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Research Article

Aerodynamic Loads of Horizontal Axis Wind Turbines under Tornado Vortices

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Abstract

With the rise in population, the demand for electricity has been escalating rapidly day by day. The importance of energy as a crucial input for the socio-economic progress of any nation cannot be overstated. Unfortunately, most of our energy demands are met by non-renewable resources that are not only limited but also cause detrimental effects on the environment. To tackle the negative effects and increasing demand for electricity, a significant shift has been observed in the past two decades towards renewable energy resources. Wind energy is one of the major resources of renewable energy, which has been making remarkable inroads into the electricity markets across the globe. Wind turbines are used to convert kinetic energy into electrical energy. However, wind energy is an intermittent power source. To obtain the optimum energy from wind, wind turbines should be designed with good aerodynamic loading. This means that they should have a high lift to drag ratio, and the mean loading and fatigue loading should be well quantified for better efficiency and durability. Although extensive research experiments have been carried out to measure the aerodynamic loads acting on horizontal axis wind turbines, there is still ample space for employing recently developed simulations to correctly predict the dynamic loads that affect wind turbines in a variety of situations. One issue with the construction of these numerical models is the absence of quantitative experimental and field measurement data to validate the outcomes of the numerical simulation. In our research, we have used a tornado-like vortex simulator present in Tongji University to characterize the aerodynamic loads acting on wind turbines under different locations, with different phase angles at respective vane angles. We found that the axial force is maximum when the tornadoes hit the rotor of a wind turbine at a phase angle of 0°. For the tangential forces, the maximum value is at 90°. However, for the vertical forces, the maximum value changes with the change of vane angle, and the maximum value is for vane 50° at a phase angle of 90°. This is a novel approach as per the authors' knowledge, and no research has been published before. In conclusion, our research provides insightful information on the aerodynamic loads acting on wind turbines under tornado-like vortex simulators, which can help in the design and development of more efficient and durable wind turbines.

Key words: *Tornado like vortices, wind turbines, tornado induced loads, tornado vortex simulator.*

1. Introduction

Tornadoes are high-impact weather phenomena that have received extensive research in meteorology, fluid dynamics, and wind engineering. Tornadoes are defined as violently rotating columns of air that connect a thunderstorm cloud with the surface [1]. Tornadoes are common throughout the world. They have a lot of destructive power, but they usually don't last long. The occurrence of Tornadoes is more in North America than the other parts in world. Every year in the United States, tornadoes do about 400 million dollars in damage and kill about 70 people on average [2].

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The number of Tornadoes in Asian countries like China, India, etc is very less than that of United States, but the damage caused by them is more. In China the total economic loss from 2007-2017 is 9.1 billion yuan and the total deaths 1771 from 1961-2011[3]. Tornadoes in India are almost negligible and a rare tornado in West Bengal, damaged 80 houses, two people died after being electrocuted. Due to the extensive damage that tornadoes can cause to structures and the environment (e.g., crops and trees), McDonald et al. [4] proposed the Enhanced Fujita (EF) scale as the successor to the Fujita (F) scale to rate tornado intensity. The EF scale is a damage-based measure of tornado strength, with EF0- and EF5-rated tornadoes being the weakest and strongest tornadoes in nature in that order. Even after several technological advances in the fields of satellite and radar meteorology over the last several decades, detailed tornado measurements in the atmosphere remain difficult and relatively scarce. The observations are limited by tornadoes' short lifespans, rapid evolution, unpredictable paths, and small scales in comparison to the rest of the thunderstorm cloud [5]. However, some observations were carried for the measurement of Tornadoes through mobile radars equipment's but there is a lack of near surface velocity measurement.

When investigating tornado-induced wind loads on structures, it is critical to understand the flow characteristics of a tornado near the ground. Tornado-like vortices have different characteristics than conventional boundary layer winds due to strong swirling effects. The spatial-temporal dynamic properties of velocity and pressure in a natural tornado are still impossible to measure or calculate theoretically. The basic flow is turbulent, gusty, and an unknown transient phenomenon.

