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Numerical evaluation of wind loads on a high-rise building by dynamic moving Tornado

HUANG Shenghong, YU yitian, Wangxin

Department of modern mechanics

University of Science and Technology of China, Hefei city, P. R. China

Abstract

Tornado is potential of severe damage to structures and has been one of important research objects in wind resistance & disaster prevention engineering. With the deteriorating of global environment in recent years, large cities are attacked by tornado occasionally. The researches of tornado effects on high-rise buildings began to receive concerns. Presently, few investigations are focused on dynamic behavior of moving tornado and its impacting wind loads on high rise buildings, and especially specific requirements and methods of structure safety design with respect to tornado attack are lacked in present code. It is necessary to begin investigations on such subject theoretically and experimentally. In this paper, the wind model of moving tornado is established and the unsteady process of a moving tornado impacting against high rise building is numerically simulated with large eddy simulation (LES), then the wind flow characteristics as well as dynamic wind loads of tornado striking against large civil structures are analyzed. The results of experimental scale are then compared with those of full scale cases, the mechanism of flow field as well as wind loads difference between them are analyzed.

Introduction

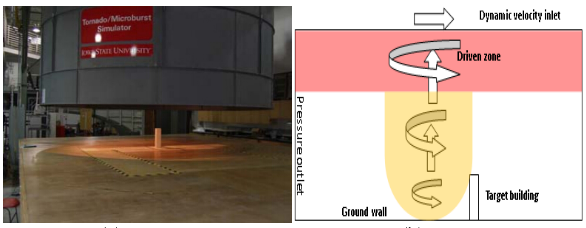
Tornado is an extreme weather in nature, one of most awesome and destructive wind. It is also one of the most important subjects of wind disaster mitigation engineering, and has aroused wide concerns of engineers and scholars all over the world. Due to characteristics of highly bursty and strong destructiveness, it is difficult to make field measurement with tornado. In early stage of investigations, wind tunnel tests have played an important role to study this kind of wind phenomenon. In recent years, with the development of computational mechanical technology, numerical simulation was becoming a more and more effective tool in study of tornados. Hassenzahl [1] conducted numerical study on a tornado vortex using vorticity confinement. Le et al [2] carried out numerical simulations on the flow field of a laboratory-simulated tornado for parameter sensitivities and validations with field measurements. Maruyama [3] calculated wind fields vortex of tornado by making use of large eddy simulation. Diwakar et al [4, 5] numerically studied velocity vectors, pressure deficit and core radius with different swirl ratios as well as the flow flied characteristics of three type tornado-like vortices. Damatty et al [6] investigated the behavior of guyed transmission line structures under tornado wind loads with numerical methods. TANG et al [7] study the tornado model and wind loads. In addition, Pham et al [8] constructed a numerical movable tornado simulator to evaluate its effects on the wind pressure distribution around a cube building using large eddy simulation.

As addressed previously, although many experimental and numerical studies have been conducted to investigate tornado flow characteristics and wind loads on building structures, most of them are focused on quasi-steady wind loads. Translating moving tornado cases were rarely reported. There were few numerical simulations conducted with moving tornado cases except Pham et al's work[8], which may be caused by technical difficulties of maintaining stability in applying both dynamic moving and rotating boundary conditions for numerical simulation of tornado vortex. In fact, compared with quasi-steady wind loads, dynamic wind loads of tornado may be more destructive to structures as discussed by Pham et al, therefore it is of great significance to investigate the dynamic behavior of moving tornado and its dynamic wind loads on structures.

To overcome the difficulties of dynamic moving tornado in numerical simulations, special techniques are developed to deal with the model of translational tornado as well as its boundary conditions. In result, the moving tornado is maintained to be moved with specified velocities and swirling intensities, the flow fields of tornado moving past high-rise building models in subscale and full scale are effectively simulated.

Numerical methods and models of dynamic tornado wind field

Generally, three special techniques are adopted to simulate a moving tornado as depicted in figure 1.



(a) (b)

Figure 1. Moving tornado model. (a) ISU Tornado wind tunnel; (b) present numerical Model

Firstly, a driven zone with a fixed tornado swirling intensity is generated in upper region of tornado wind field, which is initialized and fixed dynamically with velocities according to tornado model. The role of driven zone is just like that of fan and swirl vane of laboratory tornado simulator, providing a power source to maintain the target tornado wind swirling and moving with the driven zone.

