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Wind-induced internal pressure response for structure with single windward opening and background leakage*

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Abstract: Theoretical analysis and wind tunnel tests were carried out to study wind-induced internal pressure response for the structure with single windward opening and background leakage. Its governing differential equation was derived by the Bernoulli equation in an unsteady-isentropic form. Numerical examples were provided to study the additive damping caused by background leakage in laminar and turbulent flow, and the influence of background leakage on fluctuating internal pressure response was quantized. A series of models for low-rise building with various opening ratios and background leakage were designed and wind tunnel tests were conducted. It is shown that the fluctuating internal pressure reduces when the background leakage are considered and that the effect of background leakage can be predicted accurately by the governing differential equation deduced in this paper.

Key words: Single windward opening, Internal pressure, Background leakage, Governing equation, Time-history analysis
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INTRODUCTION

In recent years, the problems about wind-induced internal pressure response for the structure with openings are gaining in popularity among researchers. Investigations about windstorm disaster occurred in China and other nations reveal that internal wind effects due to wall openings are the main reason for the damage of structures (Shanmugasundaram *et al*., 2000; Sun *et al*., 1995). Thus, as for wind resistance of important architectures, it is necessary to consider internal wind loads, and this subject is becoming a major direction for wind engineering research.

Based on the assumption of full correlation for internal pressures, it is prospective to study internal pressure response by aerodynamics theories. 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. Vickery (1986) considered structural flexibility by using the conception of modular ratio, and the transfer equation considering structural flexibility was deduced. Sharma and Richards (1997a) studied internal pressure transient response by using computational fluid dynamics (CFD) method, and the equivalent viscosity coefficient was used to consider additive damping in opening boundary. Meanwhile, Sharma and Richards (1997b) derived the complete theory about internal pressure transient response considering structural flexibility, and a two degrees of freedom (DOF) model was used to describe the coupling effect of structure and internal pressure. However, researchers need to pay attention to a new factor, that is, the effect of background leakage. Stathopoulos and Luchian (1989) studied the internal pressure transient response for the structure with single

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windward opening and background leakage by experimental investigation. They confirmed that the peak point of internal pressure transient response may reduce greatly, and pointed out that the effect of internal pressure can be ignored when the background leakage is considered. Vickery and Bloxham (1992) studied the effect of background leakage in wind tunnel test and held on that the damping of internal pressure response increases and the resonance response deduces while background leakage is considered. Vickery also pointed out that the effect of background leakage can be ignored when the background leakage area is less than 10% of windward opening, but the estimated result for RMS (root mean square) internal pressures may be conservative. Therefore it is obvious that the study of background leakage is still in the phase of experimental research. Theoretical explanation about the effect of background leakage has never been reported, thus it is difficult to make further research without theoretical supports.

In this paper, low-rise buildings are selected as the research objects. The problem is simplified through proper assumptions. The governing differential equation for structure with single dominant opening considering background leakage is derived by using the unsteady isentropic Bernoulli equation, mass conservation law for air, and state equation for heat-insulating air. Numerical examples are provided to study the additive damping due to background leakage in laminar and turbulent flow. And quantization of the influence on fluctuating internal pressure response is presented. A series of low-rise building models with various opening ratios and background leakage were designed and wind tunnel tests were conducted for verification.

THEORY

Fundamental assumptions

(1) The internal pressures are almost fully correlated over all well connected regions of the interior.

(2) A single dominant opening exists on windward wall, and its area is large enough compared with background leakage.

(3) The effect of inertia for background air leakage is not considered.

(4) Mean pressures of leeward side are closed, and leeward fluctuating pressure is negligible compared with interior. Thus a single mean pressure coefficient is used to consider wind pressure of leeward side.

(5) The state transformation of air is adiabatic, and the equation of state controlling the transformation of volume and pressure of air is:

$$PV^{\gamma}=P_0V_0^{\gamma}, \tag{1}$$

where, γ is the specific heat ratio for air and γ=1.4; P_0 and V_0 are the internal pressure and internal volume respectively for equilibrium state. Differentiating Eq.(1), the following equation is obtained:

$$\mathrm{d}P=-\frac{\gamma p_{\mathrm{a}}}{V_0}\mathrm{d}V, \tag{2}$$

where, p_{a} is the barometric pressure, i.e., internal pressure for equilibrium state and p_{a}=101300 Pa.

