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Verification of Generated Time History Wind Loads Using Computational Fluid Dynamics

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SUMMARY
In this study, time history wind loads are generated using CFD analysis and a modified spectral representation method. Positive skewness of the background component in along-wind and correlations of load components are considered in the time history generation process. Verification of the generated time history wind loads using CFD results is suggested and discussed.

Keywords: Wind Load, Computational Fluid Dynamics, Time History Generation

1. INTRODUCTION

1.1. Motivation

In order to implement the wind resistant design of a building, accurate determination of wind load should be preceded. To the best of the authors' knowledge, wind tunnel experiment is recognized as the most reliable method to determine wind loads on building. However, at the same time, computational fluid dynamics (CFD) is emerging as an alternative thanks to the rapid development of computational capabilities. Moreover, due to its unbounded advantages of 3D modeling, CFD analysis exerts a strong capability in simulating wind flows around buildings and calculating the wind load. Therefore, CFD analysis is highly promising in that engineers could understand the aerodynamics of the building in the preliminary design stage. From this point of view, it is not surprising that building design standards (AIJ-RLB, 2015) allow the results of CFD analysis to be used in calculating wind loads.

Despite having these strengths, CFD analysis would be used more often in real-world engineering practices only if two essential limitations are addressed. The first of the two limitations is that it is not always clear whether the analysis results are reliable. In order to utilize the analysis results for structural design, verification of the results is very important. However, one might struggle to do so if the wind tunnel experiment results do not exist for the target building, such as in the initial design stage. The other one of the two is that CFD analysis, especially large eddy simulation (LES), is computationally expensive. In order to determine the wind load based on the analysis results and apply it to the structural design of the building, correct estimation of the peak load is essential. Structural design requires 600 seconds of analysis, as most building design standards require. Here, using only one single set of 600 seconds analysis results can lead to biased results, so it is recommended to use an ensemble average of at least 5 to 10 sets of analysis results. Performing LES analysis 5 to 10 times for various attack angles is not too practical to be applied in engineering practices.

In this study, therefore, generation of time history wind load is conducted to address the aforementioned limitations. A thorough process of generating random time history wind loads from power spectral density (PSD) functions is devised, including a procedure of validating and verifying the CFD analysis results based on the open access Tokyo Polytechnic University (TPU) wind tunnel experiment data (TPU Aerodynamic Database, 2003). In addition, consideration is made on the skewness of the along-wind distribution and correlation between load components for generation process.

2. CFD ANALYSIS SETUP

2.1. Domain and Settings for Analysis

Setting appropriate domain of analysis and grid is the most basic, but at the same the most essential and challenging. If the size of the domain is not large enough, reverse flow may occur, which deteriorates the accuracy of the analysis. Moreover, short upstream region would result in larger aerodynamic force due to occurrence of larger velocity gradients (Niu and Younis, 2022). Conversely, even if the size of the upstream is too long, the profiles of turbulence kinetic energy and turbulence dissipation rate may be excessively developed, which results in large decay of two profiles.

Therefore, in this study, domain of analysis is determined using the AIJ (Tominaga et al., 2008) and COST (Franke, 2006) guidelines. The size of the upstream is set to 12 times the building depth (D). The lateral boundary is offset from the building by 15D to avoid reflections and the height of the domain is 30D. The resulting blockage ratio is far less than 3～5%, which is the recommended values in the guidelines. The resulting domain used in the study is shown in Fig. 1.

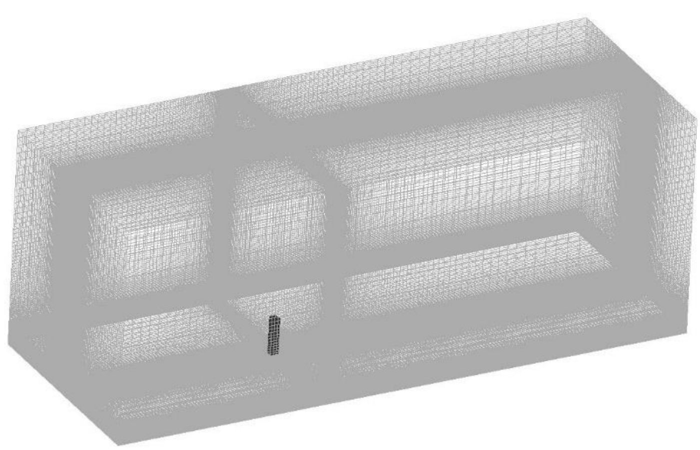

Figure 1. Domain of analysis.

With the domain, numerical simulations are implemented using LES models. The realizable $k - \varepsilon$ model and the dynamic Smagorinsky model are employed to close the filtered equations. For a time integration, the second-order implicit method is employed and the time-step size is set to 0.0005, which gives Courant number below 0.7 in the analysis.

3. GENERATION AND VERIFICATION OF TIME HISTORY WIND LOAD

3.1. Modified Spectral Representation Method and Verification

In addition to the spectral representation method (Shiozuka and Deodatis, 1991), time history wind loads have been derived and utilized in the autoregressive method (Huang, 2012) or the method using Monte Carlo simulation (Athanasiou et al., 2022). However, in most building design standards, wind load profile is provided on the basis of the frequency domain analysis. Therefore, time history generation based on PSD function has the advantage of being convenient because it can be directly applied from the standards. In this context, time history wind loads using a modified spectral representation method (Jeong, 2022) is used and verified in this study.

In the modified method, the authors generated skewed time history wind loads based on the fact that the background component of along-wind is positively skewed. The authors first generated time history wind loads $X(t)$ using the original spectral representation method as shown in Eq. (1). In the equation, $S(f_i)$, f_i, and θ_i indicate one-sided PSD, frequency, and random phase angle, respectively. Then, by dividing the loads by signs and multiplying amplification factors, (i.e. X^+ and X^- are values of generated time history wind loads with positive and negative signs, while A_1 and A_2 are amplification factors), $X(t)$ is modified as shown in Eq. (2).

$$X(t) = \sum_{i=1}^{n} \sqrt{2S(f_i)\Delta f} cos(2\pi f_i t + \theta_i) \quad (1)$$

$$X_{modified} = A_1 X^+ + A_2 X^- \quad (2)$$

Then, by utilizing the skewness of the background component in along-wind and the condition that area of the PSD function that corresponds to square of standard deviation σ_x should be the same, the skewed time history wind loads are suggested as follows in Eq. (3). In this research, PSD functions of wind loads are derived by the result of CFD analysis and skewed time history wind loads are generated by utilizing the modified method. Thorough verification process is conducted by comparing results from CFD analysis and wind tunnel experiment.

$$X_{suggested} = A_1 X^+ + A_2 X^- - \frac{(A_1 - A_2)\sigma_x}{\sqrt{2\pi}} \quad (3)$$

4. CONCLUSIONS

In the study, skewed time history wind loads were generated using CFD analysis. Time history wind loads were generated in the manner suggested in the authors' previous study, which utilizes a concept of skewness. With the suggested method, the authors expect to drastically reduce the excessive computational cost incurred when performing CFD analysis 5 to 10 times to derive ensemble averages of the results. The analysis results were verified by comparing with the wind tunnel experiment results. In the process, consideration was made on the correlation between load components.

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