A Numerical Study of the Effects of Moving Tornado-Like Vortex on a Cube

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ABSTRACT: A numerical movable tornado simulator using Large Eddy Simulation has been constructed to generate the tornado-like vortices and used to evaluate the effects of the translational moving of the vortices on the wind pressure distribution around a cube building. The performance of the simulator has been verified in comparison with the previous experimental results. Although, wind pressure on the surface of the cubic was almost constant in time inside the stationary tornado-like vortices, the pressure was changed significantly when the vortices were translated. The significant changing has also clarified from the wind flow around the cubic with strong whirl vortices and vertical wind components.

KEYWORDS: Tornado-like Vortices, Cubic, Wind Pressure, LES Model, Moving Effect

1 INTRODUCTION

Damages caused by tornado are often due to the destroy or damage on the walls or roofs and tiles of building, those things are then scattered and wrap around a new building or structure to create a new damage. In order to reduce the damages, better understanding of flow field and wind pressure acting on building in tornado needs to be clarified.

Because of the sudden and local occurrence of a tornado, it was found that the measurement of a flow field near the ground in a tornado was difficult1). Some meteorological numerical simulations in the meso-scale tried to elucidate the generation mechanism of a tornado that needed to model a giant cumulonimbus cloud, in which dozens of kilometers wide was in two orders of magnitude of the tornado. The scale of the simulation would become too large to evaluate the flow field near the ground as well as the wind pressure acting on building in detail2). On the other hand, several studies3,4) to better understand tornado structure used physical models that simulate tornado-like vortices as a flow field of tornado near the ground below a cumulonimbus cloud. Some experiments4) indicated the changing in structure of vortex by Reynolds number and swirl ratio. Recently, Yang et al.5) showed the appropriateness of the physical model in modeling the flow field of tornado in comparison with field measurement’s results. However, most experiments were carried out in 1/1000 to 1/10,000 of real scale. Because of the constraints of the experimental devices, it was difficult to investigate in detail the structure of the vortices as well as the changing in wind pressure of the building. Numerical simulation using computational fluid dynamic is expected as one of effective method to solve the problem6,7).

While those studies made an effort to evaluate the flow field and wind loads on building the in tornado-like vortices, most of them ignored the translational movement of the vortices that could be an important reason of damages caused by tornado. In recent years, some researcher8,9) tried to design the prototype of the experimental apparatus that could translate a vortex forcibly. Selvam et al.9) proposed a numerical simulator using the Rankine-Combined Vortex Model (RCVM) to simulate the effect of translational movement of the tornado on the forces acting on buildings. Although, this model did not include the vertical velocity, which did occur inside the vortex core of actual tornado, it was found that the forces were higher than the results in the
straight boundary layer wind in the vertical direction. Some new model including the vertical velocity needs to be considered for better understanding.

In this study, a numerical movable tornado simulator using Large Eddy Simulation and dynamic mesh generation has been developed. The performance of the simulator has been verified in comparison with the wind velocity profile and wind pressure distribution of previous experiment. The simulator was then used to evaluate the effects of translational moving of the tornado-like vortex on wind flow field and the wind pressure distribution on a cube building.

2 NUMERICAL MOVABLE SIMULATOR

Schematic of the movable tornado simulator is shown in Fig.1. A Ward-type tornado simulator has been modeled basing on the dimensions of the stationary simulator model of Matsui’s experiment. Simulator included a convergent zone of $h=20\text{cm}$ height with a shear inflow layer of direction $\theta$, a convection zone with an exhaust outlet and was moved with the translational velocity $U_{\text{mov}}$. Table 1 shows the analysis conditions and those conditions in the actual atmosphere. The scale is about 1/1000–1/10000. As the same as previous studies, the swirl ratio ($S = d/4h \times \tan \theta$) was considered to be the main dimensionless quantity. The ratio of translational velocity and maximum velocity obtained inside the vortex ($U_{\text{mov}}/U_{\text{max}} = 0.6/12$) is in the range of 0–30/90 in the actual phenomena.

Fig.2 illustrates the mesh of convergent zone in the plan view (a), close-up of the stationary mesh area in the convergent zone (b) and mesh of computational domain. Moving meshes with sliding interfaces were adapted to model the moving of tornado from left to right. In order to minimize the effects of the moving meshes, a stationary mesh zone around the building was modeled. Dynamic layering method was also adapted to split or merge mesh cells to maintain the quality of mesh around the building. Computational model had 779 thousand mesh cells.

Navier-Stokes equations for incompressible flow including the continuous equation and momentum equations were solved using Fluent 6.3 software. LES turbulence model was used in which small eddies were modeled using the standard Smagorinsky model. Governing equations were discretized by the finite volume method. A central difference scheme for convective terms and a second-order implicit scheme for unsteady terms were used.

