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Wind-induced internal pressure fluctuations of structure with single windward opening*

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Abstract: A frequency domain method for estimating wind-induced fluctuating internal pressure of structure with single windward opening is presented in this paper and wind tunnel tests were carried out to verify the theory. The nonlinear differential equation of internal pressure dynamics and iteration algorithm were applied to calculate fluctuating internal pressure and time domain analysis was used to verify the accuracy of the proposed method. A simplified estimation method is also provided and its scope of application is clarified. The mechanism of internal pressure fluctuation is obtained by using the proposed method in the frequency domain and a new equivalent opening ratio is defined to evaluate internal pressure fluctuation. A series of low-rise building models with various openings and internal volumes were designed for wind tunnel tests with results agreeing well with analytical results. It is shown that the proposed frequency domain method based on Gaussian distribution of internal pressure fluctuations can be applied to predict the RMS internal pressure coefficient with adequate accuracy for any opening dimensions, while the simplified method can only be used for structure with single dominant opening. Helmholtz resonance is likely to occur when the equivalent opening ratio is adequately high, and controlling individual opening dimension is an effective strategy for avoiding Helmholtz resonance in engineering.

Key words: Single windward opening, Internal pressure, Iteration algorithm, Equivalent opening ratio, Wind tunnel test
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INTRODUCTION

The wind loads of the exterior-protected construction of buildings are decided based on the pressure difference between the external and internal pressure. The failures of low-rise building roof and wall in high wind events are caused by a combination of large internal and external force acting in the same direction. A large opening in the building envelope, caused by the failure of a door or window may generate large internal pressures in strong wind conditions, and therefore is an important design consideration. It has long been wind engineering practice to study external pressure by using wind tunnel test while internal pressure is more difficult to capture accurately because the simulated envelope flexibility and internal volume are very likely to influence the internal pressure compared with external pressure. Hence the mechanics of internal pressure fluctuation and theoretical estimation of RMS internal pressure are gaining in popularity among researchers.

The basic analysis of internal pressure transient response in the case of sudden opening was first carried out by Holmes (1979), who treated the building as a Helmholtz acoustic resonator and described the transient response by a second-order, non-linear, ordinary differential equation. Liu and Saathoff (1982), Vickery and Bloxham (1992), Sharma and Richards (1997) presented similar equations to describe transient response of internal pressure. Studies showed that the transient response of internal pressure

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exhibits damped oscillatory behavior with an initial overshoot which could be significantly higher than the mean external pressure at the opening. However this overshoot phenomenon occurs only in smooth flow situations, in real life, it is lost amidst fluctuations in a turbulent wind as shown by experimental studies of Stathopoulos and Luchian (1989), Vickery and Bloxham (1992). Thus, understanding of steady state response of internal pressure in the presence of an opening is more important than understanding of transient response of internal pressure in the case of sudden opening.

In the presence of an opening, a building is known to behave like a Helmholtz acoustic resonator, and the steady state response of internal pressure can also be controlled by the above-mentioned differential equation, based on which, Vickery and Bloxham (1992) linearized the differential equation by assumption of Gaussian distribution for internal pressure fluctuation, and developed a simple predictive method to examine the steady state behavior of internal pressure fluctuation. However, the theory may be restricted to structure with one single dominant opening. This paper presents a more accurate method to estimate internal pressure fluctuation with iterative algorithm. The accuracy of the method is verified by time domain analysis. A more proper definition of equivalent opening ratio is proposed to evaluate internal pressure fluctuation and the critical equivalent opening ratio is put forward for avoidance of Helmholtz resonance. A wind-tunnel model-scale test with different opening conditions was conducted to verify the theoretical studies, and the results are in good agreement with predictions.

REVIEW OF PREVIOUS WORK

The problem of a sudden windward wall opening in a non-porous rigid building was considered by Holmes (1979), who first described the transient response of internal pressure by a second-order, non-linear ordinary differential equation by treating the building as a Helmholtz acoustic resonator. Liu and Saathoff (1982) conducted a fluid mechanics analysis of the problem and used the unsteady-isentropic form of the Bernoulli equation to derive a similar equation:

$$\frac{\rho_a L_e V_0}{\gamma c A_0 p_a}\ddot{C}_{pi} + \frac{\rho_a q V_0^2}{2(\gamma c A_0 p_a)^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pw}, \quad (1)$$

