Effect of tornado size on forces on thin 2D cylinder

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ABSTRACT:

A two dimensional study is conducted to compute the tornado forces on a thin, circular cylinder. A modified version of the 2D model, reported in Selvam et al. (2002), is used to simulate a detailed flow field around the cylinder. The flow features for different sizes of tornadoes, holding the size of the cylinder constant, are computed and compared. The maximum tangential velocity and translational velocity of all simulated tornados are assumed to be the same. The changes in mean values of drag and lift forces during the tornado impact are compared. The results provide better understanding of flow-structure interactions between thin structures subjected to tornado-like wind.

Keywords: Tornado size, thin structures, tornado forces, two-dimensional

1. INTRODUCTION

Every year tornados are the cause of significant property damage and loss of human life. To decrease the loss of life and reduce these damages, there is a need to have a better understanding of tornado forces. Images of destruction caused by tornadoes show that thin structures such as utility poles, traffic lights, street signs or lamp posts are very sensitive to tornado-like vortex. However, to the authors' knowledge, no studies have been conducted on tornado forces when planar size of the structure is much smaller then the size of tornado.

The first study of tornado forces on a building was conducted by Wen (1975). Because his analysis did not consider fluid structure interaction, the results were too conservative for design. Selvam et al. (2002) introduced a 2D model for tornado simulations that computed the tornado-structure interactions in detail. He found that tornado forces are about 5 times less than it was suggested by Wen (1975). Sengupta et al. (2008) compared forces obtained from the 3D experiment with values provided by ASCE for design purposes. He also studied the influence of translational velocity of tornado on tornadic wind forces. Sengupta concluded that experimental values of tornado forces on a cubic building are about 1.5 times higher than those provided by ASCE. This conclusion is comparable with results obtained by Selvam and Millett (2005) from their computer model. The other experimental study was conducted by Yang at al. (2011). It provides detailed information about the flow field around a high-rise building model. They analyzed influence of the building orientation angle and the distance between tornado and building on tornado forces. The effect of translational speed on dynamic response of different buildings was analyzed by Dutta at al. (2002). He computed tornado forces on a building based on tornado velocity record and found out that the higher translational velocity, the bigger response of a structure it produces. Recently Alrasheedi (2011) studied the influence of different building plan areas on tornado forces. He found that the larger the building plan area is, the smaller the tornado forces are; in other words, the thinner the structure is, the greater its wind sensitivity is. However, Alrasheedi and Selvam (2012) did not use fine enough grid resolution to capture vortex shedding and other wind sensitivity issues.

In this work a modified version of 2D model reported in Selvam et al. (2002) is used. At each time step, drag and lift forces are calculated. The CFD model is based on a finite difference procedure. Turbulence is considered using large eddy simulation. The tornado vortex is modeled using Rankin Combined Vortex Model as reported in Selvam and Millett (2003 and 2005). In all simulations the size of the tornado is varied while holding the size of the cylinder (structure) constant. The flow features, such as the velocity field, pressure and forces for various tornado sizes are analyzed using visualizations. The computed forces are compared to study the effects of the tornado size on the considered structure. The comparison includes the mean values of forces, their amplitudes and time of impact of different tornado size.

2. COMPUTER MODELING

2.1. Tornado wind model

The CFD model is based on a finite difference procedure. Turbulence is considered using large eddy simulation (LES) as reported in Selvam et al. (2002) and Selvam and Millett (2003 and 2005). The Reynolds number 1000 is considered. As was shown by Selvam and Paterson (1993), it is possible to solve wind engineering problems with low Reynolds number flow by direct simulation with a large number of grid points. The tornado is implemented using Rankin Combined Vortex Model (RCVM). It assumes that tangential velocity of tornado, $V\theta$, increases linearly with the distance from tornado center, r, when $r < r_{max}$. For $r > r_{max}$, tangential velocity is hyperbolically decreasing (see Fig. 1), this is called free vortex region. Here r_{max} is a maximum radius of force vortex region and it will be considered as a size of the tornado.