(6) The effect of structural flexibility is ignored, and the building is considered as rigid construction.

Derivation of equation

The simplified model of wind-induced internal pressure response for structure with single windward opening and background leakage is shown in Fig.1.

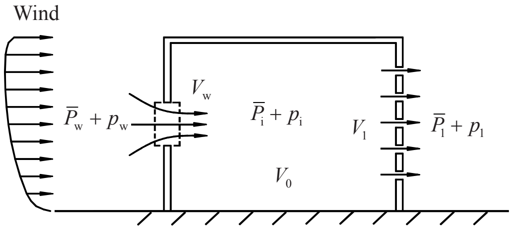


Fig.1 Simplified model for structure with single windward opening and background leakage

Using the unsteady-isentropic form of the Bernoulli equation (Vickery and Bloxham, 1992), the relationship of pressure drop and airflow rate for windward opening can be obtained as:

$$P_{\mathrm{w}}-P_{\mathrm{i}}=\frac{1}{2}C_{\mathrm{L}}\rho_{\mathrm{a}}V_{\mathrm{w}}\left|V_{\mathrm{w}}\right|+\rho_{\mathrm{a}}L_{\mathrm{e}}\dot{V}_{\mathrm{w}}, \tag{3}$$

where, P_{w} and P_{i} are the transient pressures of windward and interior respectively, C_L is the loss coefficient, V_w is the airflow rate for windward opening, ρ_a is the pressure of the ambient air and ρ_a=1.22 kg/m^3, L_e is the effective length of the air slug at the opening:

$$L_e = L_0 + C_I\sqrt{A_w}, \tag{4}$$

where, L_0 is the physical length of the opening and can be ignored for general buildings, C_I is the inertia coefficient, A_w is the windward opening area. Using the third fundamental assumption, the relation of the air leakage rate for background leakage and the pressure drop for leeward side can be expressed as:

$$P_i - P_l = C'_L \rho_a V_l^2/2, \tag{5}$$

where, P_l is the transient pressure of leeward side, C'_L is the loss coefficient for background leakage. Using the fourth fundamental assumption, the expression of V_l is:

$$V_l = U_h\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}, \tag{6}$$

where, C_{pi} is the transient internal pressure coefficient, $\bar{C}_{pl}$ is the mean pressure for leeward side, U_h is the reference wind velocity. Using the principle of mass conservation, the following equation can be obtained:

$$\rho_i(A_w V_w - A_l V_l) = V_0\frac{\mathrm{d}\rho_i}{\mathrm{d}t} + \rho_i\frac{\mathrm{d}V_0}{\mathrm{d}t}, \tag{7}$$

where, A_l is the total area of background leakage, ρ_i is the air density of the interior. Because the internal capacity is not changed and only the density of internal air is changed, Eq.(2) may be transformed to the new form which shows the relationship of internal pressure and internal air density:

$$\mathrm{d}P_i = \frac{\gamma p_a}{\rho_i}\mathrm{d}\rho_i. \tag{8}$$

The following equation is obtained by Eqs.(6)~(8):

$$V_w = \frac{V_0 q}{\gamma p_a A_w}\dot{C}_{pi} + \frac{A_l U_h}{A_w}\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}, \tag{9}$$

where, q is the reference wind pressure. Differentiating Eq.(9), the following equation can be obtained:

$$\dot{V}_w = \frac{V_0 q}{\gamma p_a A_w}\ddot{C}_{pi} + \frac{A_l U_h}{2A_w\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}}\dot{C}_{pi}. \tag{10}$$

Substituting Eqs.(9) and (10) into Eq.(3) yields the transfer equation for internal pressure response considering background leakage:

$$\begin{aligned}&\frac{\rho_a L_e V_0}{\gamma p_a A_w}\ddot{C}_{pi} + \frac{\rho_a L_e A_l U_h}{2A_w q\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}}\dot{C}_{pi}\\&+\frac{C_L\rho_a q V_0^2}{2(\gamma p_a A_w)^2}\left(\dot{C}_{pi} + \frac{A_l U_h \gamma p_a}{q V_0}\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}\right)\\&\cdot\left|\dot{C}_{pi} + \frac{A_l U_h \gamma p_a}{q V_0}\sqrt{(C_{pi} - \bar{C}_{pl})/C'_L}\right| + C_{pi} = C_{pw}.\end{aligned} \tag{11}$$

where, C_{pw} is the transient pressure coefficient for windward opening. If the total area of background leakage is equal to zero, the above equation can be identical to the transfer equation reported by Vickery and Bloxham (1992):

$$\frac{\rho_a L_e V_0}{\gamma p_a A_w}\ddot{C}_{pi} + \frac{C_L\rho_a q V_0^2}{2(\gamma p_a A_w)^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pw}. \tag{12}$$

