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Variation of Flying Debris' Trajectory with Different Tornado-like Flow Fields

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Abstract

Tornado-like vortices were generated by numerical fluid dynamics. The flow characteristics of generated vortices were examined by comparing with the typical models of tornado. Flying debris in the generated vortices were also computed and the trajectories of debris were obtained. The variation of the velocities of flying debris were clarified.

Introduction

In case of tornado attack, a lot of flying debris will be born by strong wind and will damage houses and buildings. Therefore, it is important to predict the impact of flying debris for prevention or mitigation of tornado damage. Prediction of the flying debris' impact were studied by the examination of marks on damaged claddings or video records of debris' trajectory. Or some experimental tests have been done by tornado simulator in laboratory. The evaluation of debris' velocity is a basis for the impact assessment. Flying motions of debris in tornado-like vortex were simulated numerically and the trajectories were recorded. Monte Carlo simulation was carried out using numerically generated vortices and model vortices, a Rankin vortex and a Fujita's tornado model [1].

Generation of vortex

Numerical calculation by Large Eddy Simulation (LES) was arranged to obtain the unsteady turbulent wind field in the vortex. The calculating scheme we used here is based on the RIAM-COMPACT [2] developed in Kyusyu University. The calculation region was designed to reproduce the tornado-like vortex in a laboratory tornado simulator as shown in figure 1. The simulator consists of a convection region and a convergence region. The equivalent configuration to the laboratory experiment of Monji et al. [3] was arranged in the calculating domain.

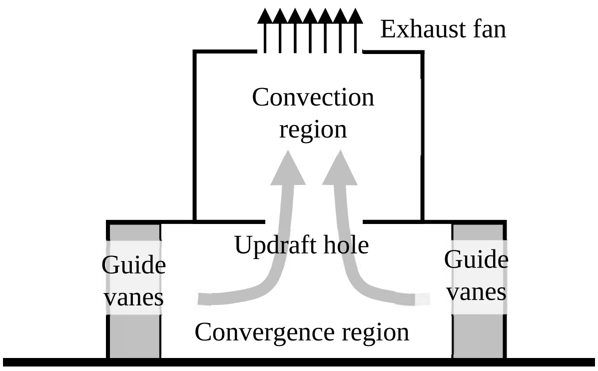
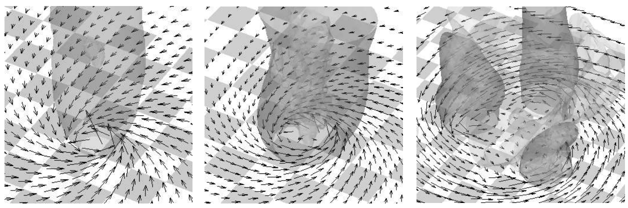


Figure 1. Tornado Simulator.

The horizontal shear was supplied by the inflows on the side walls of convergence region. The intensity of vortices was controlled by the wind speed and the distribution of inflow wind speed. The inflow velocities were arranged to conserve the total mass flux over the calculation region. A series of unsteady flow fields of vortex were generated and examined the flow characteristics with varying the calculating conditions [4]. Three typical vortices are presented in figure 2. They include a single core type vortex without a down-flow region, indicated by a non-negative mean vertical velocity component in the core: i.e. one cell type (Figure 2a). Hereafter 'mean' denotes time averaging. Others are a single core type vortex with a down-flow region in the core: i.e. two cell type (Figure 2b) and a multi-core type vortex with multiple suction vortices (Figure 2c).



a. One cell type b. Two cell type c. Multi-core type

Figure 2. Pictures show instantaneous shots of typical vortices near the ground generated in the numerical tornado simulator. Dark blue areas show low pressure region, i.e. vortex core. Light purple areas show the regions with upward flows. Arrows show the velocity vectors. The length of checker board is equal to the radius of maximum tangential velocity, R_{tm} in figure a, b and to $3R_{tm}$ in figure c.

These vortices were used for the simulation of flying debris as shown in next section. Rankin vortex "equation (1)" and Fujita's tornado model [1] "equations (2), (3), (4)" were also used.

Rankin vortex:

$$V_T(R) = C_T \frac{R}{R_{tm}} V_{tm} \qquad (0 \leqq R \leqq R_{tm})$$

$$V_T(R) = C_T \frac{R_{tm}}{R} V_{tm} \qquad (R_{tm} < R) \qquad (1)$$

Where V_T is the tangential speed at the distance R from the center of a vortex, V_{tm} is the maximum tangential speed at the radius of maximum tangential speed, R_{tm}. The radial speed was set as $V_R = C_R V_T$ and the vertical speed $W = C_W V_T$. The constants C_T, C_R and C_W are 0.894, 0.5 and 0.667, respectively [5].