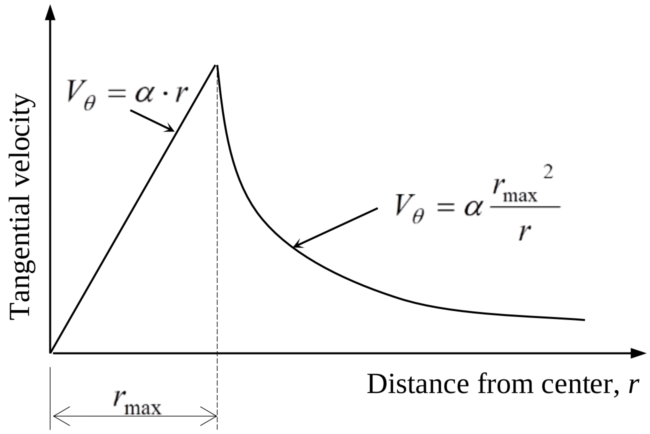

Fig.1. Rankin Combined Vortex Model

The tornado is moving with translational velocity, V_t. Further details regarding formulation of tornado model are given in Selvam (1993).

2.2. Description of the problem

The tornado's path is illustrated on Figure 2. The tornado moves along *x*-direction and coincides with the cylinder after a time lag. All parameters used in the model are non-dimensional. The non-dimensional length, velocity and time are calculated as follows:

$$L^* = L/L_{ref} \tag{1}$$

$$U^* = U/V \tag{2}$$

$$t^* = t \cdot V/L_{ref} \tag{3}$$

Where L, U and t are dimensional length, velocity and time; L_{ref} and V are, respectively, referenced length and referenced velocities. All (both non-dimensional and dimensional) parameters of the problem are provided in Table 1.

Table 1. Computational model parameters

	α	r_{max}	D	V_t	V_θ	V_{max}	t
Non-dimensional	0.75 – 6.0	4.0 – 0.5	1.0	1.0	3.0	4.0	320
SI units	0.75 – 6.0	80 – 10 (m)	20 (m)	20 (m/s)	60 (m/s)	80 (m/s)	320 (s)

Where: D is a diameter of the cylinder, α is a tornado constant, V_{max} is a sum of translational velocity, V_t, and maximum tangential velocity, V_θ, obtained form RCVM model.

The space domain is a circular region of diameter about 40 units. It consists of 43 radial points and 73 points around tangential direction. The grid is finer around boundary of the cylinder to properly capture all wind sensitivity issues. The smallest spacing in radial direction is about 0.003D, while on the edge of the domain, spacing is about 2 units (Figure 3).

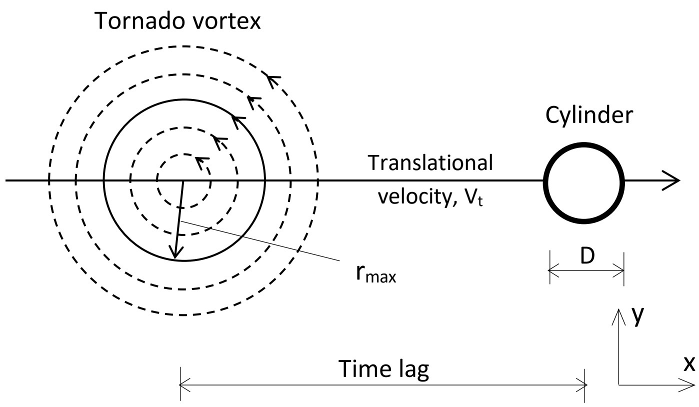

Fig.2. The path of tornado

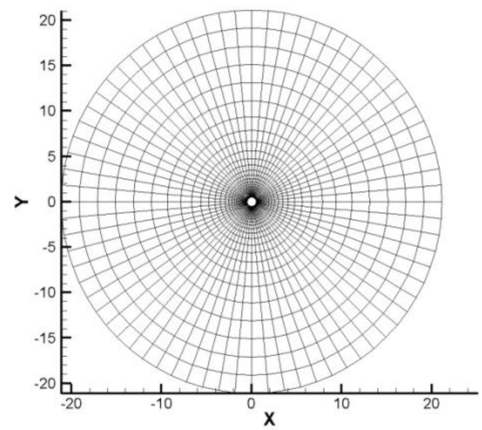

Fig.3. Computational domain with defined grid

The velocities are assumed to be zero on the surface of the cylinder, which is called no-slip condition. The time domain is taken to be 320 and the time step of calculations is 0.001. It was proven in Selvam et al. (2002) that these values correctly describe tornado formation and its magnitude. The time lag, the estimated length of time when the centre of tornado coincides with the centre of cylinder, is equal to 160. However, due to the flow – structure interaction there is a few seconds delay.

