Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 7, No. 1, February, 2023

Wind Turbine Blade Dynamics Simulation under the Effect of Atmospheric Turbulence

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Abstract

Wind energy is one of the fastest growing sources of renewable energy because of its cleanliness and sustainability. Due to the turbulent nature of wind, a wind turbine experiences severe dynamic loading and faces the danger of fatigue failure. In addition, severe blade deflections imply failure by tower strikes. For this reason, the study of blade deflections under different turbulence conditions is of high importance. In this work, a wind turbine's blade is simulated under different turbulent conditions. Four different wind fields are generated with a mean wind velocity of 12 m/s and turbulence intensities of 1, 10, 25, and 50%. The blade deflections are calculated in the out-of-plane and in-plane directions as a time-marching series with different blade azimuth positions. The higher the turbulence intensity, the severer the fluctuations of the deflections around its mean value. For the 50% turbulence intensity, the standard deviation of the out-of-plane deflection is 600% larger than that of the 1% turbulence intensity case. The maximum deflections increase significantly as well. A maximum of 3.78 m of out-of-plane tip deflection leads to the danger of a tower strike. And a positive tip deflection of 0.07 m in the in-plane direction indicates that the blade goes against its natural behavior and against the inertial loads while rotating. Continuous monitoring of wind conditions is a must, to put the turbine on brake in cases of gusts and severe turbulence. In areas of high turbulence, downwind turbines can provide a better alternative to allow blade deflections without the danger of tower strikes.

Keywords:
Renewable Energy;
Structural Dynamics;
Turbulence;
Wind Turbines;
Wind Energy.

Article History:

Received: 23 July 2022
Revised: 22 September 2022
Accepted: 03 October 2022
Available online: 07 November 2022

1- Introduction

In the contemporary world, the need for energy increases to satisfy the increasing demands of humans. Conventional sources of energy depend mainly on fossil fuels; however, this includes several environmental problems. In addition, fossil fuels are facing the danger of depletion. It is an urging demand to reduce the dependence on fossil fuels to reduce greenhouse gases (GHG) to save the planet and reduce the global warming crisis [1]. Renewable energy sources are the key to achieving this goal. Different sources of renewable energy include solar [2], geothermal [3], wind [4], tidal [5], and sea wave energy [6]. Hybrid energy systems have also gained the attention of researchers to improve the efficiency of power production compared to single-source energy systems [7-10]. Among the renewable energy sources, wind energy is one of the most promising sources for its cleanliness and sustainability. New installations of wind energy are achieved every year. The year 2020 has been a record of wind energy installations, with 93 GW of new installations worldwide, recording 53% year-over-year growth [11].

With the increased interest in wind energy, many research attempts were made, either to find innovative methods of wind energy harvesting or to increase the efficiency of conventional wind turbines. Innovations include wind energy generation through airborne systems like kites or airborne vehicles that are connected to a generator on the ground through a tether [12, 13] or bladeless wind turbines that produce energy through vortex generators [14, 15].

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DOI: http://dx.doi.org/10.28991/ESJ-2023-07-01-012

Research on wind turbines, on the other hand, is concerned mainly with the improvement of the energy harvesting efficiency of a wind turbine and hence reducing the cost of energy (CoE), optimizing the layout of a wind farm, and increasing the lifetime of a wind turbine. There are several approaches to increasing the efficiency of a wind turbine. These approaches include but are not limited to applying different control techniques on a wind turbine, namely, pitch control, yaw control, and torque control. Optimization and artificial intelligence techniques are widely used to optimize the control strategy for better power production [16-19]. Another approach to improving the efficiency of wind turbines is the optimization of the blade profile in the design phase. Optimization of the airfoil distribution, chord and thickness distribution, or twist angle can play a major role in a wind turbine's performance. Flow control methods can be useful as well, slots, slats, or other turbulence-generating surfaces can improve the aerodynamics of a wind turbine [20-22].

The second concern in wind energy research is wind farm site selection and layout optimization. Site selection requires forecasting to estimate the wind velocities on an annual basis [23, 24]. Wind power is directly proportional to the cube of wind velocity, and hence, the higher the wind velocity, the higher the annual energy production in a wind farm. However, higher wind velocity indicates higher aerodynamic loads, and accordingly, structural considerations should be followed for a safe design. Layout optimization is important as well to make use of all the land possible for energy production. Usually, Computational Fluid Dynamics (CFD) technique is used to simulate a wind farm before optimization of its layout [25, 26].

For a wind turbine to be effective, it should be operable for as long as possible. Usually, wind turbines are designed to last for 20 years of operation [27]. A wind turbine failure can be catastrophic, especially for large-scale wind turbines. In addition to losing millions of dollars for the capital cost of the turbine and for losing the power fed to the grid by the turbine, blades of enormous size can be dangerous if broken suddenly. Reasons for the failure of a wind turbine can be bird strikes, fatigue loading on the blades, and the blades striking the tower. In such cases, when the turbine is located in the path of birds' immigration or in cases of severe gusts and typhoons, it is advised to put the turbine on the brake mood. In cold areas where icing of the blade occurs, ice-structure interaction can also play a major role in the structural performance of the blade [28]. The main concern of this work is the blade dynamics under severe loading conditions.

Many research attempts have studied fatigue loading under turbulent conditions. Haselibozchaloee et al. [29] have made a comprehensive review on fatigue damage in offshore wind turbines. They reviewed different methodologies to model fatigue in wind turbines, different influences of materials, and wind and wave conditions. They concluded that it is a very complex process to model fatigue behavior due to the stochastic nature of loads and inaccuracies or discrepancies in the material properties.

Chanprasert et al. [30] have performed Large Eddy Simulations (LES) to study the fatigue loading due to wake interactions between wind turbines arranged in line. They found that yaw control for the downstream row of turbines had a negative influence on fatigue loading compared to fixed yaw, despite a constancy in the output power. Gao et al. [31] have performed a multiaxial assessment of the fatigue of offshore turbines. They found that shear strains are one of the most crucial factors affecting fatigue on the blades.

Del Campo and Estrada proposed a simplified model to analyze the fatigue of wind turbine structures. This model is based mainly on non-Gaussian translation and provides a computationally economical methodology for fatigue analysis. It can be used for the preliminary structural design of wind turbine structures [32]. Other models were used and compared for their computational time and accuracy by Katsikogiannis et al. [33]. They found that the computational cost could be reduced by 96% by combining fully coupled and simplified methods.

Residual fatigue in wind turbines' parts can lead to damage as well. Casado et al. [34] have performed an experimental analysis to study the fatigue of bolts in operating wind turbines. This analysis can be useful to plan the replacement of bolts before they cause damage to the turbine blades. However, the most crucial factor in a wind turbine's fatigue is the dynamic loads on the blades. The turbulent nature of the wind plays a major role in the dynamic loading of a wind turbine. It has been found that higher turbulence intensities can shorten the lifetime of a wind turbine [35].

In addition to the influence of fatigue loading caused by turbulence on the lifetime of a wind turbine, severe turbulence can lead to severe deflections on the blade. These deflections can cause a blade-tower strike if they exceed a certain limit. It is important to understand the effect of atmospheric turbulence on the blade dynamics and, hence, take an informed decision to avoid catastrophic failure.