A cube of width $B=0.1h$ was set up at the center of floor of the simulator. Wind speed $U_0=6\text{m/s}$ was kept constant at the outlet boundary, whose outflow’s volume was $0.3\text{m}^3/\text{s}$, to generate the upward flow in the convection zone. A same volume of inflow with angle $\theta=60\text{deg}$ was applied to the inlet boundary to generate a tornado-like vortex with a swirl ratio $S=0.65$. Walls of simulator were modeled as the moving wall boundaries. Walls of cubic were no-slip boundaries.

In order to clarify the effect of translational movement of the tornado-like vortices, two case studies have been simulated with translational moving velocity $U_{\text{mov}}=0$ and 0.6m/s as the stationary condition and the moving condition, respectively. In case 1, the numerical simulator was not moved ($U_{\text{mov}}=0\text{m/s}$), hereinafter referred to the case of the stationary condition. The wind flow field was generated from the analysis conditions to obtain the wind pressure acting on a cubic. In case 2, the numerical simulator was firstly set up in the 0.4m left-hand side of the cube. After 7000 steps of an approach run, which was enough to generate a tornado-like vortex, the simulator was moved to the right hand side with a translational velocity of $U_{\text{mov}}=0.6\text{m/s}$, hereinafter referred to the case of the moving condition. Wind pressure acting on the cubic was estimated during the vortex’s passing. Each simulation was carried out for 16s at time increment of 0.001s.

Because of time-space changing of wind speed and static pressure in the tornado-like vortices, the method using in straight boundary layer to estimate the wind pressure coefficients cannot be applied. In this study, the pressure coefficient was obtained by the following equation.

$$C_p = (P - P_0)/0.5\rho V_0^2$$

(1)
Figure 1. Schematic of movable tornado simulator

Figure 2. Meshes of numerical model

Figure 3. Wind velocity and ground surface pressures in comparison with experimental results

Table 1. Dimensions of the movable simulator and analysis conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Numerical study</th>
<th>Real Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upward hole diameter</td>
<td>D</td>
<td>0.3m</td>
<td>1~3km</td>
</tr>
<tr>
<td>Convergent zone height</td>
<td>h</td>
<td>0.2m</td>
<td>0.5~2km</td>
</tr>
<tr>
<td>Convection zone diameter</td>
<td>D1</td>
<td>1.6m</td>
<td>-</td>
</tr>
<tr>
<td>Exhaust outlet diameter</td>
<td>d</td>
<td>0.25m</td>
<td>-</td>
</tr>
<tr>
<td>Convection zone diameter</td>
<td>D2</td>
<td>1.2m</td>
<td>-</td>
</tr>
<tr>
<td>Swirl ratio (d/4htan θ)</td>
<td>S</td>
<td>0.65</td>
<td>0.05~2</td>
</tr>
<tr>
<td>Inflow angle</td>
<td>θ</td>
<td>60deg</td>
<td>-</td>
</tr>
<tr>
<td>Outlet volume</td>
<td>Q</td>
<td>0.3m³/s</td>
<td>10³~10⁸ m³/s</td>
</tr>
<tr>
<td>Outlet velocity</td>
<td>U₀</td>
<td>6m/s</td>
<td>-</td>
</tr>
<tr>
<td>Maximum tangential velocity</td>
<td>U_max</td>
<td>12m/s</td>
<td>70~90m/s</td>
</tr>
<tr>
<td>Translational moving speed</td>
<td>U_mov</td>
<td>0, 0.6m/s</td>
<td>0~30m/s</td>
</tr>
<tr>
<td>Cubic building width</td>
<td>B</td>
<td>0.02m</td>
<td>20~200m</td>
</tr>
</tbody>
</table>
Where, $P$ is the wind pressure, $P_s$ is the maximum wind pressure far enough away vortex, $\rho$ is the density of air. $V_0$ is the reference wind speed which was calculated from the difference between the maximum wind pressure of the ground surface and the minimum wind pressure at the center of the vortex that obtained in a stationary condition of the simulator without any cubic. Following the definition, the pressure coefficient at the floor surface is mathematically between -2 to 0 when the vortex is assumed as the Rankine vortex. The pressure coefficient of -1 will also match to the position of the maximum wind speed of the vortex.

Fig. 3 illustrates a comparison of tangential velocity and ground surface pressure distributions between experiment and simulation in the stationary condition without any cube. The simulated results showed a good agreement with experimental ones. In addition, the wind pressure coefficient is between -2 to 0, and at the coefficient of 1, the tangential component of wind speed can be seen that nearly becomes the maximum.

