Characteristics of wind load on a 3:2 rectangular cylinder in accelerating flows

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SUMMARY:
The accelerating flow is one of the most important non-stationary wind flow types, which influences the wind load on the structures in many ways. Some observed special characteristics induced by accelerating flow distinguish it from the normal wind. To study the transient aerodynamics involved in this issue, the most representative 3:2 rectangular cylinder is taken as an object to carry out a sectional model wind tunnel test at first. The CFD simulation is also introduced to simulate a series of accelerating flows with different wind velocities and acceleration. A mathematical method, variational mode decomposition (VMD), is then used to decompose the non-stationary wind loads into three principal components, which are a time-varying mean component, an attenuated fluctuating component, and a stable fluctuating component. The first two components show obvious transient characteristics during the wind acceleration time, which may not only be controlled by the flow acceleration but also related to the wind velocity at the start of the acceleration process. The stable fluctuating component, on the other hand, is generally consistent with the counterpart in the normal wind.

Keywords: accelerating flow, 3:2 rectangular cylinder, variational mode decomposition, wind tunnel test, CFD

1. INTRODUCTION

The structural damage caused by strong winds in extreme weather can be heard across the world in recent years. This type of abnormal wind field usually occurs with a thunderstorm, downburst, or other severe convection systems, with obvious transient characteristics, thus having a strong impact on the extreme wind load on structures, making the investigation of wind load in transient flows of great importance. Among others, the accelerating flow is more conducive to mechanism analysis, so it is regarded as a representative sample to carry out the investigation. Some research has been conducted by pioneers. Studies in the water tunnel observe the transient overshooting phenomenon and confirm its impact on force coefficients (Sarpkaya and Ihrig, 1986). Takeuchi et al. also observe the overshooting phenomenon in wind forces on the elliptic and rectangular cylinders (Takeuchi and Maeda, 2013; Takeuchi et al., 2017). Yang and Mason (2019) compare the force coefficients of rectangular cylinders in steady and accelerating wind flow and suggest that both initial flow condition and body side ratio influence transient aerodynamics. Brusco et al. (2022) analyze the time-frequency characteristics of signals associated with vortex-shedding induced by accelerating flows and notice that the Strouhal number can be moderately lower during the transients. On this basis, the decomposition algorithm VMD will be introduced in this study to find out the principal components of non-stationary wind load induced by accelerating flows, thus investigating the non-stationary characteristics in terms of each component.

2. DATA ACQUISITION

2.1. Wind Tunnel Test Arrangement

As shown in Fig. 1, the wind tunnel tests on a section model of a 3:2 rectangular cylinder were carried out in the TJ-5 Wind Tunnel at Tongji University. The wind tunnel test section is 1.5m wide and 1.8m high. The cross-section of the test model was a 3:2 rectangular, which is 100mm wide and 150mm deep. No correction for tunnel blockage was made.

2.2. CFD Model and Parameters

The CFD software FLUENT is employed to carry out the simulation. As shown in Fig. 2, the computational domain is 6m in the along-wind direction and 1.5m/3.75m in the cross-wind direction, where 1.5m simulates the wind tunnel size for reliability validation and 3.75m is used to eliminate the influence of blockage ratio. Fig. 3 presents mesh in the overall view and near the model. The grid size along the model is around 1mm, and the height of the first layer grid is 0.05mm, thus the maximum y+ value is about 0.5. The k-ε-Realized model is utilized for Reynolds average numerical simulation. The time step is 0.0001s, which maintains the Courant number less than 0.5.