The study of turbulence intensity effects on wind turbines has been approached by many research attempts. However, all the attempts considered only power performance and fatigue effects [36-39]. The study of blade deflections under the same wind speed but with different turbulence intensities is absent from the literature. It is important to study blade deflections to avoid tower strikes. In this context, this work introduces a study of the effect of atmospheric turbulence on blade dynamics. An aeroelastic simulation is performed on the WindPact 1.5 MW wind turbine under different turbulence intensities. A wind field is generated for a mean wind speed of 12 m/s, but with four different turbulence intensities, starting with 1% up to 50% turbulence. The blade deflections are studied for each case under the effect of turbulence.

2- Turbine Model and Methodology

In this section, the turbine chosen for simulation as well as the methodology followed will be discussed.

2-1- Wind Turbine Model

The wind turbine chosen for the implementation of this study is the WindPact 1.5 MW wind turbine [40, 41]. It has been chosen for the availability of sufficient data for simulation, as well as being of a relatively medium scale in order to observe the blade dynamics clearly. The WindPact was originally a project made by the National Renewable Energy Laboratory (NREL) to study the scaling effect on the cost of energy. It has different configurations with capacities ranging from 0.75 MW to 5 MW. The Wind turbine is shown in Figure 1 and the main features of the chosen configuration of 1.5 MW are shown in Table 1.

Figure 1. WindPact 1.5 MW Wind Turbine

Table 1. Properties of WindPact 1.5 MW Turbine

Property	Value
Rotor Diameter (m)	70
Hub Height (m)	84
Rated Rotor Speed (rpm)	20.5
Rated Wind Speed (m/s)	12.5
Rated Power (MW)	1.5
Hub Overhang (m)	3.3
Tower Base Diameter (m)	5.663

2-2- Turbulent Wind Field

Wind is turbulent by nature. The two main reasons for wind turbulence are the friction with the topography of Earth, and the unequal heating of different layers of air above ground. Turbulence can be defined simply as the fluctuation of wind speed around its mean value over a specified range of time. This range could be on a long-term basis (annually), on a daily basis (diurnal), or over a time scale of fewer than 10 minutes like in the case of wind gusts. It is a complicated process to describe turbulence accurately, so it is usually represented by a statistical property called turbulence intensity. Turbulence intensity (I) can be calculated simply by dividing the standard deviation (σ) of wind speeds, by the mean wind speed (U) over a range of time as in Equation 1.

$$I = \frac{\sigma}{U} \tag{1}$$

Atmospheric turbulence can be represented by many mathematical models. Some models are time-dependent and are usually used in CFD simulations, like the k-ε turbulence model. Other models are based on the frequency domain, they provide a spectral model for turbulence and are best suited for deterministic models. Among these models is the von Karman spectral model. However, the von Karman model gives a better representation of turbulence in wind tunnel tests. Atmospheric turbulence on the other hand is better represented by the Kaimal spectral model [35].

Kaimal spectral model can represent the spectral density function of the wind's longitudinal components (S_u) as a function of the frequency (n), longitudinal wind speed's standard deviation (σ_u), mean wind speed (U), and a length scale (L_u) depending on the surface roughness and height above ground [42]. The spectral density function for Kaimal's model is shown in Equation 2.

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{4nL_u/U}{(1+6nL_u/U)^{5/3}} \tag{2}$$

To generate a wind field for the simulation, the NREL open-source software TurbSim has been used [43]. The rotor geometry and position are used as inputs to generate a wind field that covers the rotor. The grid size should be larger than the rotor diameter and cantered at the hub height. Spectral model is also chosen among several models, Kaimal spectral model in this case. Turbulence intensity can be defined according to the IEC standards for wind turbines, with its three classes A, B, and C for low, medium, and high turbulence respectively. It can also be defined as a percentage.

In this simulation, a mean wind speed of 12 m/s and four turbulence intensities have been chosen. A very low, almost laminar 1% turbulence intensity, then increasing gradually to 10, 25, and 50% turbulence intensities, so that the effect of turbulence is shown clearly. The four different wind fields are generated, Figure 2 shows the longitudinal wind speed at hub height for all cases.

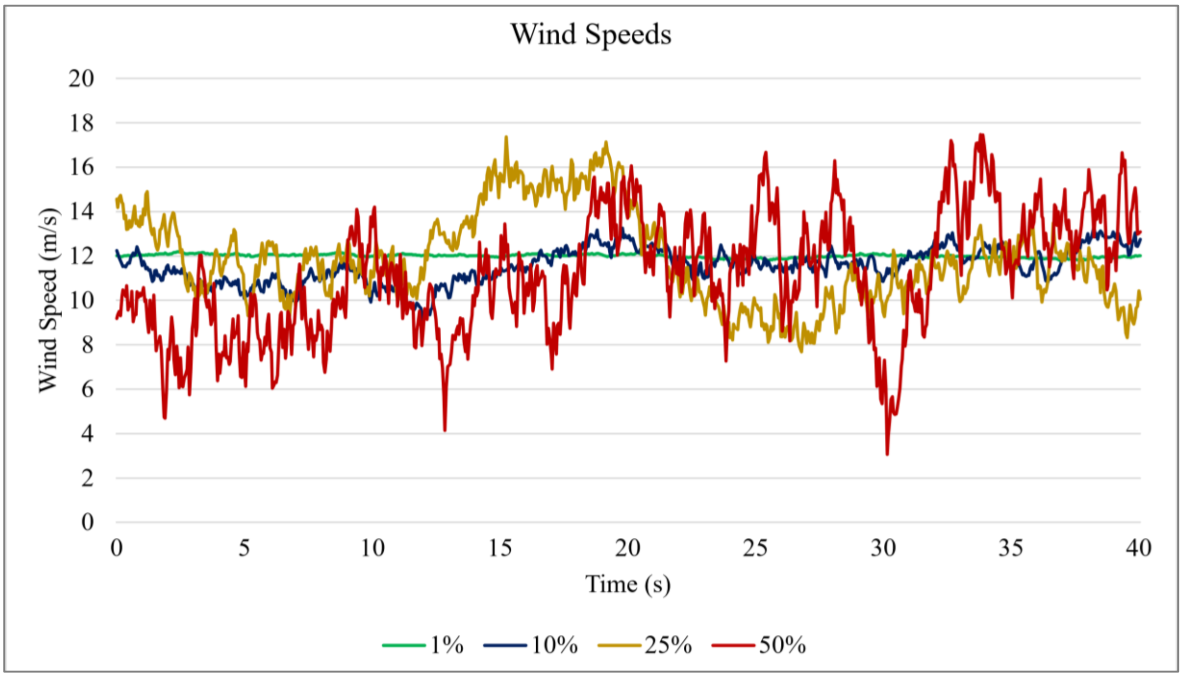

Figure 2. Wind Speeds at Hub Height

The effect of turbulence is clear on the wind speeds. The very low turbulence intensity of 1% in the green line, is almost constant at the mean value of 12 m/s. The higher the turbulence intensity, the higher the randomness in the wind speeds. The turbulence intensity of 10% changes around the mean value slightly, however, the 50% turbulence intensity shows severe and totally random fluctuations around the mean value. These fluctuations are the main reason for the fatigue loads over the wind turbine blades.

2-3- FAST Simulations

The generated wind field, together with the wind turbine geometry and aerodynamic properties, are used as inputs to the aeroelastic simulation using the open-source software FAST [44]. It uses deterministic models to calculate the aerodynamic loads using the Blade Element Momentum (BEM) theory, then use beam theory for the structural behavior, while coupling between them in an aeroelastic manner.