Tornado-like flows were first simulated experimentally in 1969 by Ying and Chang [6]. They designed and built a tornado-like vortex generator and then used the simulator to investigate the velocity field, chang [6] was the one who physically simulate tornado induced loads on structure. Later ward[7] improved the simulator designed by chang[6], by using guide vanes to provide angular momentum to converge the flow. The guide vanes were placed on the ground with the assumption that the vortex structure near the ground was primarily governed by mechanical angular momentum supply. This cylindrical tornado chamber's simple structure included a rotating mesh screen at the periphery to provide and control circulation, as well as a fan at the top to provide updraft. At Purdue University [8] used the TVC design concept to create a tornado simulator. The Purdue simulator had the benefit of autonomous control over the geometric aspect ratio (which is the ratio between the inflow height and the updraft radius), In addition to the swirl ratio and radial Reynolds number, the inflow depth and updraft radius can be adjusted separately. The sharp edge of the updraft hole influenced the main flow, and a circulating cell formed in the upper chamber. The TVC designed and built at Kyoto University was made up of four fans arranged in an annular ring around the inflow region as the source of circulation. This simulator's configuration was changed in order to reduce vortex unsteadiness and vibration while increasing simulation accuracy[9]. Lund and Snow [10] used Laser Doppler Velocimetry to examine the velocity field of tornadoes that were simulated in the second Purdue University TVC (LDV). They demonstrated how the boundary layer combined with the modified Rankine vortex flow exhibits similar characteristics in the radial profiles of the tangential and radial velocities. Vanes were utilized in place of the revolving wire mesh to allow for different inflow angles, and a movable flow straightener was used in the convection zone. In 2001, Texas Tech University (TTU) built a Ward-type simulator with an updraft radius of 0.19 m and an inflow height ranging from 0.064 m to 0.19 m [11]. It was then modified this simulator with the intention of performing experiments for wind engineering rather than atmospheric science applications. Updraft and circulation were provided in this simulator by a blower at the top of the convective chamber and 16 slotted jets at the inflow [12]. They investigated the three-dimensional flow field characteristics as well as the surface static pressure distribution. They compared the results to full-scale measurement data from the Manchester, SD tornado in May 1998 [13] and the Spencer, SD tornado in June 2003.). [13;14] obtained a length scale of 1:3500 for the simulations and demonstrated that the measured surface pressures were in good agreement with the full-scale data.

Haan et al. [15] built a large tornado vortex simulator for wind engineering applications at Iowa State University in the United States, which was a modification of the Ward-type tornado vortex simulator. The guide vanes in this simulator are positioned high to allow vertical flow circulation during the tornado generation process. This simulator consists of a circular duct (5.49 m in diameter) suspended from an overhead crane and allowing translation along a 10.36 m long ground plane. The updraft is provided by a fan located in the centre of the duct. The design concept was based on the rotating forced downdraft technique, which directs the flow from the updraft downward while rotating it via vanes in an annular duct surrounding the inner region. Hashemi Tari et al. [16] quantified the turbulent characteristics of a tornado-like vortex for the first time. They measured Particle Image Velocimetry (PIV) for various swirl ratios in a modified version of the ISU simulator. Hashemi Tari et al. discovered that increasing the swirl ratio increases the mean radial and tangential velocity components, as well as normal and shear stresses. Furthermore, they demonstrated that the vortex touch-down case corresponds to the maximum turbulent kinetic energy production.

To understand the TLV various numerical and experimental works have been carried out by various researchers using different models, Numerical simulations have been a valuable tool in the study of Tornado like vortices, providing great flexibility in inflow and boundary conditions, various turbulence parameterizations, and model adjustments. However, the accuracy of turbulence modelling—that is, the peak values of velocity and pressure in numerical models—remains below that of physical experiments [17;18;19]. There have been numerous attempts to experimentally test wind loads on generic structures exposed to simulated tornado-like vortices with the help of tornado-like vortex simulators. Jischke and light [20] at Wind loads on rectangular models were studied in a Ward-type tornado simulator using three model locations. Bienkiewicz and Dudhia [21] investigated the effects of swirl ratio and surface roughness on a tornadic flow field and measured pressures on a cubic model in the simulator's centre. Mishra et al. (2008) compared wind loads on a TTU-VSII cubic model to those exposed to a boundary-layer flow. Sengupta et al. (2008) investigated the load on a cubic building during a microburst and a tornado, taking into account both quasi-steady and transient wind. Sabareesh et al. [22;23] investigated the properties of internal pressures and net local roof wind force for buildings as well as the impacts of building location and ground roughness on surface pressures on a cubic building. Case et al. [24] investigated tornado-induced loads on low-rise buildings with different geometry and orientation, whereas Razavi and Sarkar [25] investigated the effect of varying the swirl ratio and translation speed of a tornado on a gable roof of a low-rise building model. Cao et al. [26] and Wang et al. [26] investigated the wind pressure distributions and wind forces on the inner and outer surfaces of a cooling tower structure that was subjected to stationary and translating tornado-like vortices.

Although a variety of physical experiments are carried out different models in tornado- like vortices, there is a limited literature available for wind turbines in tornado-like vortices, Due to the complexities of laboratory simulation of wind turbine-tornado interaction, only a few limited numerical studies have been developed. AbuGazia et al. [27] identified the location of the peak forces exerted by the three-dimensional winds of a stationary Tornado like vortices (TLV) acting from several positions around a wind turbine by using a built-in-house numerical model. Lopez, Juan P., et al [28] Experimental study was conducted to analyse the loads induced by a tornado-like vortex (TLV) on horizontal-axis wind turbines (HAWT). They have found that the overall forces and moments depend on the location and orientation of the wind turbine system with respect to the tornado vortex centre.

