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# WIND TUNNEL EXPERIMENT FOR UNSTEADY INTERNAL PRESSURE IN BUILDING

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**Abstract.** *The windowpanes and roofs of buildings may sometimes be damaged by strong winds. The resultant forces of the wind pressures from outside and inside of a building act on these parts. In the large indoor volume which has a big opening, the influence of internal pressure may become large by the so-called Helmholtz resonance. In this research, the wind tunnel experiment which modeled internal volume as well as outside shape of building was conducted, and the unsteady internal pressure were investigated.*

## 1 INTRODUCTION

Recent investigations of wind induced disasters have shown that damage to buildings has occurred to claddings such as walls, window panes and roofing materials (e.g. Matsui et. al. 2005). These components are affected by forces resulting from external and internal pressures. External pressures are often evaluated by wind tunnel experiments. Internal pressures, however, are not as easily obtained because the measuring conditions for internal pressures require more items (Holmes, 1979). It is also difficult to reproduce internal conditions. As a result, there few wind tunnel experimental results of internal pressures have been obtained. Holmes (1979), Vickery (1986) and Harris (1990) have reported the importance of evaluating internal pressures and their mathematical modeling for a single internal volume, while some field investigations (Kato et. al. 1997, Ginger et. al. 1997) and numerical studies (Sharma, 1997) have been conducted. However, not enough studies have been conducted on this topic.

This paper reports a study of internal pressures in a building, including their unsteadiness. A wind tunnel experiment was conducted on a building model whose internal conditions were partially modeled. Mathematical modeling of internal pressures for a few connected volumes is proposed and some case studies are shown.

## 2 WIND TUNNEL EXPERIMENT

### 2.1 Outline of wind tunnel experiment

Figure 1 shows the 1/100 scaled building model used for the wind tunnel experiment. The model contains three internal volumes, A, B and C, which are connected with tubes. The largest internal volume, A, is adjoining to the external wall with a large opening. Volume A was connected with tubes to volume C through volume B. The model was assumed as an office building with a warehouse (volume A). Volume B corresponded to stair halls and corridors. Volume C corresponded to an office room with a window to outside. The tubes were 25 mm in diameter. In the tubes, restrictors (5 mm diameter, 20 mm long) could be introduced to correspond to doors with louver windows.

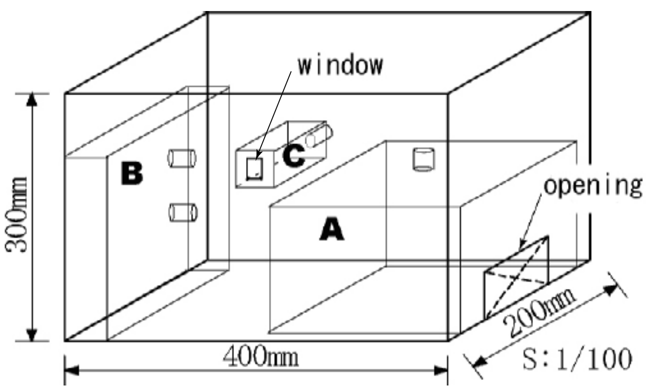



Figure 1: Model of building with internal volume for wind tunnel experiment

### 2.2 Experimental conditions and scaling law

Experimental conditions for each case are shown in Table 1. 16 experimental cases were conducted for different opening conditions of volume A, with or without restrictors and window conditions of volume C. The incident flow was a turbulent boundary layer corresponding to category III of AIJ mean wind speed profile, whose power law index was 0.2. The wind speed was set at 10 m/s at the building height. Temporal pressures were measured with 5 kHz sampling frequency for 30 seconds. Wind direction was defined as 0 degree when it blows right angle to the opening.

Equation (1) derived from the scaling law means the model was required to preserve the geometrical proportion if the wind speeds in full and model scales are identical.

$$\frac{[V_0]_m}{[V_0]_f} = \frac{[A]^{3/2}{}_m}{[A]^{3/2}{}_f}\frac{[\overline{U}]^2{}_f}{[\overline{U}]^2{}_m} = \frac{[L]^3{}_m}{[L]^3{}_f}\frac{[\overline{U}]^2{}_f}{[\overline{U}]^2{}_m} \tag{1}$$

where $V_0$, $A$, $U$, $L$ indicate the internal volume, the reference area, the reference wind speed and the reference length. Subscript $f$ and $m$ indicates full and model scale, respectively.