This software integrates several modules to include the aerodynamics, servo dynamics, elasticity, and operating conditions, into an aeroelastic simulation. A time series including several aerodynamic loads and blade and tower deflections is the result of this simulation. In this work, the changing factor is the different wind fields with different turbulence intensities. The process of the FAST simulation is shown in Figure 3.

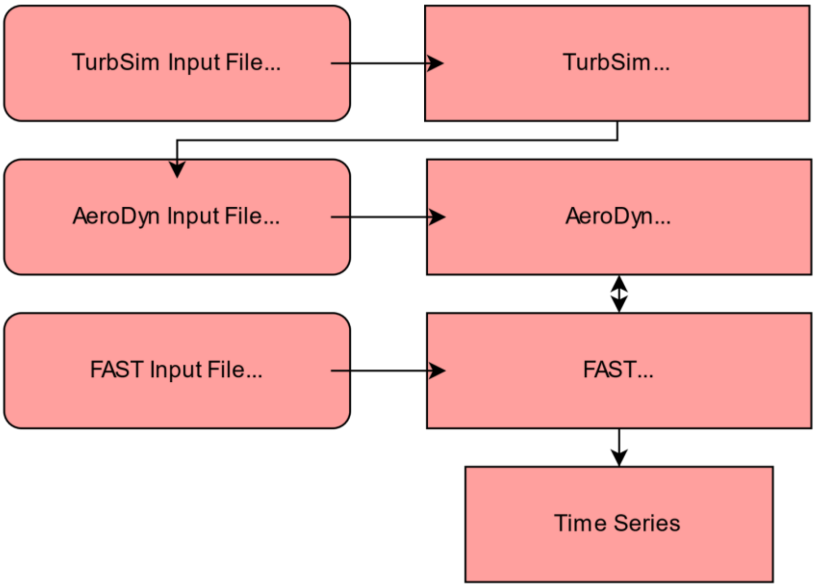

Figure 3. **FAST Simulation Procedure**

In the following section, the simulation results for the four turbulence intensities will be shown, namely, the blade deflections in the out-of-plane and in-plane directions.

3- Results and Discussion

The simulation is defined for 40 seconds of simulation to reduce the processing time and show the severe variation due to turbulence during a short period of time. The main concern of this work is the blade tip deflections for the different turbulence intensities. The two main deflections are the out-of-plane and in-plane of rotation of the rotor, compared to the undeflected position along the blade axes.

3-1- Blade Tip Out-of-Plane Deflection

The rotor plane is considered as the reference to the undeflected blade along the blade axes. A time marching series has been generated for the blade's out-of-rotor's plane deflection along the blade length. The most deflected section is at the blade tip. The time behavior of blade tip deflection has been studied. Figures 4 to 7 show the out-of-plane deflections for the 1, 10, 25, and 50% turbulence intensities respectively.

