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Occupant comfort evaluation of high-rise building under wind loads using LES

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Abstract: The wind-induced vibration comfort level of a wind-sensitive high-rise building was analyzed. The wind-induced aerodynamic stresses on the building were evaluated using the large eddy simulation (LES) technique. The narrowband synthesis random flow generation (NSRFG) method was used as the inflow turbulence generator for LES. Then, the extreme value of the acceleration on the top of the building is selected as the occupant comfort index of the wind-induced vibration, which was calculated using the story shearing equivalent model and compared with reference values obtained by structural design software SAP2000. The results show that the wind factors present an increasing trend as the height increases. The LES can effectively capture details. The predicted peak values of the wind-induced responses are less than those produced by SAP2000, showing that the comfort analysis of wind-induced vibration is conservative using the present structural design software.

Key words: high-rise building; large eddy simulation (LES); comfort analysis; wind-induced vibration; random flow generation

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With the rapid development of lightweight materials and construction technology, high-rise buildings have become easier to build[1]. With the increasing height of the buildings, the structural stiffness will decrease, indicating that wind-induced vibration could become a critical issue. Due to complicated aerodynamic effects such as buffeting, vortex shedding, galloping, and flutter, design codes following quasi-static analysis of wind loading are unsuitable for evaluating occupant comfort in high-rise buildings[2-4]. Slender high-rise buildings are widely recognized to be susceptible to turbulence-induced buffeting among these aerodynamic effects[5]. As a result, it is significant to conduct occupant comfort evaluation of the high-rise buildings considering the turbulence-induced buffeting for wind-resistant design. Some work on occupant comfort evaluations of high-rise buildings using boundary layer wind tunnels has been reported[6-8]. However, conducting wind research on unconventional high-rise buildings is a complex task due to the multiple flow conditions arising from fluid-structure interaction, which increases the construction time and expense[9]. In addition to wind tunnel tests, the computational fluid dynamics (CFD) technique has become a popular and dependable tool in the field of computational wind engineering due to the rapid development of improved turbulence models and increasing computational power, which may provide abundant flow information while reducing time and cost to solve the wind-related issues compared to wind tunnel experiments[4, 10].

Turbulence modeling has unique difficulty in effectively simulating separated flows around blunt structures. Large eddy simulation (LES) is a potential unsteady turbulence modeling technique in which the large-scale eddies are explicitly resolved while the small-scale eddies are modeled using subgrid-scale (SGS) models[11]. Some studies have been carried out to evaluate the occupant comfort of high-rise structures using LES[4, 12-14], which proves that the LES solutions are suitable for occupant comfort evaluation and present a reasonable prediction of the mean pressure distribution at high Reynolds numbers[15]. The basic aim of LES is to generate adequate inflow turbulence with given turbulent characteristics. The methods for generating inflow turbulence are broadly categorized into three types: recycling methods, precursor databases, and synthetic turbulence methods[16]. For the former two kinds of methods, the generated turbulence has a definite physical meaning but is time-consuming and difficult to satisfy specific turbulent characteristics[17]. To overcome the above issues, synthetic turbulence methods are widely adopted to generate inflow turbulence for LES. The random flow generation (RFG) procedure is one of the most widely used synthetic methods[18]. Sequentially, many studies have been conducted to modify the RFG approach[19-22]. Currently, numerical simulation utilizing the LES has become one of the available research techniques for gaining a deeper understanding of the behavior of high-rise buildings subjected to turbulent wind loads.

The primary goal of the present study is to use LES to conduct a computational evaluation of occupant comfort

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in a high-rise building under turbulent wind stress. Firstly, we briefly introduce the engineering background of a high-rise building. Then, the wind-induced aerodynamic load is obtained using the LES, and the occupant comfort is evaluated and compared with that calculated by other design software.

1 Engineering Background and Numerical Model

1.1 Description of the Xuanwu-Ⅱ Hotel

The second stage of the Xuanwu-Ⅱ Hotel project is located at No. 193, Central Road, Nanjing, Jiangsu Province. It is adjacent to Tongjia Lane in the north. The structural height is 218.8 m, and there are 48 floors. Fig. 1 depicts the architectural rendering and plan view of a standard story. The floor height is listed in Tab. 1.