2. Experimental setup

2.1 wind turbine model

The model we have used in our experimental work is a wind turbine that was made in auto CADD with a dimensions of tower height of 75mm and rotor diameter of 60 mm, the prototype for this will be 75m tower height and 60m rotor diameter, the scale ratio between prototype and model is 1:250 . The aerofoil blade we used for our wind turbine models is same as (S809) used by the ref [29] because of its high lift to drag ratio so that it can generate more power. The dimensions of aerofoil a\and more information can be found about this through this reference [29].

2.2 Tornado simulator

An air column that is quickly rotating and appears in conjunction with a cumuliform cloud is referred to as a tornado. A supercell thunderstorm is so named because it can last for several hours in the nearly constant configuration of a rotating updraft—emerges when a specific kind of cumuliform cloud is present. This cloud type produces the most intense variety of tornadoes. In the laboratory experimental works and numerical simulation, a supercell type tornado is used because it lasts long.

A tornado-like vortex simulator present in Tongji University (fig.1)is used to generate updraft tornado like flow to study the aerodynamic loads acting on wind turbines. The mechanism for generating the tornado-like vortex is similar to that at Iowa State University, USA[15]. A circular duct 1.5 m in diameter and 1.009 m in height is suspended overhead with a 0.5 m-diameter updraft hole (ro=250 mm) holding a controlling fan (maximum flow rate is 4.8m3/s, and maximum rotational speed is (3500 rpm) to generate a strong updraft. The simulator floor could be adjusted up and down, enabling a range of heights for the inflow layer (H=150 mm–550 mm). Both the fan and guide vanes are placed on the top, which allows more spaces to conduct model tests to determine the tornado effects. The primary factor affecting the flow structure generated inside the simulator is the orientation angle of the guiding vanes, which may be changed from 10° to 60° to obtain various swirl ratios. The above-mentioned swirl-ratio parameter takes into account the momentum change brought on by whirling effects. The inflow height(H) can vary from 0.15m-0.55m.

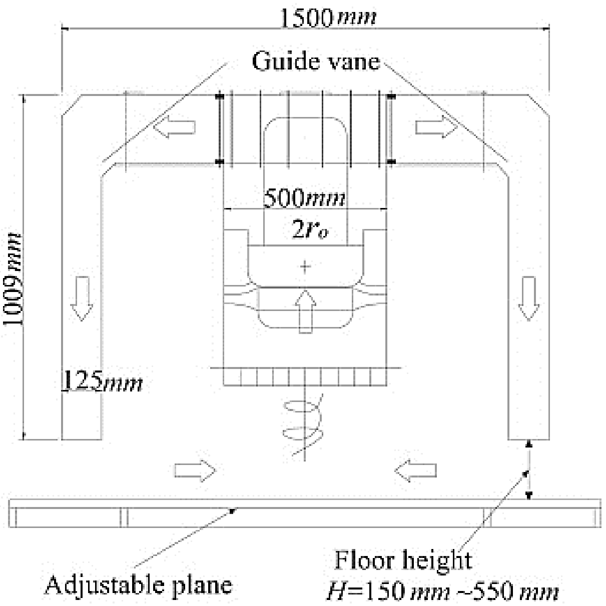


Fig 1. Tornado vortex simulator present in Tongji University

2.3 Experimental Parameters

The vane or guide angle is the first parameter to be considered, ranging from 20° to 60° with an increase of 10° increments per test. The inflow velocity increases as the vane angle increases, and the maximum inflow velocity is obtained at a vane angle of 50° as displayed in table 1. The aspect ratio (a) is determined by the inflow height to the radius of duct of the simulator, where a=H/ro=400/250=1.6, with ro being the radius of the circular duct of the tornado vortex simulator and H being the inflow height.

The second crucial parameter is the variation of distance along the -x to +x direction from the centre of the wind turbine model. The total distance ranges from -180mm to 180mm, with increments of 40mm from -180mm to -100mm and 100mm to 180mm, respectively. The positions, on the other hand, have an increment of 20mm, resulting in a total of 15 positions (-180,-140, -100, -80, -60, -40, -20, 0, 20, 40, 60, 80, 100, 140, 180). The tests were conducted for a stationary tornado with the centre located at each of the 15 locations.

