Wind Tunnel Investigation of Fluctuating Pressure inside Building

풍하중에 의한 건물내부 압력의 동적변화에 관한 연구

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요 약

본 연구는 모형건물의 풍동실험을 통하여 건물내부에 작용하는 풍하중의 동적변화를 조사 연구하였다. 실험에 사용된 모형건물은 건물외부에 작용하는 풍하중이 건물 내부에 전달될 수 있는 개구부가 설치된 직육면체 형태의 구조물인데 실험시 개구부의 면적과 방향을 변화하고 정상류와 난류 상태의 풍하중을 사용하였다. 주어진 실험 조건하에서 건물내부 압력의 진동주파수를 알 수 있는 power spectrum 과 내부압력의 동적변화량을 알 수 있는 RMS를 측정하여 분석하였는데 분석된 실험 결과는 비교적 최근에 제안된 이론과 일치 하였다.

ABSTRSACT

The nature of fluctuating air pressure inside building was studied by testing a building model in a wind tunnel. The model has a single room and a window opening. Various opening conditions were tested in both laminar uniform wind and turbulent boundary-layer wind. The RMS and the spectra of the fluctuating internal pressure were measured. The test results support a recent theory which predicts the behavior of internal pressure under high wind based on aerodynamic analysis.

Introduction

The internal pressure of buildings, induced by high wind, affects the safety of buildings, almost as much as the external pressure does. However, in contrast to the external pressure, the internal pressure has been traditionally neglected, and become a subject of research only in recent years.

In 1970, Euteneuer[1] analyzed the transient response of the internal pressure caused by the sudden failure of a window. Because he used an approach that neglected the inertia effect of the air flow entering the opening, the result does not reveal any periodic oscillation of the internal pressure.

Stathopoulos et al.[2] in 1979, carried out a wind tunnel investigation of the internal pressure

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이 논문에 대한 토론은 1991년 3월 30일까지 본 학회에 보내주시면 1991년 9월호에 그 결과를 게재하겠습니다.

of low-rise buildings. The study showed the intensity of the internal pressure fluctuations under various degrees of building permeability and with various areas of building openings. It did not report any spectral measurement and did not mention whether their internal pressure oscillated at any predominant frequency.

In 1979, Homes[3] was the first to report that a building with a single room and a single opening behaves like a Helmholtz resonator in acoustics. Based on the Helmholtz resonator model, he derived equation to describe the oscillation of internal prerssure induced by wind. Later in 1981, Liu and Saathoff[4] developed a more rigorous mathematical model to solve the same problem by using the special form of Bernoulli Equation.

In the wind tunnel study presented herein, the variation of the internal perssure was investigated to verify the theoretical equations derived by Liu and Saathoff[4] and to see if amplification or resonance of the internal pressure occurs for different wind conditions.

Theories for Internal Pressure Oscillation

When a window or door is suddenly opened by or in a strong winds, the internal pressure of building changes rapidly and starts to oscillate within a short time. This internal pressure oscillation can be explained as follows:

Following the sudden breakage of a windward window or door by a strong wind, air rushes into the building and the internal preessure rises rapidly. This rise does not cease when the internal pressure, p_i, reaches the value of the external pressure, p_e. The inertia of the air causes p_i to rise to a level higher than p_e before the flow stops. Then, the higher pressure inside the building causes air to move of the building and p_i to decrease with time. The reverse flow does not stop until p_i becomes somewhat less than p_e. After the reverse flow has stopped, air rushes back into the building again as it did in the beginning of the first cycle.

The internal pressure oscillating in this manner can be predicted from the following equation dervied more than a century ago by Helmholtz:

$$f_H = \frac{A^{1/4}}{\pi^{5/4}} \sqrt{\frac{nRT}{2V}} \tag{1}$$

Where f_H is the Helmholtz frequency; A is the area of the opening; n is the polytropic exponent (equal to 1.4 for adiabatic air); R is the engineering gas constant for air; T is the absolute temperature of the air and V is the internal volume of the room. The equation used by Holmes[3] to predict the variation of internal pressure is

$$\frac{\rho L V}{A n p_a} \ddot{C}_{pi} + \frac{\rho q V^2}{2(knAp_a)^2} |\dot{C}_{pi}| \dot{C}_{pi} + C_{pi} = C_{pe} \tag{2}$$

