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STOCHASTIC MODELING OF THE DYNAMICS OF A WIND TURBINE USING MATLAB AND MSC.ADAMS

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Abstract. Due to the reduction of available fossil energy resources and also safety problems and high cost of nuclear energy, the number of researches related to renewable energies, especially wind energy is increasing. This paper presents a simplified wind turbine model in MATLAB and MSC.ADAMS. The vibration of the blade tip is analyzed considering uncertainties in several parameters, such as wind speed, material and dimensional properties. A probabilistic approach together with the Monte Carlo method is used to propagate these uncertainties throughout the numerical model and to perform a sensitivity analysis. A comparison between results of solving the equations using MATLAB, and simulation of wind turbine using discrete flexible link in MSC.ADAMS design evaluation is presented.

1 INTRODUCTION

Windmills have existed for more than 3,000 years and have greatly facilitated agricultural development. The windmill is the oldest device for exploiting the energy of the wind. The first electricity-producing wind turbine was constructed by Charles F. Brush in the United States in 1887. Brush's machine had a 17-m-diameter rotor, consisting of 144 blades, and a 12-kW generator (Sørensen Jens Nørkær, 2011). In 1918 approximately 3% of the Danish electricity consumption was covered by wind turbines. Because of supply crises, renewed interest was paid to wind energy during World War II (Sørensen Jens Nørkær, 2011). Wind power has established itself as a major source of non-polluting, inexhaustible renewable energy. During the last decades wind power has evolved as a strong alternative to fossil fuels in the electricity generation industry. The World Wind Energy Association's Estimate for the future is a global capacity of 600,000 MW by 2015 and more than 1,500,000 MW by 2020 (Crozier Aina, 2011).

Today, state-of-the-art wind turbines have rotor diameters of up to 120 m and 5-MW installed power, and these are often placed in large wind farms with a production size corresponding to a nuclear power plant. Nowadays in researches, wind is found as one of the possible and powerful energy sources. Although research in wind energy has taken place for more than a century now, there is no doubt that wind-energy competitiveness can be improved through further cost reductions, collaboration with complementary technologies, and new innovative aerodynamic design (Sørensen Jens Nørkær, 2011). Figure 1 shows the past record and projection of the accumulated capacity of wind energy from 1990 to 2012 (Sangyun Shim, 2007).

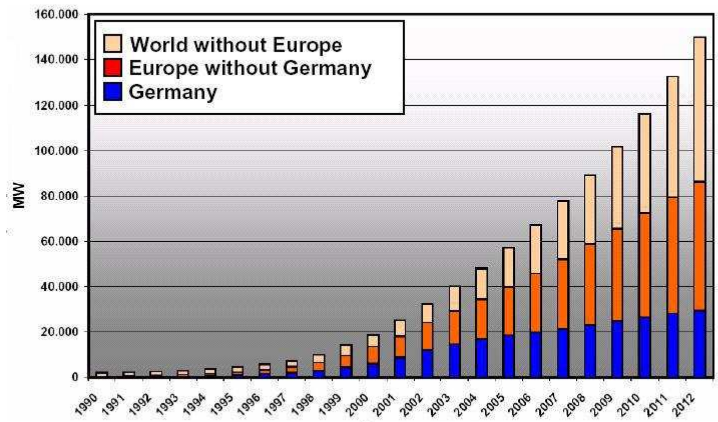

Figure 1: Accumulated capacity of wind energy (Sangyun Shim, 2007)

In general case, there are many parameters contributing to the behavior of a wind turbine, such as: low level jet, turbulent wind, wake turbulence, tidal and storm surge depth variation, buoyancy of support, extreme wave and scour. A scheme of these effects is shown in Figure 2.

To study wind turbine behavior, we consider wind turbine as a mechanical system that has characteristics such as blade airfoil properties, material properties, geometry, mass and inertia properties, transmission system behavior and structural stiffness and damping. These parameters together define the response of the system to its inputs. Environmental effects such as wind power, mooring or support excitation and electric network loads are inputs for the system and any response of system to inputs due to system characteristics, are outputs of the system. In this paper deflections of blade of wind turbine and rotational velocity of rotor are considered as outputs of system.

In section 2, a literature survey of previous researches about dynamics of wind turbines is presented. In section 3, a mathematical model of a rotating flexible blade and the equations of the deflection of its tip are presented. In section 4 uncertain parameters are introduced. In section 5, numeric results for the deterministic model obtained using MATLAB and MSC.ADAMS are shown and compared and in section 6, the stochastic model are offered and compared.