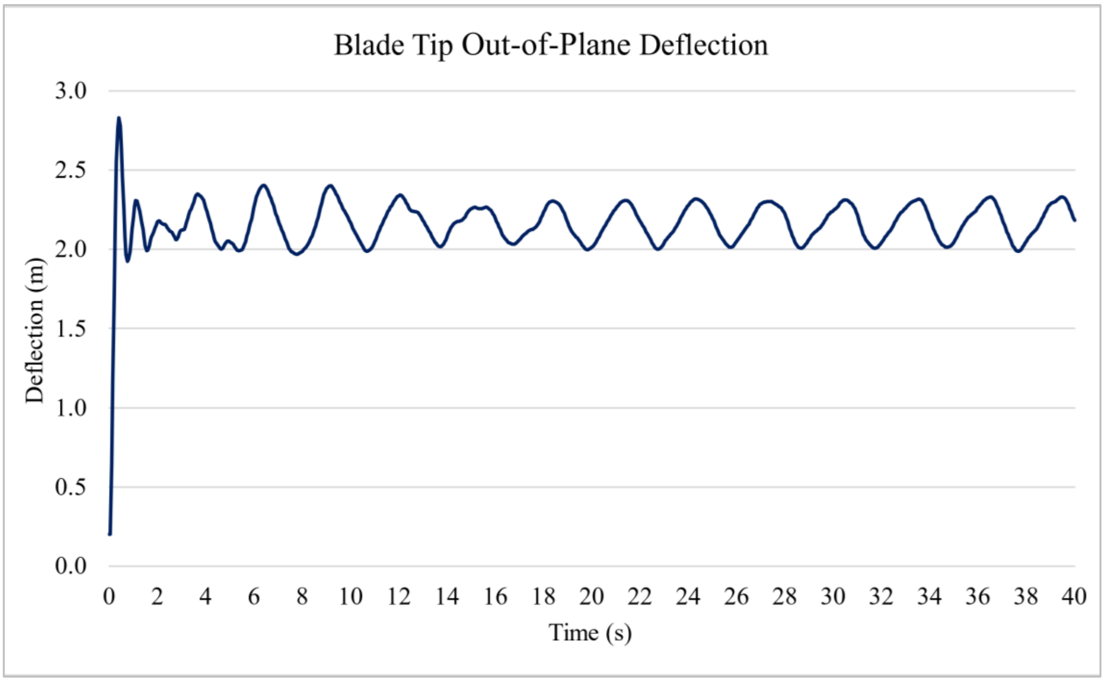

Figure 4. **Blade Tip Out-of-Plane Deflection - 1% Turbulence Intensity**

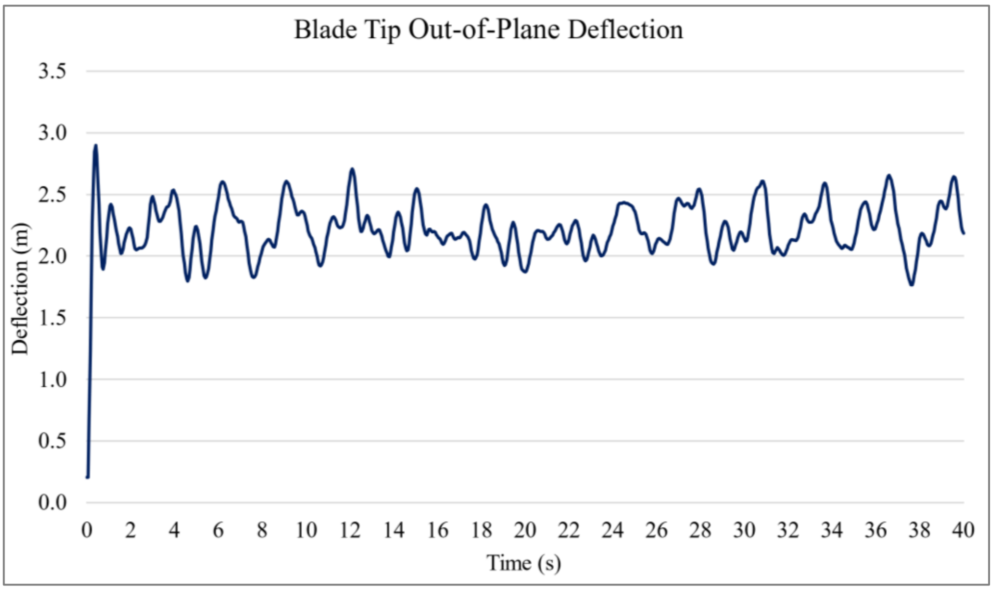

Figure 5. Blade Tip Out-of-Plane Deflection - 10% Turbulence Intensity

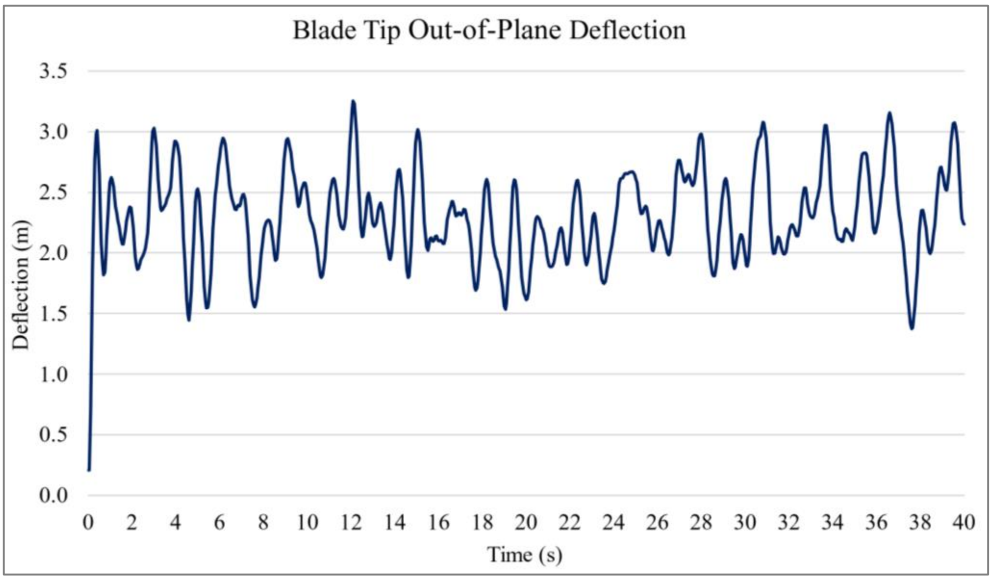

Figure 6. Blade Tip Out-of-Plane Deflection - 25% Turbulence Intensity

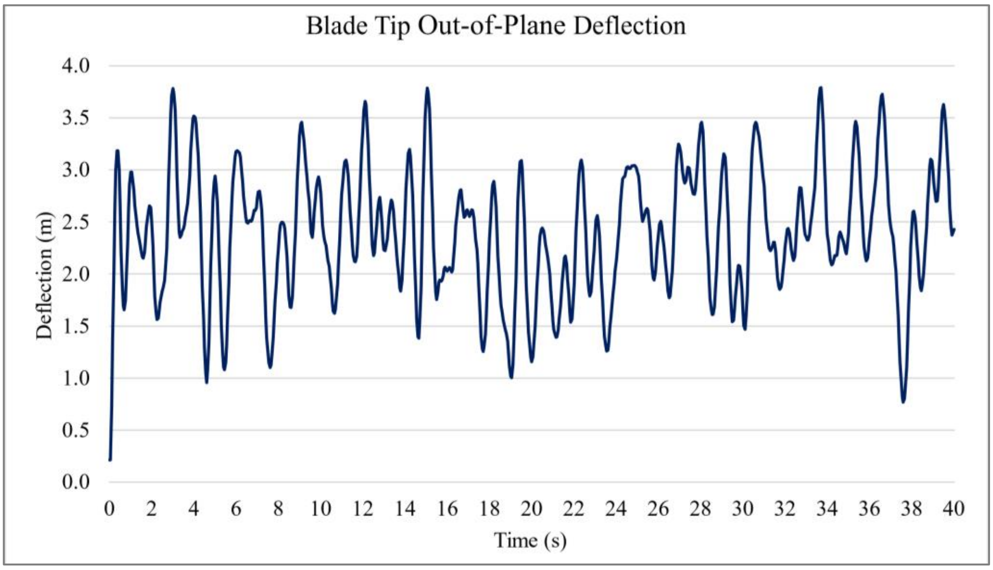

Figure 7. Blade Tip Out-of-Plane Deflection - 50% Turbulence Intensity

The effect of turbulence can be clearly seen from the figures. The normal behavior of blade tip deflection is a sinusoidal wave as it rotates in the azimuth direction. This sinusoidal behavior is due to the change in the azimuth position, and the effect of gravitational loads on the blades. It has a different effect when the blade is in the upright position of Zero azimuth than when the blade is rotated 180°. This behavior can be seen only in the case of 1% turbulence intensity. As the turbulence intensity increases, fluctuations in the sinusoidal behavior increase.

There is less regularity in the blade deflections as the intensity increases. Not only do the fluctuations increase, but also the magnitudes of maximum deflection increase. For the 1% turbulence intensity, the deflection oscillates regularly between the values of 2 m to 2.4 m. For the highest turbulence intensity of 50%, the deflections can reach up to 3.8 m. Recall from Table 1 that the hub overhang is 3.3 m, this means that there is a big chance that the blade will strike into the tower and cause a catastrophic failure.

Another interesting output to observe is the change of deflection with the azimuth angle. As mentioned earlier, normal behavior is a sinusoidal wave because of the azimuth position of the blade. Thus, it is expected to have the same deflection at the same azimuth angle for each complete rotation. To check the effect of turbulence on this behavior, the blade tip deflection is plotted again, against azimuth angle instead of time. Figures 8 to 11 show the blade tip deflections with azimuth angle for the four turbulence intensities.

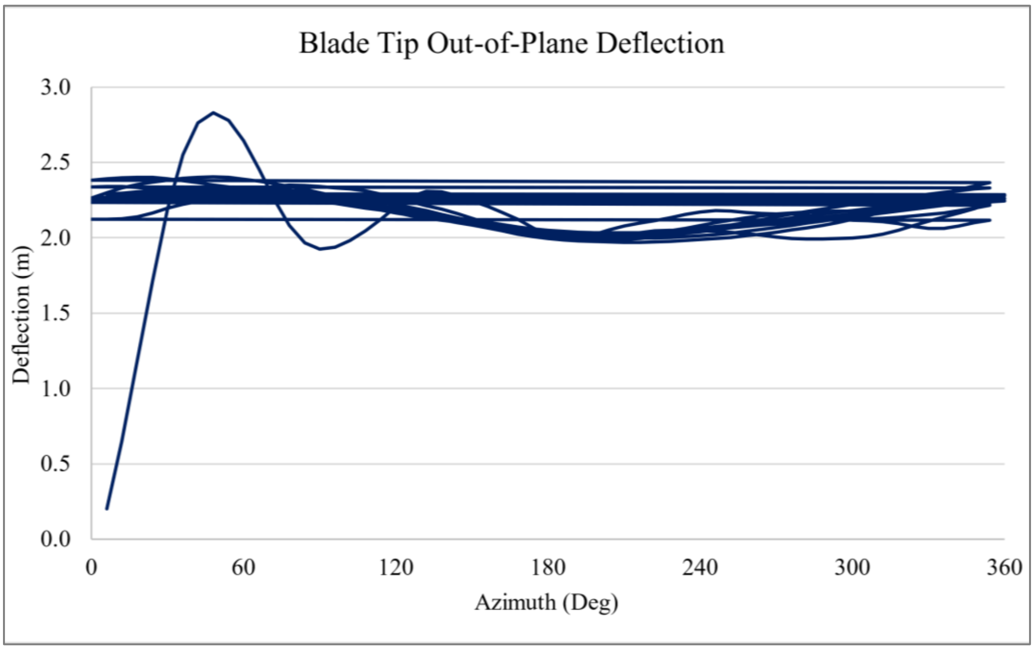

Figure 8. Blade Tip Out-of-Plane Deflection with Azimuth Angle - 1% Turbulence Intensity