Where C_{pi} and C_{pe} are, respectively, the internal and external pressure coefficients; dot and double dot on C_{pi} represent, respectively, the first and second derivatives with respect to time, t; ρ and p_a are, respectively, the density and pressure of the ambient air; q is the dynamic pressure(stagnation pressure); k is the orifice coefficient of the opening and L is the length of the air plug at the opening. For a building or Helmholtz oscillator without neck

$$L = \sqrt{\frac{\pi A}{4}} \tag{3}$$

Eqn.(2) was derived by assuming that a building cavity behaves like a Helmholtz oscillator which in turn is analogous to a mechanical vibration system. The first, second, third and fourth terms in eqn.(2) represent, respectively, the inertia, viscous damping, elastic and forcing-function terms. Without the viscous-damping and forcing terms, solution of eqn.(2) yields eqn.(1).

In 1981, Liu and Saathoff[4] derived an equation for the variation of internal pressure by using the unsteady form of the Bernoulli equation for isentropic compressible flow. Assuming that the air density variation is small, their result leads to

$$\frac{\rho LV}{kAnp_a}\ddot{C}_{pi}+\frac{\rho qV^2}{2(knAp_a)^2}|\dot{C}_{pi}|\dot{C}_{pi}+C_{pi}=C_{pe} \qquad (4)$$

The only difference between eqns. (2) and (4) is the presence of the orifice contraction coefficient, k, in the first term of eqn.(4). By setting the damping and force-function terms of eqn.(4) to be zero, the solution of equation yields

$$f_H=\frac{A^{1/4}}{\pi^{5/4}}\sqrt{\frac{knRT}{2V}} \qquad (5)$$

Comparing eqns.(1) and (5) shows that the two equations differ by a factor k in the square root sign. The difference is due to the presence of k in the coefficient of the first term of eqn.(4) which does not exist in the first term of eqn.(2). The wind tunnel data presented herein provided a check on the validity of eqn.(5).

Experimental Set-Up

Wind tunnel

The tests were carried out in the Civil Engineering Wind Tunnel of the University of Missouri-Columbia. The tunnel had a test section of 910mm width×910mm height×3.05m length. Without using artifical roughness and spires, the wind through the tunnel has a uniform velocity across the test section and a low intensity of less than 1% of the mean velocity. Such wind is hereafter referred to as the "laminar uniform wind".

Tests were also conducted in a simulated atmospheric boundary-layer wind obtained by using spires and artificial roughness on the floor. The wind tunnel floor upstream and downstream from the building model was covered with the cubic roughness of 2cm width×2cm depth×2cm height. Four spires were installed at the test section entrance to provide a thick boundary layer than would otherwise be available. The spires were triangular shaped plywood pieces of 1cm thick, 45cm height and 8cm wide at the base. The mean velocity profile and turbulent intensity were measured with a pitot tube and a hot-wire anemometer(TSI Model 1054a). At the location of the building model in the wind tunnel, the mean-velocity of the boundary layer wind, U, can be approximately represented by a power-law equation with an exponent of 0.43 as follows :

$$U=U_0\left(\frac{h}{\delta}\right)^{(0.43)} \qquad (6)$$

where the boundary layer thickness δ is 51cm ; U_0 is the free stream velocity ; and U is the velocity of the air at the heught, h. The longitudinal component of turbulent wind, occurring near the height of the window of the test model, was approximately 10% of the freestream mean velocity. The maximum speed of the wind tunnel was 29.0m/s. All the experiments were carried out at this maximum wind speed because that Reynolds number was expected to have negligible effect on the test results.

Building model

The building model was a block-type, flat-roofed, single room building made of 0.5cm thick transparent acrylic plates. The inside dimensions of the building model were 14cm width×14cm depth×29cm height. The model had two window openings, each 4cm×4cm, one on the windward wall and the other on the leeward wall. The window openings was simulating the condition of a window broken or left open during a wind storm. The two windows on both windward and leeward side were not open at the same time. When one was open, the other was closed. The area of each opening could be reduced to 3cm×3 cm, 2cm×2cm, 1cm×1cm, 0cm×0cm, simply by plugging the opening of building model with a piece of acrylic plate having smaller or no opening. The centers of the openings were always located at the same place.