(a) (b)

Fig. 1 Basic layout of the Xuanwu-Ⅱ Hotel. (a) Architecture rendering; (b) Plan view of the standard story

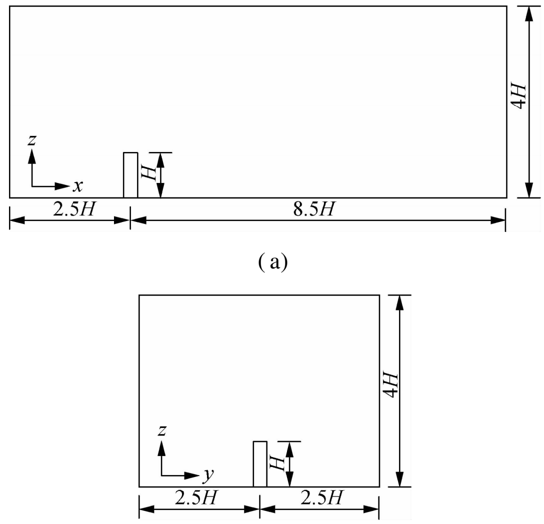
Tab. 1 Floor height m

Floor No.	Floor Height/m
1	5.6
2, 3	5.4
4-6, 11, 22, 33	4.5
7-10, 12-14	3.9
15-21, 23-30	4.8
31, 32, 34-45	4.1
46, 47	6.15
48	6.4

The building site belongs to the mid-latitude zone, which is dominated by the humid southern subtropical monsoon. The strong southeast typhoon from the Pacific Ocean is the main wind that attacks the building.

1.2 Numerical model

As shown in Fig. 2, the computational domain covers $11H$ (H is the building height) in the streamwise direction ($-2.5 < x/H < 8.5$), $5H$ in the spanwise direction ($-2.5 < y/H < 2.5$), and $4H$ in the vertical direction. The above-mentioned arrangement is based on the recommendations[19], which can eliminate the obstacle effects caused by buildings on boundary conditions. In this study, the length scale, velocity scale, and time scale are 1/300, 1/5, and 1/60, respectively.



(b)

Fig. 2 Computational domain. (a) x-z plane; (b) y-z plane

The structured mesh is produced for the entire domain. The first near-wall grid has a grid height of 3 mm, and the overall mesh number exceeds 3.7 million. The non-dimensional wall distance y^+ of the first near-wall grid node is less than 10. The reference wind velocity at 10 m height is 1.85 m/s. The standard wall functions are employed to resolve the log-layer region. The whole structured mesh is constructed using the meshing tool Pointwise V18.1 R1.

In this case, the velocity inlet is chosen as the intake boundary with specific wind characteristics, while the outlet is modeled as the outflow boundary. The symmetrical boundary condition is used by the side and top walls. The ground (bottom wall) has a no-slip boundary condition with an equivalent sand roughness length of $0.5y^+$, say 1.5 mm[23].

2 Evaluation of Occupant Comfort

2.1 Generation of inflow turbulence

The NSRFG method was utilized to generate the inflow turbulence for LES evaluation of occupant comfort and is introduced as follows[22]:

$$u_i(x,t) = \sum_{p=1}^{N} \sqrt{2S_{u,i}(f_p)\Delta f}\sin(k_{j,p}\tilde{x}_{j,p} + 2\pi f_p t + \varphi_p) \tag{1}$$

where u_i represents the wind speed in along-wind, across-wind, and vertical directions when $i = 1, 2, 3$, respectively. $j = 1, 2, 3$ denote the x, y, z directions, respectively. $S_{u,i}(f_{p,i})$ represent the turbulent wind spectra in the i-th direction at frequency f_p, and Δf is the frequency bandwidth. $\varphi_p \sim U(0, 2\pi)$ is the random phase angle obeying uniform distribution. $\tilde{x}_{j,p}$ can be regarded as the dimensionless location of the simulation points. $k_{j,p}$ can be determined based on the divergence-free condition of the turbulent flow field. More details about the NSRFG method can be found in Ref. [22].

Based on the user-defined function, the NSRFG approach is embedded in CFD code (ANSYS/Fluent 19.0). The DEFINE_ON_DEMAND macro is used to initialize wind characteristics, while the DEFINE_ADJUST macro is the kernel code that allows the NSRFG method approach to be achieved. Using the DEFINE_PROFILE macro, the generated inflow turbulence is assigned to the inlet grids using the DEFINE_PROFILE macro.

The inflow turbulent characteristics are referred to Ref. [22], where $\alpha = 0.22$ for urban terrain. The von Karman spectra are used as the target turbulent wind spectra. In NSRFG, the number of spectral segments is set to 2 000. The total number of inflow meshes is 10 486. The simulation was conducted on a workstation (96 cores with Intel(R) Xeon(R) Platinum 8163 CPU @ 2.50 GHz). The unstable LES simulation time-step is selected as 0.002 s. A total of 13 000 time steps were resolved in order to achieve a statistically steady result of 26 s, with the last 16 s of the simulated result being used for analysis. The Reynolds number in the model height is approximately 5.74×10^4. The wall-adapting local eddy-viscosity model was chosen as the LES SGS model. To decouple the wind and pressure in the Navier-Stokes equation, the pressure-implicit with splitting of operators algorithm is used. The second-order implicit scheme and the bounded central difference scheme were used for time discretization and momentum discretization, respectively.

