Wind Engineering Joint Usage/Research Center FY2024 Research Result Report

Research Field: Wind Hazard Mitigation/Wind Resistant design
Research Year: FY2024
Research Number: 24242007
Research Theme: Aerodynamic forces and pressures of retractable roof depending on Reynolds number and internal volume

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Budget [FY2024]: 390,000Yen

*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
*Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

This study aims to investigate how the presence of a large central roof opening and variations in internal volume affect wind pressure characteristics on the interior roof surface of an open long-span dome structure. Particular focus is placed on the interaction between Helmholtz resonance and vortex shedding, and their role in amplifying internal pressure fluctuations.

While most previous studies have addressed internal pressure responses in buildings with relatively small openings—either functional or caused by local damage—the internal pressure dynamics of structures with large, centrally located openings remain less understood. Such openings, commonly found in modern dome-type or retractable roof systems, promote extensive airflow interaction, leading to internal pressure responses that differ significantly from those in enclosed structures. In these cases, the interaction between external turbulence and the internal air mass may trigger resonant phenomena, such as Helmholtz resonance, depending on the configuration and volume of the internal space.

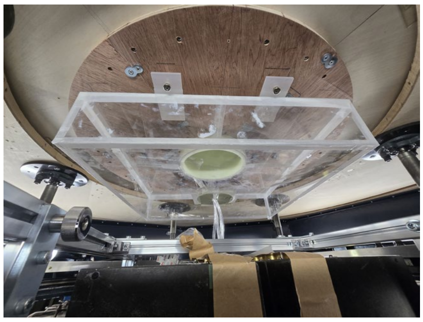
When the frequency of vortex shedding induced by flow separation at the roof edges approaches the natural frequency of the enclosed air, a strong resonant condition—known as vortex-driven Helmholtz resonance—can emerge. This interaction may amplify internal pressure fluctuations considerably, increasing the likelihood of extreme values and imposing additional demands on structural and cladding performance.

To investigate these phenomena, wind tunnel tests were conducted on a scaled dome model with a 50% central opening, under four internal volume conditions ranging from a sealed configuration without additional cavity to progressively larger cavity volumes. The study analyzes the internal pressure responses in terms of mean and standard deviation, power spectral density (PSD), skewness, and kurtosis to evaluate how volume scaling influences frequency characteristics and non-Gaussian properties.

2. Research Method

Wind tunnel tests were conducted using a 1:300 scale rigid model of an open dome roof (60 m full-scale diameter) with a 50% central opening. Internal volume was varied across four cases—V0 (no cavity), Vs (theoretically scaled volume), V1 (smaller than Vs), and V2 (larger than Vs)—as shown in Figure 1 and Table 1.

(a) Model



(b) Cavity

Figure 1. Configuration of test model and cavity installation

Table 1. Summary of internal volume for each case

Case	Internal volume of model (m^3)
V0	0.0031
Vs	0.0312
V1	0.0230
V2	0.0577

Pressure taps were installed along a single line on the roof surface, and wind direction was varied from 0° to 350° at 10° intervals to capture the full distribution of wind pressure (see Figure 2). Key parameters such as mean pressure coefficient, standard deviation, power spectral density (PSD), skewness, and kurtosis were analyzed. The tests were conducted under suburban terrain conditions (power law index = 0.10), with a turbulence intensity of 16.6% measured at the maximum roof height. Figure 3 shows the profiles of mean wind speed and turbulence intensity applied in the wind tunnel tests.