Four pressure thansducers were used for measuring external pressure: two were mounted on the windward wall at 1cm above and below the 4cm×4cm openings, and two were mounted near the leeward opening at the same relative locations. Another two pressure transducers were mounted inside the building model. The use of two pressure transducers on each wall and inside proviede a check of the consistency or lack of consistency of the data collected.

Similitude

To obtain dynamic similitude of two flow fields between model and prototype, the ratio of forces actiong on the model and the prototype should be the same. In the wind tunnel experiments, surface tension and gravity effects are nonexistent. The variation of air density is expected to be very small since wind speed is much less than one-third of the sonic velocity. Also, friction action of air due to the viscous effects is neglihible, and pressure force is dominant in this experiment. Note that the fluctuating pressure in eqns. (2) and (4) is expressed in terms of pressure coefficient which is dimensionless number. It is apparent now that since the air density diffenence between model and prototype is negligible, variation of air pressure in prototype can be predicted from model measurements.

Signal measuring procedure

The pressure transducer signals were connected to a set of amplifiers/filters(ITHACO 4210). The ITHACO could be used either as a band-pass filter, a band-reject filter, or a DC-coupled low-pass filter. For the pressure fluctuation intensity (RMS) and power specturm measurements, the low-pass filter was set at 1kHz and the high-pass filter was set at 0.01Hz. These settings were justified because the resonance frequency of fluctuating pressure was expected to be in the 50-200Hz. For the measurement of the temporal mean pressure,the instrument was used as a DC-coupled low-pass filter which only passed frequencies lower than 0.01Hz.

The outputs of the amplifier/filters were connected to a seven-channel magnetic tape recorder (AMPEX SP300). The signal on the tape was analyzed on a mini-computer(TEKTRONIX 4052 Graphic System). A program was used to control the A/D converter and the ROM pack. The subroutines stord in ROM pack computes the spectra and the correlation functions. Results of the computation were both displayed on a terminal screen and plotted by the computer.

Test Results

Power spectra in laminar uniform wind

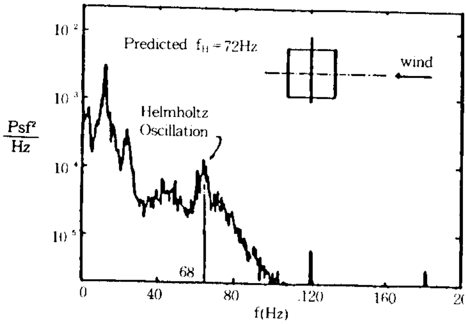
Power spectral analyses were made to determine the frequency distributions of the wind-induced fluctuating pressures--both internal and external. The Helmholtz frequency indicated by the spectral peak of each case were compared to the Helmholtz frequency calculated from eqn.(5) using $n=1.4$(adiabatic air), $k=0.88$, $R=287\mathrm{Jkg^{-1}K^{-1}}$, $T=$

293K and $V=0.00568\,m^3$. As will be shown later, $k=0.88$ is an average value that yields best agreement between theory and experiment for the model used in this study.

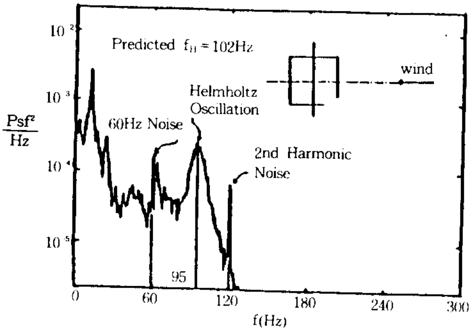
Figs.1(a)–(b) gives the power spectra of the internal pressure fluctuations for the four window size areas with the window open on the windward side. Fig.1(a) shows that for the 10×10mm opening, the theoretical Helmholtz frequency was 72Hz, whereas that indicated by the spectrum was 68 Hz. This small difference is partially due to the influence of a 60Hz harmonic noise present in the measurement. Figs. 1(b)–(d) show that the measured Helmholtz frequcney for 20×20, 30×30, 40×40mm openings was, respectively, 95, 120, and 144Hz. They are within 93% of predicted value. The spectra of the internal pressure fluctuations caused by a leeward window opening of different sizes are shown in Fig.2(a)–(d). Much larger fluctuations of internal pressure was detected in this case than in the case of windward openings. The reason for this larger fluctuation is that although the laminar–uniform–wind upstream condition contained little turbulence and hence little pressure fluctuation, the downstream region of building model was affected by the turbulent wake generated by the model. The large fluctuations of the external pressure on the leeward wall induced a large internal pressure when opening existed on the leeward wall.

