal pressure response was found to be guided by the external pressure fluctuations over the dominant opening and presence of background leakage did not influence the internal pressure variance significantly. However, for the case of dominant opening with porosity ratio 70%, the effect of inertia (acceleration dependent term in the discharge equation) was reported to
be prominent as indicated by the close agreement between measured data and numerical simulation based on multiple discharge equation. The simulation based on single discharge equation produced higher values because it did not take into the account the mitigating effects of background leakage. For the case of configuration consisting of only leakage holes (representing a nominally sealed but leaky building), numerical simulations were carried out using the multiple discharge equation as well as continuity equation. The multiple discharge equation provided better agreement with the measured data while the results based on continuity equation showed greater energy content at high frequencies due to ignorance of compressibility effects. Their observations were further supported by Kopp et al. [10] 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. 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 [5] and Harris [11] 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 [12], 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. A linear model is also presented by lumping of the leakages on the leeward side and gain functions of internal pressure fluctuations over the windward external pressure as a function of porosity ratio have been obtained using the proposed model. It is found that the linear model provides a simplified alternative to the non-linear model without much compromise on accuracy.

**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.
Assuming, the instantaneous area averaged windward external pressure coefficient at the opening \( (C_{pwW} = p_{ww} / q) \) to be greater than the instantaneous internal pressure coefficient \( (C_{pi} = p_i / q) \) i.e. \( (C_{pwW} > C_{pi}) \), 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:

\[
\rho l_e \dot{v} = q(C_{pwW} - C_{pi}) - C_L \frac{\rho}{2} v^2 \nabla \cdot \nabla \nabla
\]

where \( \rho \) is the density of air inside the building cavity, \( l_e \) 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, \( C_L \) \( = \left[ 1 - (A_W / A_W W W L)^4 \right] / c^2 \approx 1/c^2, A_W < A_W W W L \) is the thin orifice-plate loss coefficient \([13]\); \( A_W, A_W W W L \) 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 \( (l_e \approx d) \), the pipe-friction losses become significant and the equation of motion through an individual leakage path assuming instantaneous internal pressure coefficient \( (C_{pi} = p_i / q) \) to be greater than the instantaneous area averaged leeward pressure coefficient \( (C_{pWL} = p_{WL} / q) \) i.e. \( (C_{pi} > C_{pWL}) \) is given by \([9]\):

\[
\rho l_{en} \dot{v}_n = q(C_{pi} - C_{pWL}) - C_{nL} \frac{\rho}{2} v^2 n v_n - \frac{3 \mu L_n}{d_n^2} v_n
\]

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 \( (C_{pWL} \text{ and } C_{L_n}) \) by an area and time averaged leeward wall external pressure coefficient \( (C_{pWL}) \) and representative loss coefficient \( (C_L) \) respectively in terms of a lumped leakage discharge equation as:
\[ C_{L}^2 v_L | v_L | = q \left( C_{pi} - \bar{C}_{pL} \right) \]  \hspace{1cm} (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:

\[ \rho (cA_W v - A_L v_L) = V_0 \frac{d\rho}{dt} \]  \hspace{1cm} (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:

\[ \frac{d\rho}{dt} = \frac{q}{\gamma P_a} \frac{dC_{pi}}{dt} \]  \hspace{1cm} (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:

\[ cA_W v - A_L v_L = \frac{V_0 q}{\gamma P_a} \frac{dC_{pi}}{dt} \]  \hspace{1cm} (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:

\[ v = \frac{V_0 q}{\gamma P_a c A_W} \frac{dC_{pi}}{dt} + \frac{A_L}{A_W \sqrt{2\rho c_L}} \left( C_{pi} - \bar{C}_{pL} \right) \]  \hspace{1cm} (7)

\[ \dot{v} = \frac{V_0 q}{\gamma P_a c A_W} \frac{d^2 C_{pi}}{dt^2} + \frac{A_L U_h}{2A_W \sqrt{C_L \left( C_{pi} - \bar{C}_{pL} \right)}} \frac{dC_{pi}}{dt} \]  \hspace{1cm} (8)

Finally, replacing \( v \) and \( \dot{v} \) 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:

\[ \rho \frac{l_v V_0}{c A_W P_a} \frac{d^2 C_{pi}}{dt^2} + \frac{A_L \rho U_h l_v}{2A_W q \sqrt{C_L \left( C_{pi} - \bar{C}_{pL} \right)}} \left\{ \frac{dC_{pi}}{dt} + \frac{A_L U_h \gamma P_a}{q V_0} \sqrt{\frac{C_{pi} - \bar{C}_{pL}}{C_L'}} \right\} + \frac{C_L \rho q V_0^2}{2(y A_W P_a)^2} \left\{ \frac{dC_{pi}}{dt} + \frac{A_L U_h \gamma P_a}{q V_0} \sqrt{\frac{\left( C_{pi} - \bar{C}_{pL} \right)}{C_L}} \right\} = C_{pi} = C_{pL} \]  \hspace{1cm} (9)

The resulting model is similar in form to a non-linear model proposed by Yu et al. [14]. 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 and Richards [4].