The third important parameter is the phase angle of the wind turbine model concerning the incoming tornado. For the current analysis, three phase angles, namely 0°, 45°, and 90°, were used, and for each phase angle, the experiment was carried out at different guide angles ranging from 20° to 60° with increments of 10° at the corresponding distance in the axial direction. This study aims to investigate the impact of these parameters on the performance of the wind turbine under tornado conditions. By varying these parameters, we can determine the maximum inflow velocity and the optimal guide angle for the wind turbine, which will improve its efficiency and performance. The study will also provide insights into how the wind turbine can be designed to withstand extreme weather conditions and contribute to the development of sustainable energy sources.

Table 1 Tornado simulator settings and its parameters

No.	Vane angle θv(°)	Aspect ratio(a)	Tangential velocity Umax (m/s
1	30	1.6	8.38
2	20	1.6	9.52
3	40	1.6	10.78
4	50	1.6	11.04
5	60	1.6	10.96

2.4 Experimental settings

The wind turbine model is fixed at the centre of tornado Vortex Simulator present at Tongji University with its base fixed at bottom of table through the bolts, the rotor of a wind turbine is a rigid 3D printing model which is glued to the cylindrical tower as shown in the figure2.

The forces are measured along the different positions from the centre of wind turbine using the force sensor MINI40, the force sensor was installed at the base of the wind turbine model and it captured the forces and moments induced by the tornado vortex simulator in X-axis, Y-axis and Z-axis directions using 6 analogue channels. The signals were obtained for each test at a sampling frequency of 200Hz and the sampling time was 60 seconds.

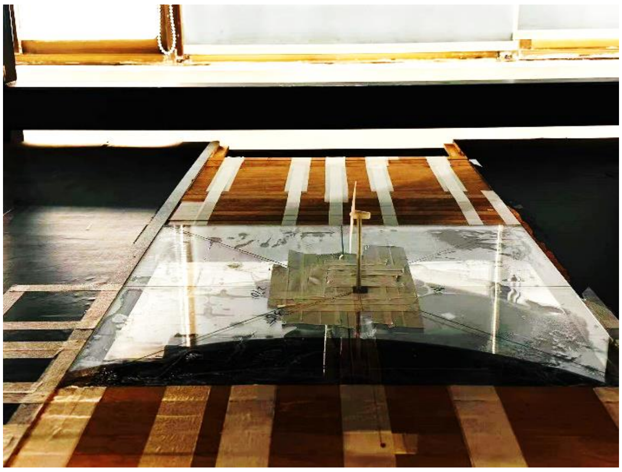


Figure 2. wind turbine setup

The rotational speed of fan is kept 1500 rpm, the total inflow height of wind turbine model is kept 400mm from the floor to the top of circular duct of the tornado vortex simulator. For each test a case for a different swirl angle and respective distance is measured using a sampling frequency of 200Hz and each test is carried for sampling time of 1 minutes (12000 samples collected). Mean values of all the forces are used for result analysis for each test, the surrounding effects are removed by subtracting the mean values of each axial distance from the reference value.

3.Tornado induced aerodynamic loads on horizontal axis wind turbines.

Tornadoes are three-dimensional vortex structure which occurs in horizontal, tangential and vertical direction inducing the aerodynamic loads in lateral/axial force (Fx,), torsional/tangential force (Fy) and uplift/vertical force (Fz) acting on the structures on which they hit respectively. Aerodynamic loads induced by tornadoes on horizontal axis wind turbines can be very high and can cause significant damage to the turbine blades, rotor, and other components. Tornadoes generate high-speed winds and turbulence, which can place stress on the structure and components of the turbine. The blades and rotor of the wind turbine can experience significant uplift forces, lateral forces, and torsional forces during a tornado. Uplift forces can cause the turbine to lift off its foundation or to collapse from below. Lateral forces can cause the turbine to sway or topple over. Torsional forces can cause a twisting motion in the turbine, leading to stress on critical components.

To reduce the impact of aerodynamic loads on wind turbines during a tornado, engineers use advanced computer modelling and simulation techniques to study the dynamics of tornadoes and their impact on wind turbines. They also use physical testing to validate their designs and ensure that wind turbines can withstand the most extreme conditions.

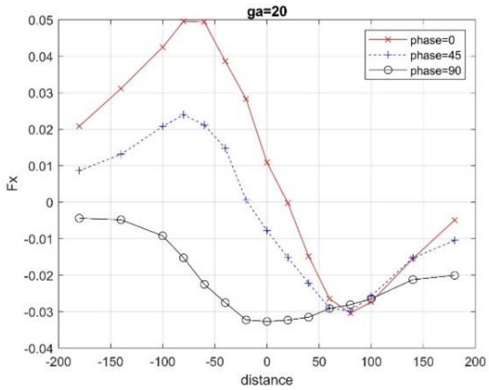
As explained in the introduction there is few numerical models conducted for wind turbines to study the tornado loads acting on horizontal axis wind turbines (HAWTs), campanglo and biegle [30] carried a numerical analysis on 3.5 megawatt horizontal axis wind turbine, they found that the highest induced loads were at the direction of phase angle = 50° and at a distance of 80m. Abu Gazi et[27] all also carried the numerical analysis of built-in house model to identify the three-dimensional loads of stationary tornado Like vortices acting from several positions. It was found that the overall minimum straining action acting on wind turbines is at phase angle of 60°. In the present paper we carried an experiment to analyse the tornado induced loads acting on HAWT at different radial distances from -180mm to 180mm from the centre of wind turbine model respectively, and also at different vane angles varying from 20° to 60° with increments of 10° in each experiment.