Power spectra in turbulent boundary-layer wind

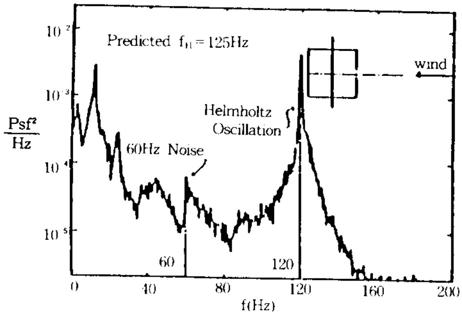
The simulated boundary layer wind at the height of window opening had 10% freestream turbulence intensity. The same experiments carried out in the uniform flow were performed in the simulated boundary layer. Figs. 3(a)–(d) give the spectra of the internal pressure fluctuations caused by a windward opening of different sizes. As can be seen from the spectra, large openings produce



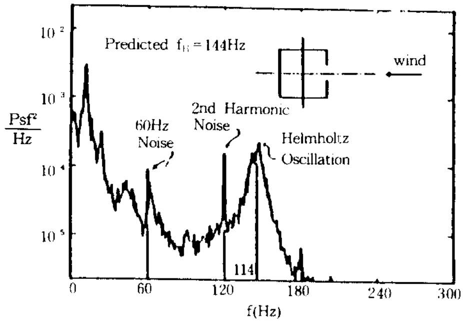
(a) 10mm×10mm Opening



(b) 20mm×20mm Opening

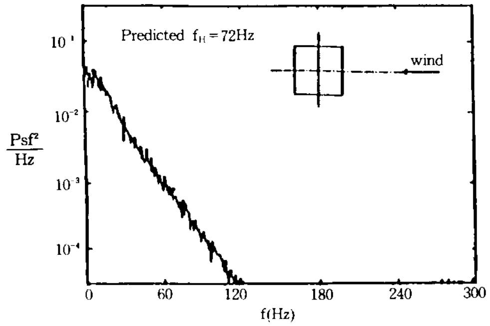


(c) 30mm×30mm Opening

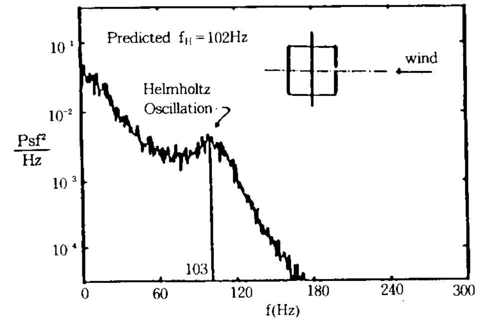


(d) 40mm×40mm Opening

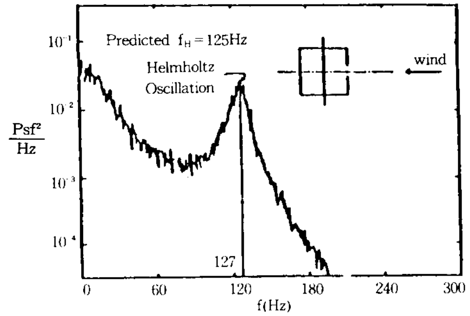
Fig. 1. Power spectra of internal pressure fluctuations with windward opening in laminar uniform wind.