The measured pressures were evaluated as pressure coefficients normalized by velocity pressure at the building height. The wind force coefficient acting on the window of volume C was also evaluated by the difference between external and internal pressure coefficients on each side of the window. With the window set free, the external pressures were evaluated by the average of measuring points adjacent to the window on the external wall. The internal pressures were evaluated by the average of measuring points set on the internal walls.

The large opening in volume A had a shutter which could be opened instantaneously. The same situation would be expected when sudden openings are made due to wind-borne debris attack on the wall.

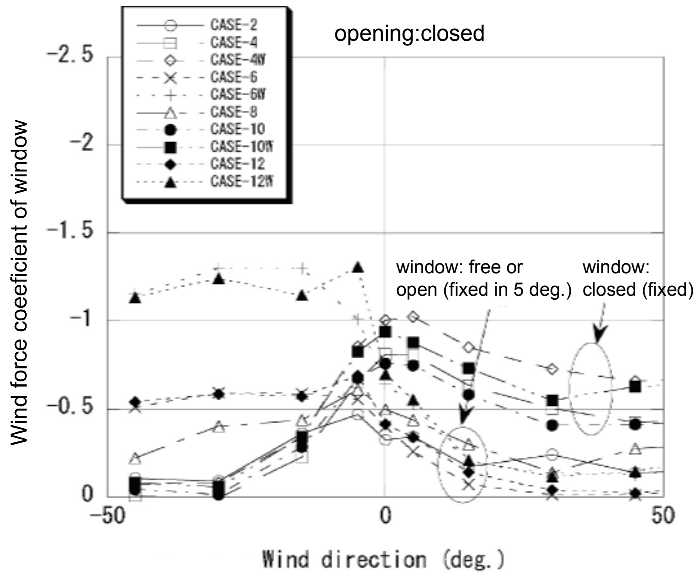
Table 1: Experimental conditions

| case | opening | window | restrictor |
|---|---|---|---|
| 1 | open | free | with restrictor |
| 2 | closed | free | with restrictor |
| 3 | open | closed (fixed) | with restrictor |
| 4 | closed | closed (fixed) | with restrictor |
| 5 | open | open (fixed in 5 deg.) | with restrictor |
| 6 | closed | open (fixed in 5 deg.) | with restrictor |
| 7 | open | free | w/o restrictor |
| 8 | closed | free | w/o restrictor |
| 9 | open | closed (fixed) | w/o restrictor |
| 10 | closed | closed (fixed) | w/o restrictor |
| 11 | open | open (fixed in 5 deg.) | w/o restrictor |
| 12 | closed | open (fixed in 5 deg.) | w/o restrictor |
| 13 | sudden opening | free | with restrictor |
| 14 | sudden opening | free | w/o restrictor |
| 15 | sudden opening | closed (fixed) | with restrictor |
| 16 | sudden opening | closed (fixed) | w/o restrictor |

