6 Internal pressures

6.1 Introduction

Internal pressures induced by wind can form a high proportion of the total design wind load in some circumstances – for example, for low-rise buildings when there are dominant openings in the walls. On high-rise buildings, a critical design case for a window at a corner may be an opening in the wall at the adjacent wall at the same corner – perhaps caused by glass failure due to flying debris.

In this chapter, the fundamentals of the prediction of wind-induced internal pressures within enclosed buildings are discussed. A number of cases are considered: a single dominant opening in one wall, multiple wall openings, and the effect of background wall porosity. The possibility of Helmholtz resonance occurring is also discussed.

6.2 Single windward opening

We will first consider the case of a dominant windward wall opening – a situation which often arises in severe windstorms – often after failure of a window glass due to flying debris. In a steady flow situation the internal pressure will quickly build up to equal external pressure on the windward wall in the vicinity of the opening – there may be some oscillations in internal pressure (Section 6.2.4), but these will die out after a short time. However, when a building is immersed in a turbulent boundary-layer wind, the external pressure will be highly fluctuating, and the internal pressure will respond in some way to these fluctuations. Since there is only a single opening, flow into the building resulting from an increase in external pressure will cause an increase in the density of the air within the internal volume; this, in turn, will produce an increase in internal pressure. The pressure changes produced by wind are only about 1% of atmospheric pressure (1000 Pa compared to atmospheric pressure of about 100,000 Pa), and the relative density changes are of the same order. These small density changes can be maintained by small mass flows in and out of the building envelope, and consequently the internal pressure can be expected to respond quite quickly to external pressure changes, except for very small opening areas.

6.2.1 Dimensional analysis

It is useful to first carry out a dimensional analysis for the fluctuating internal pressures, resulting from a single windward opening to establish the non-dimensional groups involved.

The fluctuating internal pressure coefficient, C_{pi} (t), can be written as:

$$C_{pi} = \frac{p_i - p_0}{\frac{1}{2}\rho_a \bar{U}^2} = F(\pi_1,\pi_2,\pi_3,\pi_4,\pi_5) \tag{6.1}$$

$$\pi_1 = A^{3/2}/V_o$$

where A is the area of the opening, and V_o is the internal volume

$$\pi_2 = \frac{p_0}{\frac{1}{2}\rho_a \bar{U}^2},$$

where p_o is the atmospheric pressure

$$\pi_3 = \rho_a \, \bar{U} A^{1/2}/\mu$$

where μ is the dynamic viscosity of air (Reynolds number)

$$\pi_4 = \frac{\sigma_u}{\bar{U}}$$

where σ_u is the standard deviation of the longitudinal turbulence velocity upstream

$$\pi_5 = \ell_u/\sqrt{A},$$

where ℓ_u is the length scale of turbulence (Section 3.3.4).

π_1 is a non-dimensional parameter related to the geometry of the opening and the internal volume, π_3 is a Reynolds number (Section 4.2.4) based on a characteristic length of the opening, π_5 is a ratio between characteristic length scales in the approaching flow and of the opening. π_2, the ratio of atmospheric pressure to the reference dynamic pressure, is a parameter closely related to Mach number.

Amongst these parameters, π_1 and π_4 are the most important. This is fortunate when wind-tunnel studies of internal pressures are carried out, as it is difficult or impossible to maintain equality of the other three parameters between full scale and model scale.

6.2.2 Response time

If the inertial (i.e. mass times acceleration) effects are initially neglected, an expression for the time taken for the internal pressure to become equal to a sudden increase in pressure outside the opening such as that caused by a sudden window failure, can be derived (Euteneur, 1970).

For conservation of mass, the rate of mass flow in through the opening must equal the rate of mass increase inside the volume:

$$\rho_i Q = \left(\frac{d\rho_i}{dt}\right) V_o \tag{6.2}$$

where ρ_i denotes the air density within the internal volume.

For turbulent flow through an orifice, the following relationship between flow rate, Q, and the pressure difference across the orifice, $p_e - p_i$, applies:

$$Q = kA\sqrt{\frac{2(p_e - p_i)}{\rho_a}} \tag{6.3}$$

where k is an orifice constant, typically around 0.6.