3.1 Analysis of tornado induced loads analysis of HAWTs.

Tornadoes are three-dimensional vortex structure which occurs in horizontal, tangential and vertical direction inducing three loads axial force(Fx,), tangential force (Fy) and vertical force (Fz)acting on the structures on which they hit respectively. In this experiment we have analysed tornado loads acting on HAWTs in a tornado Vortex Simulator present in the Tongji University Shanghai, China. Mean force analysis was carried out for different phase angles(direction of with respect to the wind turbine) with different guide angles at different radial positions as given below:

3.1.1 Mean load analysis of axial force (Fx) at phase angle of 0°,45° and 90°.

The analysis of the mean load induced by tornadoes in horizontal axis wind turbines (HAWTs) is conducted at various guide angles, as depicted in figures (a, b, c, d, and e) for different phase angles. The results show that the mean forces increase as the distance increases up to the core value of the tornado, after which the values decrease. The distance where the maximum axial forces occur is approximately x=100 mm in both directions. A comparison was made, and it was discovered that the axial load is highest when the vane angle is 50° for all phase angles in figure 3 (d). However, for individual phase angles, the axial force (Fx) is highest for phase angle 0 when the vane angle is set at 60°, as shown in figure 4(e). For phase angle 45°, the axial forces are almost the same for all vane angles, but for phase 50°, it is different. The axial force (Fx) is highest for phase angle 90° when the vane angle is 50°. As shown in table 1, the tangential velocity is highest at that vane angle, and hence, it is expected that the maximum axial force for all phase angles is at the vane angle of 50°. The overall maximum axial force is at phase angle 0° for all phase angles. It means that when the wind turbine's rotor faces parallel to the direction of the tornado flow, the axial forces are more significant than those of other phases, such as 45° and 90°.



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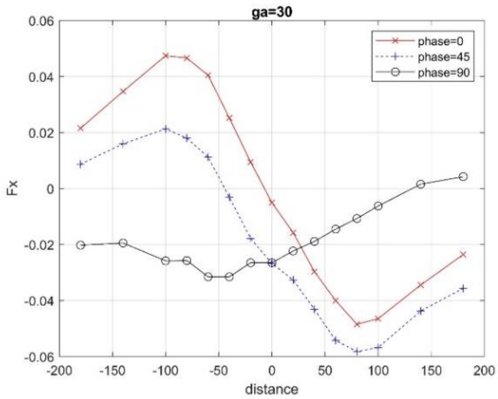

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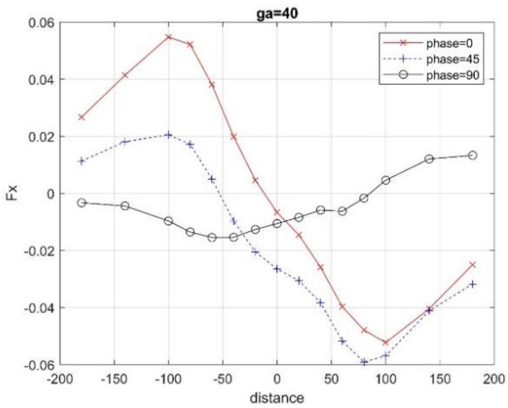

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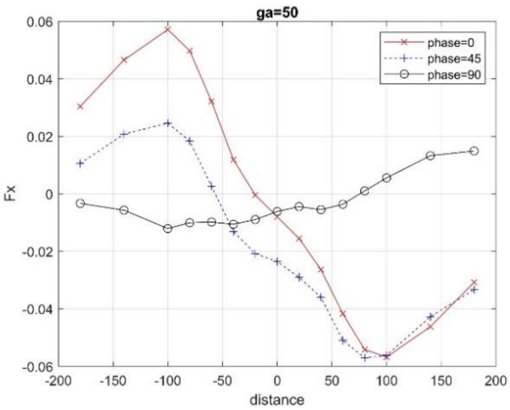