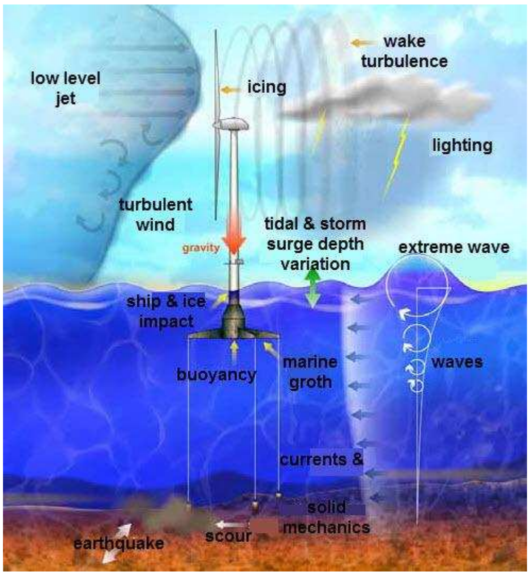

Figure 2: General parameters affecting wind turbine model (Matha Denis, 2009)

2 LITERATURE SURVEY

There are many works related to general design of offshore wind turbines. Matha Denis, (2009) investigated variable Floating platform support structures, studying various aerodynamic and hydrodynamics load which exert on blade and structure of offshore wind turbine. Sørensen Jens Nørkær, (2011) reviewed the most important aerodynamic research topics in the field of wind energy. He used the blade-element momentum theory along with guidelines for the construction of airfoil data. Crozier Aina, (2011) introduced the design of tension-leg-platforms support structures for the 10 MW reference wind turbine using FAST code to simulate a fully coupled Aero-Hydro-Servo-Elastic Model. Bagbanci Hasan, (2011) studied the influence of the environmental conditions on wind turbine design loads for a monopole foundation by analyzing the bending moment at the tower base and tower root for various values of water depth, tower height, pile diameter and turbulence mode, using FAST code.

With focus on blade dynamics, there are few works related to the dynamics of a rotating cantilever beam which can be used in the study of wind turbine blade dynamics. T. R. Kane, et al., (1987) studied the behavior of a cantilever beam built into a rigid body that is performing a specified motion of rotation and translation. Effects such as centrifugal stiffening and vibrations induced by Coriolis forces are accommodated automatically, rather than with the aid of ad hoc provisions. Li, D., et al., (2005) studied the coupling relationship between the space rotating movement of horizontal axis wind turbine blade and its elastic distortion using multi-body dynamics and finite element discretization of a large scale wind turbine blade. Venkatanarayanan Ramakrishnan and Brian F. Feeny, (2011) developed the nonlinear partial differential equation of the in-plane motion of a wind turbine blade subject to gravitational loading and which accommodates for aerodynamic loading using the extended

Hamilton principle. Seungmin Kwona et al., (2013). derived the equations of motion of a rotating wind turbine blade undergoing gravitational force while considering tilt and pitch angles.

Many authors, studied structural behavior of wind turbine using different approaches, such as, finite elements method. Also there are many structural studies on the blade and the tower as a coupled system. Fallahi .B, et al., (1994) studied modeling the flexibility for a beam with tip mass with the approach of Timoshenko beam with geometric stiffening. Donghoon Lee, et al., (2002) worked on structural dynamic analysis of horizontal axis wind turbines based on representing a multi-flexible-body system with both rigid and flexible body subsystems. The rigid-body subsystems such as nacelle and hub are modeled as interconnected sets of rigid bodies. The flexible-body subsystems such as blades and the tower are modeled using geometrically exact, nonlinear beam finite elements. Larsen Jesper Winther, (2005)'s work deals with the formulation of non-linear vibrations of a wind turbine wing described in a wing fixed moving coordinate system, considering structural model as a Bernoulli-Euler beam with due consideration to axial twist. Ahlström Anders, (2005) developed a finite element model for simulation of the dynamic response of the structure of a horizontal axis wind turbines using the commercial finite element software, MSC.Marc. The aerodynamic model, used to transform the wind flow field to loads on the blades, which is a Blade-Element/Momentum model. Wayman E.N. Sclavounos and P.D., (2006) used methods for the coupled structural, hydrodynamic, and aerodynamic analysis of floating wind turbine systems in the frequency domain by coupling the aerodynamics and structural dynamics code, FAST. Sangyun Shim, (2007) developed a numerical time-domain model for the fully coupled dynamic analysis of an offshore floating wind turbine system including blade-rotor dynamics and platform motions. Jonkman J.M., (2007), developed a comprehensive simulation tool for modeling the coupled dynamic response of offshore floating wind turbines. The simulation tool was then applied in a preliminary loads analysis of a wind turbine supported by a barge with catenary moorings. Kessentini S., et al., (2010) developed a mathematical model of a horizontal axis wind turbine with flexible tower and blades with flapping flexures of the tower and blades. They investigated the effects of the pitch angle and blade orientation on the linear vibrations of the wind turbine. Larsen J.W, et al., (2007) analyzed the coupled nonlinear equations of motion of a rotating Bernoulli-Euler beam including nonlinear geometrical and inertial contributions via Monte Carlo simulations.