NUMERICAL ANALYSIS

Analysis of nonlinear damping characteristic for windward opening

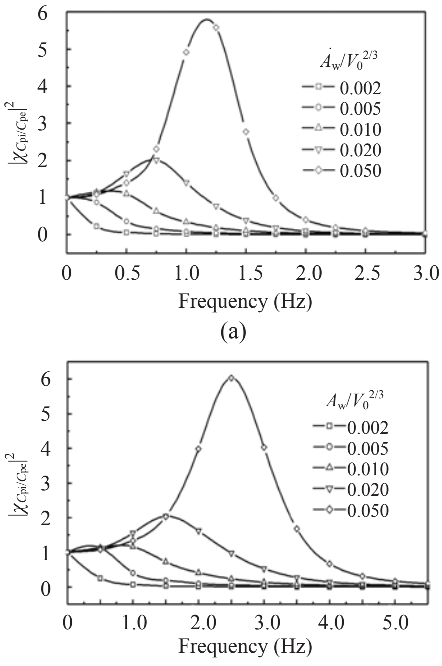
It is necessary to discuss the nonlinear damping of internal pressure response ignoring background leakage before discussing the additive damping of the background leakage. Yu *et al.*(2007) got the internal pressure gain using iterative algorithm. While, in this paper, the time-history integration analysis is used to obtain the internal pressure gain, and the method is more convictive. In this section, the following parameters are used: C_I=0.886, C'_L=2.68 (Vickery and Bloxham, 1992), C_L=2.5 (Sharma and Richards, 1997b). The external pressure coefficient time history is a sinusoidal curve:

$$C_{pw} = 0.7 + \left|C_{pe}\right|\sin(2\pi ft - \pi/2), \tag{13}$$

where, $|C_{\mathrm{pe}}|$ is the amplitude of external pressure coefficient assumed to be 0.3, f is the excited frequency. The Runge-Kutta method is used to solve Eq.(12), and the steady-state amplitude of internal pressure can be obtained. The internal pressure gain can then be expressed as:

$$\left|\chi_{C_{\mathrm{pi}}/C_{\mathrm{pe}}}\right|^2 = \left|C_{\mathrm{pi}}(f)\right|^2 / \left|C_{\mathrm{pe}}\right|^2 . \tag{14}$$

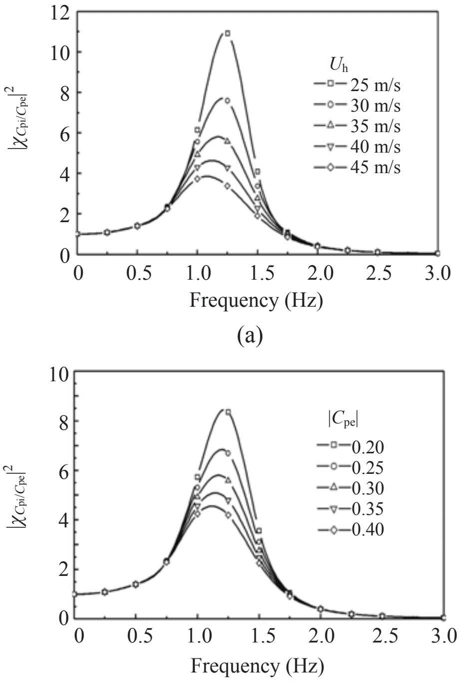
The results for U_{h}=35 m/s and V_0=10000 m^3 or V_0=1000 m^3 with variant opening ratio (expressed as $A_{\mathrm{w}}/V_0^{2/3}$) (Yu *et al.*, 2004) are shown in Figs.2a and 2b. It is clear that, as opening ratio decreases, the damping of the internal pressure response increases while the Helmholtz 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 frequency region. Compared Figs.2a and 2b, the damping characteristic for structure with the same opening ratio is similar in spite of variant internal volume. Thus the opening ratio is the key factor, which controls the damping characteristic for internal pressure response. Besides, the reference velocity and external pressure fluctuation amplitude also affect damping characteristic for internal pressure response. Assuming that the internal volume is 10000 m^3, the opening ratio is 5%, the internal pressure gain curves for variant reference velocity (with $|C_{\mathrm{pe}}|$=0.3) and for variant external pressure fluctuation amplitude (with U_{h}=35 m/s) are shown in Figs.3a and 3b, respectively. It can be seen that the damping of internal pressure response increases with the increase of the reference wind velocity or the increase of the external pressure fluctuation amplitude.