where γ is the specific heat ratio for air, ρ_a and p_a are the density and pressure of the ambient air respectively, A_0 is the opening area, c is the discharge coefficient of the opening, L_e is the effective length of the air slug at the opening, V_0 is the building volume, C_{pi} and C_{pw} are the internal and external pressure coefficients, respectively, $q=0.5\rho_a\bar{U}_h^{\,2}$ is the reference dynamic pressure based on the ridge-height velocity $\bar{U}_h$. Vickery and Bloxham (1992) argued that a contracted flow region does not ensure an unsteady flow situation and therefore c should not appear in Eq.(1). Substituting $1/c^2$ as the loss coefficient C_L which is more applicable to different opening types, the governing equation is thus given by:

$$\frac{\rho_a L_e V_0}{\gamma A_0 p_a}\ddot{C}_{pi} + \frac{C_L \rho_a q V_0^2}{2(\gamma A_0 p_a)^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pw}, \quad (2)$$

where $L_e = L_0 + C_I\sqrt{A_0}$ and L_0 is the physical length of the opening, C_I is the inertia coefficient. Sharma and Richards (1997) described the computational and experimental modeling of the transient response of internal pressures to sudden openings in buildings and showed that the discharge coefficient c should appear in the equations but the variation of c depends upon the orifice feature and flow characteristic. A discharge coefficient c, an inertia coefficient C_I and a loss coefficient C_L are therefore used:

$$\frac{\rho_a L_e V_0}{\gamma c A_0 p_a}\ddot{C}_{pi} + \frac{C_L \rho_a q V_0^2}{2(\gamma A_0 p_a)^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pw}. \quad (3)$$

These equations show that the internal pressure behaves as a single degree of freedom mechanical system but with non-linear damping. The undamped oscillation frequency of the internal pressure referred to as the Helmholtz frequency is thus given by:

$$f_H = \frac{1}{2\pi}\sqrt{\frac{\gamma c p_a A_0}{\rho_a L_e V_0}} \quad (4)$$

If the opening's physical length can be neglected as for most buildings, the Helmholtz frequency can be expressed as:

$$f_{\mathrm{H}}=\frac{1}{2\pi}\cdot\frac{a_{\mathrm{s}}A_0^{1/4}}{\sqrt{(C_{\mathrm{I}}/c)V_0}},\tag{5}$$

where a_s is speed of sound in air, C_I/c is necessary for evaluation of the Helmholtz frequency and can be extracted directly in the experiment.

PREDICTION OF INTERNAL PRESSURE FLUCTUATION FOR STRUCTURE WITH SINGLE WINDWARD OPENING

Detailed approach for $\sigma_{C_{\mathrm{pi}}}$ estimation

For a structure with a single windward opening, the problem of interest is the prediction of the RMS internal pressure when the spectrum of the external pressure fluctuations is given. It is difficult to obtain the explicit expression of the gain function for internal pressure response due to poor understanding of non-linear damping characteristics. Firstly the non-linear damping must be linearized as:

$$\left|\dot{C}_{\mathrm{pi}}\right|\dot{C}_{\mathrm{pi}}=\beta\sigma_{\dot{C}_{\mathrm{pi}}}\dot{C}_{\mathrm{pi}},\tag{6}$$

where β is equivalence coefficient which can be obtained from different linearity method. Equating the energy dissipated by the sum of the non-linear and linear damping terms to that dissipated by the equivalent linear damping term suggested by Chaplin *et al.*(2000), β is equal to $8\sqrt{2}/3\pi$. As assumed by Vickery and Bloxham (1992), the internal pressure is of Gaussian distribution and the mean value of $\dot{C}_{\mathrm{pi}}$ as well as flow velocity at orifice is zero for a sealed building, β is equal to $\sqrt{8/\pi}$. $\sigma_{\dot{C}_{\mathrm{pi}}}$ is the RMS value of $\dot{C}_{\mathrm{pi}}$ and it can be calculated in the following section. With Eq.(6), the linearized governing equation is given by:

$$\ddot{C}_{\mathrm{pi}}+2\xi_{\mathrm{eq}}\omega_{\mathrm{H}}\dot{C}_{\mathrm{pi}}+\omega_{\mathrm{H}}^2C_{\mathrm{pi}}=\omega_{\mathrm{H}}^2C_{\mathrm{pw}},\tag{7}$$

where $\omega_H=2\pi f_H$ is the angular Helmholtz frequency, the equivalent damping ratio ξ_{eq} can be expressed as:

$$\xi_{\mathrm{eq}}=\frac{C_{\mathrm{L}}cqV_0\beta\sigma_{\dot{C}_{\mathrm{pi}}}}{4\omega_{\mathrm{H}}\gamma L_{\mathrm{e}}A_0p_{\mathrm{a}}}.\tag{8}$$