2.3. Nomenclature

In each time step velocities and pressures, of the flow, are calculated through Navier-Stokes equations. From this data, drag and lift force coefficients are obtained as follows:

$$C_D = F_x \big/ \left(0.5 \rho V^2 D\right) \tag{4}$$

$$C_L = F_y \big/ \left(0.5 \rho V^2 D\right) \tag{5}$$

where F_x, F_y are forces of x and y direction acting on the cylinder, ρ is density of air, V is the translational velocity which is considered as reference velocity and D is the diameter of the cylinder, which is assumed to be the referenced length.

3. TORNADO FORCES FOR DIFFERENT TORNADO SIZES

3.1. Results and discussion

The tornado radius is varied from 0.5 units (the same as cylinder radius) to 4.0 units (8 times bigger than cylinder) with a spacing of 0.5 units. That is, a total of 8 different radii are considered in the computations. For each simulation the flow features, such as the velocity field, pressures and forces are analysed using visualizations. Example of such data for r_{max}=3.0 is shown on figures 4-7. It can be observed that tornado vortex is developed in the flow. The close-up view on the cylinder (Fig. 5.) illustrates the vortex shedding effect. This flow pattern is characteristic for circular cylinders. Because the Reynolds number is considered to be 1000, the regular vortex shedding from two sides of the building occurs. This pattern of vortices is called a von Karman vortex street.

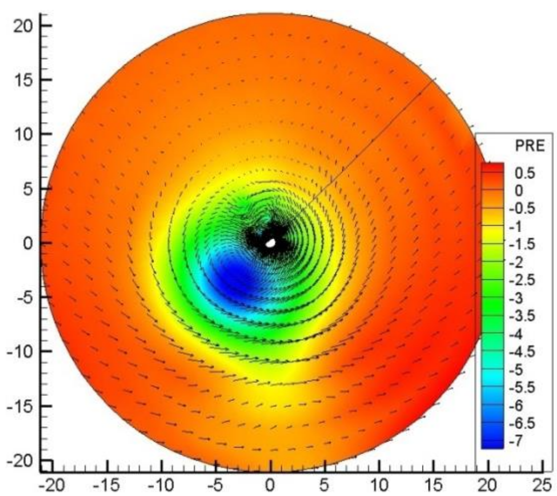

Fig. 4. Flow vector diagram for t =160 s

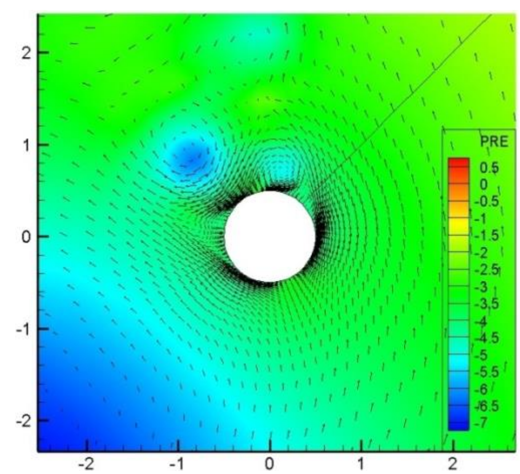

Fig. 5. Close-up view for wind flow around the cylinder

In case of 2D studies, drag (C_D) and lift (C_L) force coefficients properly describe an impact of tornado vortex on the structure (Fig. 6,7). When the tornado is far away from the cylinder there is free stream flow. For free stream flow at R_e=1000, the mean values of drag and lift force coefficients are respectively 1.4 and 0.0. The amplitude of drag force is about 0.2 and the amplitude of lift force is about 1.1. The Strouhal number is about 0.21. The results are the same as reported in Selvam and Qu (2002).