(a)

(b)

Fig.2 Gain curves for different internal pressure. (a) V_0=10000 m^3; (b) V_0=1000 m^3



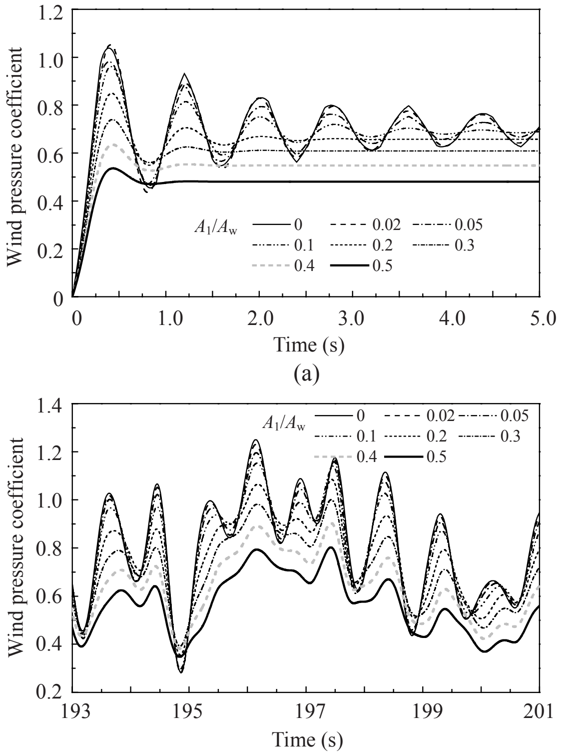
(a)

(b)

Fig.3 Influence of (a) reference wind speed and (b) external pressure fluctuation on gain curves

Analysis of additive damping for background leakage

The additive damping effects for background leakage can be analyzed by internal pressure transient response time histories and internal pressure response gain curves. Assuming leeward mean wind pressure coefficient as −0.4, internal volume as 10000 m^3, opening ratio as 5%, reference wind velocity as 35 m/s, external pressure coefficient as a constant of 0.7, the effect of variant background leakage (A_1/A_{w}) on internal pressure transient response time histories in laminar flow is shown in Fig.4a. It is clear that, with the total area of background leakage increasing, the peak value of internal pressure transient response decreases, the damping of system increases, and the mean internal pressure coefficient decreases. When the ratio of the total background leakage area to the windward opening area exceeds 0.2, the oscillation of internal pressure vanishes. A typical fluctuating wind pressure time history is used as external motivation. The effect of variant background leakage on internal pressure transient response time histories in turbulent flow is shown in Fig.4b. It can be seen that the peak value of internal pressure transient response decreases, the time history moves towards negative wind pressure and the fluctuation of pressure reduces when considering the background leakage. Thus, the additive damping effect is definitive no matter in laminar flow or in turbulent flow.



(a)

(b)

Fig.4 Influence of background leakage on internal pressure response (a) in laminar flow and (b) in turbulent flow

In order to obtain the effects of background leakage on internal pressure gain, the same time history described in Eq.(13) is used. The parameters are the same as those used for Figs.3a and 3b with U_h=35 m/s and $|C_{pe}|$=0.3. The internal pressure response gaincurves with variant background leakage are shown in Fig.5. It is clear that the peak value of internal pressure resonance decreases with background leakage increasing. Figs.3a and 3b show that the additive damping of background leakage has effect not only on internal pressure resonance response but also on internal pressure background response.

