Numerical evaluation of internal pressure in a low-rise building model in a tornado-like vortex

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SUMMARY

This paper presents a study in which the internal pressure inside a building model subjected to tornado-like loading is evaluated based on measured external pressure. The relationship between the internal pressure and external pressure is modelled by discharge equations. The discharge coefficient and flow exponent in the discharge equations are identified using unscented Kalman filter (UKF). The internal pressure is estimated by solving the discharge equations with measured external pressure near the opening on the building model as the input. The effectiveness of the numerical approach is illustrated using the pressure measurements from an experiment in which a low-rise building model is tested in a tornado-like vortex.

Keywords: tornadic loading, internal pressure, discharge equation

1. INSTRUCTIONS

Internal pressure inside a building depends critically on the openings in the building envelope. Because internal pressure can account for a large portion of the overall wind loading, many studies have been conducted to study how openings affected the internal pressure. Holmes (1979) modeled the internal pressure as a Helmholtz resonator and showed that this model can effectively capture the major characteristics of the internal pressure based on given external pressure. Subequently, many more studies were conducted to model internal pressure (e.g., Ginger, 2000; Sharma, 2003; Vickery, 1986) in a building with a large opening. In addition, Oh et al. (2007) proposed a method to determine the internal pressure in a building with multiple openings using discharge equartions. Regardless of the model, the key for effective application of these models is the determination of the model parameters. In this study, the unscented Kalman filter is used to identify the discharge coefficient and flow exponent in the discharge equations that are used to model the internal pressure inside a low-rise building with a large opening. The effectiveness of the method is illustrated by comparing the measured internal pressure inside a low-rise building model translating through a tornado-like vortex with the numerically determined internal pressure based on measured external pressure. In addition, a parametric study is used to show the influence of the discharge coefficient and flow exponent in the accuracy in determining the internal pressure through discharge equations.

2. METHODOLOGY

For a building with a single dominant opening, the relationship between the external and internal pressures can be modeled by the discharge equations (Oh et al. 2007):

$$\rho l_e \ddot{x} + \left(\frac{1}{k}\right)^{1/n} \left(\frac{\rho}{2}\right)^{1/2n} \dot{x}\left|\dot{x}\right|^{(1/n)-1} + \frac{32\mu l_0}{d^2}\dot{x} = p_e - p_i \tag{1}$$

$$\rho A x = \frac{\rho V_0}{\gamma P_{ref}} p_i \tag{2}$$

where p_e is the external pressure at the opening; p_i is the internal pressure. ρ is the density of air; A is the area of the opening. l_e is the effective length of the opening (taken as $l_0 + 0.89\sqrt{A}$, l_0 being the thickness of the wall); d is the opening diameter; μ is the dynamic viscosity of air; k is the orifice discharge coefficient; n is the flow exponent; x, $\dot{x}$ and $\ddot{x}$ are the moving distance, velocity and acceleration that the "air slug", respectively; V_0 is the internal volume; $\gamma = 1.4$ is the polytropic gas constant of the air; P_{ref} is atmospheric pressure. Discharge coefficient k and flow exponent n are the parameters that need to be determined, and previous studies suggested various values for different turbulence intensities and opening conditions. However, since those previous studies are for boundary-layer type winds, those values may not be applicable for tornado-like flow. In this study, the UKF (Wan et al. 1999) is used to identify k and n in the discharge equations that are used to model the relationship between the external and internal pressures of a building model in a tornado-like flow.