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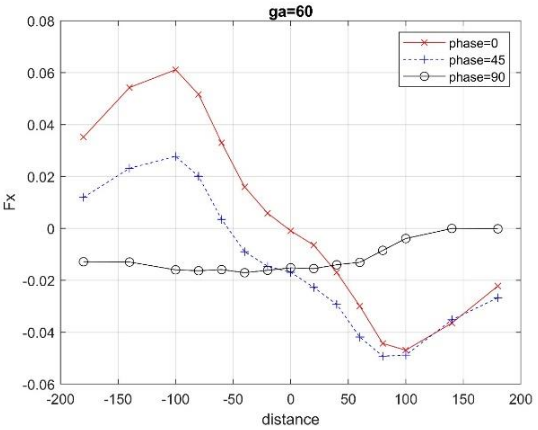


(e)

Figure 3. Axial force analysis under tornado vortex simulator

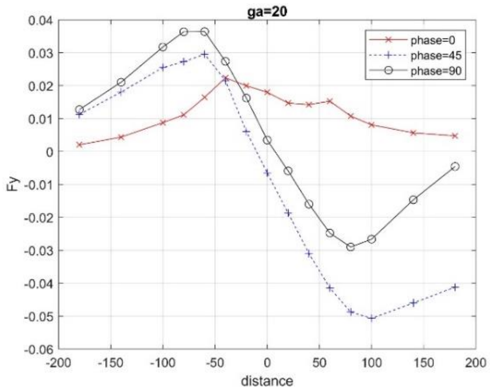
3.1.2 Mean tornado induced load analysis of Fy in tangential direction at phase angle of 0°,45° and 90°.

The figures 4 (a,b,c,d&e) below illustrate that different vane angles carry out tornado induced tangential mean loads at different phase angles. It has been discovered that as the distance of the tornado centre increases from the model's centre, the tangential forces increase gradually up to a specific point, which is the core of the tornado. After that, the forces start to decrease, forming a bell curve shape. The tangential force is maximum for all the vane angles when the phase angle is 90°, and the distance at which the force is at its maximum is x=100m from both the left and right side of the wind turbine model as shown in figure 4 (a,b,c,d&e).

Figure 4a shows the tangential force analysis at vane angle =20 at different phase angles (0,45 and 90) and it indicates that the maximum tangential force occurs at phase angle 90. As we increase the vane angle from 20 to 30, the tangential forces increase due to the increase in velocity (table 1), and the peak value of tangential force is found when the vane angle is 50 and the phase angle is 90. This implies that when the rotor of a wind turbine is directly facing the incoming wind flow, the tangential forces are at their maximum and have the most significant impact on the wind turbines.

A similar trend is observed for the phase angle =45, but the values are slightly lower than when the phase angle is 90 for all the vanes. This means that when the rotor's surface area is facing towards the incoming tornado, the tangential forces are at their maximum, and the same trend was observed in the lattice structure observations by [31]. The analysis of the tangential force results also confirms the analysis of section 3.1.1 axial force as both forces are drag in nature, and they are opposite to each other. These forces change with the change of phase angles, respectively.

Therefore, it can be concluded that the tangential forces on wind turbines increase and reach a peak value when the rotor of the wind turbine is facing the incoming wind flow directly. At this point, the tangential forces have the most significant impact on the wind turbines. The results show that the tangential forces are maximum when the phase angle is 90°, and the distance at which the force is at its maximum is x=100m from both the left and right side of the wind turbine model. The results of the analysis of tangential forces validate the analysis of section 3.1.1 axial force as both forces are drag in nature and change with the change of phase angles. Furthermore, the lattice structure observations also confirm the maximum tangential forces when the rotor's surface area is facing towards the incoming tornado.



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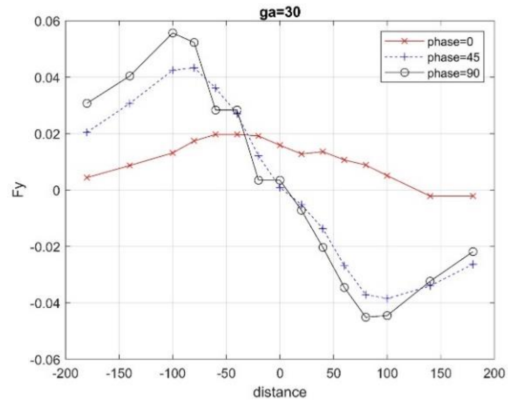

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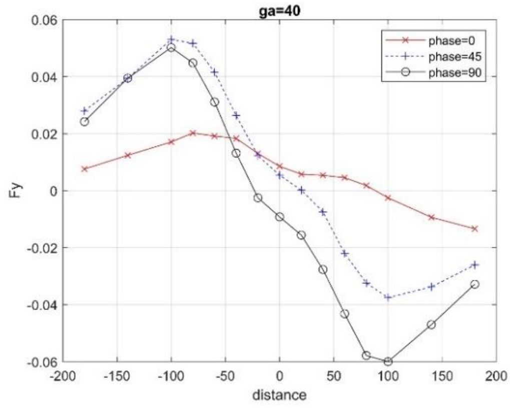