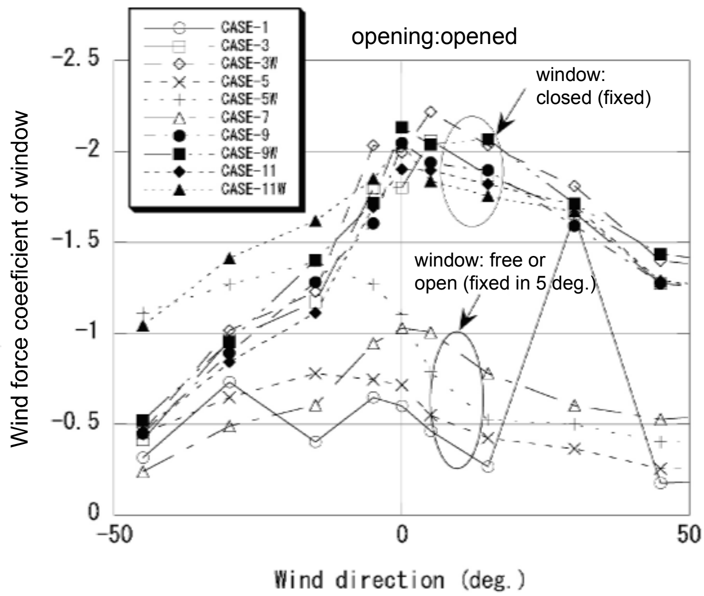
## 3 RESULTS OF WIND TUNNEL EXPERIMENTS

### 3.1 Comparison between cases with and without opening

Figure 2 (a) and (b) shows the variations of wind force coefficients on the window in volume C according with wind direction. The wind force coefficients with the opening showed higher negative values than those without the opening. The negative sign of the wind force coefficient, hereafter, indicates from inside to outside. When the window was closed, the wind force coefficient of the window showed higher negative values (around -2) in the range of wind direction between 0 and 30 degrees. These values are higher than that defined in the Japanese building law for "enclosed buildings". However, they are lower than that defined for "open buildings". This means that the internal pressure should be higher than that defined for "enclosed buildings". If a conservative design is required, the internal pressure for "open buildings" should be adopted.




(a) Opening: closed




(b) Opening: opened

Figure 2: Wind force coefficient of window when opening is closed and opened.

### 3.2 Effect of restrictor

Figure 3 shows the effects of the restrictor. Some cases show higher values without the restrictor than with the restrictor, while other cases show almost the same trend.

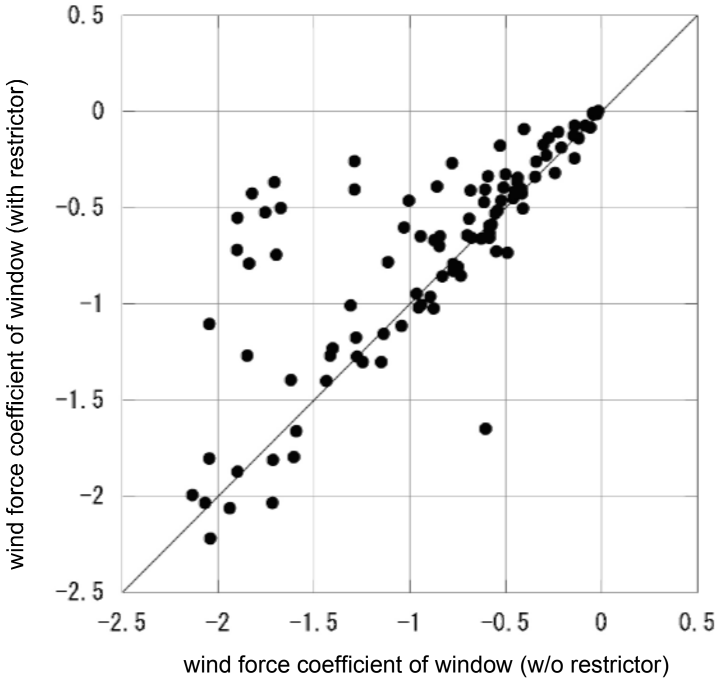



Figure 3: Comparison between wind force coefficients of window with and without restrictor

### 3.3 Effect of sudden opening

Cases from 13 to 16 in the Table-1 were experiments for sudden windward openings. Some of them showed the transient oscillation in the temporal variation of wind force of the window. Figure 4 shows an example of transient oscillation of wind force coefficients of the window when a sudden opening occurs. In the figure, the abscissa indicates reduced time $t^*(=tU/L$, $U$ wind speed at building height, 10m/s, $L$ reference length 0.2m in the experiment). For all cases the occurrence of the transient oscillations were indicated in Table 2. While there were little appearance of the oscillation in case 13 and 14 where the window had small gaps, there were some transient oscillations in case 14 and 15 where the window was closed. Oscillations were clearly seen in cases without restrictors. These oscillations seemed to indicate Helmholtz's resonance.

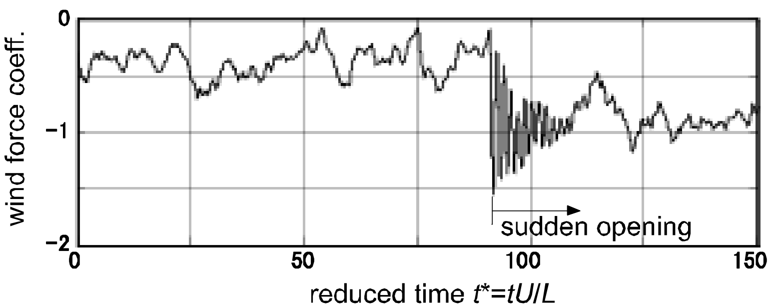



Figure 4: Transient oscillation of wind force of window due to sudden opening

Table-2 Occurrence of transient oscillation of wind force coefficient at window due to sudden opening