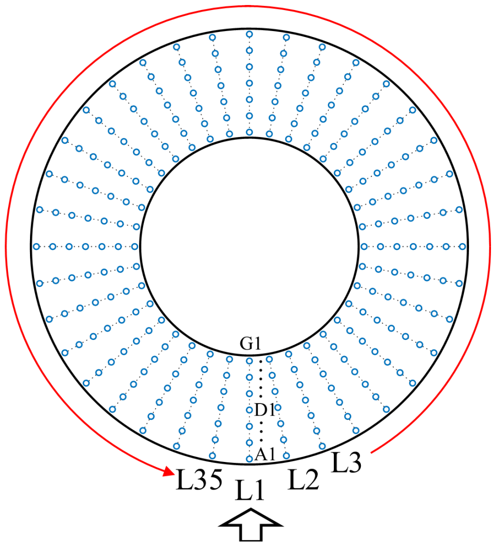


Figure 2. Pressure tap arrangement on inner and outer roof surfaces

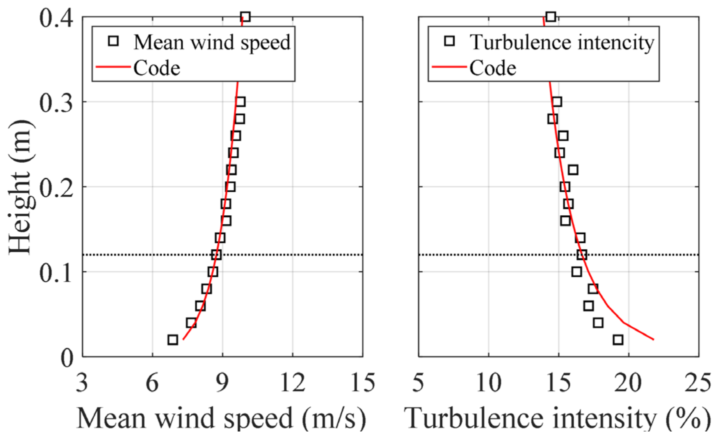


Figure 3. Profiles of mean wind speed and turbulence intensity in the wind tunnel

3. Research Result

3.1 Mean and standard deviation

As shown in Figure 4, both the mean and standard deviation of internal pressure coefficients were found to vary significantly with internal volume. V0 and Vs cases showed stronger pressure magnitudes near the windward and leeward edges, highlighting the influence of internal volume on spatial pressure distribution.

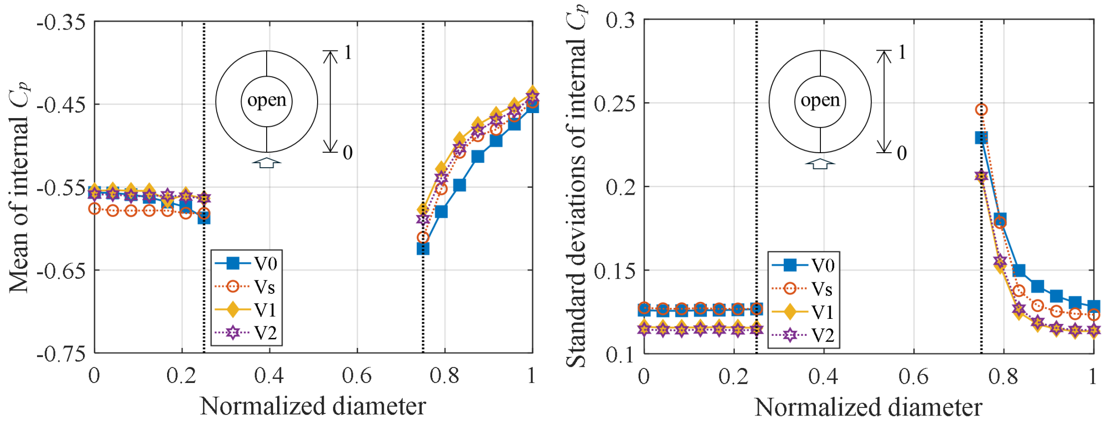
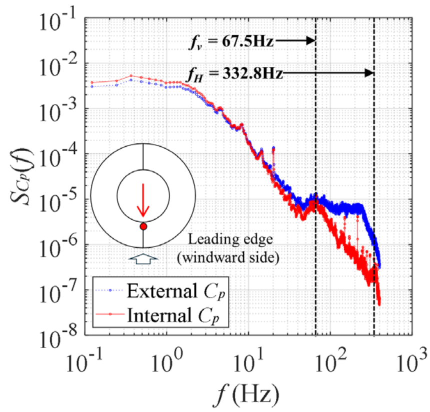


Figure 4. Mean and standard deviation of internal pressure coefficients according to volume

