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Computational modelling in the prediction of building internal pressure gain functions

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Abstract

This paper describes a methodology based on computational and analytical modelling techniques in the prediction of building internal pressure gain functions. It first involves computational modelling of the transient response following a sudden opening, which predicts both the Helmholtz frequency and the damping characteristics fairly accurately. The parameters derived by fitting the analytical model to the computed response are then used in the prediction of the gain function. Good agreement is obtained between measured and predicted internal pressure gain functions for the case of a cylinder and a 1 : 50 scale model of the TTU test building.

Keywords: Computational modelling; Internal pressure; Sudden opening; Helmholtz resonance; Gain function

1. Introduction

The safety of a building structure in strong winds depends as much on internal pressure as it does on external pressure. Two of the key issues concerning internal pressure are the level of overshoot in the transient response following a sudden dominant opening, and the subsequent steady-state (resonant) response to fluctuating external pressure in the presence of the opening. Various researchers, including Stathopoulos and Luchian [1], Vickery and Bloxham [2], and Yeatts and Mehta [3] have shown that the first of these is of little significance since the transients are lost amidst turbulence induced fluctuations and the overshoot if any is usually smaller than the peak internal pressure attained at steady-state. The steady-state response of internal pressure to wind turbulence in the presence of a dominant opening, which is a Helmholtz resonance type of response as first shown by Holmes [4], is therefore of

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greater significance in determining the ultimate design pressure. Despite the fact that in real life, the initial transient response is relatively unimportant, a proper understanding of the transient behaviour is however necessary in order to be able to predict correctly the steady-state (resonant) response to fluctuating external pressure. An understanding of the transient response results in two of the key parameters, firstly the natural or Helmholtz frequency and secondly the damping coefficient, required in the prediction of the resonant response.

For the limiting case of a rigid non-porous building with a dominant windward wall opening, a number of experimental and analytical studies in the past (see, e.g., Refs. [4–6]), have increased our understanding of internal pressure behaviour. Sharma and Richards [7] recently applied computational modelling for the first time in a study of the transient response behaviour of building internal pressure to sudden openings. It was shown that the computer model, based on the commercial package PHOENICS™, predicts the Helmholtz oscillation frequency as well as the damping characteristics fairly accurately. The study also established through computational flow visualisation, that formation of a vena-contracta does take place past the opening, despite the unsteady nature of the flow.

This paper describes an extension of the study discussed in Ref. [7] to utilise the transient response obtained from computational modelling in predicting the building internal pressure gain function which is important in the study of the steady-state response. The studies discussed in Ref. [7] and in this paper are part of a more comprehensive study on building internal pressure described in detail by Sharma [8].

2. Theoretical considerations

It can be shown [7,8] that the differential equation governing the dynamics of internal pressure in the presence of a dominant opening is of the form:

$$\frac{\rho_a L_e \forall_o}{\gamma c A_o p_a}\ddot{C}_{p_i} + C_L \frac{\rho_a q \forall_o^2}{2(\gamma A_o p_a)^2}|\dot{C}_{p_i}|\dot{C}_{p_i} + \frac{(\mu_{eff}/\Delta r)PL_e\forall_o}{\gamma c^2 A_o^2 p_a}\dot{C}_{p_i} + C_{p_i} = C_{p_e}. \quad (1)$$

The linear damping term arises as a result of apertrure wall shear stresses and is significant only at model-scale or for very small openings. The Helmholtz frequency f_{HH} is readily obtained from Eq. (1), and is dependent on the area of the opening A_o, the building volume $\forall_o$, and the effective length of the air slug that oscillates at the opening L_e:

$$f_{HH} = \frac{\omega_{HH}}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{\gamma c A_o p_a}{\rho_a L_e \forall_o}}. \quad (2)$$

In these equations, ρ_a, p_a, γ, and μ_{eff} are the density, pressure, specific heat ratio, and viscosity of ambient air respectively, $\forall_o$ is the building internal volume, c and C_L are the discharge and loss coefficients for the opening of area A_o and circumferential perimeter P, L_e is the effective length of the air jet/slug at the opening (physical length

L_o), and Δr is a distance used in defining the wall shear stress in the aperture. Internal and external pressures are represented by the internal and external pressure coefficients $C_{p_i} = p_i/q$ and $C_{p_e} = p_e/q$ where $q = \frac{1}{2}\rho_a \overline{U}_h^2$ is the reference dynamic pressure based on the ridge-height velocity $\overline{U}_h$.