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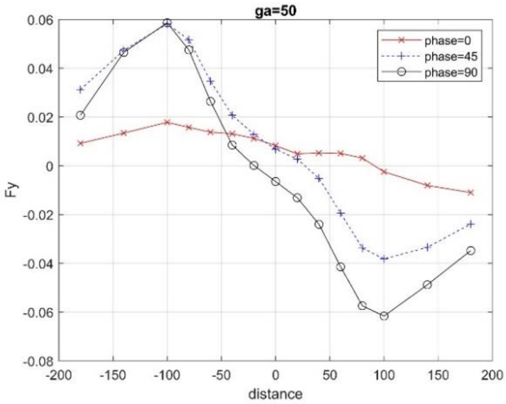

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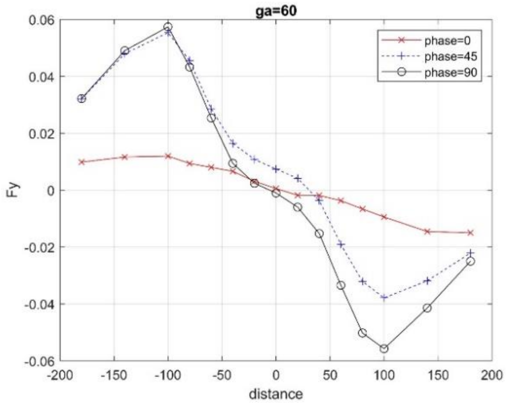


(e)

Figure 4 Tangential force analysis under tornado vortex simulator

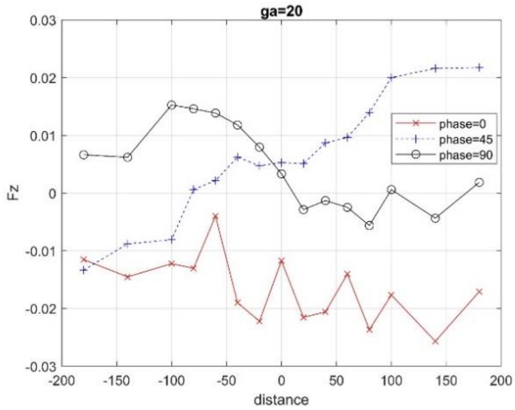
3.1.3 Mean tornado induced mean load analysis of Fz in vertical direction at phase angle of 0°,45° and 90°.

The interaction between a tornado and a horizontal axis wind turbine result in vertical mean force acting on the turbine's horizontal axis. This force is carried at different phase angles and vane angles at various radial positions from the centre of the turbine model, as explained in section 2.3.2. It is important to note that the vertical force varies for different phase angles, and gives variable peaks by changing the phase angles. Unlike axial and tangential forces, there is no common trend in case of vertical forces, as explained in sections 3.1.1 and 3.1.2.

Upon observing figure 5a, it is noted that the vertical forces increase with distance from the centre up to a certain point where x=100 to 140 mm. Subsequently, the magnitude of the forces shows a complete decrease. Interestingly, the maximum vertical loads occur at a different axial distance (x=-140mm) than the previous force analysis for axial and tangential loads, as seen in figure 5d. Specifically, the maximum vertical loads occur for phase angle 90 and vane angle 50.

Similarly, for vane angle 20, the maximum vertical load occurs at phase angle 45 and distance x=140mm. The same trend is observed for phase 0 and vane angle 60, as shown in figure 8e. The overall maximum vertical force is observed when the phase angle is 90, the vane angle is 50, and the distance is at x=-140mm upstream side of the wind turbine model.

To summarize, the mean analysis of tornado induced loads on horizontal axis wind turbines reveals that the most unfavourable position occurs when the axial distance is x=100, the phase angle is 90, and the vane angle is 50. It is important to note that all tornado loads (axial, tangential, and vertical loads) are maximum in this unfavourable position.



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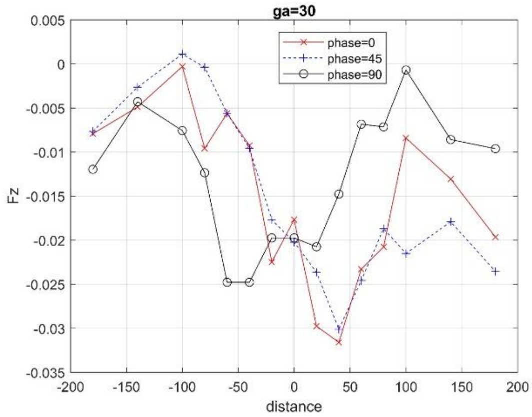