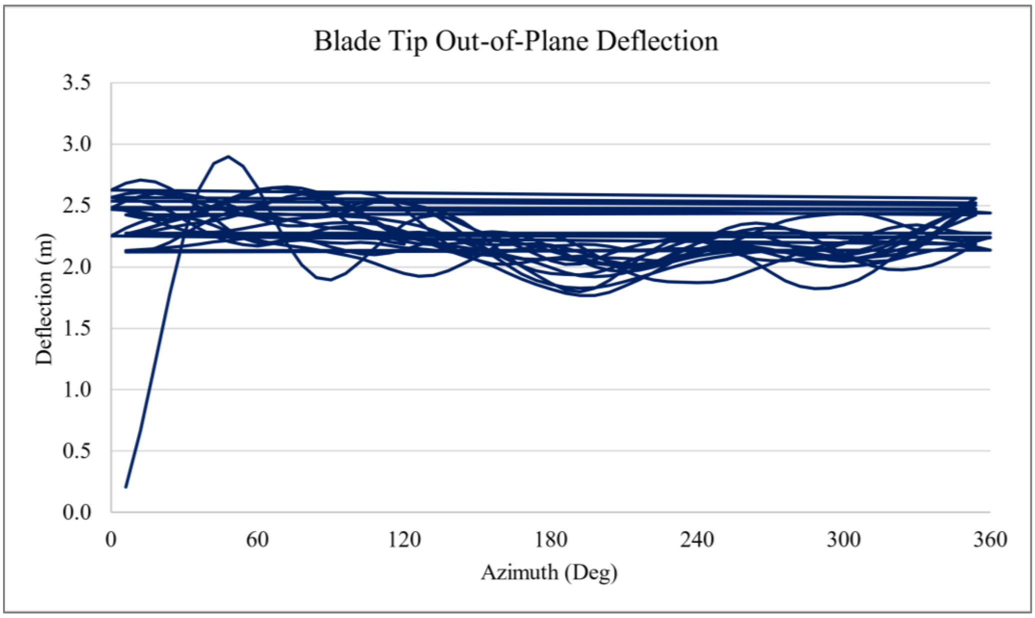

Figure 9. Blade Tip Out-of-Plane Deflection with Azimuth Angle - 10% Turbulence Intensity

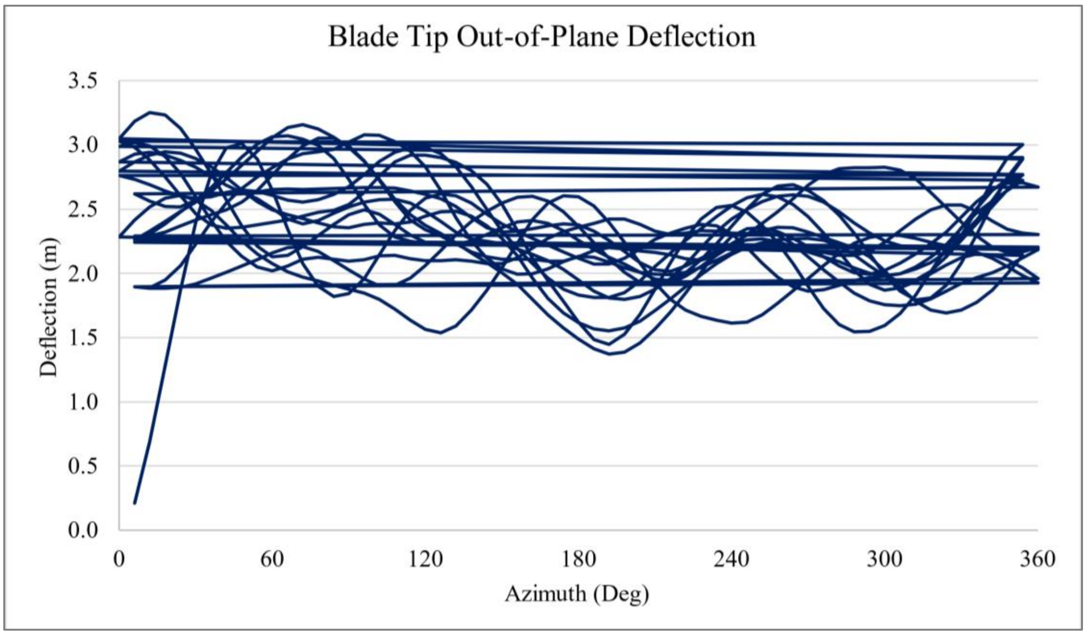

Figure 10. **Blade Tip Out-of-Plane Deflection with Azimuth Angle - 25% Turbulence Intensity**

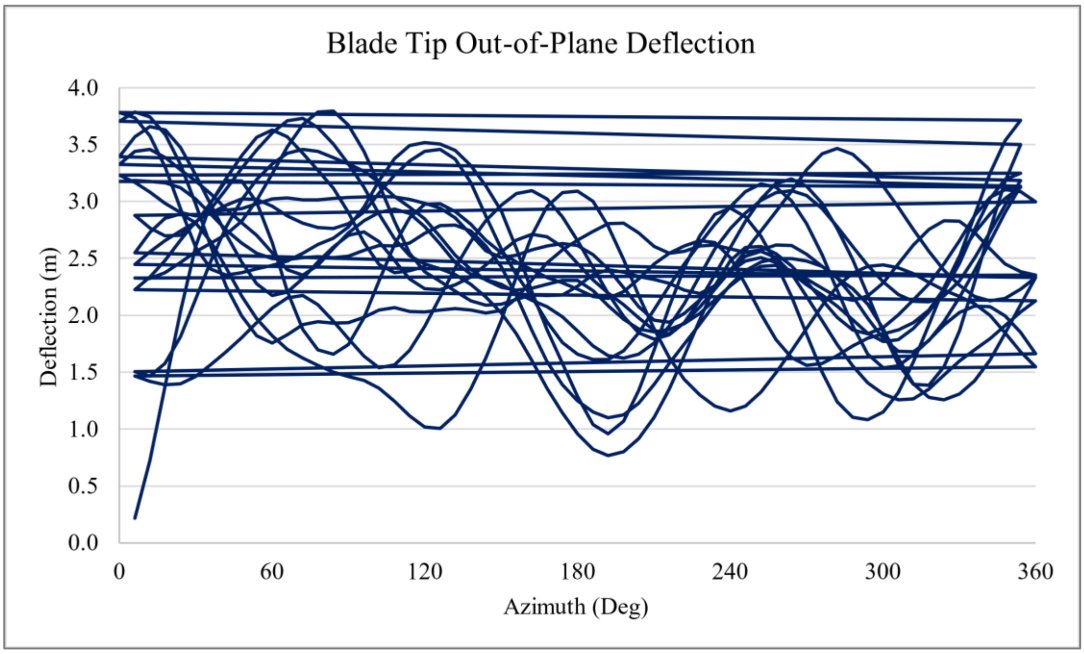

Figure 11. **Blade Tip Out-of-Plane Deflection with Azimuth Angle - 50% Turbulence Intensity**

For the 1% turbulence intensity in Figure 7, the behavior of the blade tip deflection looks almost the same for every rotation of the blade. It can be clearly observed that the blade follows a certain and constant path along its rotation in the azimuth plane. It deflects with the same value at each azimuth position, thus having a regular behavior that is good for the fatigue loads over the blade.