In order to determine the previously ill-defined parameters, namely the discharge coefficient c, the loss coefficient C_L, and the effective length of the air slug L_e, appropriate guidelines were developed. This was possible from computational and experimental modelling of sudden openings on a range of building and cavity models, as well as from spectral measurements in the wind tunnel. The details of this study are contained in Ref. [8], and only the results summarised hereafter are considered appropriate in the context of the present discussions. The guidelines involve classification of openings into thin and long openings according to the ratio of its physical length L_o to the effective radius $r_{eff} = \sqrt{A_o/\pi}$ as follows:

1. For *long openings* when $L_o/r_{eff} > 1.0$:

$$c = 1.00, \quad C_L = 1.50, \quad L_e = L_o + 1.73\sqrt{A_o/\pi}.$$

2. For *thin openings* when $L_o/r_{eff} < 1.0$:

$$c = 0.60, \quad C_L = 1.20.$$

(a) Window near the centre of the wall (i.e. away from side walls, floor, and the roof):

$$L_e = L_o + 1.39\sqrt{A_o/\pi}.$$

(b) Window near side wall or door near the floor:

$$L_e = L_o + (1.17\text{–}1.29)\sqrt{A_o/\pi}.$$

(c) Door at the corner of the wall (i.e. adjacent to the side wall and the floor):

$$L_e = L_o + 1.61\sqrt{A_o/\pi}.$$

It is important to note that the discharge coefficient c appears because flow contraction can take place past the opening thus reducing the inertia of the effective air jet/slug. Its presence therefore in the governing equations determines the inertia of the air slug and therefore the Helmholtz frequency, and does not in any way represent the losses through the opening. When a transient response of internal pressure to a step change in steady external pressure (i.e. that does not fluctuate) is obtained from computational modelling, the unknown parameters in Eq. (1) may be readily obtained by fitting the numerical solution to Eq. (1) to the computed response.

In order to obtain the gain function from Eq. (1), it must first be linearised. This is possible by equating the energy dissipated by the sum of the non-linear and linear damping terms to that dissipated by an equivalent linear damping term $c_{eq}\dot{C}_{p_i}$. If as assumed by Vickery and Bloxham [2], that internal pressure is of Gaussian distribution (this applies when excitation, in this case external pressure, can be approximated as being of Gaussian distribution), then an estimate of the equivalent damping term is determined by integration to yield:

$$c_{\mathrm{eq}} = \sqrt{8\pi}\frac{C_L q \forall_o f_{\mathrm{HH}} \tilde{C}_{p_i}}{\gamma(L_e/c)A_o p_a} + \frac{(\mu_{\mathrm{eff}}/\Delta r)P}{\rho c A_o}. \tag{3}$$

In this expression, $\tilde{C}_{p_i}$ is the root-mean-square value of internal pressure coefficient fluctuations, which may be determined from equations derived by Vickery and Bloxham [2]. The linearised equation:

$$\ddot{C}_{p_i} + c_{\mathrm{eq}}\dot{C}_{p_i} + \omega_{\mathrm{HH}}^2 C_{p_i} = \omega_{\mathrm{HH}}^2 C_{p_e} \tag{4}$$

is readily (Laplace) transformed to obtain an expression for the gain function of internal pressure over the external:

$$|\chi_{p_i - p_e}| = \frac{|C_{p_i}|}{|C_{p_e}|} = \left[\left(\frac{\omega_{\mathrm{HH}}^2 - \omega^2}{\omega_{\mathrm{HH}}^2}\right)^2 + \left(\frac{\omega c_{\mathrm{eq}}}{\omega_{\mathrm{HH}}^2}\right)^2\right]^{-1/2} \tag{5}$$

where $\omega = 2\pi f$ is the angular frequency. If a computational model can be made to predict both the Helmholtz frequency and the damping characteristics correctly, this approach may be used to obtain the coefficients of the terms in the differential equation, and subsequently the gain of internal pressure over the external.