Fujita's tornado model:

$$V_T(R,Z) = F_R(R) F_H(Z) V_{tm} \qquad (2)$$

Where $F_R(R) = R/R_{tm}$ $(0 \leqq R \leqq R_{tm})$, $= R_{tm}/R$ $(R_{tm} < R)$ and $F_H(Z) = (Z/H_i)^{ko}$ $(Z < H_i)$, $= \exp(-k(Z/H_i - 1))$ $(H_i \leqq Z)$.

$$V_R(R) = 0 \qquad (R \leqq nR_{tm}),$$

$$=\frac{V_{tm}\tan\beta}{1-n^2}\left(1-\frac{n^2}{(R/R_{tm})^2}\right) \qquad (nR_{tm}<R<R_{tm}),$$

$$=V_t\tan\beta \qquad (R_{tm}<R) \qquad (3)$$

Where $\tan\beta=-A(1-(Z/H_i)^{1.5})$ ($Z< H_i$) and $\tan\beta= B\{1-\exp(-k(Z/H_i-1))\}$ ($H_i \leqq Z$). The vertical wind speed $W(Z)$ is given in the range of $nR_{tm}<R_{tm}<R_{tm}$ as follows;

$$W(Z)=\frac{3}{28}\frac{0.55(1-\nu^2)V_{tm}}{1-\nu^2}A(16(Z/H_i)^{7/6}-7(Z/H_i)^{8/3})$$

$$(Z\ \ H_i),$$

$$=\frac{0.55(1-\nu^2)V_{tm}B\exp(-k(Z/H_i-1))}{k(1-\nu^2)}\{2-\exp(-k(Z/H_i-1))\}$$

$$(H_i \leqq Z) \qquad (4)$$

Where nR_{tm} is the radius of inner core, H_i is the height of outer inflow, $=0.55(1-n^2)$ R_{tm}, n=0.9-0.7exp(-0.005 R_{tm}), k_o=0.167, k_o=0.03, A =0.75 and B=3kA/((k_o+1)(k_o +2.5)) as given in [1].

Computation of Flying Debris

A piece of flying debris was assumed to be a 'compact' object which has a constant drag coefficient independent on the attack angle of the relative wind. The computation of flying debris was carried out by integrated the governing equations of debris' motion [4]. The characteristics of the vortex for numerical calculation were referred form a regulatory guide [6]. Four vortices, type I, II, III in table 1, were arranged as [6] and type IV in table 1 was selected as a tornado with typical magnitude in Japan.

Specification of vortex			
Type (m/s)	V_{tm} (m/s)	R_{tm} (m)	U_{tr} (m/s)
I	82	46	21
II	72	46	18
III	57	46	14
IV	84	30	16

Table 1. Specification of vortices used in the computation of debris. Type I, II and II are referred from a regulatory guide [6]. Type IV has a typical magnitude of tornado in Japan. U_{tr} is the translational speed of vortex.

The aerodynamic spectrum of flying debris was controlled by parameter C_DA/m [m^2/kg]. Where C_D is the drag coefficient, A is the frontal area and m is the mass of debris. Debris with larger value of C_DA/m flies further and faster. C_DA/m = 0.027 corresponds to a wooden plank and C_DA/m = 0.007 to an automobile [6]. The interaction forces between the missiles and the wind were ignored in the calculation of vortex. Time series of wind velocity in the numerically generated vortex were recorded and used for calculating the relative velocity to the debris. The vortex assumed to move with the translational speed U_{tr}. Debris was released in the vortex at a height distributed with uniform distance within the square area of 6R_{tm}. A large number of debris, 625×100 times for numerically generated vortex and 2401×100 times for model vortices, was release in the vortex for Monte Carlo simulation and the trajectories were recorded. The maximum ground speed of debris, V_{Gmax} was obtained for different vortex such as one cell, two cell, multi-core, Rankin vortex and Fujita model as shown in figures 3 and 4.

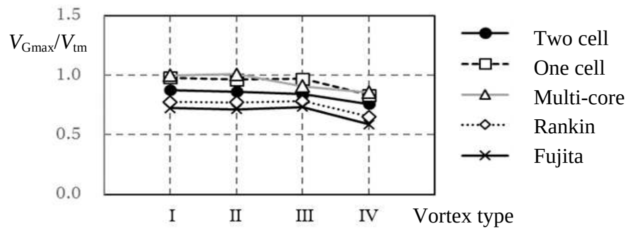


Figure 3. Variation of maximum ground speed of debris with vortex type. C_DA/m is 0.01[m^2/kg], release height is 40m.The debris flies in one cell or multi core vortex and type I shows largest maximum ground speed ratio, V_{Gmax}/V_{tm}.

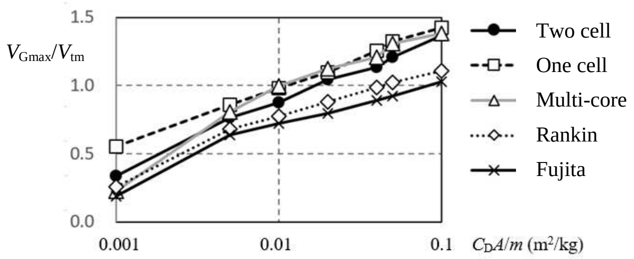


Figure 4. Variation of maximum ground speed of debris in type I vortex with aerodynamic parameter C_DA/m. Release height is 40m. The debris flies in the one cell vortex and with large value of C_DA/m shows largest maximum ground speed ratio, V_{Gmax}/V_{tm}.

Conclusions

Three different types of tornado-like vortices; one cell vortex, two cell vortex and multi-core vortex, with unsteady turbulent flows were generated numerically by LES. Debris flying in the three vortices and two model vortices; Rankin vortex and Fujita's tornado model, was calculated numerically. The trajectories were recorded by changing the intensity of vortex and the value of aerodynamic parameter of debris. The characteristics of flying debris were examined and the variation of maximum ground speed, V_{Gmax}, was clarified. The debris flying in one cell vortex shows the largest maximum ground speed ratio to the maximum tangential speed, V_{tm}.

Acknowledgments

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