3. ILLUSTRATIVE APPLICATION

3.1 Experimental Configuration

To facilitate an illustration of the application of the method, a 1:100 model of a building with a nominally flat roof that is 13.8 m in length, 9.3 m in depth and 3.9 m in height was tested in a tornado simulator at Texas Tech University (Chen et al. 2023). In the tests, the model was mounted on the center section of the simulator floor and translated with the floor at a speed of 1.25 m/s along a path through the center of a two-celled tornado-like vortex. The pressures acting on the external and internal surfaces of the model were measured while it traslated. Table 1 summarizes the major characteristic of the vortex when the floor was stationary. Here, the swirl ratio and radial Reynolds number as defined by by Church et al. (1979) are estimated based on the velocity of the flow along a vertical line at the edge of the updraft hole of the simulator, and the internal aspect ratio is defined as the ratio of the height of the confluent region to the radius of the updraft hole. The core radius of the vortex is taken as the radial distance between the location of the maximum mean tangential velocity and the nominal time-averaged vertical axis of the vortex. More details of the vortex can be found in Chen et al. (2023). Figure 1 (a) shows an exploded view of the building model with a rectangle representing a dominant opening on one of its walls and small circles indicating the locations of the pressure taps on the external surfaces of the model. The opening ratio, which is defined the area of the opening cross section to the total external surface area of the model, is 0.63%. To satisfy dynamic similarity between the internal pressures in the full-scale building and the building model, a sealed box was attached to the bottom of the model. The total volume enclosed by the model and the box were determined according to the volume scale suggested by Holmes (1979), $V_m/V_f = (L_m/L_f)/(U_m/U_f)$, where V, L and U represent volume, length and wind speed, respectively, and subscripts m and f indicate model and full scales, respectively. The velocity scale, U_m/U_f is chosen to be 1:4. Figure 1 (b) shows the orientation of the translating model relative to the rotating direction of the vortex, represented by the arrows along the circle of radius r_c, for a typical experimental configuration. A fixed coordinate system, x-o-y, with its origin at the center of the vortex at the floor level and the x axis aligned with the direction of model translation is defined to locate the model. For each configuration, the test was repeated 115 times to enable a good estimation of the loading statistics. The parameters k and n in the discharge equations were identified based on measurements from each test run. The mean values of *k* and *n* from the 115 runs are 0.1 and 0.79, respectively.

Table 1. Characteristics of simulated tornado-like vortex.

Swirl Ratio	Internal aspect ratio	Radial Reynolds number	Maximum mean tangential velocity (m/s)	Core radius r_c (cm)	Height of maximum mean tangential velocity z_c (cm)
0.83	0.5	6.1×10^5	11.5	46	6

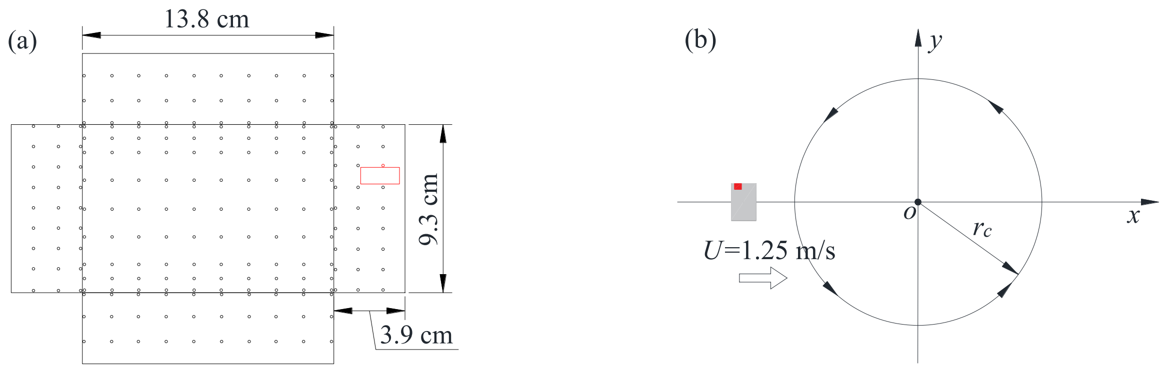

Figure 1 (a) Building model and (b) test configuration.

3.2 Illustrative results

Figure 2 shows a comparison of the internal pressure coefficient, C_{Pi}, estimated based on an example measurement and numerical solution. It is seen that the numerical result closely matches the measurement. In addition, according to the evolutionary power spectral density (EPSD, 1/Hz) functions of C_{Pi} shown in from experimental and numerical results shown in the numerical solution is able to effectively reproduce the frequency composition of the internal pressure as the model translates through the vortex. In particular, the numerical solution successfully captures the narrowband component with a characteristic frequency of 2.73 Hz and the resonance with a Helmholtz frequency of about 55 Hz in the internal pressure.