3 RESULTS AND DISCUSSIONS

3.1 Wind Pressure Distributions on a Cube

Fig. 4 illustrates the wind velocity time series at the 0.75$h$ height, which is on the top of the cube. Comparing to the result in the stationary state, the wind velocity increased in 7.6~8.2s and decreased in 8.2~8.6s as a sudden gust wind occurring when the simulator was passing. Fig. 5 and Fig.6 show the maximum and minimum wind pressure time series acting on each surface of cube in the stationary state and moving state of simulator. A plus (+) mark including A, B, C, D, E letter indicates a developed view of the surfaces of the cube. The rotational direction and translational direction of the tornado-like vortex are also described together. In the stationary condition, wind pressure acting on each surface of the cube becomes almost constant in time. The pressure coefficients on the roof and side surfaces are between 0.0 to -1.0 that is similar to the values obtained by the previous experiment7). On the other hand, in the moving condition, a large wind pressure does not occur when the center axis of the simulator is approaching. After the central axis passed the cubic, the pressures change rapidly at 8.2s. The maximum and minimum pressures are up to +3 and -3, simultaneously, whose range is larger than the range of -2 to 0 in assumption of Rankine vortex which has been mentioned above. Incidentally, the position at the time of 8.2 seconds is the same as the position of approximately 0.05m from the vortex center (Fig.3a) that corresponds with the maximum wind speed of the tangential direction of the vortex.

Fig. 7 and 8 shows the vorticity contours and distribution of wind pressure acting on the ground and surfaces of cube at 8.2s. A square in figure (b) is the roof and figure (c) shows the developed view of the surfaces of the cube. In the stationary condition, the vortex axis and minimum pressure distribution are biased in the rotational direction at a position 0.05m away. It can be explained by the effect of the presence of cube. Detail for the effects of cube in dimensions will be discussed in next section. In addition, the wind pressure distribution and vorticity contour in the analysis has been confirmed to be a nearly steady state. On the other hand, in the case of moving, the tornado-like vortex has been almost hit to the cube as shown in Fig.7(a), resulted in a strong negative pressure at the corner ② of the roof as shown in Fig.7(c). A strong positive pressure near the corner① and negative pressures at the other side corners are also found.

In order to clarify the characteristics of wind pressure caused by the translational moving effect of the tornado-like vortex, the flow field in the vicinity of the cube is investigated. Fig.9 (a) and (b) show wind velocity contour and vector in the horizontal plane of $z=0.8B$ at the time of 8.2s. The flow separates and creates one small vortex at the corner ① and one large vortex at the
corner ④ that reattaches to other sides of cubic. The points of separation and reattachment are corresponding with the regions of strong positive and negative pressure in Fig.8(c). Although, these separation vortices are found as similar as the vortices in the boundary layer flow, the generated flow field around the cubic is typically whirled up, as shown in Fig.9(a). Moreover, a sudden changing in wind speed is also found at the separation points, with a strongly rising up flow field at the reattachment points. Fig.9 shows the contour and vector of wind speed in the vertical plane of x=-0.4B. A large upward flow near the corner ② has been occurred corresponding to the strong negative pressure obtained in the roof as shown in Fig.8(c). Consequently, it can be found that a complex three-dimensional flow formed by the swirling and strong upward flow caused a strong locally negative pressure in the vicinity of the cube from the tornado-like vortex.

Figure 4. Wind velocity time series at 3/4h height on the top of cube (left: stationary, right: moving)

Figure 5. Maximum (left) and minimum (right) wind pressure acting on the cube in stationary condition of simulator

Figure 6. Maximum (left) and minimum (right) wind pressure acting on the cube in moving condition of simulator
Figure 7. Vorticity contour and pressure distribution in the stationary condition

Figure 8. Vorticity contour and pressure distribution in the moving condition at time of 8.2s

Figure 9. Wind flow field around a cube (left: wind velocity contour, right: vector of wind velocity)
3.2 Wind vortices around a Cube

In order to clarify the effect of dimensions of cubic in the tornado-like vortex, a simulation with a cube of $B=0.5h$ was also carried in the stationary condition. Vorticity magnitude was estimated from the wind flow of stationary and moving simulators and visualized in 3D volume rendering. Fig.10 illustrates the vortex in the stationary condition with cube of $B=0.1h$ and $B=0.5h$. When the width of cube became large, the tornado-like vortex was separated into small vortices. The small vortices were occurred around the corner of the cubic and turn in the tornado direction. In other hand, the moving of the vortex before and after passing the cubic is shown in Fig.10. When the vortex is moving, the core of vortex was bent under effect of ground. Strong vortices are also found around the cubic from the tornado-like vortex.

Figure 10. Wind flow around cubes (left: $B=0.1h$, right: $B=0.5h$) in stationary condition

(a) $t=8.0s$  (b) $t=8.1s$

(c) $t=8.2s$  (d) $t=8.3s$

Figure 11. Wind flow around a cube ($B=0.1h$) in moving condition
4 CONCLUSION

A numerical movable tornado simulator using LES has been developed to evaluate the effects of
the moving of the tornado-like vortices on the wind pressure distribution and wind flow around a
cube. Although, the wind pressure on the surface of the cubic is almost constant in time inside
the stationary tornado-like vortices, the pressure is changed significantly under moving of the
vortices when the vortices were passing. The significant changing was also clarified from the
wind flow around the cubic with strong whirl vortices and vertical wind components.

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