| case | 13 | 14 | 15 | 16 |
|---|---|---|---|---|
| window condition | free | free | closed fixed | closed fixed |
| restrictor | with | w/o | with | w/o |
| wind direction (deg.) | transient oscillation -:none，Δ: slight，○:a little ●:significant | | | |
| -45 | - | - | Δ | Δ |
| -30 | - | - | - | ○ |
| -15 | Δ | - | Δ | ○ |
| -5 | - | - | Δ | ○ |
| 0 | - | - | - | ● |
| 5 | - | - | ○ | ● |
| 15 | - | Δ | Δ | ● |
| 30 | - | - | ○ | ○ |
| 45 | - | - | Δ | Δ |

# 4 HELMHOLTZ MODEL FOR SOME INTERNAL VOLUMES CONNECTED IN SERIES

To evaluate the transient oscillation of internal pressures in the experiment, three internal volumes connected in series were modeled in the same manner as the Helmholtz's oscillator model. Figure 5 shows the modeled building that contains three volumes connected in series with openings. The equation of motion was set up for virtual air slugs at the openings as the balance of inertial force, pressure loss at the openings and difference pressures between connected volumes. The final expression was derived as Eq. (2) assuming small deformation of internal pressures and larger internal volumes than virtual air slugs.

$$\boldsymbol{M}\ddot{x} + \boldsymbol{C}\dot{x} + \boldsymbol{K}x = \boldsymbol{F} \tag{2}$$

where displacement of the air slag $\boldsymbol{x} = \{x_1, x_2, x_3\}$, mass matrix

$$\boldsymbol{M} = \begin{bmatrix} \rho_0 l_{e1} A_1 & 0 & 0 \\ 0 & \rho_0 l_{e2} A_2 & 0 \\ 0 & 0 & \rho_0 l_{e3} A_3 \end{bmatrix},$$

damping matrix

$$\boldsymbol{C} = \begin{bmatrix} \rho_0 A_1 |\dot{x}_1| \dfrac{1}{2\zeta} & 0 & 0 \\ 0 & \rho_0 A_2 |\dot{x}_2| \dfrac{1}{2\zeta} & 0 \\ 0 & 0 & \rho_0 A_3 |\dot{x}_3| \dfrac{1}{2\zeta} \end{bmatrix},$$

stiffness matrix

$$\boldsymbol{K} = \begin{bmatrix} \dfrac{\gamma A_1^2 P_0}{V_1} & -\dfrac{\gamma A_1 A_2 P_0}{V_1} & 0 \\ -\dfrac{\gamma A_1 A_2 P_0}{V_1} & \gamma A_2^2 P_0 \left( \dfrac{1}{V_1} + \dfrac{1}{V_2} \right) & -\dfrac{\gamma A_2 A_3 P_0}{V_2} \\ 0 & -\dfrac{\gamma A_2 A_3 P_0}{V_2} & \dfrac{\gamma A_3^2 P_0}{\left( \dfrac{1}{V_2} + \dfrac{1}{V_3} \right)} \end{bmatrix},$$

and external force vector $\boldsymbol{F} = \{-(P_e - P_0)A_1, 0, 0\}$. $\rho_0$, $l_e$, $A$, $\zeta$, $\gamma$, $V$ and $P_0$ are air density, equivalent length of air slug, area of openings, pressure loss coefficient, volume of internal space and atmospheric static pressure, respectively. Subscripts 1, 2 and 3 indicate that the valuables are for volume A, B and C, respectively.