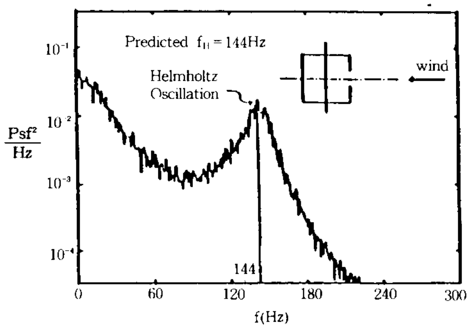
(a) 10mm×10mm Opening



(b) 20mm×20mm Opening

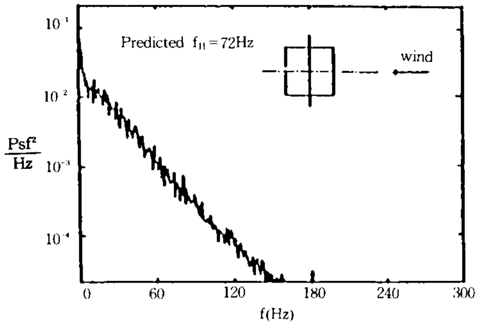


(c) 30mm×30mm Opening

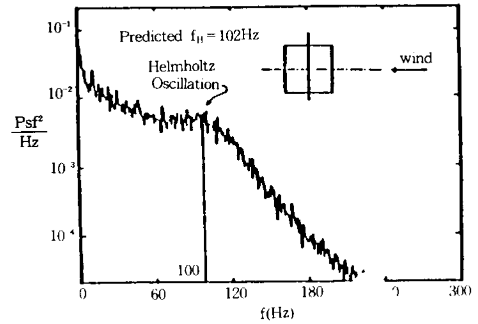


(d) 40mm×40mm Opening

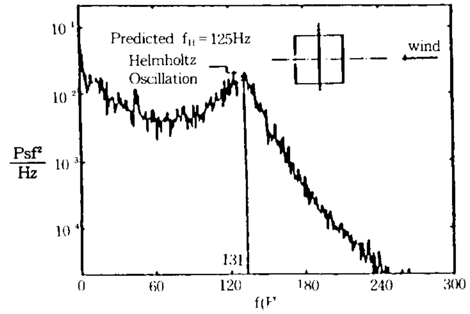
Fig. 2. Power spectra of internal pressure fluctuations with leedward opening in laminar uniform wind.



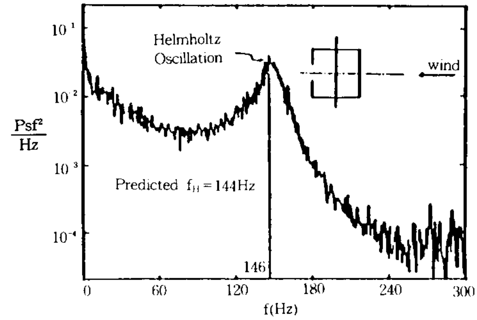
(a) 10mm×10mm Opening



(b) 20mm×20mm Opening



(c) 30mm×30mm Opening



(d) 40mm×40mm Opening

Fig. 3. Power spectra of internal pressure fluctuations with windward opening in turbulent boundary-layer wind.

large Helmholtz peaks. The measured peaks again agreed closely with those predicted from eqn. (5).

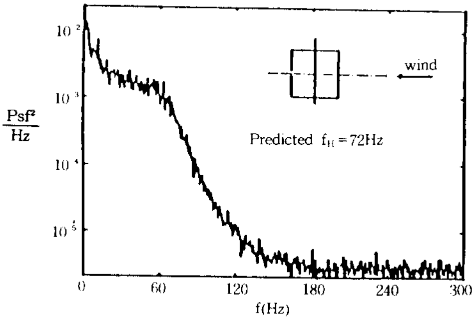
When the opening was on the leeward wall, the spectra of the internal pressure measured were given in Figs. 4(a)-(d). The Helmholtz peak was evident for all the openings greater than 10×10mm.