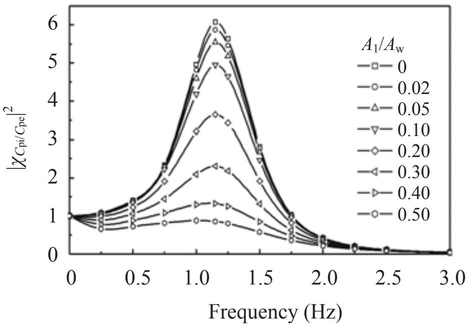


Fig.5 Influence of background leakage on gain curves for internal pressure

Time domain estimation of fluctuating internal pressure for structure with single windward opening and quantization of the damping effect of background leakage

Assume the oncoming wind velocity spectrum as Davenport spectrum. The quasi-steady assumption is used to simulate external pressure coefficient time history, and the Runge-Kutta method is used to solve the transfer equation, then the fluctuating internal pressure coefficient for structure with single windward opening is obtained. With the opening ratio as horizontal ordinate, Fig.6 presents the ratio curves of the RMS internal and external pressure coefficient with reference wind velocity as 25 m/s and 35 m/s, and with internal volume as 10000 m^3 and 1000 m^3, respectively. It can be seen that the RMS internal pressure coefficient decreases with the reference wind velocity increasing, which agrees well with the effect of reference wind velocity on the damping of internal pressure response. When the opening ratio is small enough, the fluctuating internal pressure increases with the decrease of internal volume, and when the opening ratio is large enough, the fluctuating internal pressure decreases with the decrease of internal volume.

Fig.7 shows the variation curves of the RMS internal pressure coefficient versus background leakage (A_1/A_w) with a reference wind velocity of 35 m/s, and an internal volume of 10000 m^3. It can be seen that the fluctuating internal pressure reduces with increasing the ratio of total background leakage area to the windward opening area, and that the reduction has positive correlation with opening ratio. It means that the damping effect of background leakage on the resonance vibration of internal pressure response is obvious, and that when the opening ratio is small enough, the damping effect of background leakage on internal pressure response can be indicated as the background vibration, thus the influence of opening ratio on it is little. Another result can be seen is that when the ratio of the total area of background leakage to the windward opening area is less than 0.1, the relative error of the estimation result of the RMS internal pressure discarding background leakage is less than 10%. In this case, the background leakage can be neglected. Obviously the result is similar to the experimental result reported by Vickery and Bloxham (1992).

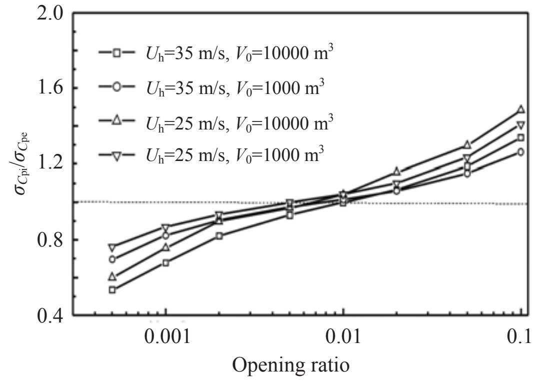


Fig.6 Estimation of RMS internal pressure coefficients

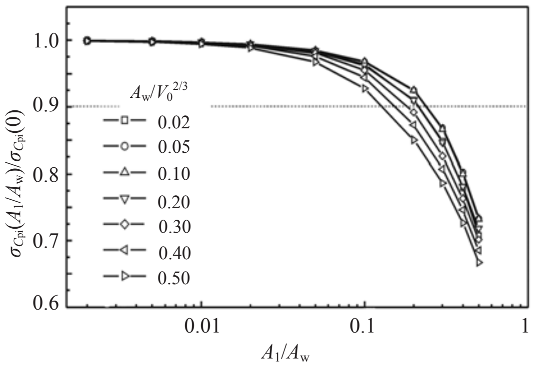


Fig.7 Influence of background leakage on RMS internal pressure coefficients

COMPARISON ANALYSIS OF EXPERIMENTAL AND THEORETICAL RESULTS

Wind tunnel test survey for rigid model

The building model was a 840 mm×540 mm×240 mm (d×b×h) rigid hexahedron structure with roof cornices. 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. Square openings were located on one of the 840 mm wide×240 mm high walls for simulating windward openings and the physical length of the openings can be neglected. Circular openings were located on another of the 840 mm wide×240 mm high walls for simulating background leakage. The details of openings arrangement and wind orientation are shown in Fig.8. In order to simulate low equivalent opening ratio with adequately large openings, the internal volume of model was exaggerated. Great care was taken to ensure that all fittings, joints and pressure tap exit points were air-tight. The states of model is listed as follows:

(i) Only single windward opening appears on model.