The expression of the gain function of internal pressure over the external pressure can be transformed from Eq.(7) as:

$$\left|\chi_{C_{\mathrm{pi}}/C_{\mathrm{pw}}}\right|=\frac{\left|C_{\mathrm{pi}}\right|}{\left|C_{\mathrm{pw}}\right|}=\frac{\omega_{\mathrm{H}}^2}{\sqrt{(\omega_{\mathrm{H}}^2-\omega^2)^2+(2\xi_{\mathrm{eq}}\omega_{\mathrm{H}}\omega)^2}}.\tag{9}$$

The internal pressure coefficient spectrum can be obtained as:

$$S_{C_{\mathrm{pi}}}(f)=\left|\chi_{C_{\mathrm{pi}}/C_{\mathrm{pw}}}\right|^2S_{C_{\mathrm{pw}}}(f),\tag{10}$$

where $S_{C_{\mathrm{pw}}}(f)$ is the external area-averaged pressure coefficient spectrum for windward opening which can be obtained directly in experiment or can be expressed theoretically as:

$$S_{C_{\mathrm{pw}}}(f)=\left|\chi_{\mathrm{aa}}\right|^2\left(\frac{2\bar{C}_{\mathrm{pw}}}{\bar{U}_{\mathrm{h}}}\right)^2S_{\mathrm{u}}(f),\tag{11}$$

where $|\chi_{aa}|^2$ is area-averaged opening external pressure—ridge height dynamic pressure admittance function, $\bar{C}_{\mathrm{pw}}$ is mean external pressure coefficient at the opening, $S_u(f)$ is the longitudinal velocity spectrum of the approaching flow. The RMS internal pressure is determined by:

$$\sigma_{C_{\mathrm{pi}}}=\sqrt{\int_0^{\infty}S_{C_{\mathrm{pi}}}(f)\mathrm{d}f}.\tag{12}$$

In the above theoretical development, the value of $\sigma_{\dot{C}_{\mathrm{pi}}}$ has been assumed to be capable of enabling linearization of the damping term so that the solution becomes an iterative process with $\sigma_{\dot{C}_{\mathrm{pi}}}$. The RMS value of $\dot{C}_{\mathrm{pi}}$ may be calculated by substituting $\left|\chi_{C_{\mathrm{pi}}/C_{\mathrm{pw}}}\right|$ with $\left|\chi_{\dot{C}_{\mathrm{pi}}/C_{\mathrm{pw}}}\right|$ which can be expressed as:

$$\left|\chi_{\dot{C}_{\mathrm{pi}}/C_{\mathrm{pw}}}\right|=\frac{\left|\dot{C}_{\mathrm{pi}}\right|}{\left|C_{\mathrm{pw}}\right|}=\frac{\omega\omega_{\mathrm{H}}^2}{\sqrt{(\omega_{\mathrm{H}}^2-\omega^2)^2+(2\xi_{\mathrm{eq}}\omega_{\mathrm{H}}\omega)^2}}.\tag{13}$$

Therefore, the spectrum and the RMS value of $\dot{C}_{\rm pi}$ are given by:

$$S_{\dot{C}_{\rm pi}}(f)=\left|\chi_{\dot{C}_{\rm pi}/C_{\rm pw}}\right|^2 S_{C_{\rm pw}}(f), \quad (14)$$

$$\sigma_{\dot{C}_{\rm pi}}=\sqrt{\int_0^\infty S_{\dot{C}_{\rm pi}}(f)\mathrm{d}f}. \quad (15)$$

The value of $\sigma_{\dot{C}_{\rm pi}}$ calculated in Eq.(14) becomes a new $\sigma_{\dot{C}_{\rm pi}}$ to be used in the iteration process. With iterations processing until the error of $\sigma_{\dot{C}_{\rm pi}}$ is small enough, the gain function for internal pressure response over external pressure response and the RMS value of fluctuating internal pressure coefficient are determined.

Time domain analysis result was used to verify the accuracy of the above-mentioned estimation method. Eq.(3) was solved for transient responses using a second order Runge-Kutta scheme for the following conditions of the Texas Tech University (TTU) test building with a windward opening:

V_0=497 m^3, A_0=1.938 m^2, c=0.88, $\bar{U}_{\rm h}$=30 m/s, $C_{\rm I}$=0.886, L_0=0, γ=1.4, $\rho_{\rm a}$=1.22 kg/m^3, $C_{\rm L}$=2.5, $p_{\rm a}$=101 300 Pa, $\bar{C}_{\rm pw}$ = 0.75.