Coefficients k and n

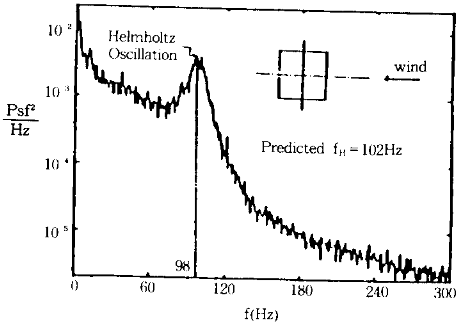
The value of k can be determined from eqn. (5) by using the measured Helmholtz resonance frequency and by assuming $n=1.4$(adiabatic condition). This was done by Rhee[5] for large number of spectral measurements for different openings and wind conditions. The range of best fit value of k in each case was found to be between 0.75 and 0.99, with average being 0.88. Thus, the average value $k=0.88$ and $n=1.4$ were used herein for the prediction of the Helmholtz oscillation frequency shown in the power spectrum graph. The results are summarized in Tables 1 through 4.

Instead of using eqn.(5), Rhee[5] also used eqn. (1) to fit his data. He found that in this case $n=1.23$ gave the best. Note that Holmes[3] also found that $n=1.2$ gave the best fit when eqn.(1) is used.

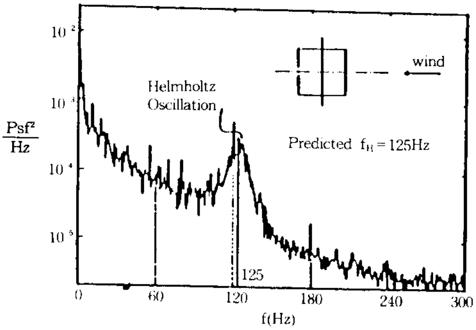
From the foregoing results, it appears that both Helmholtz's equation, eqn.(1) and Liu's equation-,ean.(5), gave equally satisfactory results. However, to use eqn.(1) one must use an n value in the neighborhood of 1.2, in addition to using an empirical value for k. On the other hand, if eqn. (5) is used, n remains 1.4(adiabatic) while a contract coefficient, k, the same as for that of a steady orifice flow, can be used. Since the Helmholtz oscillation involves rapid variation of pressure of relatively small amplitude, the process is expected to be adiabatic. Therefore, it appears that eqn.(5) is more appropriate than eqn.(1).



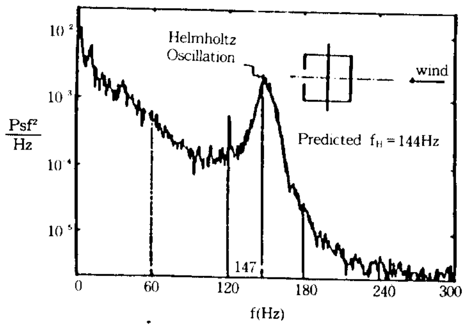
(a) 10mm×10mm Opening



(b) 20mm×20mm Opening



(c) 30mm×30mm Opening



(d) 40mm×40mm Opening

Fig. 4. Power spectra of internal pressure fluctuations with leeward opening in turbulent boundary-layer wind.

Coefficients $C_{\bar{p}}$ and $C_{p'}$

The mean pressure coefficient, $C_{\bar{p}}$, and the RMS values of the fluctuating pressure, $C_{p'}$, corresponding to the mean pressure were measured for each of experiments. The results were also summarized in Tables 1 through 4. Table 1 shows that with a windward opening in a laminar uniform wind of 1 % freestream turbulence, the values of $C_{\bar{p}}$ of the internal pressure were approximately the same as that of the external pressure on windward wall. They were in the range of 0.95 −0.98. The values of $C_{p'}$ were approximately 0

TABLE 1 Values of f_H, k, $C_{\bar{p}}$ and $C_{p'}$ for windward opening in laminar uniform wind.

Size of opening (cm×cm)	Predicted f_H based on $k=0.88$ (Hz)	Internal pressure				External pressure on windward wall				Ecternal pressure on leeward wall			
		f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$
1×1	72	68	0.781	0.95	0.02	–	–	0.95	0.01	–	–	−0.76	0.14
2×2	102	95	0.762	0.96	0.02	95	0.762	0.93	0.01	–	–	−0.76	0.14
3×3	125	120	0.811	0.96	0.02	120	0.811	0.91	0.01	–	–	−0.76	0.13
4×4	144	144	0.876	0.98	0.02	144	0.876	0.91	0.01	–	–	−0.78	0.14