Concerning uncertainty modeling, (Cheng P.W, et al., 2002), simulated the statistical uncertainties concerning flap moment at the blade root and the overturning moment of the support structure of an offshore wind turbine. The uncertainties are treated with Bayesian analysis. Xiong, et al., (2010) developed a dynamic response analysis of the blade of horizontal axis wind turbines using finite element method. Bertagnolio F, et al., (2010), using a conditional simulation technique for stochastic processes, derived the drag and pitching moment by definition a model based on a spectral representation of the aerodynamic lift force. Sørensen J.D and Toft H.S, (2010) described how uncertainties in wind turbine design related to computational models, statistical data from test specimens, results from a few full-scale tests and from prototype wind turbines can be accounted for using the Maximum Likelihood Method and a Bayesian approach.

3 MATHEMATICAL MODEL

The deflections of blade tip have three components, one in the radial direction which is the direction of the longitudinal axis of the blade and is called radial or centrifugal deflection. The other one is the transversal deflection of the blade tip due to the lift force in the plane of rotation and is called in-plane deflection and is in the direction of a vector in the plane of motion that is perpendicular to radius. The last one is in the direction of rotation axis and is perpendicular to the plane of rotation and is called out of plane deflection.

All of these deflections are caused by centrifugal forces, aerodynamic forces and the gravitational force. Figure 3 shows the directions of these components. The moving frame that is connected to the blade is the reference frame to derive the equations of deflections of the blade's tip.

To obtain the mathematical model, some simplifying assumptions are made. First we assume that the rotation is about a fixed axis normal to the rotor disk, which means that the tower of wind turbine and its nacelle are fixed. Then the only moving parts are flexible blades which are rotating about a fixed axis, and all blades at rest lay on the same plane that is perpendicular to the axis of rotation.

The second assumption is that the material and the geometrical properties of the blades are constant and they do not change when the body of the blades deforms due to the dynamic forces. It means that the strain is assumed to be small.

The third assumption is that the material properties of the blade such as module of elasticity and density are constant, also the cross sectional area of the blade is constant along the longitudinal axis.

The fourth assumption is that we can neglect the structural damping of the blade vibrations.

As the fifth assumption, we assume that the wind direction is always perpendicular to the rotation plane of the blade and it is constant at any time. Also we assume that when the rotor of wind turbine rotates, we can neglect the drag that is produced by the relative motion of the blade with respect to the air that surrounds it.

And finally, we assume that the angle of attack of the blade is constant, which means that wind and the chord of the cross section of the blade always have a constant angle.

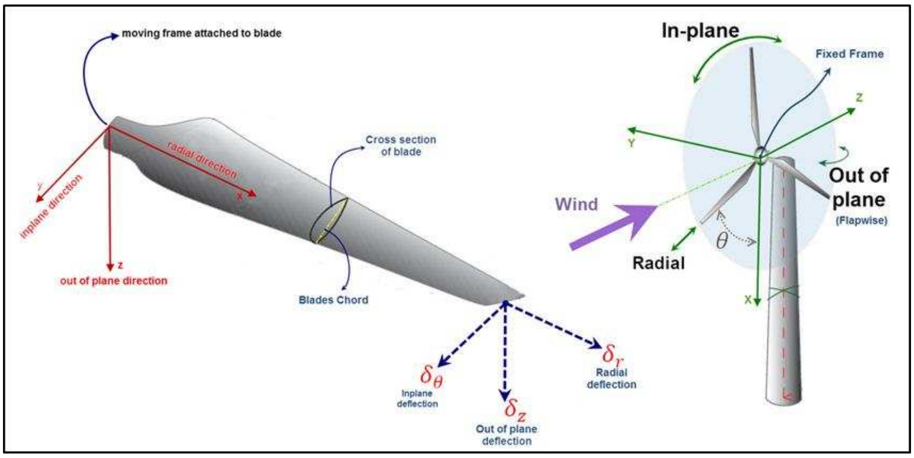

Figure 3: Components of deflection of blade tip

3.1 Rotor motion

The motion of the rotor is caused by the wind speed, therefore the wind speed is the source term and the total lift force on the blade, which is in the direction of y axis of the blade's reference frame, is given by:

$$F_L = \frac{1}{2}\int_A \rho_{air}.v_{wind}^2.C_L.dA \tag{1}$$

Where, A is the reference area of the blade, which is the area of projection of the blade on the plane of the rotation, ρ_{air} is the density of air, v_{wind} is wind speed normal to the rotation plane of blades, C_L is the coefficient of lift on the blade, which we assume that is constant along the longitudinal axis of the blade.

Due to our assumptions, the chord h of the blade is constant along the longitudinal axis of the blade, we say that $A = hR$ where, R is the length of each blade which is the radius of rotation of wind turbine as well. The direction of the lift force is always in the direction of rotation, which means that it is perpendicular to radius and in the plane. Thus, Eq. (1) becomes:

$$F_L = \frac{1}{2}\rho_{air}.v_{wind}^2 C_L.h.R \tag{2}$$

Now, for the rotational equation of the rotor with n blades, and due to the assumption of uniform distribution of the lift along the longitudinal axis of the blade (Bagbanci Hasan, 2011; KÜHN M.J 2001; Perdana Abram, 2008), we have:

$$n\int_0^R x\frac{F_L}{R}dx - T_G(\dot{\theta}) = J\ddot{\theta} + C\dot{\theta} + K\theta \tag{3}$$

Where, T_G, is the resisting torque against the rotation of the rotor, J is polar moment of inertia of the set of rotor and blades about the rotation axis, and finally, C and K are the rotational damping and the rotational stiffness of combined system of the rotor, transmission system and the electric generator. We assume that the plane that contains the axis of tower and the axis of rotation, is the reference plane to measure the angle θ; also each blade will have the same response when passes a specific angle, θ.

The importance of Eq. (1) is that we need the solution of this equation to solve the Eqs. (7), (10) and (12) related to the blade deflections; see sections, 3.2, 3.3 and 3.4.

From previous works, the general form of angular velocity response to wind speed (Jah A.R, 2011; Manwell J.F, et al., 2002; KÜHN Martin Johannsen. 2001), is known. In many physical phenomenas, like vehicle drag force, tire resisting moment and etc., the resisting force is estimated by quadratic force. We also used the quadratic form, $T_G(\dot{\theta}) = K_G\dot{\theta}^2$ for the resistance torque in Eq. (3). With this choice, the angular velocity response follows the expected form.

3.2 Radial deflection of tip

Radial deflection is caused by the centrifugal forces and the gravity force component along the x axis of the blade; then, the normal force in each cross section of the blade in the distance r of rotating axis is:

$$F(r) = g\,cos(\theta)\int_r^R \rho_b A_c dx + \omega^2\int_r^R \rho_b A_c x dx \tag{4}$$

Where, in this equation, negative direction is the direction toward the center of the rotation, A_c is the cross sectional area of the blade, ρ_b is the material density of the blade and ω is the rotational velocity of rotor, which is the time derivative of θ. Integrating the terms of Eq. (4) we have:

$$F(r) = \rho_b A_c\left(g.cos(\theta)(R-r) + \frac{1}{2}\omega^2(R^2 - r^2)\right) \tag{5}$$

Therefore the radial deflection of the blade tip with $r = R$ is given by:

$$\delta_r = \int_0^R \frac{F(r)}{EA_c}dr = \frac{\rho_b g}{E}.cos(\theta)\int_0^R (R-r)dr + \frac{\rho_b}{2E}\omega^2\int_0^R (R^2 - r^2)dr \tag{6}$$

Then:

$$\delta_r = \frac{\rho_b g}{2E} cos(\theta) R^2 + \frac{\rho_b \dot{\theta}^2}{3E} R^3 \tag{7}$$

3.3 Flapwise (out of plane) deflection

To derive the out of plane and also the in-plane deflection equations, we assume a cantilever beam with the Euler-Bernoulli model as the blade of the wind turbine.