3. Computational modelling of the sudden opening

Some of the advantages of computational modelling of the transient response to a sudden opening include the possibility of a three-dimensional solution, the ability to monitor both pressure and velocities internally and in the vicinity of the opening, and the capability of flow visualisation in the ensuing unsteady flow. With experimental modelling on the other hand, only pressures can be measured with ease, while measurement of velocities and visualisation of flow near the opening would be quite difficult, if not impossible.

Computational modelling of sudden openings in the present study is the same as that described in Refs. [7,8], and which is based on the commercial package PHOENICS™. The package uses a finite volume code to solve the conservation equations for mass, momentum, turbulence kinetic energy (TKE) per unit mass k and the rate of dissipation of TKE ε. The solution algorithm is a variant of SIMPLE (Semi-Implicit Method for Pressure Linked Equations), in which velocities are obtained by solving the momentum conservation equations using the most recent estimates of the pressure field that is corrected by the imbalances in the mass conservation equations. Other conservation equations are then solved and the procedure iterated until convergence.

Three types of sudden opening problems may be studied, that include either a boundary layer onset flow [9], a smooth onset flow, or no onset flow but with an initial internal–external pressure difference (hereafter referred to as static tests). It has previously [7,8] been shown that the static sudden opening test is sufficient in determining the unknown parameters. In the simulation of a sudden opening, the building is first modelled by blocking appropriate cells/cell faces, and then obtaining a steady solution corresponding to the conditions prior to the creation of the opening. In the case of static sudden opening tests, internal and external pressures are set to the desired values. A sudden opening is created by removing the cell/cell face blockages corresponding to the window or door opening and the transient solution advanced over many time steps. The number of sweeps at each time step is usually determined so as to obtain a balance between convergence requirements and the cost in terms of computation time. The time step size is typically of the order of 1/100th of the expected period of Helmholtz oscillations $1/f_{\mathrm{HH}}$, but may usually be increased considerably without compromising accuracy to any significant level. It should be noted that the time step size determines the suddenness of the creation of the opening, and may therefore also be varied to achieve various degrees of opening rapidity. This is a major advantage of computational modelling since in the experimental simulation of sudden openings, the time for the creation of an opening is usually not controllable.

Since the physics of the problem involves compressible flow, it is essential that the isentropic density formulation

$$\frac{p}{\rho^{\gamma}} = \frac{p_{\mathrm{a}}}{\rho_{\mathrm{a}}^{\gamma}} = \mathrm{const} \tag{6}$$

is invoked for the entire flow field. Note that it is the compressibility of the air that leads to the changes in internal pressure.

4. Experimental measurement of the internal pressure gain function

Sharma and Richards [10] have recently shown that the relevant forcing function for the internal pressure system is the external area-averaged pressure over the extent of the opening. The internal pressure gain function may therefore be determined experimentally from a measurement of the internal pressure spectrum $S_{p_i}(f)$ and the spectrum of external area-averaged pressure $S_{p_e}(f)$ from the relation for a linear system:

$$|\chi_{p_i - p_e}| = \sqrt{S_{p_e}(f)/S_{p_i}(f)}. \tag{7}$$

The external area-averaged pressure spectrum is measured without the opening, over an area covering the extent of the opening, while the internal pressure spectrum is measured in the presence of the opening. For the tests described later in this paper, measurements were conducted in a 1 : 50 scale wind tunnel boundary layer flow, simulating full-scale conditions at the Texas Tech. University (TTU) facility (i.e. full-scale equivalent roughness length $z_o = 29$ mm and 4 m height turbulence intensity $I_u = 0.18$). Internal pressure was measured using a restricted tubing having a flat response up to 200 Hz, while the external pressure with a 10 input manifold pneumatic averaging system having a flat response up to 300 Hz. The pressure signals were transmitted to Honeywell 163PC differential pressure transducers, and the electrical outputs were then digitised using a Keithley-Metrabyte DAS1602 analogue to digital converter on an IBM compatible personal computer.