For the 50% turbulence intensity though, it is a completely random behavior. The blade can have a maximum deflection at a certain azimuth angle in one rotation, then it has a much less value of deflection in the next rotation, then it can increase again. This random bahevior and phase change in the deflections increase the damage equivalent loads in the fatigue analysis. It also implies the danger of a tower strike as the blade rotates.

3-2- Blade Tip In-Plane Deflections

Similarly, the blade tip in the plane of the rotor deflections are studied. Usually, the in-plane deflections have small values since it is difficult to bend in the edgewise direction due to the blade geometry. It will be bending against the chord length which is much larger than the blade thickness. The behavior against time is calculated and plotted for all turbulence intensities. Only the 1% and 50% turbulence intensities results will be shown in Figures 12 and 13.

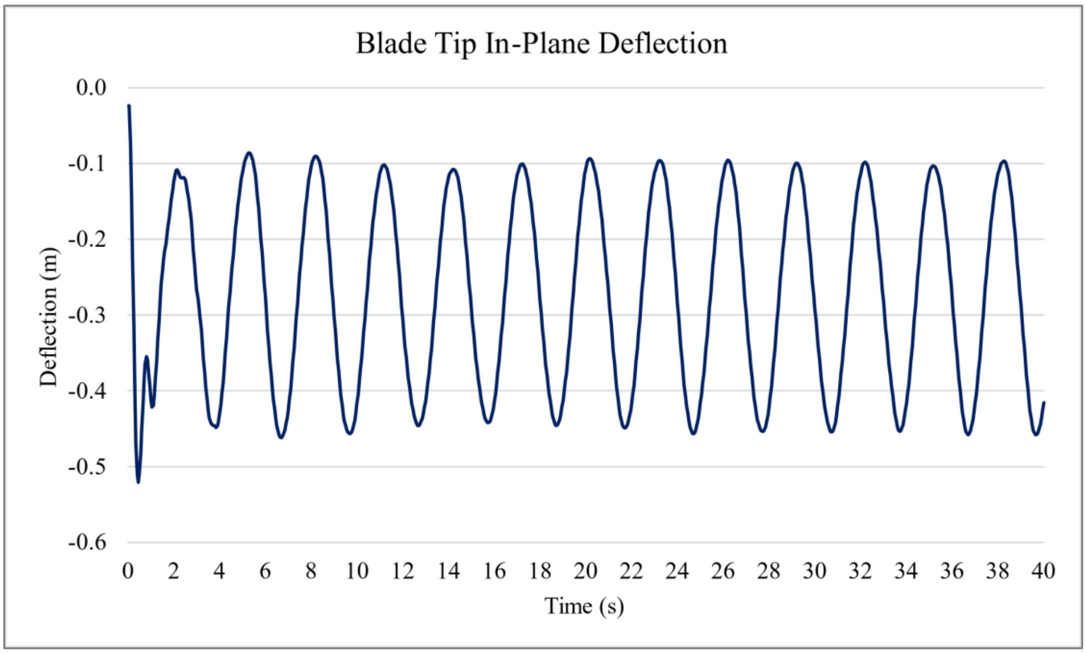

Figure 12. Blade Tip In-Plane Deflection - 1% Turbulence Intensity

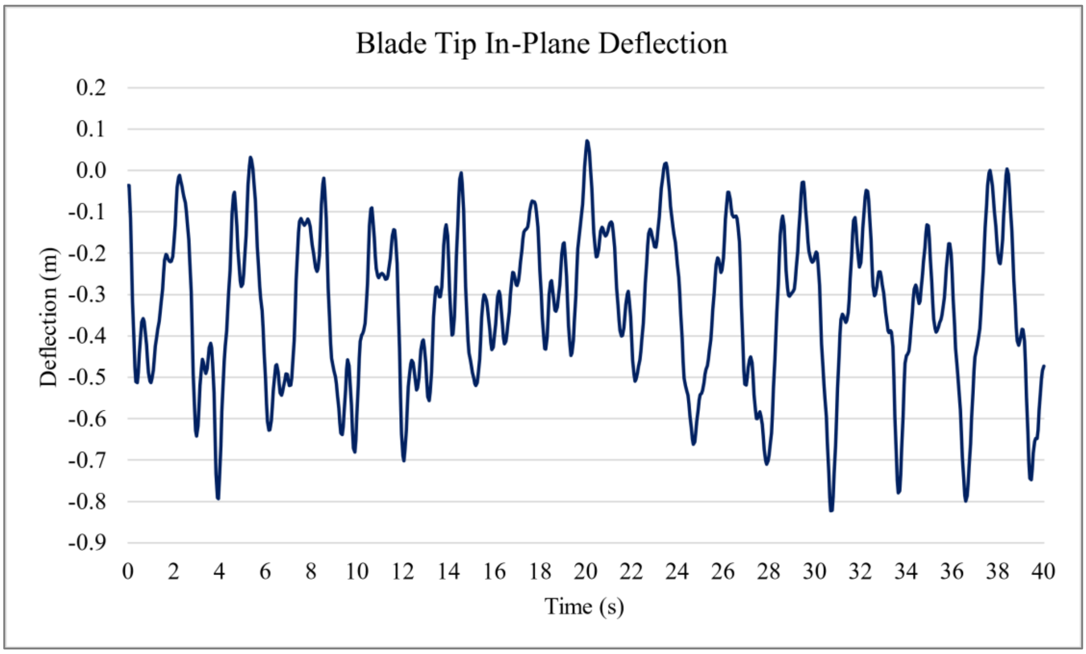

Figure 13. Blade Tip In-Plane Deflection - 50% Turbulence Intensity

The range of values for the 1% turbulence intensity is between -0.1 and -0.45. It is negative because the blade moves backward in the same plane of rotation due to the rotor speed in operation. It also has a sinusoidal behavior due to the gravitational effect on the blade when it moves against gravity half the cycle, and with gravity the other half. For the low turbulence, the blade encounters a normal behavior which is regular due to the dynamic nature of the turbine rotor.

On the other hand, for the higher turbulence intensity, the randomness in the deflections increases. It can no longer be described as a sinusoidal wave. In addition, it can be observed in Figure 12 that there are some occurrences when the deflection has a positive value. Although it is of a small value, but a positive value means that the blade deflects ahead of its rotation direction. This is dangerous to the blade structure as it is unusual behavior for the blade to bend on the other side of the edgewise direction. It may also cause buckling in the leading edge, and hence, the blade costing thousands of US dollars should be replaced.

Behavior against the azimuth position of the blade is studied for the in-plane deflections as well. Figures 14 and 15 show the blade tip in-plane deflections plotted against azimuth position for the 1% and 50% turbulence intensities respectively.