Assuming an adiabatic law relating the internal pressure and density,

$$\frac{p_i}{\rho_i^{\gamma}} = \text{constant} \tag{6.4}$$

where γ is the ratio of specific heats of air.

Substituting from (6.2) and (6.4) in (6.3), and integrating the differential equation, the following expression for the response, or equilibrium, time, τ, when the internal pressure becomes equal to the external pressure, can be obtained:

$$\tau = \frac{\rho_a V_o \bar{U}}{\gamma k A p_o}\sqrt{C_{pe} - C_{pio}} \tag{6.5}$$

where the pressures have been written in terms of pressure coefficients:

$$C_{pe} = \frac{p_e - p_o}{\frac{1}{2}\rho_a \bar{U}^2}$$

and

$$C_{pi} = \frac{p_i - p_o}{\frac{1}{2}\rho_a \bar{U}^2}$$

and C_{pio} is the initial value of C_{pi}, (i.e. at $t = 0$)

Example

It is instructive to apply equation (6.5) to a practical example. The following numerical values will be substituted:

$$\rho_a = 1.20 \text{ Kg/m}^3; \; V_o = 1000 \text{ m}^3; \; \bar{U} = 40 \text{ m/s};$$
$$\gamma = 1.4; \; k = 0.6; \; A = 1.0 \text{ m}^2; \; p_o = 10^5 \text{ Pa};$$
$$C_{pe} = +0.7; \; C_{pio} = -0.2$$

Then the response time,

$$\tau = \frac{1.2 \times 1000 \times 40}{1.4 \times 0.6 \times 1.0 \times 10^5}\sqrt{0.7 - (-0.2)} = 0.54 \text{ seconds}$$

Thus, even for a relatively large internal volume of 1000 cubic metres, equation (6.5) predicts a response time of just over half a second for the internal pressure to adjust to the external pressure, following the creation of an opening on the windward face of 1 square metre.

6.2.3 Helmholtz resonator model

In the previous example, inertial effects on the development of internal pressure following a sudden opening were neglected. These will now be included in a general model of internal pressure, which can be used for the prediction of the response to turbulent external pressures (Holmes, 1979).

The Helmholtz resonator is a well-established concept in acoustics (Rayleigh, 1896; Malecki, 1969), which describes the response of small volumes to the fluctuating external pressures. Although originally applied to the situation where the external pressures are caused by acoustic sources, it can be applied to the case of external wind pressures 'driving' the internal pressures within a building. It also describes the low-frequency fluctuations felt by occupants of a travelling motor vehicle, with an open window. Acoustic resonators made from brass or earthenware, based on this principle, were used to improve the acoustic quality in the amphitheatres of ancient Greece and Rome (Malecki, 1969).

Figure 6.1 illustrates the concept as applied to internal pressures in a building. It is assumed that a defined 'slug' of air moves in and out of the opening in response to the external pressure changes. Thus mixing of the moving air either with the internal air or the external air is disregarded in this model of the situation.

A differential equation for the motion of the slug of air can be written as follows:

$$\rho_a A \ell_e \ddot{x} + \frac{\rho_a A}{2k^2}\dot{x}|\dot{x}| + \frac{\gamma p_o A^2}{V_o}x = A\Delta p_e(t) \tag{6.6}$$

The dependent variable, x, in this differential equation is the displacement of the air 'slug' from its initial or equilibrium position. The first term on the left-hand side of equation (6.6) is an inertial term proportional to the acceleration, $\ddot{x}$, of the air slug, whose mass is $\rho_a A\ell_e$, in which ℓ_e is an effective length for the slug. The second term is a loss term associated with energy losses for flow through the orifice, and the third term is a 'stiffness' associated with the resistance of the air pressure already in the internal volume to the movement of the 'slug'.