Ginger and Letchford (1999) considered that the quasi-steady method may be satisfactorily used for determining the design wind loads on the windward wall center. Sharma and Richards (2004) pointed out that the quasi-steady method may overestimate peak pressure on windward wall and attenuation is obvious (i.e. $|\chi_{\rm aa}|^2$<1) above a certain cut-off frequency. In this section the attenuation in the high frequency region has been ignored and $|\chi_{\rm aa}|^2$=1 is used. The external pressure coefficient is given by a random time history which is simulated by spectral representation using the pressure coefficient spectrum determined by Eq.(11) taking Davenport spectrum as the longitudinal velocity spectrum of the approaching flow. Solutions were obtained for up to 500 s in order to get the steady-state time history. Time histories of the internal and external area-averaged pressure coefficient are transformed to corresponding spectra by FFT. So the internal pressure gain function may be determined from the internal pressure coefficient spectrum and the external area-averaged pressure coefficient spectrum from the relation for a linear system:

$$\left|\chi_{C_{\rm pi}/C_{\rm pw}}\right|=\sqrt{S_{C_{\rm pi}}(f)/S_{C_{\rm pw}}(f)}. \quad (16)$$

Fig.1 shows the internal pressure gain function obtained from time domain analysis and frequency domain analysis with $\beta=8\sqrt{2}/3\pi$ and $\beta=\sqrt{8/\pi}$. It was apparent that the result obtained in the frequency domain with $\beta=\sqrt{8/\pi}$ agreed well with the numerical solutions for the actual non-linear model obtained with immediate integration method. This result increases the confidence in predicting the frequency response characteristics of internal pressure response by using linearity method combined with iteration algorithm. The magnitude of damping is generally under predicted for $\beta=8\sqrt{2}/3\pi$ with this conclusion being valid for structure with various internal volume and opening area. The errors may be focused on the linearity method based on energy dissipation assumption with sinusoidal exterior pressure fluctuations, which may deviate from actual situation in the turbulent onset flow. Apparently, the internal pressure fluctuations calculated by the linear method based on equivalent energy dissipation provide a conservative prediction compared with the results obtained by time domain analysis. As a result, $\beta=\sqrt{8/\pi}$ is used for all numerical calculation in the frequency domain presented in the following sections.

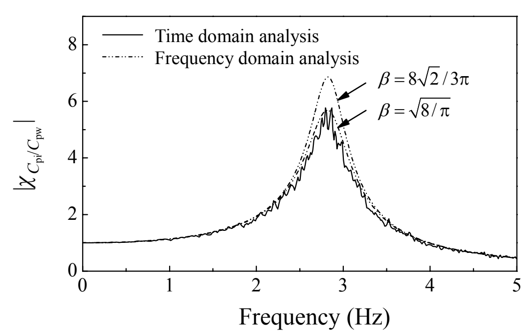

Fig.1 Comparison of predicted gain functions

Fig.2 shows the gain of the internal pressure with respect to the external pressure for the TTU building with single windward opening in turbulent onset flow. It is clear that, as opening area decreases, the damping of the internal pressure response increases while the Helmholtz frequency decreases. When the opening area is small enough, the phenomenon of Helmholtz resonance vanishes and the internal pressure fluctuation is significantly attenuated with respect to the external pressure fluctuation in the high pressure region. Ginger and Letchford (1999) confirmed that external pressure fluctuations at frequencies above a characteristic frequency f_c are attenuated and not passed effectively into a nominally sealed building. It is clear that the dynamic characteristic of internal pressure fluctuation for nominally sealed build is similar to that for sealed building with single windward opening when the opening is small enough.

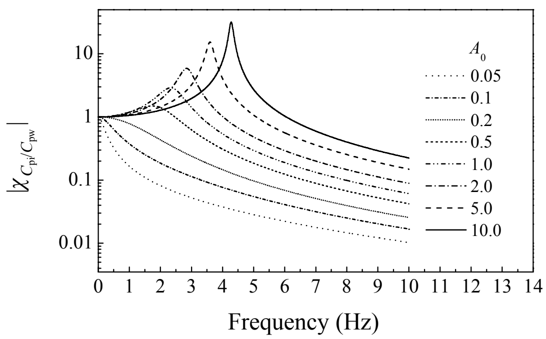

Fig.2 The gain of the internal pressure with respect to the external for the TTU building