5. Results for a cylindrical model

On the basis outlined earlier, the response of the cylinder illustrated in Fig. 1, having internal dimensions 247 mm long and 140 mm internal diameter; a 19 mm long and 25 mm diameter aperture, was measured in the wind tunnel turbulent boundary layer flow. The relevant parameters for this test were as follows:

$$A_o = 4.909 \times 10^{-4}\ \mathrm{m}^2, \quad \forall_o = 3.803 \times 10^{-3}\ \mathrm{m}^3, \quad L_o = 19\ \mathrm{mm}, \quad P = \pi(25\ \mathrm{mm}),$$

$$f_{\mathrm{HH}}(\text{measured}) = 97\ \text{Hz which gives } L_e/c = 0.04\ \mathrm{m},$$

$$\tilde{C}_{p_i}(\text{measured}) = 0.237, \quad q = 27\ \mathrm{Pa}.$$

The initial conditions from the wind tunnel test were duplicated for computational modelling of the corresponding sudden opening problem under static conditions. The transient response of internal pressure thus obtained is shown in Fig. 2. It exhibits an oscillation frequency of 97 Hz. Eq. (1) was fitted to the first three to four cycles of the computed response using $C_L = 1.5$, $c = 1.00$ and $\mu_{\mathrm{eff}}/\Delta r = 0.16\ \mathrm{kg\,m^{-2}\,s^{-1}}$. These parameters yield a value for the equivalent damping coefficient $c_{\mathrm{eq}} = 32.6\ \mathrm{s}^{-1}$. The fitted transient response of internal pressure also appears in Fig. 2.

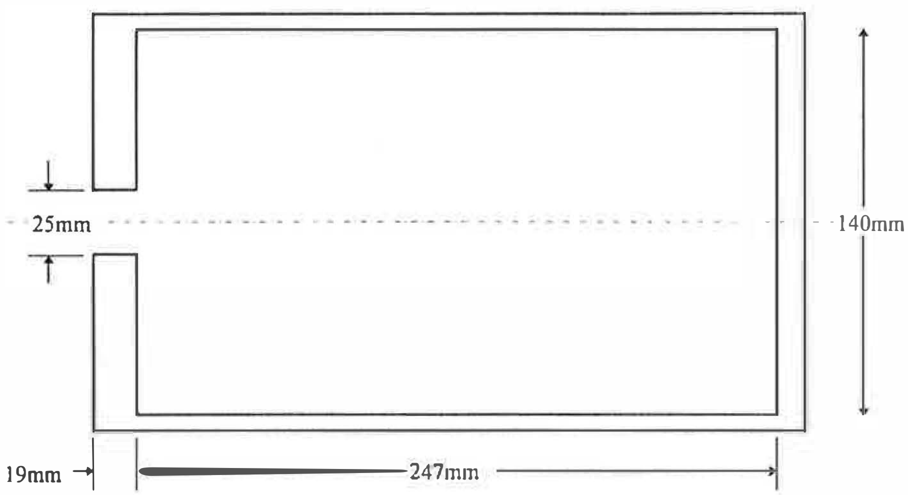

Fig. 1. Details of the cylindrical model.

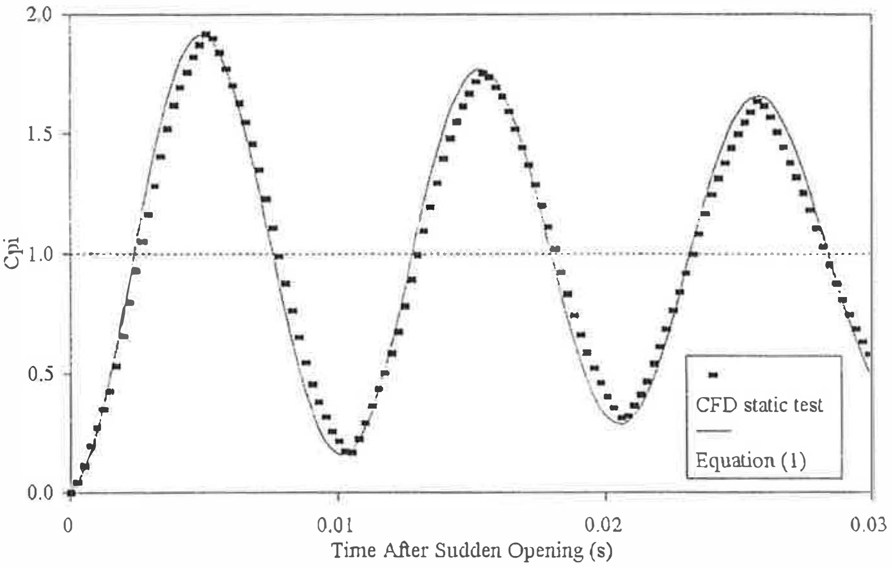

Fig. 2. Computational and analytic responses for the cylinder.