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

\[
f_{HH} = \frac{1}{2\pi} \sqrt{\frac{\gamma A_W c p \rho}{\rho l_e V_0}}
\]  

(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.

**LINEAR ANALOGY: GOVERNING EQUATIONS**

Figure 2 presents an analogous linear system with a windward dominant opening and a leeward opening (representing combined area of lumped leakages) through which air jets of mass \(\rho c A_W l_e\) and \(\rho c A_L l_e L\) (being the effective length of the air slug oscillating through the leeward opening) respectively oscillates as air-spring systems with damping coefficients \(c_{j1}\) and \(c_{j2}\). The internal pressure in the system is considered to behave linearly.

When the air jets through the windward and leeward openings are displaced by \(X_W\) and \(X_L\) respectively, the change in volume is given by:

\[
\Delta V = V - V_0 = -c_1 A_W X_W + c_2 A_L X_L
\]  

(11)

Assuming volume changes to be small, the isentropic gas law for air can be written as:

\[
-q \frac{\Delta c_{pi}}{\Delta V} \approx -q \frac{d c_{pi}}{dV} = \frac{\nu P_A}{V_0}
\]  

(12)
Equations (11) and (12) can be used to express internal pressure coefficient \( C_{pi} \) in terms of air slug/jet displacements as:

\[
C_{pi} = \frac{\gamma P_a}{q V_0} (c_1 A_w X_1 - c_2 A_L X_2)
\]  

(13)

By summation of forces acting on the air slug/jets, and using the above relations, the equations governing the motion of the air slugs are obtained as:

\[
\ddot{X}_1 + \frac{c_{js}}{\rho c_A w_1} \dot{X}_1 + \frac{\gamma P_a c_A A_w}{\rho l e V_0} X_1 = \frac{c_{psW}}{\rho l e} + \frac{\gamma P_a c_A A_L}{\rho l e V_0} X_2
\]

(14)

\[
\ddot{X}_2 + \frac{c_{j2}}{\rho c_A w_2} \dot{X}_2 + \frac{\gamma P_a c_A A_L}{\rho l e V_0} X_2 = -\frac{c_{psL}}{\rho l e} + \frac{\gamma P_a c_A A_L}{\rho l e V_0} X_1
\]

(15)

The procedure to obtain exact solutions of equations (13) through (15) is too cumbersome; however the equations can be Laplace transformed into frequency domain to obtain the transfer functions between internal and external pressures (both windward and leeward) as presented:

\[
\left| \frac{C_{psW}}{C_{psL}} \right| = \frac{\sqrt{w_{11}^2 (w^2 - w_2^2 w_a^2) + w^2 w_{22}^2 w_{11}^2 + [w_{11}^2 (-w^2 w_c + w w_b^2) - w_{22}^2 w_{11}^2 w w_j^2]}}{\sqrt{[(w^2 + w_{11}^2)(w^2 - w_2^2) - (ww_{j1})(w^2 - w_2^2 w_c + w w_b^2)]^2 + [(w^2 + w_{22}^2)(-w^2 w_c + w w_b^2) + (ww_{j2})(w^2 - w_2^2 w_c^2)]^2}}
\]

(16)

\[
\left| \frac{C_{psL}}{C_{psW}} \right| = \frac{\sqrt{(w_{22}^2 w_c^2)^2 + (ww_{j2} w_{22}^2)^2}}{\sqrt{(w^2 - w_2^2 w_c)^2 + (-w^2 w_c + w w_b^2)^2}}
\]

(17)

where \( w = 2\pi f \) is the frequency of the exciting external pressure, \( w_{11} = \sqrt{\frac{\gamma P_a c_A A_w}{\rho l e V_0}} \) and

\( w_{22} = \sqrt{\frac{\gamma P_a c_A A_L}{\rho l e V_0}} \) are the undamped angular Helmholtz frequency of the building volume under windward and leeward opening respectively. In equations (16) and (17), \( w_{j1}, w_{j2}, w_a, w_b \) and \( w_c \) are defined as:

\[
w_{j1} = \frac{c_{js}}{\rho c_A X_1} \]

(18)

\[
w_{j2} = \frac{c_{j2}}{\rho c_A X_2} \]

(19)

\[
w_a = w_{11}^2 + w_{22}^2 + w_{j1} w_{j2}
\]

(20)

\[
w_b = w_{j1} w_{22} + w_{j2} w_{11}
\]

(21)

\[
w_c = w_{j1} + w_{j2}
\]

(22)