Simplified approach for $\sigma_{C_{pi}}$ estimation method

As suggested by Vickery and Bloxham (1992), if the equivalent damping ratio is much smaller than 1, the spectrum of internal pressure can be expressed as the sum of background aspect and resonance aspect, which permits the approximate computation of the variance of C_{pi} from the relationship:

$$\sigma_{C_{pi}}^2 = \int_0^\infty S_{C_{pw}}(f)\mathrm{d}f + \frac{f_H \pi}{4\xi_{eq}} S_{C_{pw}}(f_H), \tag{17}$$

where $S_{C_{pw}}(f_H)$ is value of $S_{C_{pw}}(f)$ at $f = f_H$ for external pressure coefficient spectrum. For the case of dominant windward opening, and the contribution of the resonant aspect is significant, then the value of $\sigma_{\dot{C}_{pi}}$ can be controlled by:

$$\sigma_{\dot{C}_{pi}}^2 = \int_0^\infty S_{C_{pw}}(f) 2\pi f \mathrm{d}f + (2\pi f_H)^2 \frac{f_H \pi}{4\xi_{eq}} S_{C_{pw}}(f_H)$$

$$\approx (2\pi f_H)^2 \frac{f_H \pi}{4\xi_{eq}} S_{C_{pw}}(f_H) . \tag{18}$$

Combination of Eqs.(8), (11) and (18), then yields:

$$\xi_{eq} = \left[\frac{(C_L V_0 \beta \bar{U}_h \bar{C}_{pw} c |\chi_{aa}|)^2 \pi f_H S_u(f_H)}{64(L_e A_0 a_s^2)^2} \right]^{1/3} . \tag{19}$$

Neglecting the physical length of the opening, the equivalent damping ratio can be improved as follows:

$$\xi_{eq} = \tau \left(\frac{\bar{C}_{pw} \bar{U}_h^2}{a_s^2} \right)^{2/3} \frac{V_0^{2/3}}{A_0} , \tag{20}$$

where τ can be expressed as:

$$\tau = \left[\frac{(C_L \beta |\chi_{aa}|)^2 \pi}{64(C_I / c)^2} \cdot \frac{f_H S_u(f_H)}{\bar{U}_h^2} \right]^{1/3} . \tag{21}$$

With the above-mentioned parameters for TTU building, the predicted equivalent damping ratios can be calculated by the detailed approach and the simplified approach; the results and the relevant errors are shown in Table 1. Note that the predicted equivalent damping ratios obtained from the simplified estimation approach agree well with detailed ones as the opening area is sufficiently large. In this case, substituting the predicted equivalent damping ratios into Eqs.(9)~(12) the RMS internal pressure coefficient can be predicted accurately. The results will be provided in the following section.

Table 1 Comparison of predicted equivalent damping ratio for the TTU building

A_0 (m^2)	Precise approach	Simplified approach	Error (%)
0.05	3.4265	4.2423	23.81
0.1	1.7750	2.0412	15.00
0.2	0.9009	0.9821	9.01
0.5	0.3583	0.3733	4.19
1	0.1759	0.1796	2.10
2	0.0855	0.0864	1.05
5	0.0327	0.0329	0.72
10	0.01577	0.01580	0.19

Evaluation of internal pressure fluctuations for structure with single windward opening

Eq.(19) shows that the damping characteristics of internal pressure fluctuation are mostly dependent on the opening feature and wind character, hence the estimation of RMS internal pressure by diagram is quiet difficult due to relevant complex parameters. Defining equivalent opening ratio as:

$$S=\left(\frac{a_{\mathrm{s}}^{2}}{\bar{C}_{\mathrm{pw}}\bar{U}_{\mathrm{h}}^{2}}\right)^{2/3}\frac{A_{0}}{V_{0}^{2/3}}. \qquad (22)$$

The power of the major parameters such as A_0, V_0 and $\bar{U}_{\mathrm{h}}$ in the parameter τ is largely lower than that in the parameter S, so that the equivalent damping ratio may be determined by S. The detailed and simplified approaches are both applied to estimate RMS internal pressure coefficients with the parameters listed in Section 3.1. The parameters A_0 and V_0 are variable in this section. Fig.3 shows an approximate relationship between the RMS internal pressure coefficient and the RMS external pressure coefficient at the opening (expressed as double of mean external pressure coefficient plus turbulence intensity for the turbulent onset flow based on the quasi-steady assumption) versus the equivalent opening ratio with the internal volume as parameter. It is shown that the internal pressure fluctuation monotonously increases with increasing equivalent opening ratio. The predicted RMS internal pressure coefficients obtained by simplified approach agreed well with that by detailed approach for S>0.24 (i.e. internal pressure fluctuation is more severe compared with external pressure fluctuation) which implies that the simplified approach is quite accurate when the Helmholtz resonance is about to occur. For S<0.24, the Helmholtz resonance vanishes and the external pressure fluctuations are not transferred into the cavity completely. Noteworthy that the curves for various internal volumes intersect together at the point S=0.24 and $\sigma_{C_{\mathrm{pi}}}/\sigma_{C_{\mathrm{pw}}}=1$, which means the definition of the equivalent opening ratio can reflect the damping characteristic of internal pressure fluctuation although the internal volume is not the same. Apparently, S_{cr}=0.24 can be defined as the critical equivalent opening ratio, and that controlling individual opening dimension based on Eq.(22) is an effective method for avoiding Helmholtz resonance.