Figure 4 shows a general distribution of the lift and drag forces on a blade and we assume that the distribution is uniform, then the drag force F_D is given by:

$$F_D = \frac{1}{2} \rho_{air} v_{wind}^2 A. C_D = \frac{1}{2} \rho_{air} v_{wind}^2 . R. h. C_D \tag{8}$$

Where the positive direction is the direction of the wind, C_D is the drag coefficient of blade which is assumed to be constant along the axis of blade and $A = hR$ is the reference area of the blade. To calculate the deflection of an Euler-Bernoulli beam, we use Eq. (9).

$$\frac{d^2}{dx^2}\left(EI \frac{d^2\delta(x)}{dx^2}\right) = q(x) \tag{9}$$

Where, E is the elasticity modulus, I is the area moment of inertia, $\delta(x)$ is the deflection of beam and $q(x)$ is the load distribution along the beam. Therefore, the equation of blade tip deflection δ_z is given by:

$$\frac{d^2}{dx^2}\left(EI \frac{d^2\delta_z}{dx^2}\right) = \frac{F_D}{R} = \frac{1}{2} \rho_{air} v_{wind}^2 . h. C_D \tag{10}$$

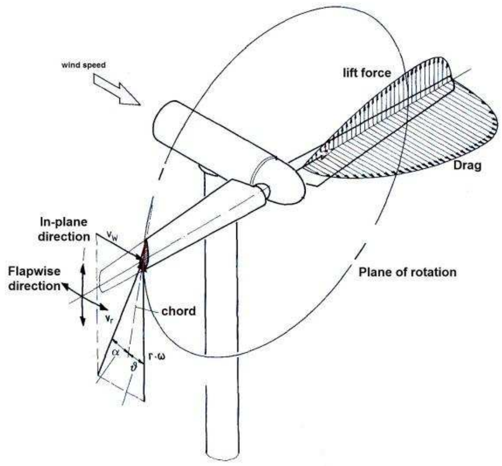

Figure 4: Lift and drag sample distribution on blade (Crozier Aina, 2011)

3.4 Inplane deflection

Forces that cause the inplane deflection of the blade are the gravitational force component normal to the blade and the lift force. Therefore, the load distribution due to the gravity and the lift is:

$$f_\theta = \frac{F_L}{R} - \frac{\rho_b}{R} A_c . R. g. sin(\theta) = \frac{1}{2} \rho_{air} . v_{wind}^2 C_L . h - \frac{\rho_b}{R} A_c . R. g. sin(\theta) \tag{11}$$

Again, using the Euler-Bernoulli equation, we have the equation for the inplane deflection:

$$\frac{d^2}{dx^2}\left(EI \frac{d^2\delta_\theta}{dx^2}\right) = \frac{1}{2} \rho_{air} . v_{wind}^2 C_L . h + \rho_b \, g. A_c . sin\,\theta \tag{12}$$

4 PROBABILISTIC MODEL

In deterministic solution we assume that all of parameters have certain values. One of the parameters that for sure has uncertainty is the wind power. Speed and direction of the wind changes time by time and to have a good estimation of system behavior, we will model it as a random variable.

Many researchers have measured wind behavior to obtain a probability distribution of wind energy and they have introduced different models. Figure 5 illustrates a graph of a typical segment of wind data.

The likelihood that the wind speed has a particular value can be described in terms of a probability density function (pdf). Experience has shown that the wind speed is more likely to be close to the mean value than far from it, and that it is nearly as likely to be below the mean as above it. The probability density function that best describes this type of behavior for turbulence is the Gaussian or normal distribution (Manwell J.F, et al., 2002). The normal probability density function for continuous data in terms of the variables used here is given by:

$$p(v) = \frac{1}{\sigma_v\sqrt{2\pi}}\exp\left(-\frac{(v_{vind}-\mu_v)^2}{2\sigma_v^2}\right) \tag{12}$$

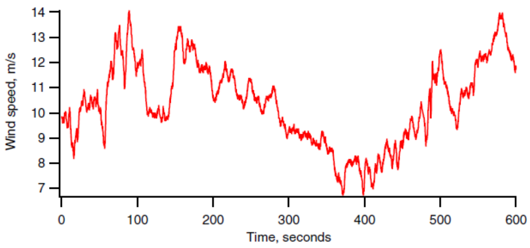

Figure 5: Sample wind data (Manwell J.F, et al., 2002)

Where, v is wind speed, μ_v is its mean value and σ_v is its standard deviation from the mean value.