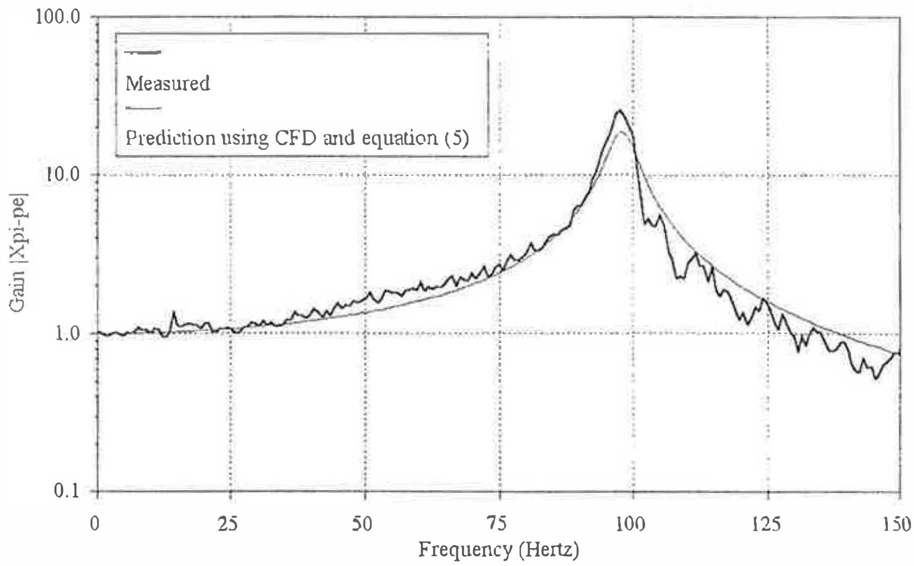

Fig. 3. Comparison of measured and predicted gain functions of internal pressure over the external for the cylinder.

Fig. 3 shows a comparison of the gain functions (square-root of admittance) obtained from the wind tunnel test and Eq. (5). The predicted gain function using computational fluid dynamics (CFD) modelling and the analytic model fitted to the transient response, is reasonably well matched with that measured in the wind tunnel test. The agreement between these results indicates that computational modelling is predicting both the Helmholtz frequency and the damping in the system fairly well.

6. Results for a 1 : 50 scale model of the TTU test building

The internal pressure to external area-averaged pressure gain function for the 1 : 50 scale model of the TTU building (illustrated in Fig. 4) was also measured in the boundary layer wind tunnel. The average dimensions of the nearly rectangular perspex model are as follows: external 276 mm × 184 mm × 80 mm; internal 264 mm × 172 mm × 67 mm. The door opening on the wall is 43 mm high, 18 mm wide and 6 mm deep. The relevant parameters for this test were as follows:

$$A_o = 7.74 \times 10^{-4}\ \mathrm{m}^2, \quad \forall_o = 3.042 \times 10^{-3}\ \mathrm{m}^3,$$

$$L_o = 6\ \mathrm{mm}, \quad P = 2 \times (18\ \mathrm{mm} + 43\ \mathrm{mm}),$$

$$f_{\mathrm{HH}}(\text{measured}) = 136\ \mathrm{Hz} \text{ which gives } L_e/c = 0.0405\ \mathrm{m},$$

$$\tilde{C}_{p_i}(\text{measured}) = 0.21, \quad q = 30.5\ \mathrm{Pa}.$$

Fig. 5 shows a comparison of the transient responses of internal pressure obtained from computational modelling ($q = 308$ Pa was used) and that obtained by fitting