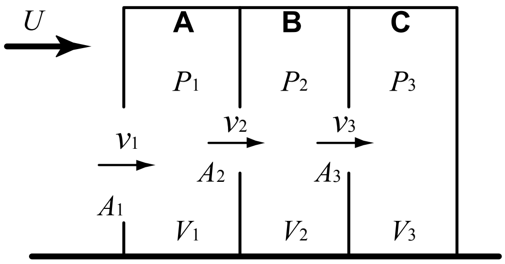
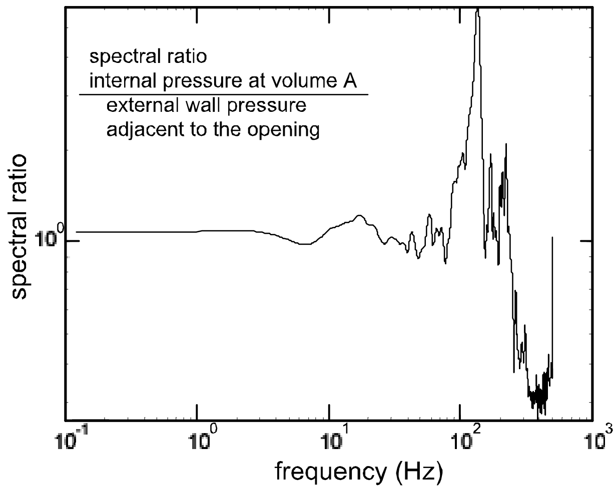
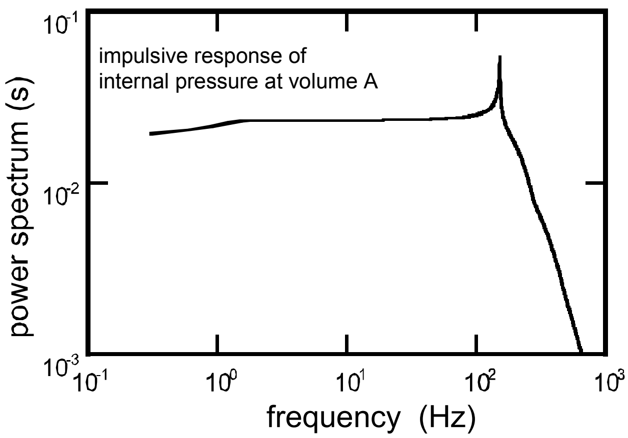



Figure 5: Building model with three internal volumes connected in series

Figure 6(a) shows a transfer function of internal pressure at volume A. The transfer function was evaluated by spectrum ratio of internal pressures at volume A to wall pressures close to the opening. The spectral ratio has a significant peak around 140 Hz. By employing the equation (1) to (4), impulsive response was calculated numerically. The spectral property of the response was evaluated as a power spectrum and is shown in Fig-6(b). The numerical model can predict the predominant frequency of 140 Hz.




(a) Spectral ratio between internal pressures at volume A to wall pressures close to the opening (experimental)




(b) Power spectrum of impulsive response evaluated by numerical model

Figure 6: Spectral properties of internal volume A (wind tunnel experiment and numerical model)

The numerical model was used to calculate transient responses of internal pressures in volumes A to C as shown in Fig-7. These were the responses under the external pressure coefficient that changed from 0 to 1 at time 0 (stepwise). The internal pressures fluctuated and arrived at a pressure coefficient of 2 that corresponded to 2 times the external pressure (pressure coefficient of 1). Their peak values are of volume C, B and A in ascending order. Even the external pressure was affected at volume A through the opening, and the internal pressure fluctuations were propagated to the connected volumes.

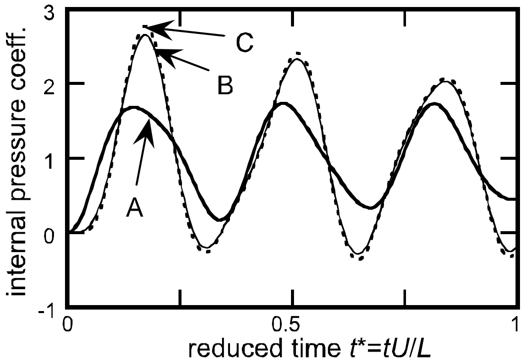



Figure 7: Transient response of internal pressures to stepwise external pressure change

## 5 CONCLUDING REMARKS

Unsteadiness of internal pressure of a building was investigated through wind tunnel experiments and numerical studies. The effect of an opening in the wall affects the internal pressures. The wind force on a window is also affected by an opening. The results of wind tunnel experiments show that the effect of openings will cause as much comparable design load as "open buildings".

The effect of a restrictor will reduce the effect of the internal pressures. Without restrictors the transient oscillation of internal pressure will be high. Transient oscillations were seen when an opening occurred suddenly.

In order to evaluate the transient response of internal pressures for some volumes in a building, a numerical model was proposed that the Helmholtz resonance model has been extended to. Some case studies were conducted to evaluate the propagation of the effect of openings on internal volumes.

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