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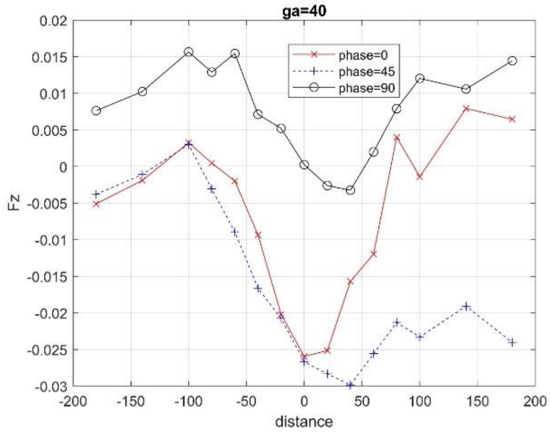

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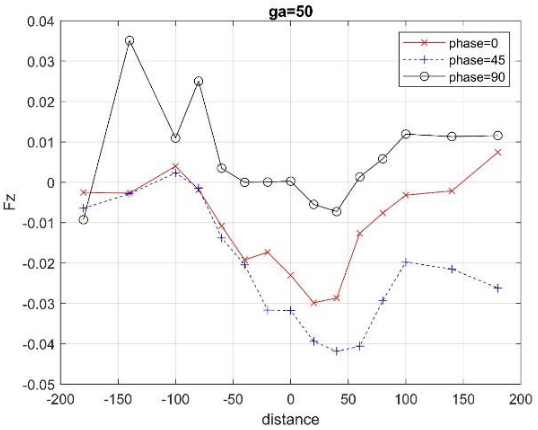

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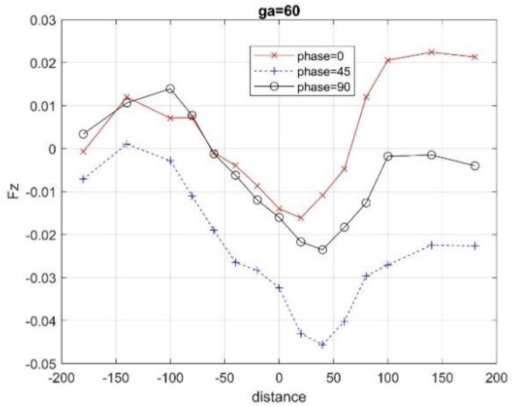

(e)

Figure 5. Vertical force analysis under tornado vortex simulator.

Conclusion

The objective of the study is to create a pioneering technique for examining the average forces produced by tornadoes on horizontal axis wind turbines through the use of a tornado vortex simulator located at Tongji University. The study will investigate the impact of tornado-induced loads on turbines at three different phase angles (0, 45, and 90) and 15 distinct positions from -180mm to 180mm, with increments of 40mm from -180mm to -100mm and 100mm to 180mm, respectively. The positions will be spaced by increments of 20mm, resulting in a total of (-180,-140,-100,- 80, -60, -40, -20, 0, 20, 40, 60, 80, 100, 140,180) positions. The vane angles will vary from 20 degrees to 60 degrees, with a 10-degree increment in each test.

The study's findings on the mean tornado load analysis can be summarised as follows.

1) Mean tornado induced load analysis is carried at various axial distances with different phase angles and it is observed that as the distance of tornado centre increases away from the centre of wind turbine model, the overall tornado loads increase first up to the core radius (x=100mm) of tornado flow and after when the distance becomes more than that of x=100mm, the effect of tornado loads decreases which results in bell shape curve shown in fig (3,4&5).
2) At the core radius of the tornado flow, the axial loads reach their peak when the rotor surface area of the wind turbine is aligned parallel, which occurs when the phase angle is 0 and the vane angle is 50, corresponding to the maximum tangential velocity.
3) When the rotor surface area of a wind turbine is aligned at a perpendicular angle, the tangential and shear forces reach their maximum potential. This occurs when the phase angle is at 90 degrees and the vane angle is set to 50 degrees, resulting in the highest tangential velocity at the core radius of x=100mm during a tornado flow. It is worth mentioning that the axial and shear forces act in opposite directions under these conditions, resulting in a dynamic and powerful system.
4) The analysis of vertical forces did not reveal any evident pattern as seen in the axial and tangential force examination, however, the forces peaked at their maximum when the phase angle was 90 and the vane angle was 50, while the largest core radius was located at approximately x=-140, on the upstream side of the rotor that faced the direction of the tornado flow.
5) The optimal placement for wind turbines situated in a tornado's path would be at a distance of 100 mm for most vane angles due to the maximum intensity of the tornado loads at the radius of the core.

The results analysed are the findings of experiments carried out for plain conditions and in future more work needs to be analysed in complex conditions like mountains, hilly terrains and offshore sites, where the possibility of tornadoes is maximum.

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