Secondly, to keep velocity consistence with the driven zone, the boundary at the top of driven zone is set up as a velocity inlet boundary, on which the velocity components are updated dynamically and synchronously with that in driven zone.

Thirdly, the initial pressure distribution in tornado is carefully treated to maintain the stability of tornado vortex. In fact, improper initialized pressure in tornado vortex will make the core radius contracting or expanding, leading to wrong wind profile, which is caused by mismatched pressure gradient and rotating wind, since the centrifugal force due to rotating of wind is mainly balanced by pressure gradient. In present paper, the pressure of tornado vortex is treated as follows: perform a steady state computation of whole computational domain with a fixed velocity of tornado, the resulted pressure field is adopted as an initial pressure field of subsequent dynamic simulation.

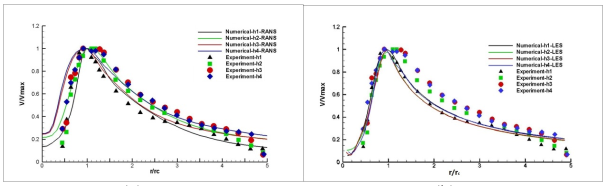
The CFD code used in the present research is the commercial software FLUENT. The dynamic tornado model proposed in this study is developed as a User Defined Function (UDF) library, which is integrated into FLUENT code by programming technique of user defined scalar and function hooks.

Validations for tornado wind field and wind loads

To check the reliability of numerical models and methods used in tornado wind field simulation, the experiments conducted by Sarkar et al. [9] are used as validation cases. In the experiments of Sarkar et al. [9], a laboratory tornado with a maximum vortex core diameter of 1.12 m is generated with tornado simulator of ISU. This simulator can produce a translational movement of tornado vortex so that quasi-steady and transient wind load effects of tornado wind on building can be tested. The target building is a 1/500 geometrically-scaled model of a tall building with a height of 432mm and a square plan dimension of 108mm. Both quasi-steady and transient wind loads with translational velocity 0.3m/s and 0.6m/s were tested by Sarkar et al.

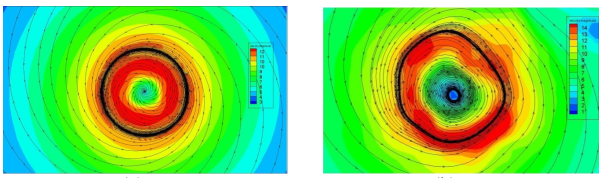
The computational domain and boundaries of validation case as well as grid refinement around building model is shown in figure 4, the target building model is same scale with experimental model (scale 1:500, and the model size: H is 432mm, B is 108mm, W is 108mm). The numerical tornado is generated with Vmax=11.0 m/s and r0=0.36 m, which are same with experimental parameters.

A single tornado wind field is firstly computed to verify the numerical tornado wind velocity distribution is similar with that of experimental by RANS and LES method in this part. Figure 2 shows the comparison of velocity distribution at different heights between numerical and measured results. It is clear that they are in good agreement with each other, validating that the numerical tornado has same velocity similarity with one generated by experimental simulator. Figure 3 shows the velocity contours at same cross section planes of wind field in RANS and LES respectively, a very well tornado vortex shape is obviously observed.



(a) (b)

Figure 2. Velocity distribution at different height. (a) RANS model (b) LES model



(a) (b)

Figure 3. Contours of velocity-magnitude. (a)H=20cm (RANS); (b) H=20cm (LES)

It should be pointed out that the velocity distributions obtained by quasi-steady simulations through RANS and LES methods are in good agreements with that of experiments.

Dynamic tornados with translation speed of 0.3m/s and 0.6m/s respectively were simulated with both RANS and LES model to compare with the experiments by Sarkar et al.

Figure 4 is the velocity-magnitude of the tornado at various moments with different translation velocity and different computational method. It is clear that new model of dynamic tornado has same velocity similarity with the experiment generated. In summary, the numerical results of dynamic tornado are in good agreement with the tornado wind field distribution characteristic of experimental model. It is also demonstrated dynamic tornado could maintain it stability in moving direction.

