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Development of a method to control wind conditions in a dome-shaped wind tunnel using CFD simulations

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SUMMARY:
In actual wind, there are not only horizontal winds but also three-dimensional wind fluctuations, and these fluctuations should have significant influence on the wind load assessment of low-rise buildings. A dome-shaped wind tunnel with multiple fans has been proposed to simulate the complex three-dimensional wind conditions during typhoons. In this study, a method of controlling wind conditions in a dome-shaped wind tunnel was investigated using computational fluid dynamics (CFD) simulations. Although the ultimate goal of this study is to control the three-component wind velocity time histories, this paper aims to control the two-component horizontal wind velocity time histories as a first step. As a control method for wind conditions, we propose a method to approach the output wind velocity to the target wind velocity by iterative calculations using transfer functions. Additionally, the proposed method is verified by CFD simulations for a dome-shaped wind tunnel. The results show that increasing the number of iterations reduces the error in this validation example.

Keywords: multiple fan, three dimension wind flow, transfer functions, Fourier transform

1. INTRODUCTION

The current wind-resistance design is based on wind loads when horizontal winds are dominant. However, it has been pointed out that under actual natural strong winds such as typhoons, the wind velocity changes every moment with strong turbulence, and its vertical profile is not dependent on the surface roughness (Maruyama et al., 2004). In addition, in actual wind, there are not only horizontal winds but also three-dimensional wind fluctuations, and these fluctuations should have significant influence on the wind load assessment of low-rise buildings. In order to simulate complex wind conditions under strong typhoon winds and to analyze the mechanism of damage to buildings in general and low-rise houses in particular, Tomokiyo et al. have been developing a dome-shaped wind tunnel with multiple fans (Tomokiyo et al., 2022). The dome-shaped wind tunnel is a pseudo-hemispherical dome consisting of triangular and rectangular faces, and a small wind tunnel with an axial fan is attached to each of the faces. It aims to reproduce three-dimensionally constantly changing wind conditions. In order to make the time history of wind velocity at a certain point in the dome-shaped wind tunnel correspond to the target time history to be reproduced, it is necessary to clarify the effect of the changes in the inflow wind at each inflow surface of the dome on that time history.

In this study, a method for controlling wind conditions in the dome-shaped wind tunnel is investigated using computational fluid dynamics (CFD) simulations. Although the ultimate goal of this study is to control the three-component wind velocity time histories, this paper aims to control the two-component horizontal wind velocity time histories as a first step. The results presented in this extended abstract are briefly reported in Japanese at the DPRI annual meeting 2023 (Takeuchi et al. 2023).

2. GENERAL SPECIFICATIONS OF CFD SIMULATION

The analytical model is shown in Figure 1. The dome-shaped wind tunnel has pseudo-hemispherical shape with a radius of 300 mm, and approximately half of its surface is used as the inflow surface and the other half as the outflow surface. In this analysis, the rear part of the dome-shaped wind tunnel is a box of 1200 mm x 1200 mm x 600 mm in order to include the area outside the outflow surfaces, and the top, sides, and back faces of the box are used as the outflow surfaces. Rectangular vertical walls were placed under the hemispherical dome for simplicity of horizontal wind control, and faces i1 to i5 in Figure 1 are set as inflow surfaces. The remaining surfaces are set as slip-type wall boundaries.

The CFD simulations are conducted in OpenFoam v2112. An incompressible flow is assumed and the pisoFoam is used as the solver. The LES model is used for the turbulence model. The tetrahedral cells are employed in the analytical model, and the maximum size of the cells in the dome region is about 30 mm. The time increment of the analysis is 0.0001 seconds.

The target point at which wind velocity is to be reproduced is located at the center of the dome at a height of 50 mm. The target wind velocity is scaled from the two horizontal components of the wind velocity time histories observed by Maruyama et al. 2004 at Maishima island in Japan. The length scale of the model is 1/50, the wind velocity scale is 1/5, and the time scale is 1/10. Additionally, it is assumed that turbulence at high frequencies cannot be generated, since wind turbulence in the dome-shaped wind tunnel is generated by controlling the axial fan speed. Consequently, this paper aims to reproduce wind turbulence at frequencies below 2 Hz by applying a low-pass filter with the frequency cut-off of 2 Hz. The wind velocity time histories created in the above-mention ed way for 20 seconds are used as the target wind velocity time histories.