A movement x in the air slug, can be related to the change in density $\Delta\rho_i$, and hence pressure, Δp_i, within the internal volume:

$$\rho_a A x = V_o \Delta\rho_i = \frac{\rho_i V_o}{\gamma p_o}\Delta p_i \tag{6.7}$$

Making use of equation (6.4) and converting the internal and external pressures to press-

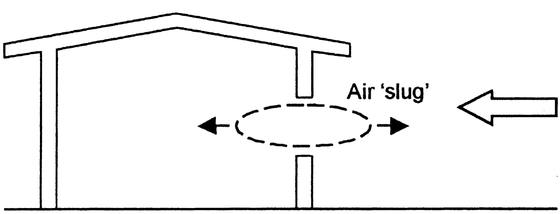

Figure 6.1 The Helmholtz resonator model of fluctuating internal pressures with a single dominant opening.

ure coefficients, equation (6.6) can be re-written in the form of a differential equation for the fluctuating internal pressure coefficient, $C_{pi}(t)$:

$$\frac{\rho_a \ell_e V_o}{\gamma p_o A}\ddot{C}_{pi} + \left(\frac{\rho_a V_o \bar{U}}{2k\gamma A p_o}\right)^2 \dot{C}_{pi}|\dot{C}_{pi}| + C_{pi} = C_{pe} \tag{6.8}$$

Equation (6.8) can also be derived (Vickery, 1986) by writing the discharge equation for unsteady flow through the orifice in the form:

$$p_e - p_i = \left(\frac{1}{k^2}\right)\frac{1}{2}\rho_a u_o^2 + \rho_a \ell_e \frac{du_o}{dt} \tag{6.9}$$

where ρ_a is taken as the air density within the volume (ρ_i), and u_o as the (unsteady) spatially-averaged velocity through the opening.

Equations (6.6) and (6.8) give the following equation for the (undamped) natural frequency for the resonance of the movement of the air slug, and of the internal pressure fluctuations. This frequency is known as the Helmholtz frequency, n_H.

$$n_H = \frac{1}{2\pi}\sqrt{\frac{\gamma A p_o}{\rho_a \ell_e V_o}} \tag{6.10}$$

Internal pressure resonances at, or near, the Helmholtz frequency, have been measured both in wind-tunnel studies (Holmes, 1979; Liu and Rhee, 1986), and in full scale.

The effective length, ℓ_e, varies with the shape and depth of the opening, and is theoretically equal to $\sqrt{(\pi A/4)}$ for a thin circular orifice. For practical purposes (openings in thin walls), it is sufficiently accurate to take ℓ_e as equal to $1.0\sqrt{A}$, (Vickery, 1986).

Equation (6.10) assumes that the building or enclosure has rigid walls and roof. Real buildings have considerable flexibility. In this case, it can be shown (Vickery, 1986) that the equation for the Helmholtz frequency becomes:

$$n_H = \frac{1}{2\pi}\sqrt{\frac{\gamma A p_o}{\rho_a \ell_e V_o[1 + (K_A/K_B)]}} \tag{6.11}$$

where K_A is the bulk modulus of air, $(\rho_a \Delta p)/\Delta\rho$, equal to $\gamma\, p_o$, and K_B is the bulk modulus for the building – i.e. the internal pressure for a unit change in relative internal volume.

The ratio K_A/K_B for low-rise buildings is in the range 0.2 to 5.

6.2.4 Sudden windward opening with inertial effects

Equation (6.8) can be solved numerically for the case of a step change in external pressure coefficient, C_{pe}, (representative of the situation after a sudden window failure). Figures 6.2(a) and (b) show the response of a 600 m^3 volume (rigid walls and roof) with opening areas of 1 m^2 and 9 m^2, respectively (Holmes, 1979). For these simulations, the effective length, ℓ_e, was equivalent to $0.96\sqrt{A}$, and the discharge coefficient, k, was taken as 0.6.

It is apparent from Figure 6.2(b) that the inertial effects are significant for the larger opening when the damping term in equation (6.8) is much smaller (note that the area, A, is in the denominator in this term). Many oscillatory cycles in internal pressure occur before equilibrium conditions are reached in this case. However, the flexibility of the walls

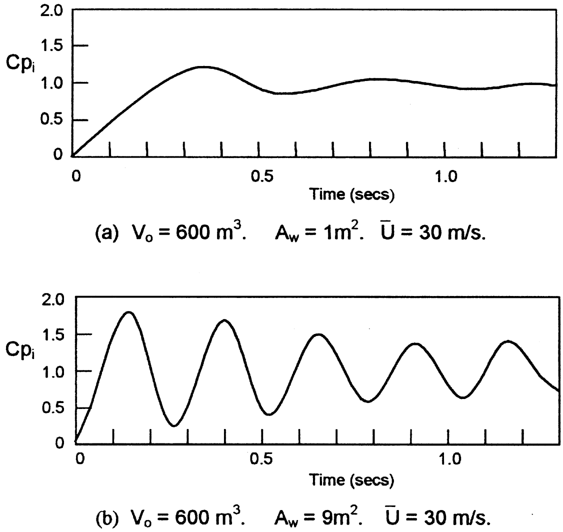

Figure 6.2 Response to a step change in external pressure, $V_o = 600$ m^3, ($\bar{U} = 30$ m/s. (a) $A = 1$ m^2 ; (b) $A = 9$ m^2.