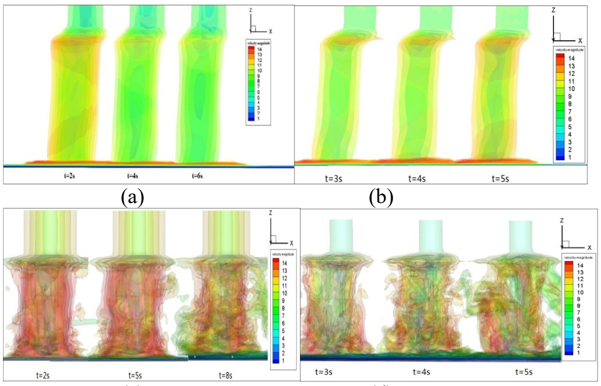
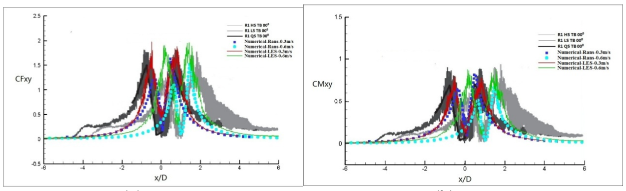


Figure 4. Vorticity-magnitude contour in translational course. (a)Translation speed 0.3m/s (RANS); (b) Translation speed 0.6m/s (RANS); (c) Translation speed 0.3m/s (LES); (d) Translation speed 0.6m/s (LES).

Figure 5 shows the force coefficients comparison between numerical results and experimental ones. It is shown that the loads histories of numerical simulation agree generally with those of experimental, especially for LES, presenting more agreements of peak loads and loads fluctuations.



(a) (b)

Figure 5. Loads coefficients comparison between numerical results and experiments. (a) Force-coefficient of xy plane; (b) Moment-coefficient of xy plane

Figure 6 shows the flow patterns of dynamic tornado impacting a high rise model simulated by RANS and LES respectively. It is observed that many small vortex induced by main vortex are presented in figures of LES, which is in accordance with loads flunctuation in loads histories.

Full scale simulation of impacting wind loads on high rise buildings by dynamic tornado F2

In this part, the wind loads characteristics of the dynamic tornado of F2 striking various high-rise buildings are simulated. Four kind of tall buildings had been selected as targets as shown in figure 7. The results are shown in figure 8-figure 10 respectively.

According to figure 8, it is interesting to observe that the impacting wind loads on high-rise building by tornado for full scale case and experimental scale case manifests both similarity and scale effects. The similarity is observed in wind loads profiles and history when the ratio of radius of maximum rotating wind velocity v.s. model scale is similar, while the scale effects is observed in difference of peak loads and its corresponding positions.

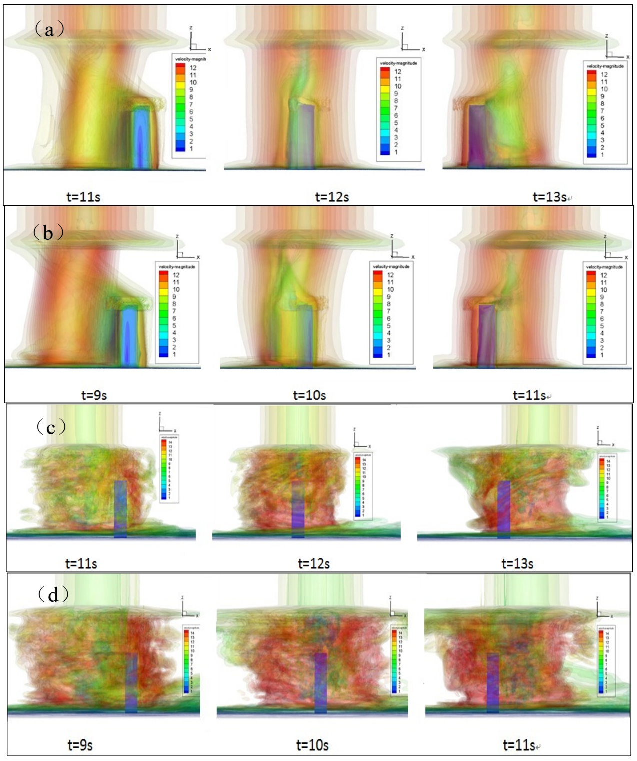


Figure 6. Flow patterns of dynamic tornado impacting a high rise model. (a)Translation speed 0.3m/s (RANS); (b) Translation speed 0.6m/s (RANS); (c) Translation speed 0.3m/s (LES); (d) Translation speed 0.6m/s (LES).

