A study of spectral behaviors of turbulent wall-pressure fluctuations

Jie Wang1, Jiao Yu1,*, Yanying Zhu1 and Kaixuan Guo1
1School of Science, Liaoning Shihua University, Fushun, China

*Corresponding author e-mail: yujiaojoy@hotmail.com

Abstract. Turbulent wall-pressure fluctuations are major sources of noise and their numerical calculations have been important topics in engineering fields. In this paper, large eddy simulation is conducted to study spectral behaviors of turbulent wall-pressure fluctuations. The roughness was simulated by using an array of 10 off-set square columns extending in the vertical directions on the bottom surface, and local downstream aerodynamic fields were numerically investigated. The wind speed fluctuations in the flow field and the pressure fluctuations at the bottom of the flow field are monitored at a certain cross-section when varying square column heights and wind turbulence conditions at the wind speed inlet. Frequency spectral characteristics are analysed and the influence factors of wall-pressure fluctuations are explored.

1. Introduction

The study of turbulent wall-pressure fluctuation is of great value in many engineering fields, and it is helpful for people to understand the mechanism of flow noise and to find out the method to reduce it. It is difficult to study the spatio-temporal characteristics of wall-pressure fluctuations using experimental methods due to the high background noise in the wind tunnel and the insufficiently high measurement accuracy of sensors. Therefore, various numerical simulation methods have been widely applied [1,2]. Among these methods, large eddy simulation (LES) is one of the most successful methodology for simulating turbulent flows, in the field of both structural wind engineering and computational fluid dynamics [3-5]. LES is increasingly used to understand the mechanism of flow-structure interactions [6] and to investigate airflow in urban areas which is closely linked with environmental problems, such as the assessments of pollutant diffusion and wind comfort [7], etc. This paper mainly simulates wind speed fluctuations and wall-pressure fluctuations by using ANSYS Fluent, and studies the statistical features of the spectral behaviors of turbulent wall-pressure fluctuations under different turbulence conditions in order to understand the change of the pressure spectral characteristics in response to the change of turbulence.

2. LES theory

Large eddy simulation is used as an intermediate method between the extremes of RANS and DNS. Turbulent flows are supposed to be composed of eddies of small and large scales. Large eddies are resolved directly in LES, and small eddies are modeled [8]. Filtering N-S equations in the physical space, we obtain:

\[
\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial (\overline{u_i u_j})}{\partial x_j} = \frac{1}{\rho} \frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j} \tag{1}
\]
\[ \frac{\partial u_i}{\partial x_i} = 0 . \]  \hfill (2)

Let \( \overline{u_i u_j} = \overline{u_i u_j} + \left( \overline{u_i u_j} - \overline{u_i u_j} \right) \), where \( \left( \overline{u_i u_j} - \overline{u_i u_j} \right) \) is called sublattice stress, then the N-S equation can be written as:

\[ \frac{\partial \overline{u_i}}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \rho}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j} - \frac{\partial \left( \overline{u_i u_j} - \overline{u_i u_j} \right)}{\partial x_j}. \]  \hfill (3)

The sublattice stress term on the right hand side of Eq. 3 is not closed. In order to realize large eddy simulation, a closure model of sublattice stress must be constructed. In this study, Smagorinsky model is adopted for modeling the sublattice stress:

\[ \overline{\tau_{ij}} = \overline{\left( u_i \overline{u_j} - u_i u_j \right)} = 2 (C_s \Delta)^2 \overline{S_{ij}} \left( 2 \overline{S_{ij}} \overline{S_{ij}} \right)^{1/2} - \frac{1}{3} \overline{\tau_{ik}} \delta_{ij}, \]  \hfill (4)

where \( \Delta \) is the filter-width, \( v_i = (C_s \Delta)^2 \left( \overline{S_{ij}} \overline{S_{ij}} \right)^{1/2} \) is the sublattice vortex viscosity coefficient.

The Smagorinsky model is the first sublattice stress model applied to LES in the fields of atmospheric and engineering studies. It assumes that an equilibrium exists between cross-scale kinetic energy flux and large scale turbulence. Despite of the development of turbulence models, the Smagorinsky model remains a popular choice for LES because of its simplicity and ease of use.

3. Methods

3.1. Large eddy simulation

Ansys15.0 Fluent is used to establish the flow field. Figure 1 shows the top view of the model. An array of 10 off-set square columns is extended in the vertical directions on the bottom surface near the entrance for roughness simulation. A limitation of the simulation of the turbulence boundary layer on the flat plate is that the turbulence level of the boundary layer is relatively low. In order to meet the requirements of high downstream wind fluctuation levels, by referring to the simulation methods of the atmospheric boundary layer, the proposed roughness element method \( [9] \) is adopted. Each cuboid serving as a roughness element has a dimension of \( 10m \times 10m \times 10m \) (length \( \times \) width \( \times \) height). The entrance is on the left and the exit is on the right. The whole region is \( 300m \times 100m \times 150m \) (length \( \times \) width \( \times \) height) in size. The meshes for calculation have a minimum size of 0.17m. Figure 2 shows the three-dimensional view of the model.