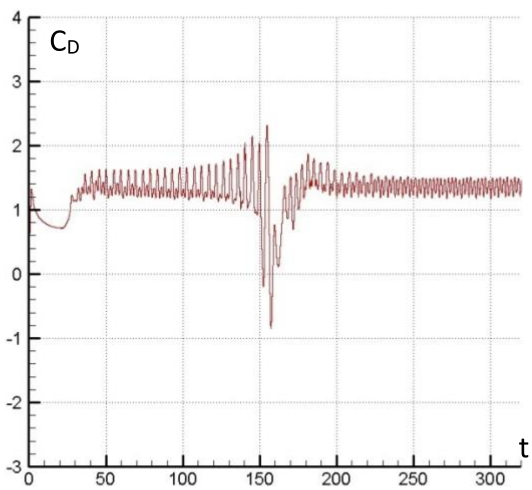

Fig. 6. Drag force coefficient for r_{max}=3.0

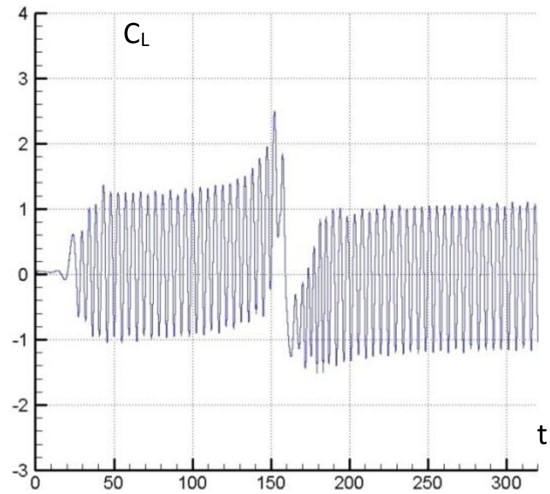

Fig. 7. Lift force coefficient for r_{max}=3.0

Over time, as is illustrated of Figures 6 and 7, the forces of free stream flow start to change. The amplitude of drag force is increasing, while the mean value remains around 1.4. The sinusoidal character of the plot is destroyed when tornado is very close to the cylinder (around t=160). The force function is highly unsteady. The amplitude of drag force is few times higher than in the free flow, also the mean value is changing. It goes down when tornado is before the building and goes up when tornado crosses the cylinder. After some time the sinusoidal character of drag force coefficient is recovered and the values approach the free flow. The lift force behaves differently than does the drag force. For free stream flow the mean value is 0, and the amplitude is about 1.1. When the tornado is approaching the cylinder, the mean value is increasing, but the amplitude is remaining constant. It is so until the tornado is close to the cylinder. As it was with drag force, the lift force function is unsteady then. The sinusoidal character is disturbed. Within this time the mean value of the force is rapidly decreasing. The unsteady character ends in the similar time as it was with drag force. After this time the lift force tends to approach the free flow state: the mean value is increasing to 0 and the amplitude is constant, about 1.1. What is important, such changes in forces are similar for all tornado sizes. Only the time and the magnitude of the alterations are different.

3.2. Mean values and amplitudes of tornado forces

In order to better capture the character of the forces during the tornado interaction, the close-up views of drag and lift forces are made on Figures 8 through 11. The tornados of radius 2.0 and 4.0 are compared. They are respectively 4 and 8 times bigger than the cylinder. It is observed that the force alterations are of the same pattern. However for smaller tornado the amplitudes and mean values of tornado forces are much smaller. Also, the time of disturbance of sinusoidal character is shorter.