It should be borne in mind that the frequency contents of the gain function curve for larger internal volume are relatively low, and that the effect of frequency response on the low-frequency turbulent wind energy is relatively large. The variation of internal pressure fluctuation with the equivalent opening ratio increasing for large internal volume is more severe than that for small internal volume. So the designer should carefully consider the internal pressure fluctuation of closed long-span roof structure when the equivalent opening ratio is large enough.

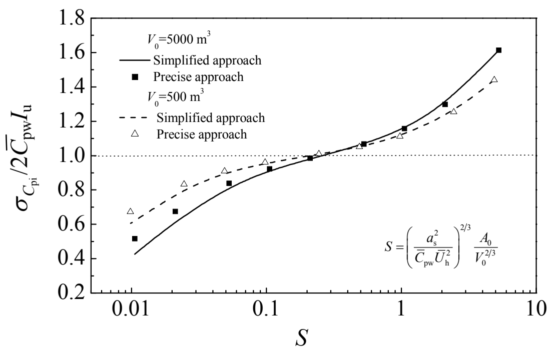

Fig.3 Comparison of predicted RMS internal pressure coefficients

EXPERIMENTAL PROCESS AND RESULTS

The building model was a rigid 840 mm (d)×540 mm (b)×240 mm (h) hexahedron structure with roof cornices. A square 2 cm×2 cm, 3 cm×3 cm, 5 cm×5 cm, 8 cm×8 cm, 10 cm×10 cm openings located on one of the larger 840 mm wide×240 mm high walls. The physical length of the opening can be neglected. Data obtained for wind orientation θ equal to 0° (wind flow is perpendicular to the 840-mm sides of the building) are presented in this paper. The details of arrangement of opening and wind orientation are shown in Fig.4. In order to simulate low equivalent opening ratio with adequately large openings, the model's internal volume was exaggerated. Detailed configurations for wind tunnel test are given in Table 3. Great care was taken to ensure that all fittings, joints and pressure tap exit points were air-tight.

The experiments were carried out in a low-speed wind tunnel using a standard suburb simulation. The

Table 3 Detailed configurations of wind tunnel test

Configuration	A_0 (cm^2)	V_0 (m^3)
1	100	0.08
2	25	
3	100	1.17
4	64	
5	25	
6	9	
7	4	

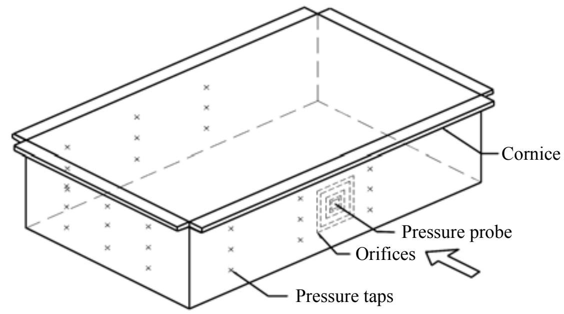

Fig.4 Arrangement of openings and pressure taps on wall

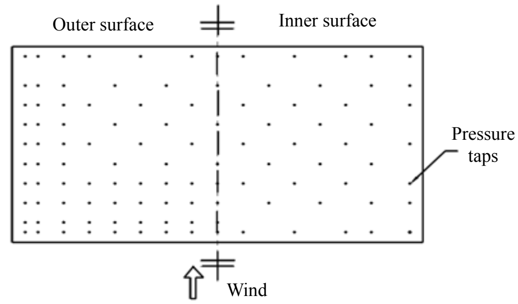

Fig.5 Arrangement of pressure taps on roof

reference wind speed for the tests was 14 m/s at a height of 240 mm. The turbulence intensity was about 18% and mean pressure coefficient was about 0.74 at the height of the opening center (i.e. h=120 mm). Pressure taps were mounted on the model surface: 73 taps on the outer surface of the roof; 42 taps on the inner surface of the roof; 9 taps each on the outer and inner surfaces of the windward wall, inner surface of the side wall, outer and inner surfaces of the leeward wall. A pressure probe was placed directly at the opening center to detect the pressure coefficients of the opening. These arrangements are shown in Fig.4 and Fig.5. The installation of restrictors in the tubing before the pressure transducers ensured that the transferred pressure signal was a true representation of the fluctuating pressure. Four electron scan livers were used and 16 channels were simultaneously sampled by a data acquisition computer. The pressure signals were low-pass filtered at 200 Hz , and sampled at 400 Hz for single run of 15 s duration. The mean, RMS pressure coefficients are defined as:

$$\bar{C}_p = \frac{\bar{p} - p_0}{0.5\rho_a \bar{U}_h^2}, \quad \sigma_{C_p} = \frac{\sigma_p}{0.5\rho_a \bar{U}_h^2}, \tag{23}$$

where $\bar{p}$, σ_p are mean and standard deviation pressure respectively in a 15-second run; p_0 is reference pressure; ρ_a is density of air in wind tunnel; and $\bar{U}_h$ is mean wind speed at roof height (i.e. h=240 mm), over a 15-second run. Woods and Blackmore (1995) confirmed that uniform internal pressure distribution is valid for structure with single opening even with large opening at least up to 25% of the wall area. The test results of internal pressure coefficient given in the following sections are averaged data from all internal pressure taps.

In the test, a pressure probe was placed at the opening center to detect the external pressure coefficients of the opening. The external pressure spectrum and the best fitting result are shown in Fig.6. Taking C_L=7.5, C_I/c=1.3 (obtained in the following paragraph), the gain function for configurations 1~7 in this experiment can be calculated by the procedure mentioned in Section 3.1 and the results are shown in Fig.7. It is clear that Helmholtz resonance is more likely to occur when the equivalent opening ratio is big enough (configurations 1~4) and the equivalent damping of the internal pressure response increases with decreasing equivalent opening ratio. When the equivalent opening ratio is small enough (configurations 5~7), the phenomenon of Helmholtz resonance vanishes and the internal pressure fluctuation is significantly attenuated compared with the external pressure fluctuation in the high frequency region. Fig.8 shows the spectrum of internal pressure coefficient for configurations 1 and 7 and the typical spectrum of external pressure coefficient of the opening. Configuration 1 reveals increase of internal pressure energy close to the Helmholtz frequency of 45 Hz. Configure 7 shows that the internal pressure fluctuations contain much less energy compared with the external pressure fluctuation, and are significantly attenuated above 0.3 Hz with a sharp drop off. These phenomena agreed well with theoretical results and are also similar to the findings on the dynamic characteristic of internal pressure fluctuation reported by Vickery and Bloxham (1992) and Ginger *et al.*(1997).

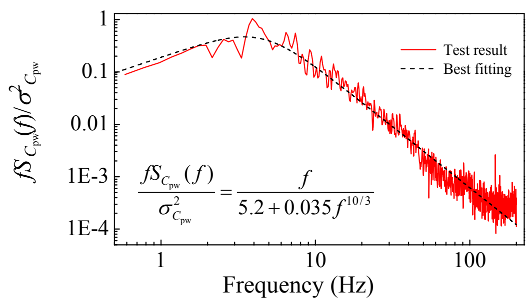

Fig.6 Fitted and measured wind pressure coefficient spectra in windward opening

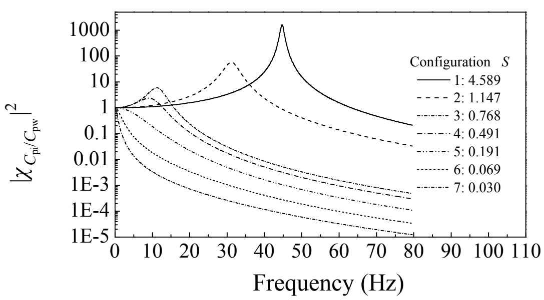

Fig.7 Gain of the internal pressure with respect to the external pressure of the building model in wind tunnel test

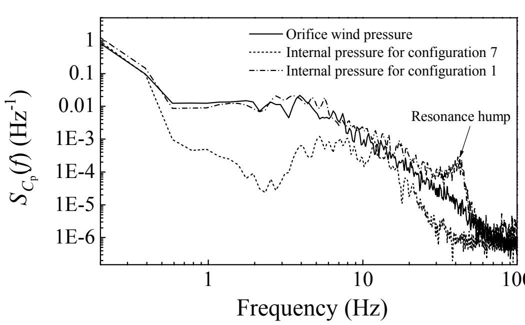

Fig.8 Comparison of internal and external pressure spectra obtained from experiment