According to the above-mentioned simulation parameters, the turbulent atmospheric boundary layer (ABL) is generated using LES. A vertical line (L_1) of monitoring points is set from the ground to the top of the computational domain at a position that is $2H$ away from the inflow surface. Furthermore, a monitoring point that is H high on L_1 is set up for calculating and verifying the turbulence power spectrum. The comparisons of the ABL profiles (mean wind speed and turbulence intensity) and the turbulence power spectral density (PSD) between the numerical results and the targets are shown in Fig. 3.

The simulated ABL profile matches the targets well, as seen in Fig. 3. However, in the high-frequency range, the simulated turbulence PSD deviates from the targets due to the modeling of small-scale turbulent vortices. In general, the present numerical wind field can be used for the following simulation.

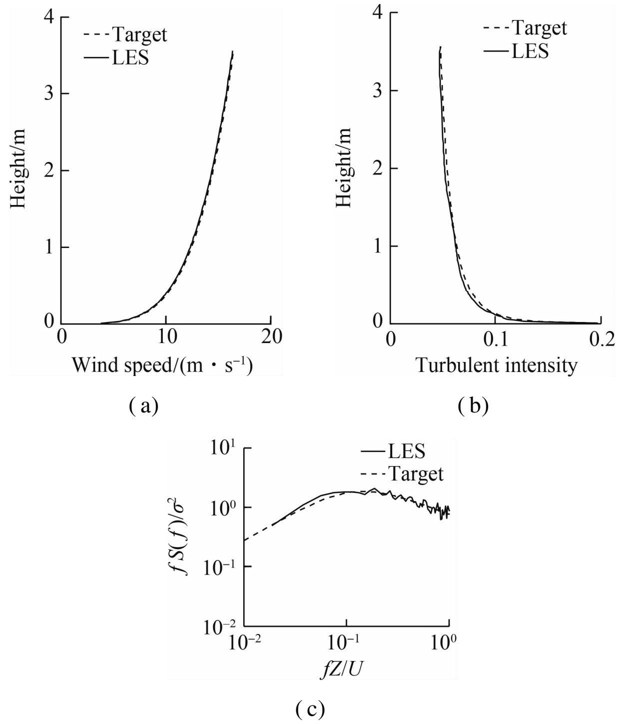


Fig. 3 Comparisons of the ABL profile. (a) Mean wind speed; (b) Turbulence intensity; (c) Turbulence PSD

2.2 Wind-induced responses

Considering the mean wind speed U_z at height z, the wind loads acting on the ith floor of the Xuanwu-Ⅱ Hotel can be calculated by[24]

$$F_x(z, t) = \mu_x(z, t) Bh(z) 0.5\rho U_z^2 \tag{2a}$$

$$F_y(z, t) = \mu_y(z, t) Dh(z) 0.5\rho U_z^2 \tag{2b}$$

where μ denotes the structural shape factor; B and D are the projected length, while h represents floor height; ρ is the air density. Since the turbulent ABL was well simulated, it was then employed to simulate the Xuanwu-Ⅱ Hotel flow. Fig. 4 depicts the instantaneous velocity contour in the X-Y planes. A negative pressure area exists behind the building, as seen in Fig. 4. There are apparently two counter-rotating vortices behind the building.

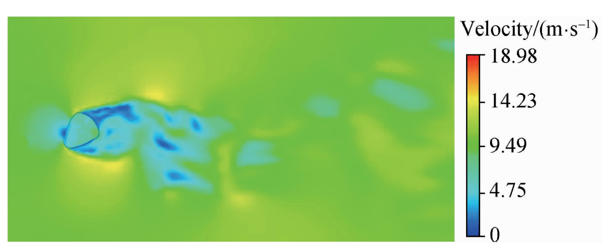


Fig. 4 The instantaneous velocity contours

The instantaneous field depicts the large and small-scale turbulent structures at the inflow and near the building walls. The LES captures and predicts strong turbulent vortex shedding and a fairly long wake zone. Fig. 5 depicts the instantaneous surfaces of equal vorticity magnitudes.