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Size of opening (cm×cm)	Predicted f_H based on $k=0.88$ (Hz)	Internal pressure				External pressure on windward wall				Ecternal pressure on leeward wall			
		f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$
1×1	73	–	–	0.54	0.10	–	–	0.92	0.01	–	–	−0.76	0.13
2×2	102	–	–	−0.76	0.13	–	–	0.90	0.02	–	–	−0.76	0.14
3×3	125	131	0.967	−0.76	0.15	–	–	0.91	0.01	–	–	−0.76	0.13
4×4	144	146	0.900	−0.76	0.16	–	–	0.92	0.02	146	0.900	−0.74	0.13

TABLE 1 Values of f_H, k, $C_{\bar{p}}$ and $C_{p'}$ for windward opening in turbulent boundary−layer wind.

Size of opening (cm×cm)	Predicted f_H based on $k=0.88$ (Hz)	Internal pressure				External pressure on windward wall				Ecternal pressure on leeward wall			
		f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$
1×1	72	–	–	1.0	0.25	–	–	0.80	0.22	–	–	−0.33	0.08
2×2	102	103	0.896	0.83	0.29	–	–	0.80	0.22	–	–	−0.33	0.09
3×3	125	127	0.908	0.83	0.34	127	0.908	0.75	0.22	–	–	−0.28	0.09
4×4	144	144	0.876	0.78	0.33	144	0.876	0.70	0.22	–	–	−0.28	0.09

TABLE 1 Values of f_H, k, $C_{\bar{p}}$ and $C_{p'}$ for leeward opening in turbulent boundary−layer wind.

Size of opening (cm×cm)	Predicted f_H based on $k=0.88$ (Hz)	Internal pressure				External pressure on windward wall				Ecternal pressure on leeward wall			
		f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$	f_H (Hz)	k	$C_{\bar{p}}$	$C_{p'}$
1×1	72	–	–	−0.35	0.16	–	–	0.88	0.24	–	–	−0.06	0.08
2×2	102	98	0.811	−0.31	0.17	–	–	0.88	0.24	–	–	−0.11	0.08
3×3	125	125	0.880	−0.31	0.20	–	–	0.88	0.25	125	0.880	−0.24	0.08
4×4	144	147	0.913	−0.31	0.15	–	–	0.88	0.24	147	0.913	−0.22	0.08

.02, 0.01, and 0.14, respectively for internal, windward external and leeward external. Note that the values of C_p' of external pressure on the leeward wall is about seven times stronger than on windward wall because of a phenomenon caused by the low upstream turbulence and the large fluctuations downstream due to the building wake.

Table 2 is the same as Table 1 except that the opening was on the leeward wall. Tables 3 and 4 are the counterparts of the Tables 1 and 2 for the model in a turbulent boundary wind of 10% free steram turbulence.

Conclusions

1. Although both eqns.(1) and (5) yield satisfactory results, the latter appears to be more appropriate because it always uses $n=1.4$, the adiabatic exponent of air. Furthermore, the effect of orifice geometry can be taken into account by adjusting the value of k, the contract coefficient. The average k values for in this study was 0.88

2. The general validity of eqn.(5) has been verified in this study by using different flows with different velocity profile and turbulence characteristics. These include a laminar uniform flow with 1% free streams turbulence and a boundary layer flow with 10% freestream turbulence.

3. Even in laminar uniform wind only 1% of freestream turbulence, the internal pressure oscillates if there is a large window opening. With little freestream turbulence, this oscillation of the internal pressure is induced by the external pressure fluctuations generated by the turbulent wake of the building. In this case, the internal pressure fluctuations are much stronger when the opening is on the leeward wall than on the waidward wall. The oscillation takes place at the Helmholtz frequency. 4. When there is a large windward opening, the higher intensity of turbulent flow increases the internal pressure oscillation.

5. For building with a single large opening, the intensity of the internal pressure fluctuation is stronger than that of the external pressure fluctuations. This has interesting implications for building safety in cases where a large door or window is open during a wind storm.

Acknowledgments

This study was supported by the National Science Foundation of the United States of America under grant CME 8012679.

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(접수일자 : 1990. 10. 26)