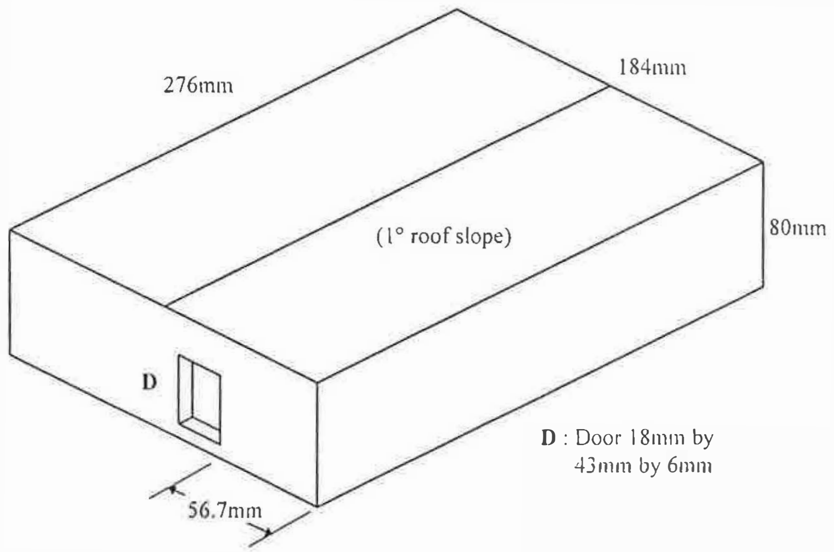

Fig. 4. Details of the 1 : 50 scale model of the TTU test building.

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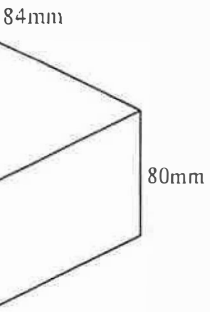

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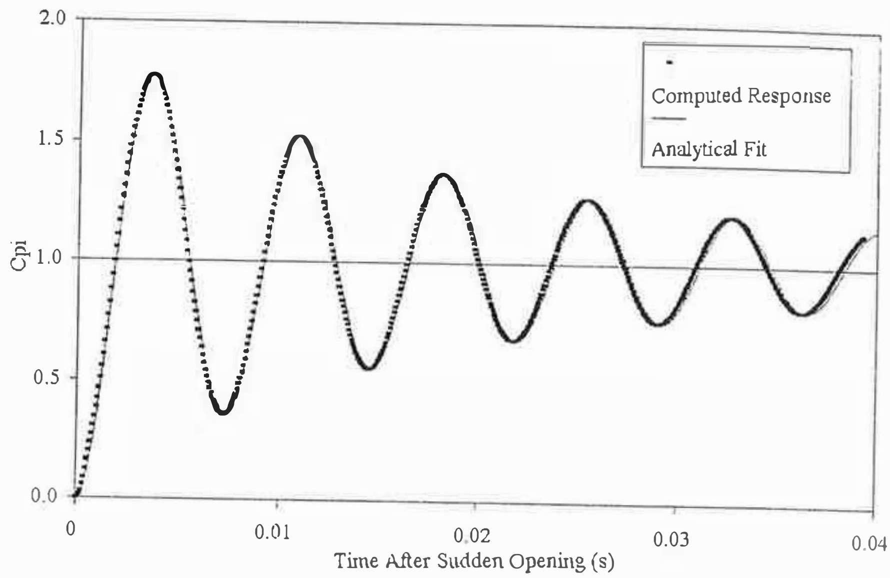

Fig. 5. Computational and analytic responses for the TTU model.

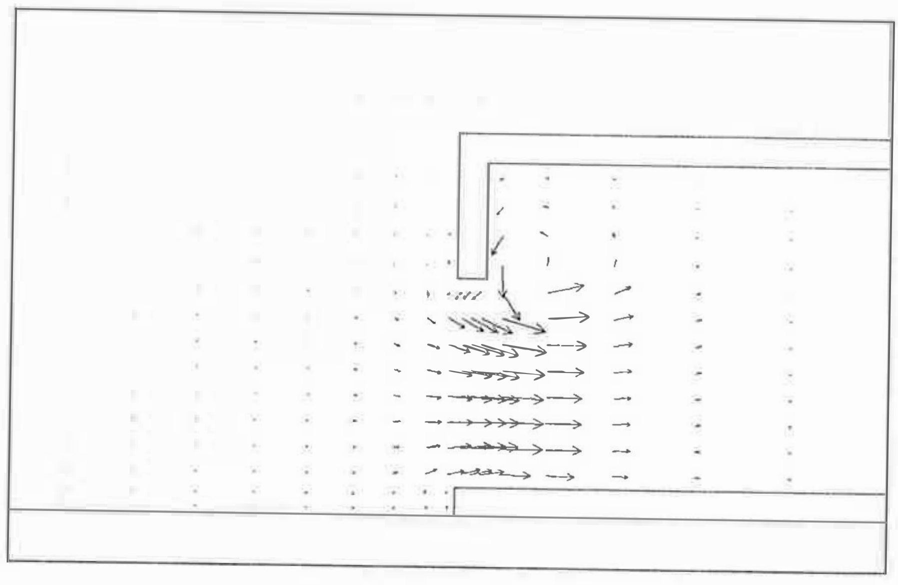

Fig. 6. Velocity vectors in the central longitudinal plane of the door showing the formation of a vena-contracta.