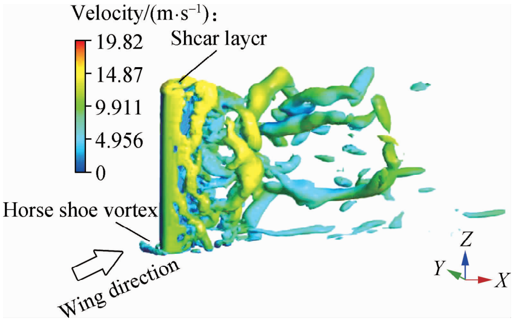


Fig. 5 Surfaces of equal vorticity magnitude

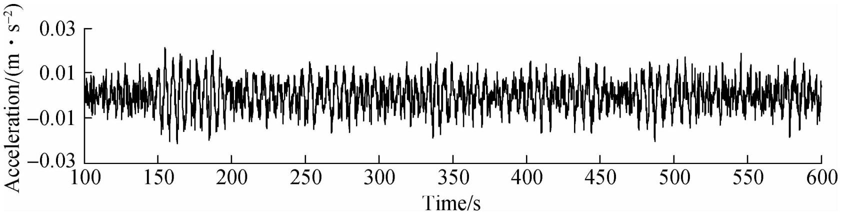
The LES effectively captures the turbulent structure, which looks like a horseshoe vortex on the upstream side near the ground, as illustrated in Fig. 5. The structural shape factor of each floor can be calculated based on Eq. (2).

The Xuanwu-Ⅱ Hotel's occupant comfort is assessed using the story shearing equivalent model. The modal frequencies are analyzed for the story shearing equivalent model and compared with that obtained by SAP2000, as listed in Tab. 2.

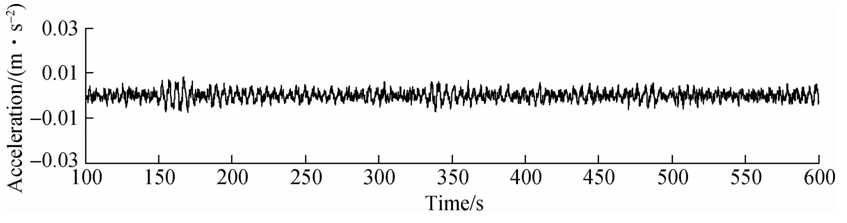
Tab. 2 Comparison of the modal frequencies

Mode description	Equivalent model	SAP2000	Error/%
Lateral bending in *X* direction	0.180 58	0.182 66	1.15
Lateral bending in *Y* direction	0.199 12	0.203 32	2.11

The error between the equivalent model and SAP2000 is less than 5%, indicating the rationality of the equivalent model. The structural wind-induced vibration for the top of the building can be obtained and adopted to evaluate occupant comfort, as shown in Fig. 6.



(a)



(b)

Fig. 6 Acceleration of the building top. (a) *X* direction; (b) *Y* direction

The maximum values of the acceleration of the building top are 0.021 2 and 0.008 2 m/s^2 in the *X* and *Y* directions, respectively. As for SAP2000, they are 0.031 1 and 0.012 9 m/s^2 in the *X* and *Y* directions, respectively. The acceleration results are smaller than the criterion restriction[25], i. e., 0.25 m/s^2, showing that the occupant comfort meets the criterion requirement. Furthermore, it is safe to use the design software SAP2000 to evaluate the occupant comfort of the Xuanwu-Ⅱ Hotel.

3 Conclusions

1) The LES captured and predicted strong turbulent vortex shedding and a relatively lengthy wake zone. The LES effectively captures the turbulent structure, which looks like a horseshoe vortex on the upstream side near the ground, as well as the shear layers.

2) The maximum value of the acceleration of the building top is 0.021 2 and 0.008 2 m/s^2 in *X* and *Y* directions, respectively, which are less than the criterion restrictions, i. e., 0.25 m/s^2.

3) It is safe to use the design software SAP2000 to evaluate the occupant comfort of the Xuanwu-Ⅱ Hotel.

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基于大涡模拟的高层建筑风振舒适度评估

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摘要：针对某风敏感高层建筑开展了风振舒适度评估研究．利用大涡模拟（LES）技术估计作用于该高层建筑的脉动风荷载，采用窄带合成随机流生成（NSRFG）算法生成 LES 的入口湍流．选用层剪切模型开展该高层建筑的风效应分析，选择顶层加速度响应极值作为该高层建筑的风振舒适度评价指标，并将分析结果与 SAP2000 计算结果进行对比分析．结果表明，该高层建筑的风载因子随高度的增加而逐渐增大，采用 LES 技术可以捕捉建筑绕流场细节．基于 LES 技术计算所得的建筑顶层风振加速度响应极值小于 SAP2000 计算结果，说明采用现有设计软件开展高层建筑风振舒适度分析是偏保守的．

关键词：高层建筑；大涡模拟；舒适度分析；风致振动；随机流生成

中图分类号：U448.27