![Figure 1. The top view of the model.](image-url)
Smagorinsky-Lilly model is used and air is chosen as the fluid. Boundary conditions are displayed in Table 1. The computational time is 900s, and the sampling rate is 1 sample/s. The velocity monitoring point and the pressure monitoring point are (-40, 0, 10) and (-40, 0, 0), respectively.

### Table 1. Boundary conditions of the numerical model.

| Zone                          | Boundary condition       |
|-------------------------------|--------------------------|
| Top of the computational domain | Free slip wall surface   |
| Bottom surface of the computational domain | No slip wall surface |
| Cuboid surface                | No slip wall surface     |
| Computational domain profile  | Symmetry                 |
| Outflow surface               | Outflow                  |
| Inflow surface                | Velocity inlet           |

Two groups of flow conditions are studied. In the first group, the mean wind speed at the inlet is kept at 8m/s and the turbulence intensity remains unchanged at 40%. Yet the heights of cuboids are changed from 10m to 30m for comparisons. In the second group, the mean wind speed at the inlet is kept at 8m/s and the heights of cuboids remain unchanged at 10m. The turbulence intensity is changed from 40% to 5% for comparisons.

3.2. **Frequency spectral analysis**

Wind speed and wall pressure data at monitoring points are exported, and frequency spectral analysis are conducted in MATLAB. Instantaneous data are first decomposed into time-averaged and fluctuating components, and then fluctuating components are extracted and studied as new data sets. Each data set is broken into nonoverlapping blocks and each block is Hamming windowed. Frequency spectra are generated in the same manner as in Ref. [10]. Pressure spectra are broken into blocks of size 256 points as a compromise between good averaging and good resolution, and the power spectral densities of blocks are averaged in calculations. The wind speed spectra are generated with all 900 points with no averaging in order to retain the low frequency components. The effects of cuboid height and turbulence intensity on wind speed fluctuations and wall pressure fluctuations are investigated at monitoring points.
4. Results and analysis

The results of wind speed spectra and pressure spectra at monitoring points are shown below. Figure 3 and Figure 4 display the obtained frequency spectra when cuboids are 10m and 30m high, respectively. It can be observed that the pressure spectral change is highly consistent with the wind speed spectral change in terms of spectral level and slope. With the increase of cuboid heights, the spectral levels in the low frequency source region increase for both wind speed and pressure spectra, and their spectra display steeper slopes in the inertial region. Extending cuboids in the vertical directions enhances the disturbance to the flow field downstream a distance behind the cuboids, and hence the local turbulence level increases significantly near the ground which yields a distinct increase in the low frequency pressure fluctuation spectral level due to the formation of bigger turbulence eddies up above.

Figure 3 and Figure 4 display the obtained frequency spectra when cuboids are 10m and 30m high, respectively. The turbulence intensity is known to be below 50% for the atmospheric boundary layer. Again, it can be seen that the pressure spectral change greatly matches the wind speed spectral change in respect of spectral level and slope. With the decrease of inlet turbulence intensity, the wind speed and pressure spectral levels do not change much in the low frequency source region, but decrease dramatically in the high frequency region. As turbulence intensity decreases, the spectral slope increases in the mid-
to-high frequency region for both wind speed and wall pressure spectra. The turbulence intensity at the inlet determines the amount of turbulent kinetic energy in the flow field. High frequency pressure spectra are linked with the inner boundary layer regions. As turbulence intensity is lowered, both large scale and small scale turbulent eddies are less, but the energy at small scales tends to be more affected by the dissipations due to the mean shear and viscous effects.

![Graph](image1)

**Figure 5.** Wind speed spectrum (a) and pressure spectrum (b) at monitoring points when turbulence intensity is 40% at the inlet.

![Graph](image2)

**Figure 6.** Wind speed spectrum (a) and pressure spectrum (b) at monitoring points when turbulence intensity is 5% at the inlet.

5. **Conclusion**

In this paper, large eddy simulation method is used to study the wind speed and pressure spectral changes with different turbulence field conditions, e.g., by changing upstream cuboids’ height and by changing wind turbulence intensity at the entrance. The influence of the height of cuboids and turbulence intensity of inlet wind on the spectral level and slope is discussed, which lays a foundation for further calculations of wind speed spectrum and pressure spectrum.

Based on the calculation results in this paper, it can be concluded that the increase in the height of the cuboids mainly elevates the scales of turbulent eddies behind the cuboids, which yields larger spectral levels of the fluctuating wind speed and wall pressure at low frequency. When the cuboids’ height remains constant, with the decrease of turbulence intensity, the spectral levels of the wind speed and wall pressure decrease at mid and high frequencies due to the fact that viscous effects become
more obvious as turbulence is less. All the obtained power spectra meet typical characteristics of the wind speed spectrum and pressure spectrum, despite that the sampling frequency is limited.

In conclusion, the amount and scales of turbulent eddies above the wall are crucial for accurate calculations of wind speed fluctuations and wall-pressure fluctuations. The preliminary numerical calculations are shown to give reasonable results, which imply that the method adopted in this paper is suitable for calculations and analysis of the changes of wind speed and wall pressure spectra in response to the change of turbulence.

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