In Eq.(3) there are three ill-defined parameters: the discharge coefficient c; the loss coefficient C_L and the inertia coefficient C_I which greatly affect the estimation of internal pressure fluctuation. The values in common usage are taken as c=0.88 (Liu and Saathoff, 1982) obtained from wind tunnel test, C_L=2.68 and C_I=0.886 (Vickery and Bloxham, 1992) obtained from free streamline theory although these values are only applicable to circular openings. Sharma and Richards (1997) pointed out that for thin rectangular openings such as windows, the values can be selected as c=0.6, C_L=1.2 and C_I=0.784. Ginger *et al.*(1997) found that loss coefficient C_L may vary from 2.5 to 45 for various orifice character, which means the loss coefficient is more difficult to determine than other coefficients. Although the characteristic coefficient of opening may be a function of the opening area, the dimension influence was ignored in this test and the value of C_L and C_I/c can thus be obtained from the internal pressure gain function for configuration 2. As assumed by Eq.(16), the internal pressure gain function can be determined from the internal pressure coefficient spectrum and the external pressure spectrum in opening which can be transformed from corresponding pressure coefficient time histories by FFT. Fig.9 shows the test curve and the theoretical curve by use of C_L=7.5 and C_I/c=1.3 for internal pressure gain function, and the two curves match each other very well.

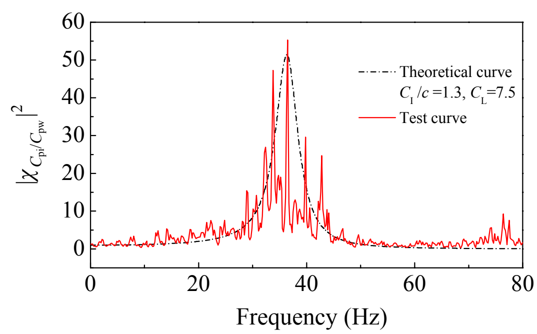

Fig.9 Identification of characteristic parameters of opening for configuration 2

Table 4 shows the experimental and theoretical results of RMS internal pressure coefficients for configurations 1~7 by using C_L=7.5 and C_I/c=1.3 and fitted pressure coefficient spectrum in opening. For comparison, Eq.(3) was solved for transient response using a second-order Runge-Kutta scheme for configurations 1~7, with orifice pressure coefficient time histories obtained directly from the experiment as C_{pw}. It can be seen that the results calculated by time domain analysis and frequency domain analysis agreed

Table 4 Experimental and theoretical results of RMS internal pressure coefficients

Configuration	Equivalent opening ratio	Test results	Theoretical results	
			Time domain	Frequency domain
1	4.589	0.3048	0.2829	0.2880
2	1.147	0.3077	0.2789	0.2799
3	0.768	0.2764	0.2996	0.2956
4	0.491	0.2778	0.2804	0.2792
5	0.191	0.2350	0.2165	0.2214
6	0.069	0.1524	0.1531	0.1478
7	0.030	0.0902	0.0969	0.1013

well with those obtained from experiment and that the maximum errors did not exceed the 10% acceptable in engineering. The results revealed that ignoring opening dimensions in the determination of characteristic parameters had little effect on the estimation of internal pressure fluctuation.

Bearing in mind the results from Table 4, when the equivalent opening ratio is small enough (S<0.24), the RMS internal pressure coefficient is smaller than the RMS external pressure coefficient ($\sigma_{C_{pw}}$ =0.265), which means the critical equivalent opening ratio S_{cr}=0.24 is applicable for structure with small internal volume even for wind tunnel models.

CONCLUDING REMARKS

Some conclusions on wind-induced internal pressure fluctuation of structure with single windward opening obtained by theoretical and experimental study are as follows:

(1) The detailed method based on Gaussian distribution of internal pressure fluctuations can be applied to predict RMS internal pressure coefficient with adequate accuracy for any opening dimensions.

(2) The simplified method can be applied to estimate RMS internal pressure coefficient of structure with single dominant windward opening. The accuracy can be acceptable for engineering application when Helmholtz resonance occurs. Otherwise, the simplified method's results may not be safely used for estimating RMS internal pressure coefficient.

(3) Adequately high equivalent opening ratio is necessary for Helmholtz resonance and the internal pressure fluctuation can be significantly attenuated with respect to the external pressure fluctuation in the high frequency region for adequately low equivalent opening ratio.

(4) The definition of equivalent opening ratio can reflect the damping characteristics of internal pressure fluctuation, and the critical equivalent opening ratio S_{cr}=0.24 can be used to control the individual opening area to avoid Helmholtz resonance.

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