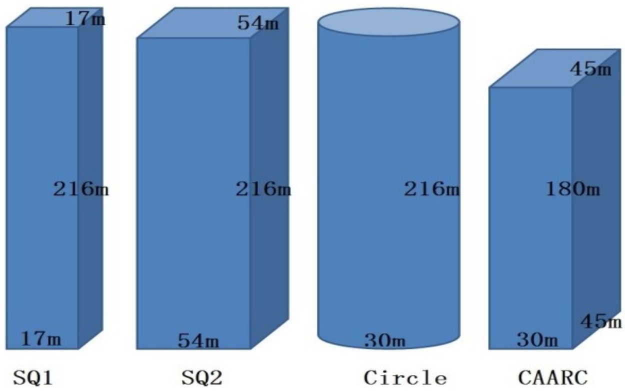
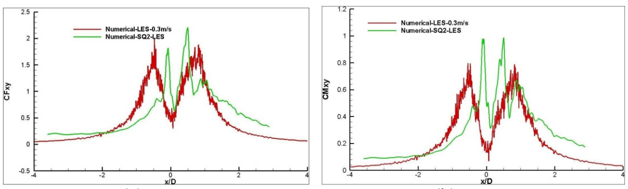
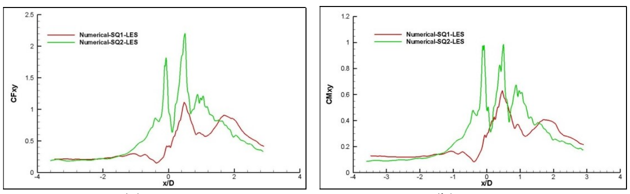


Figure 7. Target high rise buildings



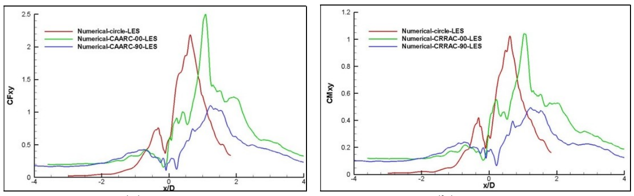
(a) (b)

Figure 8. Force coefficients comparison between sub-scale and full scale cases. (a) Force-coefficient of xy plane; (b) Moment-coefficient of xy plane.



(a) (b)

Figure 9. Force coefficients comparison between SQ1 and SQ2 cases; (a) Force-coefficient of xy plane; (b) Moment-coefficient of xy plane.



(a) (b)

Figure 10. Force coefficients comparison between Circle and CAARC cases. (a) Force-coefficient of xy plane; (b) Moment-coefficient of xy plane.

For figure 9, it is observed that the wind loads of tornado striking on high-rise building are related with size of target building. For small size case, the loads are characterized by dual peak profiles, and impacting effects and unsteadiness are relatively small, while for large size case, the loads are characterized by multi-peak profiles with strong unsteadiness and large impacting effects. In process of tornado striking on relatively large size high-rise building, the main vortex is observed to be broken into several vortices, then a complicated interaction and coupling among vortices as well as wake flow of building is observed. No similar mechanical phenomenon has ever been reported in open literatures of tornado investigation.

Finally, For figure 10, Force coefficients comparison between target buildings with different cross section are compared. It is revealed that: the wind loads response of tornado impacting is related with cross configuration of building when other conditions such that building height and tornado scale etc. are same. Generally the building with rectangle cross section has largest peak loads, which is changed with attack angle of moving tornado.

Conclusions

There exist technical difficulties of maintaining stability of tornado in applying both dynamic moving and rotating boundary conditions for numerical simulation of tornado vortex. Setting a driven zone with a fixed tornado swirling intensity in upper region of tornado wind field is an effective and efficient method to overcome this difficulty.

The wind loads of tornado striking on high-rise building is observed to be related with size of target building. For small size case, the loads are characterized by dual peak profiles, and impacting effects and unsteadiness are relatively small, while for large size case, the loads are characterized by multi-peak profiles with strong unsteadiness and large impacting effects. In process of tornado striking on relatively large size high-rise building, the main vortex is observed to be broken into several vortices, then a complicated interaction and coupling among vortices as well as wake flow of building is observed. No similar mechanical phenomenon has ever been reported in open literatures of tornado investigation.

The comparison of impacting wind loads on high-rise building by tornado for full scale case and experimental scale case manifests both similarity and scale effects. The similarity is observed in wind loads profiles and history when the ratio of radius of maximum rotating wind velocity v.s. model scale is similar, while the scale effects is observed in difference of peak loads and its corresponding positions.

The full scale simulations reveal that: the wind loads response of tornado impacting is related with cross configuration of building when other conditions such that building height and tornado scale etc. are same. Generally the building with rectangle cross section has largest peak loads, which is changed with attack angle of moving tornado.

Acknowledgements

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