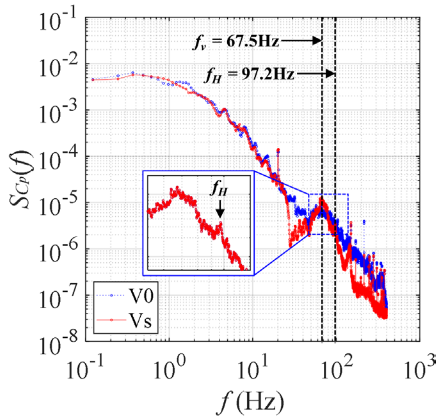
3.2 Power Spectral Density (PSD)

To understand the frequency characteristics of internal pressure fluctuations, PSD analysis was conducted for each internal volume condition. The focus was on the interaction between vortex shedding frequency (f_v) and Helmholtz resonance frequency (f_H), and how their proximity or separation affects the amplification of pressure fluctuations.

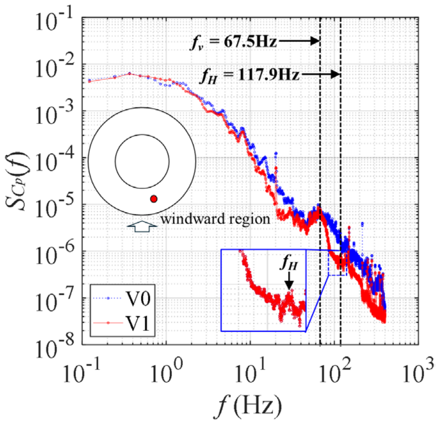
- In V0, the PSD shows a relatively broad energy distribution with high-frequency peaks (~332.8 Hz) attributed to unrealistic Helmholtz resonance due to the small internal volume.
- Vs exhibits a clear interaction between vortex shedding and Helmholtz resonance around 67.5 Hz, where energy is significantly amplified, and the frequency band is broadened.
- In V1, the Helmholtz frequency increases to around 117.9 Hz, causing the interaction with vortex shedding to weaken.
- In V2, the Helmholtz frequency (~88 Hz) is closest to the vortex shedding frequency, but resonance energy is suppressed—likely due to acoustic reflection and energy dispersion in the oversized cavity.



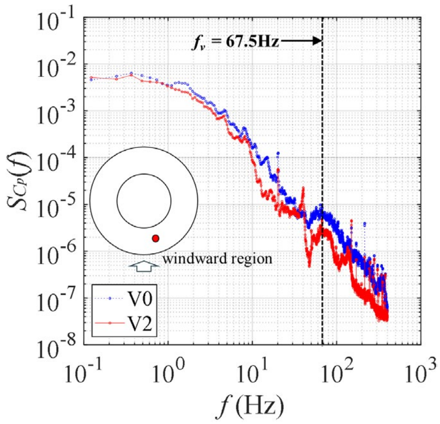
(a) V0



(b) V0



(c) V1



(d) V2

Figure 5. PSD at the windward edge for all volume conditions

- A similar pattern is observed at the leeward edge: Vs shows the most intense energy near the vortex shedding frequency, reinforcing the idea that resonance–shedding coupling affects the entire internal surface.

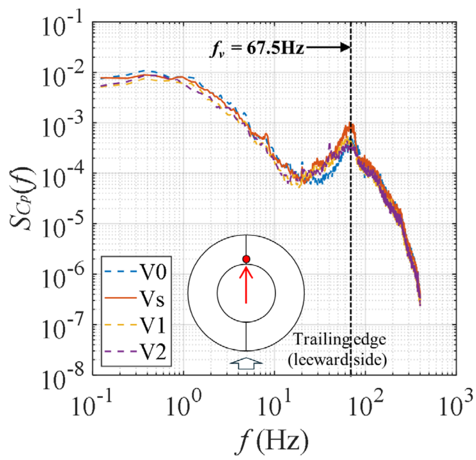


Figure 6. PSD at the leeward edge for all volume conditions

These findings highlight the importance of scaling internal volume appropriately to capture representative resonance behavior and prevent spurious high-frequency responses in model-scale testing.

3.3 Statistical Characteristics

Scatter plots of skewness and kurtosis (Figure 7) were used to evaluate the non-Gaussian nature of internal pressure distributions under different internal volume conditions. Among the four cases, the Vs condition, which corresponds to the theoretically scaled internal volume matching full-scale behavior, exhibited the most pronounced deviation from Gaussian distribution.