3. METHOD TO CONTROL WIND CONDITIONS IN DOME-SHAPED WIND TUNNEL

Figure 2 shows an overview of the control system from the input wind velocity to the output wind velocity. In this system, the input wind velocity is given, converted to the inflow wind velocity in five faces (faces i1 to i5), and after running the analysis, the wind velocity (output wind velocity)

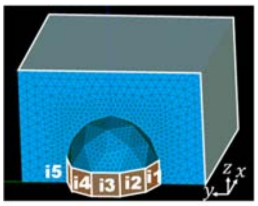

Figure 1. Analytical model. (Takeuchi et al. 2023)

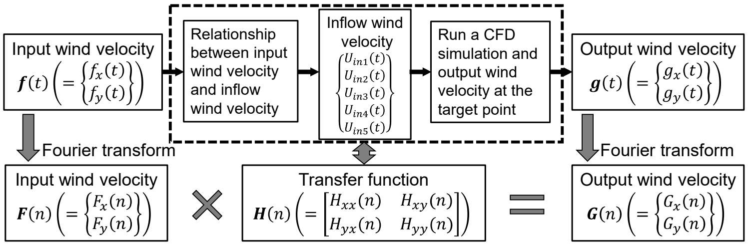

Figure 2. Outline of Analytical system. (Takeuchi et al. 2023)

at the target point is obtained. The relationship between the input wind velocity and the inflow wind velocity is obtained from the preliminary analysis results with various steady-state wind inputs to faces i1 to i5. Considering the process from giving the input wind velocity, $\boldsymbol{f}$(t), to obtaining the output wind velocity, $\boldsymbol{g}$(t), as a single system, the relationship between the Fourier-transformed input wind velocity, $\boldsymbol{F}$(n), and output wind velocity, $\boldsymbol{G}$(n), can be generally expressed using the transfer function, **H**(n), as follows.

$$\boldsymbol{G}(\mathrm{n}) = \mathbf{H}(\mathrm{n}) \cdot \boldsymbol{F}(\mathrm{n}) \tag{1}$$

Note that **H**(n) is a transfer function that varies with the input wind velocity. Let $\boldsymbol{g_t}$(t) be the output wind velocity when the reproduced target wind velocity is perfectly reproduced, $\boldsymbol{f_t}$(t) be the input wind velocity at that time, and $\boldsymbol{G_t}$(n) and $\boldsymbol{F_t}$(n) be the Fourier transforms of each, then their relationship is expressed as follows.

$$\boldsymbol{G_t}(\mathrm{n}) = \mathbf{H_t}(\mathrm{n}) \cdot \boldsymbol{F_t}(\mathrm{n}) \tag{2}$$

Since it is difficult to obtain $\boldsymbol{f_t}$(t) directly from the above relationship, in this analysis, an approximation of $\boldsymbol{f_t}$(t) is obtained by performing iterative calculations to reduce the error, as shown in the following.

For the *i*-th iteration, when the wind velocity time history $\boldsymbol{f_i}$(t) is set as input and the output wind velocity time history $\boldsymbol{g_i}$(t) is obtained, the relationship between the corresponding Fourier transforms $\boldsymbol{F_i}$(n) and $\boldsymbol{G_i}$(n) can be expressed using the transfer function $\mathbf{H}_i$(n) as follows.

$$\boldsymbol{G_i}(\mathrm{n}) = \mathbf{H_i}(\mathrm{n}) \cdot \boldsymbol{F}_\mathrm{i}(\mathrm{n}) \tag{3}$$

The time history of the difference between the output wind velocity and the target wind velocity is as follows.

$$\Delta\boldsymbol{g_i}(\mathrm{t}) = \boldsymbol{g_t}(\mathrm{t}) - \boldsymbol{g_i}(\mathrm{t}) \tag{4}$$