Figure 1. Test model in the wind tunnel

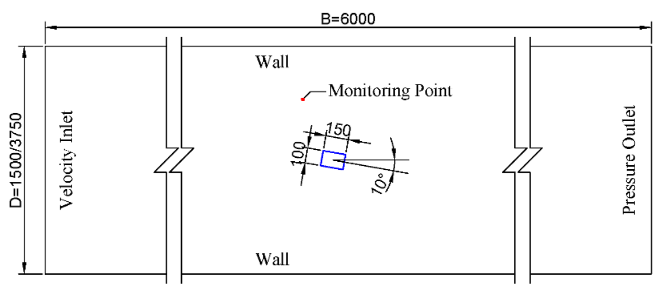


Figure 2. CFD computational domain

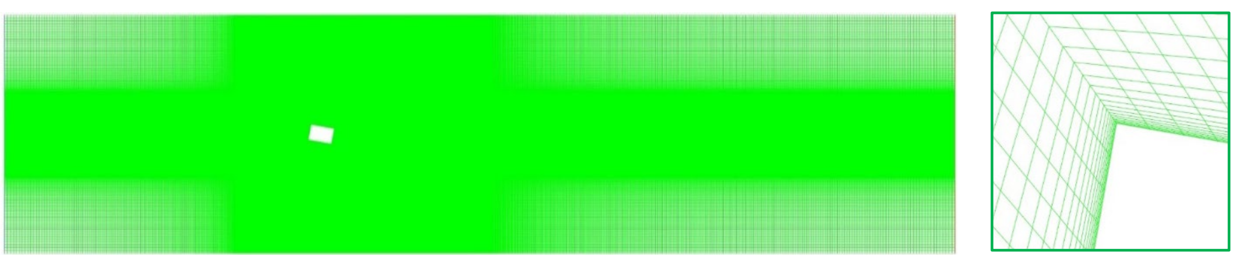
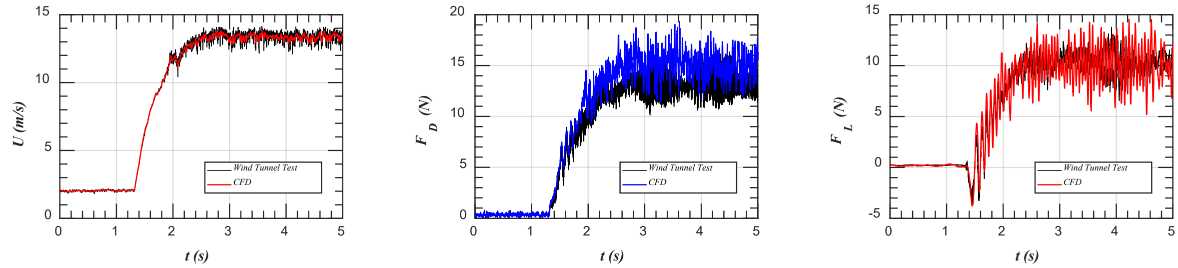


Figure 3. CFD mesh arrangement

2.3. Validation of CFD Simulation

Among others, the most distinctive case under 10° angle of rotation is discussed in this study. To validate the accuracy of CFD simulation, a typical accelerating flow recorded in the wind tunnel test, accelerated from 2m/s to 13m/s, has been applied to CFD. And a turbulent intensity of 0.01 and a turbulent viscosity ratio of 1 are assigned to them. As shown in Fig. 4, the CFD computed wind loads on the test model are basically consistent with the wind tunnel test recorded ones. Therefore, the feasibility of CFD simulation in the accelerating flow related study is demonstrated, and the following discussion will be based on CFD simulated results.



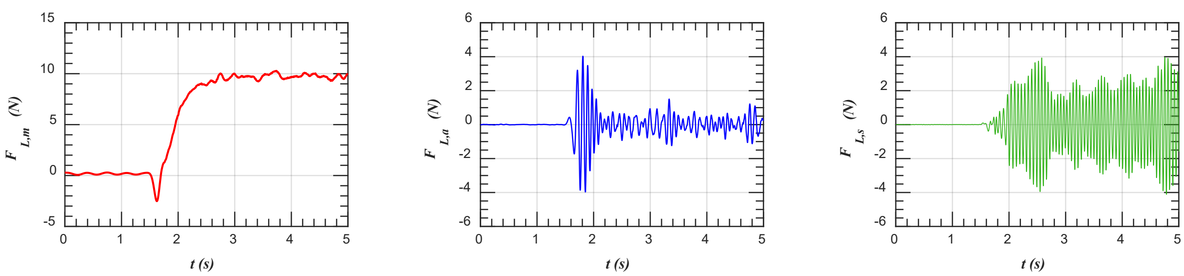
(a) Wind velocity (b) Drag force (c) Lift force

Figure 4. Accelerating flow and wind loads in wind tunnel test and CFD simulation