and roof of real buildings, discussed in the previous section, also increases the damping term (Vickery, 1986), and hence cause more rapid attenuation of the oscillations.

6.2.5 Helmholtz resonance frequencies

Section 6.2.3 discussed the phenomenon of Helmholtz resonance in the interior of buildings, when there is a single opening, and equations (6.10) and (6.11) gave formulae to calculate the Helmholtz frequency, given the opening area, internal volume and flexibility of the roof and walls.

Applying equation (6.10) for the Helmholtz resonance frequency, and setting $p_o = 10^5$ Pa (atmospheric pressure), $\rho = 1.2$ kg/m^3 (air density), $\gamma = 1.4$ (ratio of specific heats), and ℓ_e equal to 1.0 $\sqrt{A}$, we have the following approximate formula for n_H:

$$n_H \approx 55 \frac{A^{1/4}}{V_o^{1/2}[1 + (K_A/K_B)]^{1/2}} \tag{6.12}$$

where K_A is the bulk modulus for air ($= \gamma p_o$), and K_B is the volume stiffness of the building structure (theoretically it is the internal pressure required to double the internal volume).

Equation (6.12) can be used to calculate n_H for typical low-rise buildings in Table 6.1 (Vickery, 1986).

Table 6.1 indicates that for the two smallest buildings, the Helmholtz frequencies are greater than 1 Hz, and hence significant resonant excitation of internal pressure fluctuations by natural wind turbulence is unlikely. However for the large arena, this would certainly be possible. However in this case the structural frequency of the roof is likely to be considerably greater than the Helmholtz resonance frequency of the internal pressures, and the latter will therefore not excite any structural vibration of the roof (Liu and Saathoff, 1982). It is clear, however, that there could be an intermediate combination of area and

Table 6.1 Helmholtz resonance frequencies for some typical buildings

Type	*Internal volume (m^3)*	*Opening area (m^2)*	*Stiffness ratio K_A/K_B*	*Helmholtz frequency (Hertz)*
House	600	4	0.2	2.9
Warehouse	5000	10	0.2	1.3
Concert hall	15 000	15	0.2	0.8
Arena (flexible roof)	50 000	20	4	0.23

volume (such as the 'concert hall' in Table 6.1), for which the Helmholtz frequency is similar to the natural structural frequency of the roof, and in a range which could be excited by the natural turbulence in the wind. However, such a situation has not yet been recorded.

6.3 Multiple windward and leeward openings

6.3.1 Mean internal pressures

The mean internal pressure coefficient inside a building with total areas (or effective areas if permeability is included) of openings on the windward and leeward walls of A_W and A_L, respectively, can be derived by use of equation (6.3), and applying mass conservation. The latter relation can be written for a total of N openings in the envelope:

$$\sum_{1}^{N} \rho_a Q_j = 0 \tag{6.13}$$

If quasi-steady and incompressible flow is assumed initially, we can assume the density, ρ_a, to be constant. Then, applying equation (6.3) for the flow through each of the N openings, equation (6.13) becomes:

$$\sum_{1}^{N} A_j \sqrt{|p_{e,j} - p_i|} = 0 \tag{6.14}$$

where the modulus, $|p_{e,j} - p_i|$, allows for the fact that for some openings the flow is from the interior to the exterior.