Compute the Fourier transform, $\Delta\boldsymbol{G_i}(\mathrm{n})$, of this difference $\Delta\boldsymbol{g_i}(\mathrm{t})$. Once the transfer function is obtained, a correction for the input wind velocity can be obtained as shown in the following equation. Note that the transfer function can be obtained by using the input and output wind velocity from the two analyses.

$$\Delta\boldsymbol{F_i}(\mathrm{n}) = \mathbf{H_i}(\mathrm{n})^{-1}\Delta\boldsymbol{G_i}(\mathrm{n}) \tag{5}$$

Compute the Inverse Fourier transform of $\Delta\boldsymbol{F_i}(\mathrm{n})$ to obtain the time history of correction $\Delta\boldsymbol{f_i}$(t). This correction is added to the input wind velocity, $\boldsymbol{f_i}$(t), and the result is used as the input wind velocity for the next iteration of the analysis, $\boldsymbol{f_{i+1}}$(t). In addition, a reduction factor γ (0.5 is used in this paper) is multiplied to $\Delta\boldsymbol{f_i}$ to consider convergence stability.

$$\boldsymbol{f_{i+1}}(\mathrm{t}) = \boldsymbol{f_i}(\mathrm{t}) + \gamma\Delta\boldsymbol{f_i}(\mathrm{t}) \tag{6}$$

By repeating the process of Eqs. (3) to (6), the output wind velocity $\boldsymbol{g_i}$(t) converges to the target wind velocity $\boldsymbol{g_t}$(t).

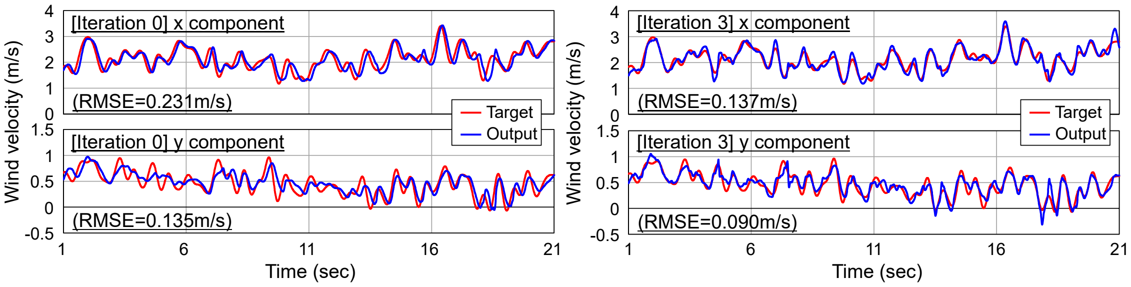

Figure 3. Comparisons of the target wind speed and the output wind velocity. (Takeuchi et al. 2023)

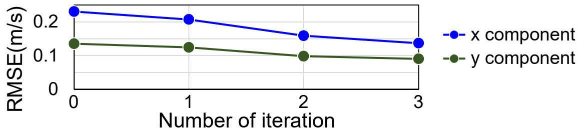

Figure 4. Relationship between the number of iterations and RMSE. (Takeuchi et al. 2023)

4. VERIFICATION RESULTS OF THE DEVELOPED METHOD

Using the above method, the CFD simulations were repeated so that the wind velocity at the target point approached the target wind velocity. In the first simulation, the target wind velocity was used as the input wind velocity. Figure 3 shows comparisons of the target wind velocity and the output wind velocity in the first simulation (iteration 0) and that after three iterations. The root mean square error (RMSE) is noted in the figure as a representative value of the error between the output wind velocity and the target wind velocity. In the first simulation, the x component was slightly out of phase and the y component did not reproduce the wind velocity variation accurately. On the other hand, after three iterations, both the x and y components were close to the target wind velocity. Figure 4 shows the relationship between the number of iterations and RMSE. It can be confirmed that the error decreased with an increase in the number of iterations.

5. CONCLUSIONS

As a method to control wind conditions in a dome-shaped wind tunnel, a method to make the output wind velocity approach to the target wind velocity by using transfer functions and iterative calculations was proposed. Furthermore, the proposed method was verified by CFD simulations. In the example, it was shown that increasing the number of iterations reduces the error. In the future, more validation cases will be conducted to confirm the validity of the proposed method.

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