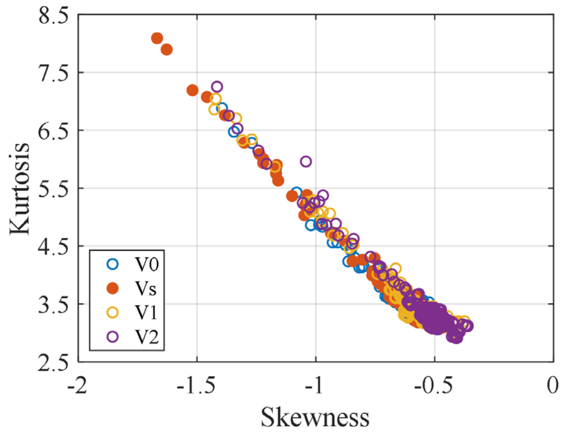


Figure 7. Scatter plot of skewness and kurtosis of internal pressure for different internal volume conditions

Specifically, data points in the Vs condition were clustered in the region with skewness values less than −0.5, indicating a strong left-skewed distribution. This suggests that negative peak pressures (suction) tend to occur more frequently and with greater intensity than positive pressures. Additionally, high kurtosis values were observed in the same condition, indicating heavy-tailed behavior and a greater likelihood of extreme pressure fluctuations.

By contrast, the V0, V1, and V2 conditions showed more compact distributions near zero skewness and lower kurtosis, reflecting weaker non-Gaussian and a more balanced fluctuation profile. These results indicate that the amplification of pressure fluctuations caused by the coupling between Helmholtz resonance and vortex shedding in the Vs case leads not only to higher spectral energy (as seen in the PSD) but also to a shift in the underlying statistical nature of the pressure signal.

From a design perspective, these findings imply that models with appropriately scaled internal volume (such as Vs) may experience more severe pressure fluctuations than conventional assumptions would suggest, especially in regions affected by separation and resonance. Therefore, incorporating non-Gaussian effects into peak pressure estimation may be necessary to ensure the safety of cladding and roof components in large dome structures with open roofs.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]
[Published papers]

1. Cheon, D.J, Kim, Y.C, Yoon S.W, Non-Gaussian properties and extreme values of net pressure on a dome with a central opening, *Journal of Building Engineering*, under review
2. Cheon, D.J, Kim, Y.C, Yoon S.W, Effects of a Large Roof Opening and Internal Volume Variation on Wind Pressure Acting on the Interior Roof Surface of a Long-Span Structure, *Architectural Institute of Korea*, under review

[Presentations at academic societies]

[Published books]

[Other]
Intellectual property rights, Homepage etc.

5. Research Group

1. Representative Researcher
Professor Sung Won Yoon

2. Collaborate Researchers
Professor Yong Chul Kim

Dr. Dong Jin, Cheon

6. Abstract (half page)

Research Theme

Aerodynamic forces and pressures of retractable roof depending on Reynolds number and internal volume

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Summary・Figures

This study examines the effect of a large central roof opening and internal volume variations on internal pressure behavior in an open long-span dome structure. Wind tunnel tests were conducted using a 1:300 scale model with a 50% central opening. Four internal volume conditions (V0, Vs, V1, V2) were tested, and internal pressure responses were analyzed through key parameters including mean and standard deviation, power spectral density (PSD), skewness, and kurtosis. The results revealed that internal volume plays a critical role in shaping both the intensity and spatial variability of internal pressure. In particular, the Vs condition, which represents the theoretically scaled volume matching full-scale dynamics, exhibited the strongest pressure amplification and the most pronounced non-Gaussian behavior. PSD analysis revealed that the interaction between vortex shedding and Helmholtz resonance at approximately 67.5 Hz leads to energy amplification in the Vs case, while other volume conditions showed weaker or unrealistic frequency responses. Statistical analysis confirmed that Vs displayed strong negative skewness and high kurtosis, indicating a higher likelihood of extreme suction events. The findings underscore the necessity of accurate internal volume scaling in model tests to ensure representative resonance characteristics. From a design perspective, the observed non-Gaussian features highlight the need to revise peak pressure estimation methods to reflect resonance-induced amplification, particularly in long-span dome structures with large roof openings.