Figure 6.3 shows a building (or a floor of a high-rise building) with five openings in the envelope. Applying equation (6.14) to this case:

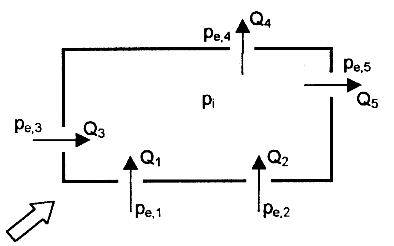

Figure 6.3 Inflows and outflows for a multiple openings.

$$A_1\sqrt{|p_{e,1}-p_i|} + A_2\sqrt{|p_{e,2}-p_i|} + A_3\sqrt{|p_{e,3}-p_i|} = A_4\sqrt{|p_{e,4}-p_i|} + A_5\sqrt{|p_{e,5}-p_i|} \tag{6.15}$$

In equation (6.15), the inflows through the windward openings on the left-hand side, balance the outflow through openings on the leeward and side walls, on the right-hand side. Equation (6.15), or similar equations for a large numbers of openings, can be solved by iterative numerical methods.

For the simpler case of a single windward opening with a single leeward opening equation (6.14) can be applied, with a conversion to pressure coefficients, to give:

$$A_W\sqrt{C_{pW}-C_{pi}} = A_L\sqrt{C_{pi}-C_{pL}}$$

This can be re-arranged to give equation (6.16) for the coefficient of internal pressure:

$$C_{pi} = \frac{C_{pW}}{1+\left(\frac{A_L}{A_W}\right)^2} + \frac{C_{pL}}{1+\left(\frac{A_W}{A_L}\right)^2} \tag{6.16}$$

Equation (6.16) can be applied with A_W taken as the combined open area for several openings on a windward wall, and C_{pW} taken as an average mean pressure coefficient, with similar treatment for the leeward/side walls. It has been applied to give specified values of internal pressures in design codes and standards (see Chapter 15), in which case the coefficients are used with mean pressure coefficients to predict peak internal pressures, making use of the quasi-steady assumption (see Section 4.6.2).

Measurements of mean internal pressure coefficients for a building model with various ratios of windward/leeward opening area are shown in Figure 6.4. The solid line in this Figure is equation (6.16) with C_{pW} taken as +0.7, and C_{pL} taken as –0.2. These values were the values of mean external pressure coefficients on the walls at or near the windward and leeward openings, respectively. It may be seen that the agreement between the measurements and equation (6.16) is good.

6.3.2 Fluctuating internal pressures

The analysis of fluctuating internal pressures when there are openings on more than one wall of a building is more difficult than for a single opening. In general numerical solutions are required (Saathoff and Liu, 1983). However, some useful results can be obtained if

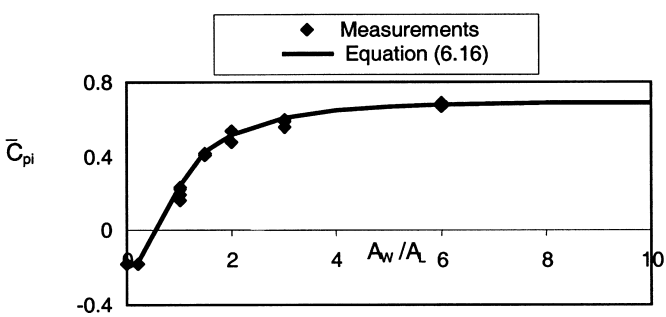

Figure 6.4 Mean internal pressure coefficient as a function of windward/leeward open area.

the inertial terms are neglected, and the damping term is linearized (Vickery, 1986, 1991; Harris, 1990). The neglect of the inertial term in comparison to the damping term is justified when there is background porosity in the walls of a building, but may not be so when there are one or more large openings.

It can be shown (Harris, 1990) that, when there is a combined open area on a windward wall of A_W and external pressure coefficient C_{pW}, and on a leeward wall with total open area A_L and external pressure coefficient C_{pL}, then there is a characteristic response time given by:

$$\tau = \frac{\rho_a V_o \bar{U} A_W A_L}{\gamma k p_o (A_W^2 + A_L^2)^{3/2}} \sqrt{C_{pW} - C_{pL}} \tag{6.17}$$

There is some similarity between equation (6.16) and equation (6.5) for a single opening, but they are not exactly equivalent. External pressure fluctuations which have periods much greater than τ are transmitted as internal pressures in a quasi-steady manner – that is they will follow equation (6.15). Fluctuations with periods of the same order as τ will be significantly attenuated; those with periods less than τ will negligible effect on the fluctuating internal pressures.