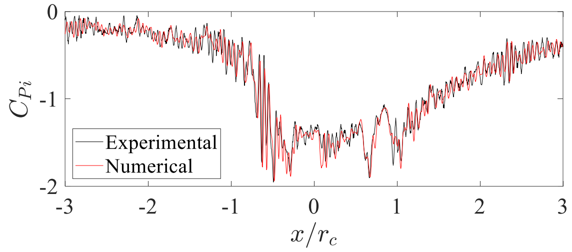

Figure 2. Comparison of C_{Pi} from experimental and numerical results.

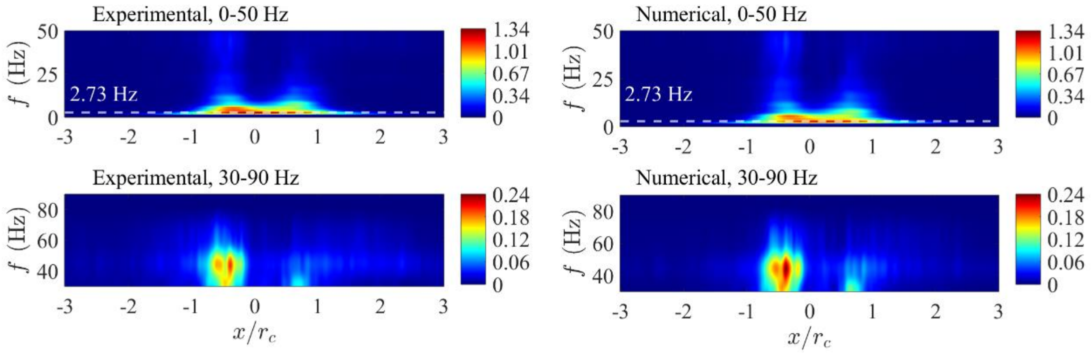

Figure 3. EPSD of internal pressures from experimental and numerical results.

Figure 4 shows the first four moments of C_{Pi} estimated based on the measurements and and numerical results. Good agreements are again observed.

Figure 5 shows the error of numerically estimated internal pressure as compared to the measurements, which is defined as… It is seen that the discharge coefficient, *k*, critically controls the accuracy of the numerical solution. As long as this coefficient is effectively identified, the influence of the flow exponent, n, is not significant.

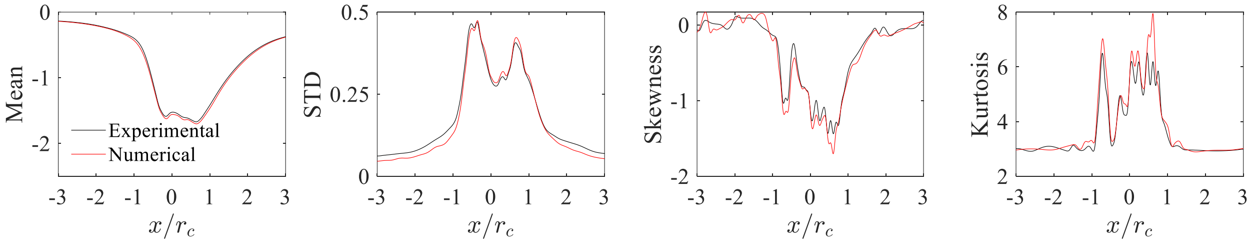

Figure 4. Comparison of first four moments of C_{Pi} from experimental and numerical results.

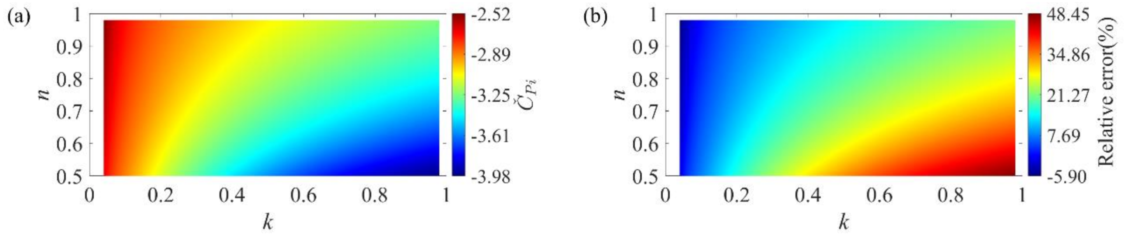

Figure 5. Error of numerical solutions for various combinations of *k* and *n* values.

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