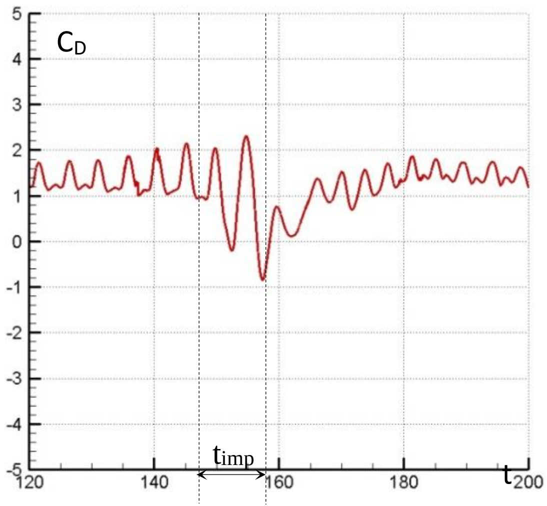

Fig 8. Drag force coefficient for r_{max}=2.0

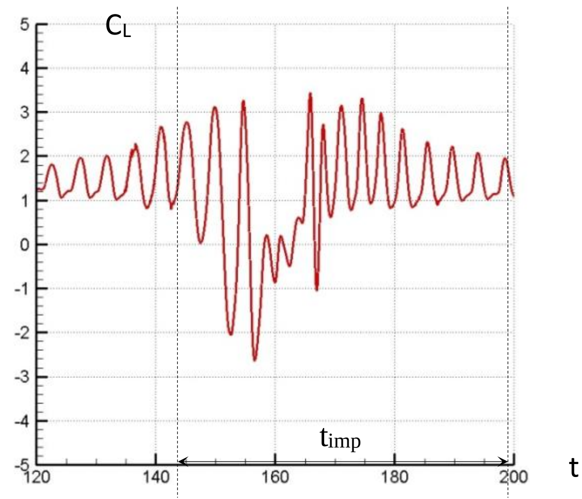

Fig. 9. Drag force coefficient for r_{max}=4.0

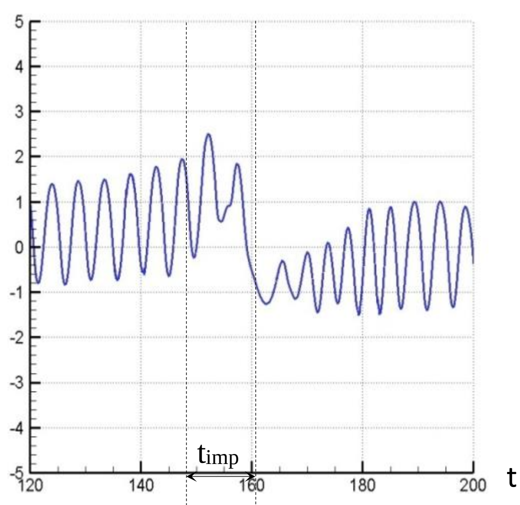

Fig. 10. Lift force coefficient for r_{max}=2.0

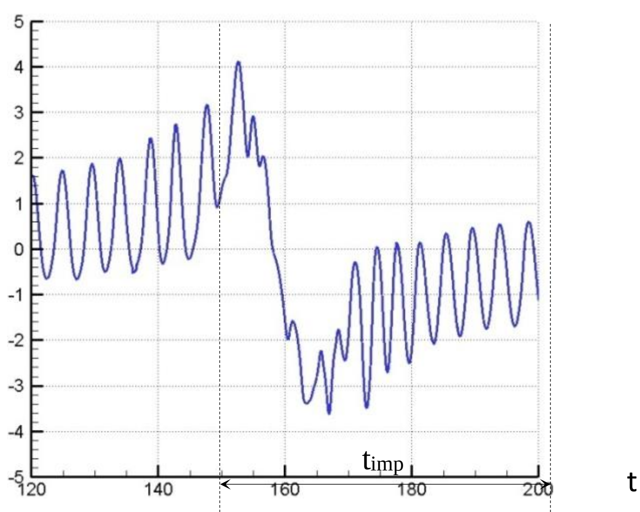

Fig. 11. Lift force coefficient for r_{max}=4.0

For tornado of r_{max}=2.0 the maximum amplitudes of drag and lift force coefficients, before the forces become unsteady, are respectively 1.6 and 1.4. While for larger tornados, they are respectively 3.0 and 1.8, which is 15 and 1.6 times higher than it was in the free stream flow. So the amplitude of drag forces increases far more rapidly than in lift forces. During the time of instability, when the tornado is close to the cylinder, the forces reach extreme values. The values are presented in Tab. 2.

Table 2. Peak values of drag and lift force coefficients for different tornado sizes

r_{max}	A	Min C_D	Max C_D	Min C_L	Max C_L
1.0	3.0	0.75	3.07	-2.05	2.57
2.0	1.5	-0.85	2.31	-1.52	2.50
3.0	1.0	-1.65	2.81	-2.45	3.48
4.0	0.75	-2.64	3.44	-3.62	4.12

For bigger tornadoes peak values of the forces are higher. Only the maximum value of drag force remains similar. Because the peak values of the forces are instantaneous, it is necessary to analyse the mean values of the forces. The plots of mean values of drag and lift forces are obtained through a smoothing algorithm using Tecplot 360 (Fig. 12, 13).