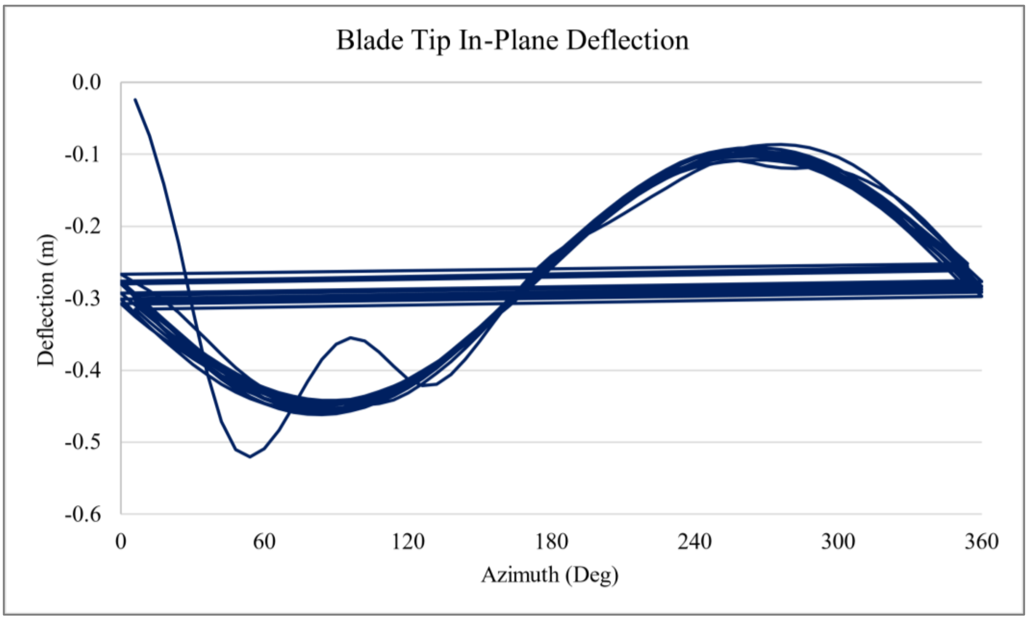

Figure 14. Blade Tip In-Plane Deflection with Azimuth Angle - 1% Turbulence Intensity

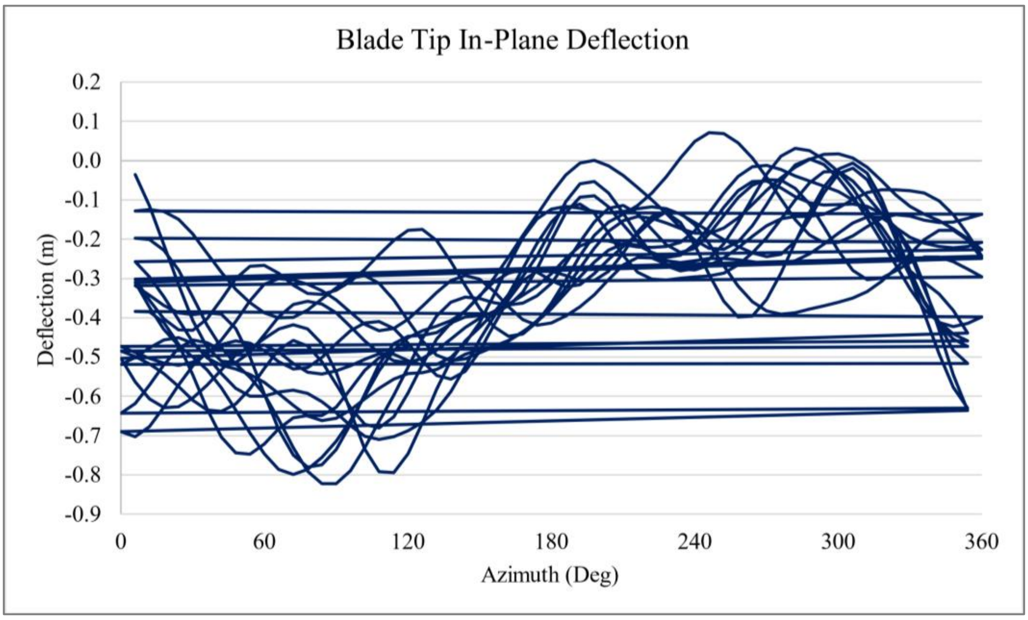

Figure 15. Blade Tip In-Plane Deflection with Azimuth Angle - 50% Turbulence Intensity

Again, it is observed that there is a smooth and regular behavior of the blade deflections at different azimuth positions for the 1% turbulence intensity. It can be seen that the blade encounters a regular position relevant to the azimuth position at each rotation, repeating its own path. This regular behavior is the key to a longer blade lifetime. The higher turbulence intensity concludes a high fluctuation in the blade deflections.

In addition, as mentioned earlier, the positive value of deflection is a major problem. From Fig. 14, the maximum positive in-plane deflection occurs at an azimuth angle of about 250°. At this position, the blade has almost finished three-quarters of one complete rotation. It is possible that the inertial load due to the blade's acceleration and the effect of the in-plane shear forces, the blade deflects against its natural position. This unnatural position is hazardous in terms of buckling in the leading edge of the blade, and thus, it is inoperable and needs to be replaced.

3-3- Simulation Results Summary

The results of the simulation can be summarized in terms of statistical properties. The first three seconds of the simulation are excluded from the statistical analysis since it is the starting phase of the blade rotation, and hence the values are exaggerated. The next 37 seconds of the simulation are analyzed statistically. The standard deviation is important since it indicates the severity of deflection variation and, hence, the fatigue response of the blade. The standard deviation of the blade deflection for the out-of-plane and in-plane directions is shown in Figure 16.