The damping coefficients (\( c_{j1} \) and \( c_{j2} \)) are determined following the linearization technique of Vickery and Bloxham [3] as:
The artificial rms internal pressure coefficient \( (\tilde{C}_{p_{12}} \text{ and } \tilde{C}_{p_{12}}) \) can either be obtained from the numerical solutions to the actual non-linear model or iteratively using the expression proposed by Sharma [15] as:

\[
\left( \frac{\tilde{C}_{p_{12}}}{\tilde{C}_{p_{12}}} \right)^3 - \left( \frac{\tilde{C}_{p_{12}}}{\tilde{C}_{p_{12}}} \right) = \frac{\pi^{1/2} \rho A_{p} \omega_{11} S_{p_{12}} (w_{11})}{2 \sqrt{\gamma}}
\]

\[
\left( \frac{\tilde{C}_{p_{12}}}{\tilde{C}_{p_{12}}} \right)^3 - \left( \frac{\tilde{C}_{p_{12}}}{\tilde{C}_{p_{12}}} \right) = \frac{\pi^{1/2} \rho A_{p} \omega_{22} S_{p_{12}} (w_{22})}{2 \sqrt{\gamma}}
\]

In equations (25) and (26), \( S_{p_{12}} (w_{11}) \) and \( S_{p_{12}} (w_{22}) \) are the values of power spectral density of windward and leeward external pressure coefficients respectively at Helmholtz frequency of \( \omega_{11} \) and \( \omega_{22} \). \( \tilde{C}_{p_{12}} \text{ and } \tilde{C}_{p_{12}} \) are the fluctuating windward and leeward external pressure coefficients obtained by integrating the respective power spectrums in frequency domain. The undamped natural frequency \( (w_r) \) of the linearized system is obtained by setting the damping terms to zero and equating the denominator of equation (16) or (17) to zero yielding

\[ w_r = \sqrt{w_{11}^2 + w_{22}^2}. \]

**RESULTS AND DISCUSSION**

**NON LINEAR MODEL: SAMPLE CALCULATION**

Numerical solutions to the 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 [16] following a step change of the windward opening area averaged pressure coefficient \( (\tilde{C}_{p_{12}} = 0.7) \) is presented in figure 3. A synthetically generated 10 seconds external pressure time history from Kaimal spectrum [17] using appropriate aerodynamic admittance as proposed by Vickery [18] was also used to force the internal pressure response of the same building configuration and presented in figure 4. A building internal volume \( (V_o) \) 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 and Richards [4]. 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 \( (\tilde{C}_{p_{12}}) \) of -0.3 and a design wind speed \( (U_{x}) \) of 30 m/s was used for the simulation purpose.
Figure 3: Time history response of wind induced internal pressure coefficient for a range of porosity ratios following a step change in area averaged external pressure coefficient

The effect of additive damping of internal pressure response with increase in background leakage is evident from both figures 3 and 4. 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 $0.6 + 0.2\sin(2\pi f - \pi/2)$ 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 an 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 5.
Figure 5: Gain of internal pressure fluctuations over area averaged windward external pressure for a range of porosity ratios

Figure 5 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 ($\frac{A^2}{V_0}$) and presented in figure 6. The results which qualitatively match to those reported by Yu et al. [14] 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 $\frac{A^2}{V_0} = 0.001, 0.002$ and 0.003 respectively. This is in agreement with the observations of Vickery and Bloxham [3] and a conservative estimate is to neglect the mitigating effect of background leakage for design purposes. However, for values of $\frac{A^2}{V_0}$ beyond 0.003, the internal pressure fluctuations decrease rapidly with a 20% decrease in internal pressure fluctuations for $\frac{A^2}{V_0} = 0.01$. 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 indoor air and envelope flexibility.
A comparison between the gains of internal pressure fluctuations over the area averaged windward external pressure for the non-linear model (already presented in figure 5) with that of the linear model obtained using equation (16) over a range of porosity ratios varying from 0.1 to 0.5 are shown in figure 7. It is to be noted that equation (16) has been derived by Laplace transforming equations (14) and (15) which assumes the internal pressure to behave linearly. An area and time averaged leeward pressure coefficient of -0.3, a root-mean square leeward pressure coefficient of 0.12 and a leeward loss coefficient of 2.68 representative of TTU test data [12] was used in the non-linear model for simulation purpose. A sinusoidal windward external pressure as used before used to force the internal pressure response up to 10 seconds.

While the undamped natural frequency ($\omega_r \approx 2.7$ Hz) of maximum gain given by the linear model shows reasonable agreement with the undamped Helmholtz frequency ($\approx 2.5$ Hz) calculated using the non-linear model, the linear model tends to slightly over predict the maximum gain for all porosity ratios probably due to the assumption of Gaussian distribution of internal pressure fluctuations used in the linearization process. Nevertheless, the general trend shown by both the models agree to a reasonable extent and it is fair to comment that the linear analogue provides a good simplification of the non-linear model.
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 like 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. The analogous linear model derived by lumping of leakages on the leeward side presents reasonably good agreement with the proposed non-linear model as evident from the gain function. It is recommended that wind tunnel and full scale studies be performed to further study the effects of background leakages in detail.

REFERENCES