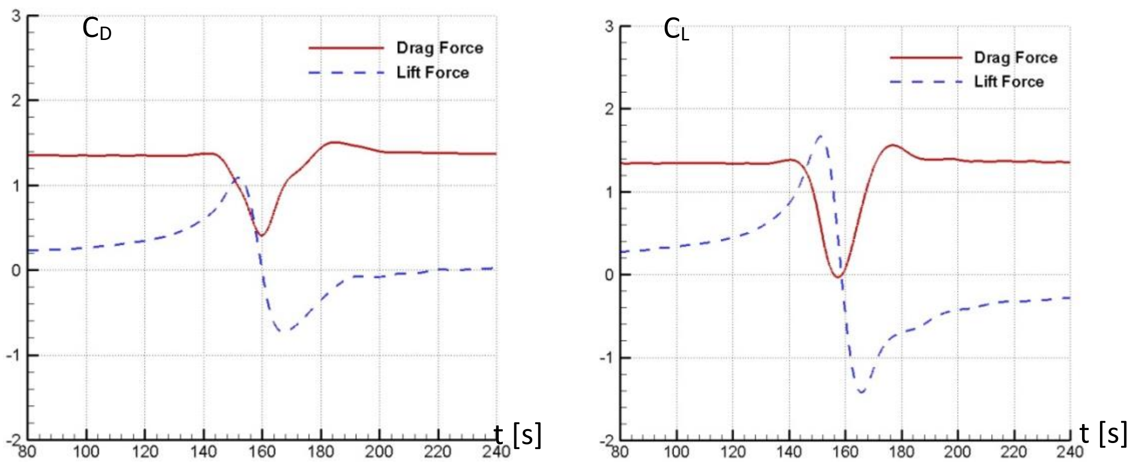

Fig. 12, 13. Mean values of drag and lift force coefficients for r_{max}=2.0 (left) and r_{max}=4.0 (right)

The extreme mean values of the tornado forces for various tornado sizes are provided in Table 3.

Table 3. Extreme mean values of drag and lift force coefficients for different tornado sizes

r_{max}	A	Min C_D	Max C_D	Min C_L	Max C_L
1.0	3.0	1.37	1.88	-0.61	0.57
2.0	1.5	0.40	1.50	-0.73	1.09
3.0	1.0	-0.02	1.56	-1.42	1.66
4.0	0.75	-0.26	1.78	-2.26	2.01

From the comparison of peak and mean values of the drag and the lift forces, it can be inferred that for bigger tornados the increase in lift force is significant. The alternation of extreme values of lift force is higher than in drag force and the impact of lift force become more substantial for thin structures.

3.3. Time of tornado impact

The time when, due to tornado, drag and lift forces increase their values varies for different tornado sizes. As can be deduced, the bigger the tornado is, the longer it interacts with the building. In the free stream case, the highest value of force coefficient is about 1.5 and it is form the drag force. During the tornado impact the forces take far more values. To measure the time of tornado impact, some criterion has to be introduced. In Table 4 and Figures 8-11, the non-dimensional time when the peak values of drag or lift force coefficients exceed 2.2 (about 50% more than in the free stream case) is presented.

Table 4. The time when the peak values of drag or lift force coefficients are more than 2.3

r_{max}	1.0	2.0	3.0	4.0
t_{imp}	20	10	36	50

The duration of time for which the forces coefficients are high increases rapidly. For tornadoes of r_{max}=4.0 it is about 4 times more than for r_{max}=2.0. Longer action of high forces has more influence on the structural response.

5. CONCLUSION

The study on the effect of different tornados sizes on a cylinder of constant size was conducted. The maximum velocity of the tornado was held the same by changing the tornado constant α. The purpose of this work was to gain an understanding as to why very thin structures such as utility poles and traffic lights are so tornado-wind sensitive. For such structures, the size of the tornado is several hundred times bigger than the size of the structure. The analysis was done for tornadoes up to 8 times bigger than the cylinder. This limit was imposed because simulation of bigger tornadoes requires bigger domain and hence more grid points, which increases the computational time. However, from conducted simulations, the clear trend of tornado forces within different tornado sizes is noticed and the results for bigger tornadoes can be projected. From the simulations it can be inferred that the bigger the tornado is, the greater the forces it will produce on a building. The lift force takes greater mean values than the drag force for thinner structures. The lift force for the tornado of radius r_{max}=4.0 is about 4 times greater than for r_{max}=1.0. On the other hand, drag force amplitudes are much higher than lift force amplitudes for thinner structures. The length of time when the tornado forces are higher than those in the free stream increases for bigger tornadoes. However, further research has to be done regarding higher tornado to structure size ratios.

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