The effect of building wall and roof flexibility is such as to increase the response time according to equation (6.18), (Vickery, 1986):

$$\tau = \frac{\rho_a V_o \bar{U} A_W A_L [1 + (K_A/K_B)]}{\gamma k p_o (A_W^2 + A_L^2)^{3/2}} \sqrt{C_{pW} - C_{pL}} \tag{6.18}$$

For 'normal' low-rise building construction, K_A/K_B is about 0.2 (Vickery, 1986; and Section 6.2.5), and the response time therefore increases by about 20%.

6.4 Nominally sealed buildings

The situation of buildings that are nominally sealed, but have some leakage distributed over all surfaces, can be treated by neglecting the inertial terms, and lumping together windward and leeward leakage areas (Vickery, 1986, 1994; Harris, 1990).

A characteristic frequency, n_c, is obtained. Pressure fluctuations below this frequency are effectively communicated to the interior of the building. n_c is given by equation (6.19) (Vickery, 1994).

$$\frac{n_c V_o}{\bar{U} A_W} = \frac{1}{2\pi} \frac{k}{1 + (K_A/K_B)} \left(\frac{a_s}{\bar{U}}\right)^2 \frac{r^{1/2}\left(r + \dfrac{1}{r}\right)^{3/2}}{\sqrt{C_{pw} - C_{pL}}} \tag{6.19}$$

where r is the ratio A_L/A_W, a_s is the speed of sound and the other parameters were defined previously. The open areas, A_W and A_L are obtained by multiplying the total windward and leeward surface areas by the average porosity. Equation (6.19) is essentially the same as Equation (6.18), with τ equal to $(1/2\pi n_c)$.

The peak internal pressure coefficient can be estimated by:

$$\hat{C}_{pi} \cong \bar{C}_{pi}\left[1 + 2g\frac{\sigma'_u}{\bar{U}}\right] \tag{6.20}$$

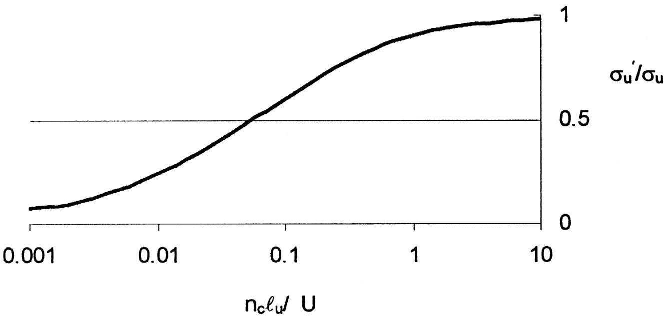

Figure 6.5 Reduction factor for fluctuating internal pressures, for a building with distributed porosity (Vickery, 1994).

where σ_u' is an effective, filtered standard deviation of velocity fluctuations that are capable of generating internal pressure fluctuation, given by:

$$\sigma'^2_u = \int_0^\infty S_u(n)/[1 + (n/n_c)]^2 dn \tag{6.21}$$

Equation (6.21) has been evaluated using equation (3.26) for the longitudinal turbulence spectrum, and σ'_u/σ_u is shown plotted against $(n_c\ell_u/\bar{U})$ in Figure 6.5 (Vickery, 1994). g is a peak factor which lies between 3.0 and 3.5. The mean internal pressure coefficient in equation (6.20) can be evaluated using equation (6.16).

Evaluation of equation (6.21) for a large warehouse building with a wall porosity of 0.0005, gave a value of σ'_u/σ_u equal to 0.7, i.e. there is a 30% reduction in the effective velocity fluctuations resulting from the filtering effect of the porosity of the building (Vickery, 1994).

6.5 Summary

The topic of internal pressures produced by wind has been covered in this chapter. The relevant non-dimensional parameters are introduced, and the response time of the interior of a building or a single room to a sudden increase in external pressure at an opening has been evaluated.

The dynamic response of an internal volume to excitation by a sudden generation of a windward wall opening, or by turbulence, using the Helmholtz resonator model, which includes inertial effects, has been considered. The effect of multiple windward and leeward openings on mean and fluctuating internal pressures, is introduced. The case of a nominally sealed building with distributed porosity is also considered.

Most of the results in this chapter have been validated by wind-tunnel studies, and, more importantly, by full-scale measurements (e.g. Ginger *et al.*, 1997).

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