(ii) Single windward opening and background leakage appear on model.

Detailed configurations for wind tunnel test are given in Table 1. The internal volume is 1.17 m^3 for state (ii).

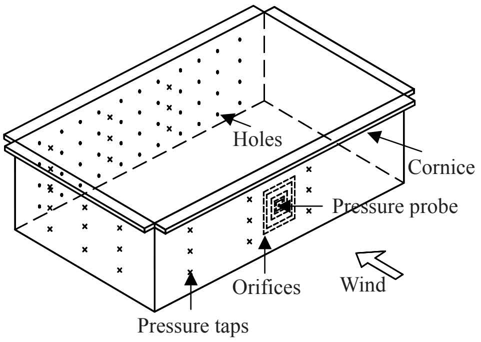


Fig.8 Arrangement of openings on model

Table 1 Configurations for wind tunnel tests

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

Configuration		A_w (cm^2)	A_l (cm^2)
	8	25	2.545
ii	9	25	5.938
	10	25	12.158

The arrangement of measuring points is identical in all configurations. All 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 surface of the windward wall, inner surface of the side wall, outer and inner surface of the leeward wall. A pressure probe was placed directly at the opening center to detect the pressure coefficients of the windward opening. These arrangements are shown in Fig.8. The experiments were carried out in a low-speed wind tunnel named NH-2 using a standard suburb simulation. The 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). 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 duration. Because the results obtained from all internal pressure measuring points are close for interior, the averaging value of results captured from all internal pressure measuring points is determined as the experimental result of internal pressure coefficients.

Certification of fundamental assumptions

The assumptions about correlation of internal pressure and leeward pressure fluctuation are confirmed in wind tunnel tests. Fig.9 shows the fluctuating internal pressure time histories captured from three measuring points in synchronism for configuration 1. It can be seen that the internal pressure time histories are almost synchronous. The correlation coefficient calculated from every two measuring points exceeds 0.99, and the results are similar for other configurations. Fig.10 is the comparison of pressure coefficient time histories for interior and leeward wall, and the result indicates that the pressure fluctuation of leeward wall can be neglected compared with internal pressure fluctuation. Above mentioned phenomena confirm that the fundamental assumptions of theoretical analysis listed in this paper are matched to experimental results.

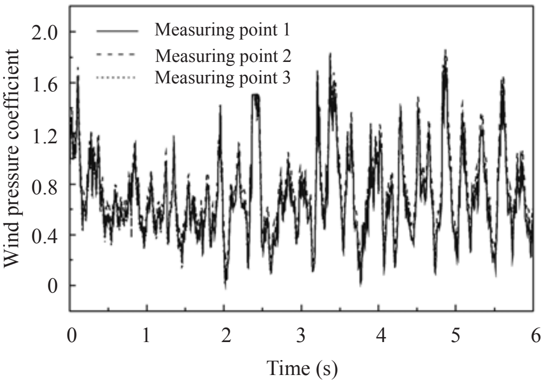


Fig.9 Internal pressure coefficient time histories

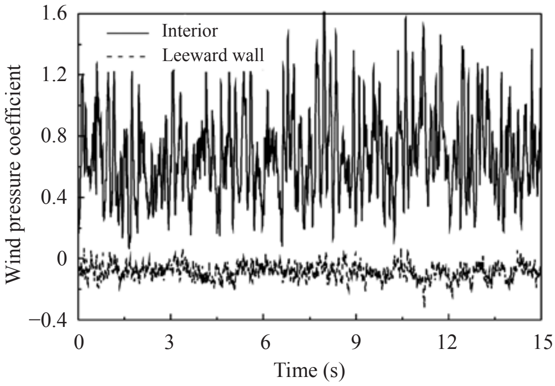


Fig.10 Comparison of internal pressure fluctuation and pressure fluctuation for leeward wall

Comparison of theoretical and experimental results

Fig.11 shows the power spectra of internal pressure coefficient for configures 1 and 7 compared with the power spectrum of pressure coefficient for windward opening. It can be seen that the Helmholtz resonance appears when the opening ratio is large enough. When the opening ratio is small enough, the Helmholtz resonance disappears and the high frequency energy of wind pressure is depressed. The experimental results are agreed with the theoretical results expressed in subsection 2.1. Fig.12 shows the comparison of internal pressure coefficient power spectra for configuration 5 (P=0), configuration 8 (P=P_1), configuration 9 (P=P_2), configuration 10 (P=P_3). It is clear that the power spectrum of internal pressure response is reduced for all frequency channels considering background leakage, which matches to theoretical analysis.