3. NONE-STATIONARY WIND LOAD ANALYSIS

3.1. Principle Component Decomposition

Compared with the drag force, the influence of accelerating flow on lift force is more distinct, hence the need for an in-depth study on potential non-stationary characters. For the convenience of discussion, a powerful decomposition algorithm, variational mode decomposition (VMD), is introduced to deal with the non-stationary wind load signal. A reasonable mode number has been set as 3 in pre-study, thus three main components shown in Fig. 5 can be divided from the lift force in accelerating flow, including a time-varying mean component ($F_{L,m}$), an attenuated fluctuating component ($F_{L,a}$), and a stable fluctuating component ($F_{L,s}$).



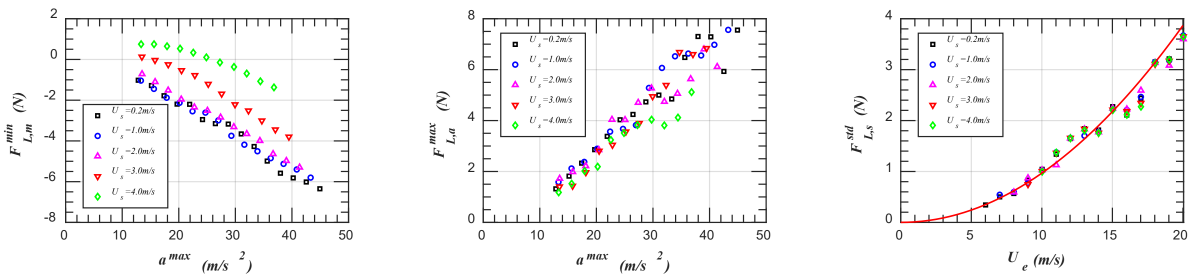
(a) Time-varying mean component (b) Attenuated fluctuating component (c) Stable fluctuating component

Figure 5. VMD decomposed components of lift force in accelerating flow

3.2. None-Stationary Character Discussion

In steady-state or quasi-steady-state, the mean component is proportionate to the square of wind velocity. However, as shown in Fig. 5(a), an obvious negative increase can be seen during the wind acceleration time, implying that the quasi-steady assumption no longer pertains. The minimum value of the negative increase ($F_{L,m}^{min}$) can be taken as a key parameter, reflecting one of the non-stationary characteristics of wind loads induced by accelerating flow. As shown in Fig. 6(a), $F_{L,m}^{min}$ almost has a linear dependence on the maximum acceleration a^{max} when the wind velocity at the start (U_s) is relatively small, while the relationship changes with the increase of U_s. In addition, it should be noted that the negative increase shown in the case of 10° angle of rotation may not exist in other angles of rotation.

Apart from the mean component, there are two main fluctuating components. The stable fluctuating component agrees with the quasi-steady counterpart on amplitude, frequency (Strouhal number), and other characteristics. The standard deviation of the stable fluctuating component ($F_{L,f}^{std}$) is shown in Fig. 6(c), confirming that $F_{L,f}^{std}$ is in direct proportion to the square of wind velocity in the end (U_e). On the other hand, the attenuated fluctuating component is aroused by wind acceleration, and its effect will be attenuated when the wind velocity becomes stable. It can be seen from Fig. 5(b), both amplitude and frequency change during the wind acceleration time. For the sake of simplification, only the maximum values are plotted in Fig. 6(b), implying that the attenuated fluctuating component is mostly controlled by the flow acceleration.



(a) Time-varying mean component (b) Attenuated fluctuating component (c) Stable fluctuating component

Figure 6. Key parameters for VMD components in different accelerating flow conditions

4. CONCLUSIONS

The accelerating flow induced non-stationary characteristics of wind load on a 3:2 rectangular cylinder are studied utilizing wind tunnel test and CFD simulation. A series of accelerating flows with different wind velocities and acceleration is simulated by CFD for parametric analysis. With the help of VMD, the non-stationary wind loads are decomposed into three principal components at first, which are a time-varying mean component, an attenuated fluctuating component, and a stable fluctuating component. Parametric analysis is then carried out in terms of each component. Transient characteristics are found in both the time-varying mean component and attenuated fluctuating component, which are controlled by not only the flow acceleration but also the wind velocity at the start.

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