Eq. (1). Note that the oscillations have a frequency of 136 Hz, in exact agreement with that obtained from spectral measurements. Fig. 6 illustrates the formation of a vena-contracta in an in-flow section of the oscillating flow cycle. In order to fit Eq. (1) to the

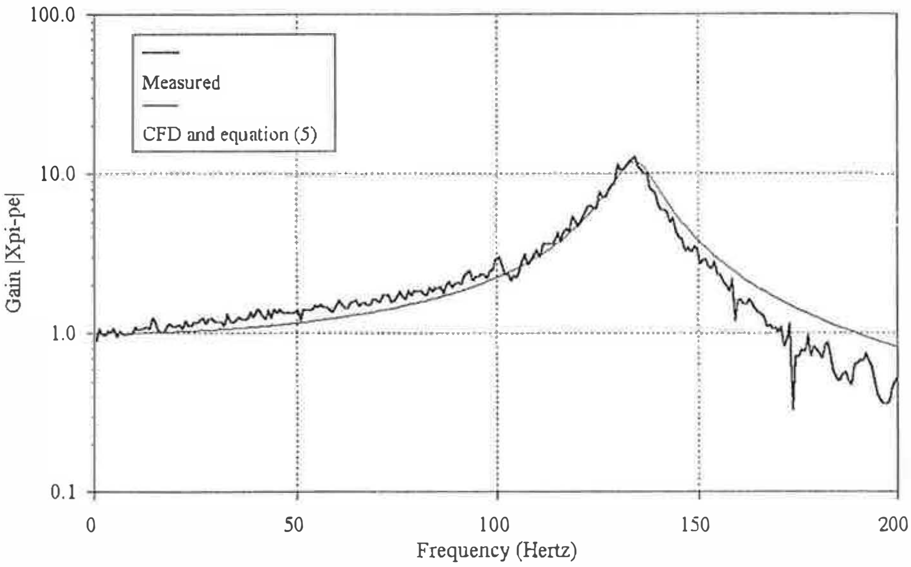

Fig. 7. Comparison of gain functions obtained from measurements and that predicted from computational modelling and Eq. (5).

computed response, the following parameters were required: $C_L = 1.20$, $c = 0.6$, $\mu_{eff}/\Delta r = 0.24\ \mathrm{kg\,m^{-2}\,s^{-1}}$.

The internal pressure gain function obtained from spectral measurements is compared in Fig. 7 with that predicted using the parameters established from computational modelling and Eq. (5). It shows that both the Helmholtz frequencies and the peak gains are well matched. The shape of the gain function is also predicted with fair accuracy, except at frequencies beyond 160 Hz – where the measured response is probably in error due to significant noise levels in the wind tunnel. The methodology of using CFD modelling in conjunction with analytical modelling may therefore be used in predicting both the transient as well as steady-state response of internal pressure.

7. Conclusions

A methodology based on computational and analytical modelling has been outlined for the prediction of building internal pressure gain function. It involves computational modelling of the transient response of building internal pressure to a sudden opening for the case of a step change in steady external pressure. Computational modelling in this manner predicts both the Helmholtz frequency as well as the damping characteristics fairly well. By fitting the analytical model to the computed response, the ill-defined parameters of the governing equation, such as the values for L_e, C_L and $\mu_{eff}/\Delta r$, are readily obtained. The gain function (Eq. (5)) obtained by linearisation of the governing equation utilises these parameters. It has been shown that for a cylindrical and a building model, good agreement is obtained between measured and predicted gain functions of internal pressure over the external area-averaged pressure. Where adequate computing resources are available, this methodology may prove to be extremely useful, particularly for complex opening and building geometry situations.

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