The time history of windward opening pressure coefficient captured in wind tunnel test is used as

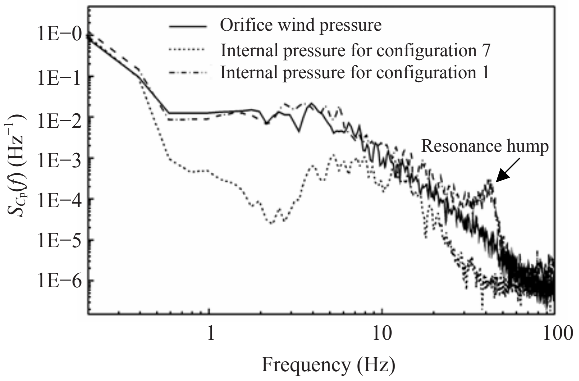


Fig.11 Power spectra of internal and orifice pressure coefficient

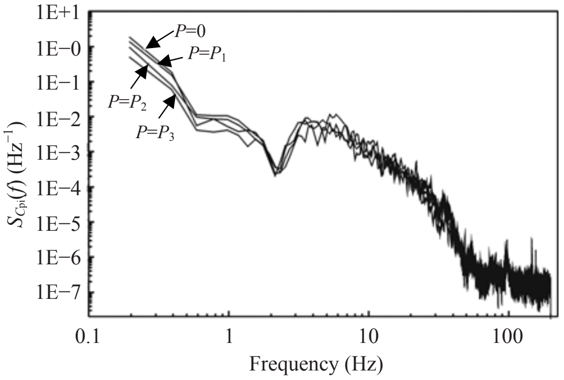


Fig.12 Influence of background leakage on power spectra of internal pressure obtained in test

motivation for calculating Eq.(11), and the opening characteristic parameters C_I=1.3 and C_L=C'_L=7.5 are defined as reported by Yu *et al*.(2007). The comparisons of theoretical and experimental results of the RMS internal pressure coefficient are listed in Tables 2 and 3. The variation rule of test result with opening ratio and background leakage is agreed well with theoretical one. The errors of the experimental RMS internal pressure coefficients and theoretical ones are small, which confirms that the equation newly deduced is reliable and that the time history analysis method is effective for theoretical analysis.

Table 2 Experimental and theoretical results of RMS internal pressure coefficients for structure with single windward opening

Configuration	Opening ratio	Experimental result	Theoretical result
1	0.05386	0.3048	0.2829
2	0.01347	0.3077	0.2789
3	0.00901	0.2764	0.2996
4	0.00576	0.2778	0.2804
5	0.00225	0.2350	0.2165
6	0.00081	0.1524	0.1531
7	0.00036	0.0902	0.0969

Table 3 Experimental and theoretical results of RMS internal pressure coefficients for structure with single windward opening and background leakage

Configuration	A_l/A_w	Experimental result	Theoretical result
5	0	0.2350	0.2165
8	0.1018	0.2198	0.2090
9	0.2375	0.2026	0.1953
10	0.4863	0.1729	0.1619

CONCLUSION

The transfer equation of internal pressure response is the basic theoretical law for investigating internal pressure response for the structure with windward opening. In this paper, the transfer equation of internal pressure response considering background leakage is deduced with proper simplification, which is a new development for theoretical research. The analysis of the influence factor to the damping effect on internal pressure response by using time history integral method, especially for additive damping analysis of background leakage, has theoretical values. The estimation of RMS internal pressure coefficients obtained with opening ratio as measuring criterion and the quantification index for the damping effect of background leakage provide reference for engineering design. Experimental results confirm that the background leakage reduces the internal pressure fluctuation, and that the effect of background leakage can be predicted accurately by the governing differential equation deduced in this paper.

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