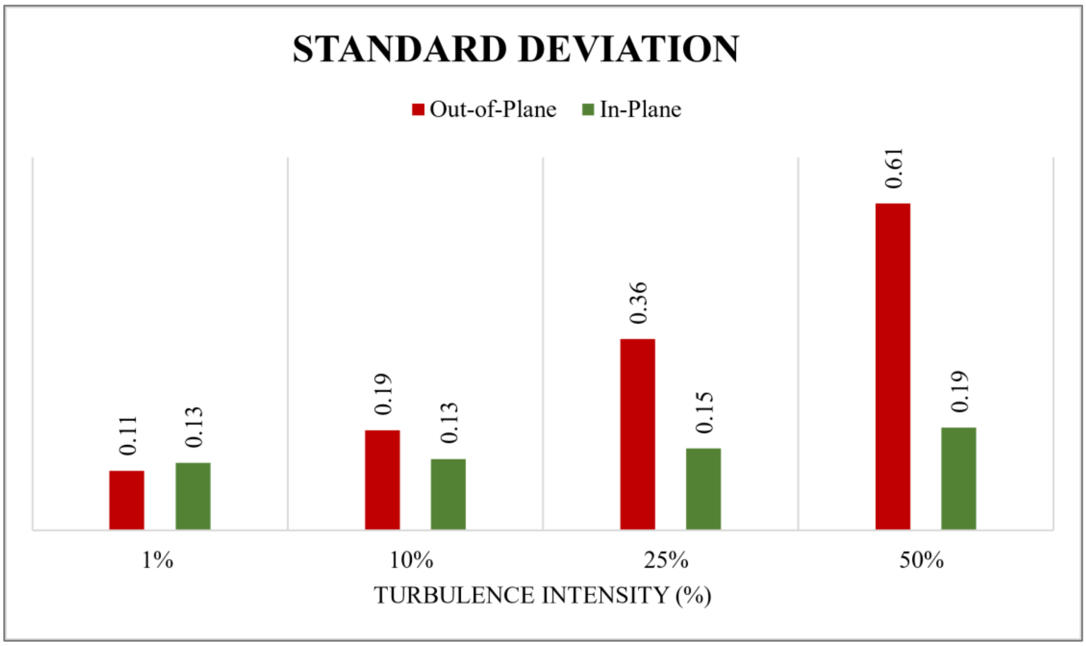

Figure 16. Standard Deviation of the Blade Deflections

For the out-of-plane deflections, the standard deviation increases dramatically. The value of 0.11 for the 1% turbulence intensity indicates that the deflections do not change much around their mean value. Then the deviation increases as the turbulence intensity increases, until it reaches the value of 0.61 for 50% turbulence intensity, with a 600% increase. This significant increase indicates the severity of blade deflection fluctuations. However, the change in the in-plane deflection's standard deviation is not as significant. This may be due to the difficulty of bending in the edgewise direction. The increase in the 50% turbulence intensity standard deviation compared to that of the 1% intensity is 170%. Nonetheless, it is still a significant value that expedites failure due to fatigue loading. Another important property to consider is the maximum value of deflection for the out-of-plane and in-plane directions. This importance comes from the fact that deflections should have maximum values to avoid tower strikes or buckling. The maximum values for deflections for all turbulent intensity cases are shown in Figure 17.

Figure 17. Maximum Value of the Blade Deflections

The maximum value of out-of-plane deflection indicates how critical it is for the blade to strike the tower. The 25% turbulence intensity is very critical since it has a maximum value of 3.25 m, compared to the hub overhang of 3.3 m. This can be solved if the rotor has a tilt angle so the blades will have clearance from the tower. Though the 50% turbulence intensity has a maximum blade deflection of 3.78 m, which means if the rotor is not tilted, it will definitely strike the tower, causing a catastrophic failure.

The in-plane deflection maximum value indicates how close the blade is to its original undeflected position. If it reaches a zero value, this means that the blade is undeflected. It has a value of -0.007 m for the 25% turbulence intensity, which means that the blade is almost undeflected against the high speed of the rotor rotation. This can produce residual stresses along the blade length since it is resisting the inertial loads of the blade. And at 50% turbulence intensity, the blade turns into a positive deflection, which, as mentioned before, is dangerous for the blade's lifetime.

Finally, the range of values for each deflection will be examined. This property indicates the range at which the deflections oscillate. The bigger the range, the further the blades move from one position to another in a short timescale, and hence, fatigue loads increase. The range for the deflections in the out-of-plane and in-plane directions is shown in Figure 18.

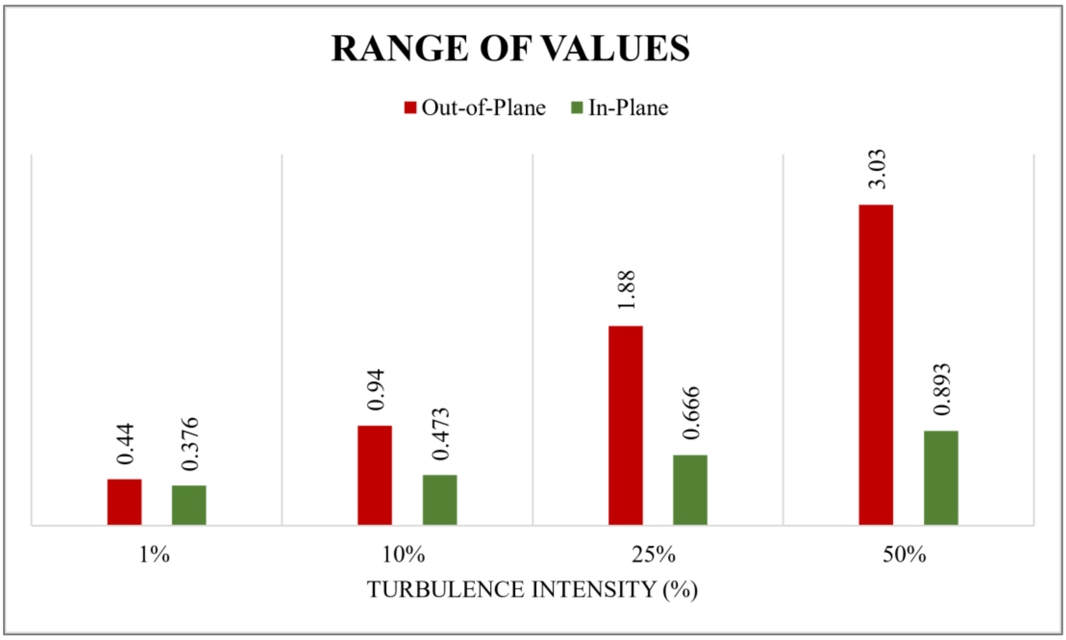

Figure 18. **Range of Values of the Blade Deflections**

For both the out-of-plane and in-plane deflections, the blade swipes a large range of deflection within a very small time variation for the higher turbulence intensity. Starting with a value of 0.44 m for the 1% intensity and going up to 3.3 m for the 50% intensity in the out-of-plane deflection, the blade vibrates very fast as the intensity increases. In addition to being critical to failure due to fatigue, faster vibrations increase the noise made by the turbine. This noise pollutes the environment and makes it difficult to install turbines close to residential areas.

4- Conclusion

In this work, the dynamics of a wind turbine's blade are investigated under the effect of atmospheric turbulence. The WindPact 1.5 MW turbine has been simulated under different turbulent wind fields, all having a mean wind velocity of 12 m/s but with turbulence intensities of 1, 10, 25, and 50%. Blade deflections are investigated in the out-of-plane and in-plane directions. The higher the turbulence intensity, the severer the fluctuations of the deflections around its mean value. For the 50% turbulence intensity, for instance, there is completely random behavior for the blade deflections, especially for the out-of-plane deflection. The standard deviation of that deflection is 600% of the value of the 1% turbulence intensity. The maximum value of deflection increases as well. A maximum deflection of 3.78 m occurs at 50% turbulence intensity. This indicates the danger of a tower strike and, hence, a catastrophic failure. In addition, the range of values increases dramatically, which increases the severity of vibrations and leads to fatigue and excessive noise.

In addition, the in-plane deflections experience a positive deflection for the 50% turbulence intensity. This means that the blade undergoes an unnatural behavior of being ahead of its rotation direction. This also indicates the danger of buckling in the leading edge of the blade, leading to the end of the blade's operation and the urgent need for replacement, which costs thousands of dollars and hence increases the cost of energy.

The deflections also vary with the same azimuth position of the blade from one rotation to the next under higher turbulence intensity. There is no regular behavior while the blade is rotating, and hence the severe variation can lead to higher damage equivalent loads, and accordingly fatigue failure. For that reason, continuous monitoring of the atmospheric turbulence in a wind farm should be important. In cases of gusts or severe turbulence that exceed a certain limit based on the turbine design, the turbine should be put on brake immediately. It is also recommended that forecasts be made ahead of turbine installation in a wind farm. If the chance of gusts occurring is high, then a downwind turbine could be safer and allow for higher deflections without the danger of tower strikes.

5- Declarations

5-1- Data Availability Statement

Data sharing is not applicable to this article.

5-2- Funding

The author received financial support from Future University in Egypt (FUE).

5-3- Institutional Review Board Statement

Not applicable.

5-4- Informed Consent Statement

Not applicable.

5-5- Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the author.

6- References

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