Figure 6 illustrates a histogram of the wind speed about the mean wind speed in the sample data of Figure 5. The Gaussian probability density function that represents the data is superimposed on the histogram.

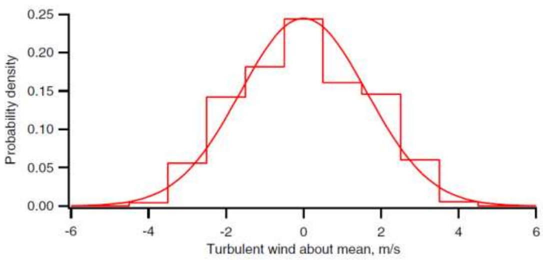

Figure 6: Gaussian probability density function and histogram of wind data (Manwell J.F, et al., 2002)

Beside the wind speed, there are parameters which are not certain, for example due to the uncertainty on manufacturing, the properties of the material, such as module of elasticity, density and geometry, are not exact. As we don't have data of the distribution of these parameters, it is better to assume a uniform distribution for them (Jaynes E. T., Bretthorst G.Larry, 2003).

5 DETERMINISTIC NUMERICAL RESULTS

To obtain numeric approximations of the equations, we use the data of a sample turbine, whose parameters shown in Table 1 (Cheney M.C., 1999; Park Joon-Young, et al., 2010).

Parameter	Sym.	Value	Unit
Wind speed	v_{wind}	12	m/s
Air density	ρ_{air}	1.15	Kg/m^3
Number of blades	N	3	-
Chord of blade	H	1.85	M
Blade length	R	45	M
Lift coefficient	C_L	1.20	-
Drag coefficient	C_D	0.08	-
Moment of inertia of blade	J_b	$7.291e6$	$Kg.m^2$
Moment of inertia of Rotor	J	$3 \times J_b$	$Kg.m^2$
Rotational damping of rotor	C	500	Nms/rad
Rotational stiffness of rotor	K	0	Nm/rad
Coefficient of rotational resistance	K_G	$4.4e5$	Nms^2/rad^2
Density of blade material	ρ_b	1600	Kg/m^3
Young modulus of blade material	E	$1.45e11$	N/m^3
Moment of cross section of blade	I	1	m^4
Cross section area of blade	A_c	0.15	m^2

Table 1: Sample wind turbine parameters

5.1 MATLAB results

First, MATLAB code is used to generate the results. Figure 7 shows the angular velocity of the wind turbine rotor which is the solution of Eq. (3).

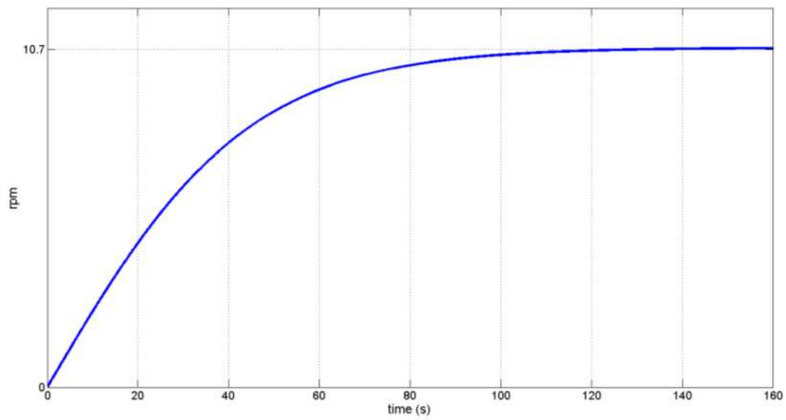

Figure 7: Deterministic solution for angular velocity of turbine rotor

As described before, we assume that the wind direction is normal to the plane of rotation of the blades and it has constant value with respect to time. In this case because of the resisting moments against rotation that grows with quadratic ratio of the wind speed, the angular velocity of rotor reaches the value of 10.7 rad/s and becomes stable after 150 seconds.

In Figure 8-a, the radial deflection of blade is shown. As shown in Eq. (7), it is the effect of the gravity and the centrifugal forces in the direction of the longitudinal axis of the blade and therefore, it is the combination of the oscillatory motion due to the term $cos(\theta)$ and the quadratic form $\dot{\theta}^2$. At time $t = 0$ the angle is zero, therefore the blade is downward and we see an initial value for the radial deflection of the blade tip, which is the elongation of the blade due to its weight. To make this clear, the deflection of two different blades which start from $\theta = 0$ and $\theta = \frac{2\pi}{3}$, are shown in Figure 9.

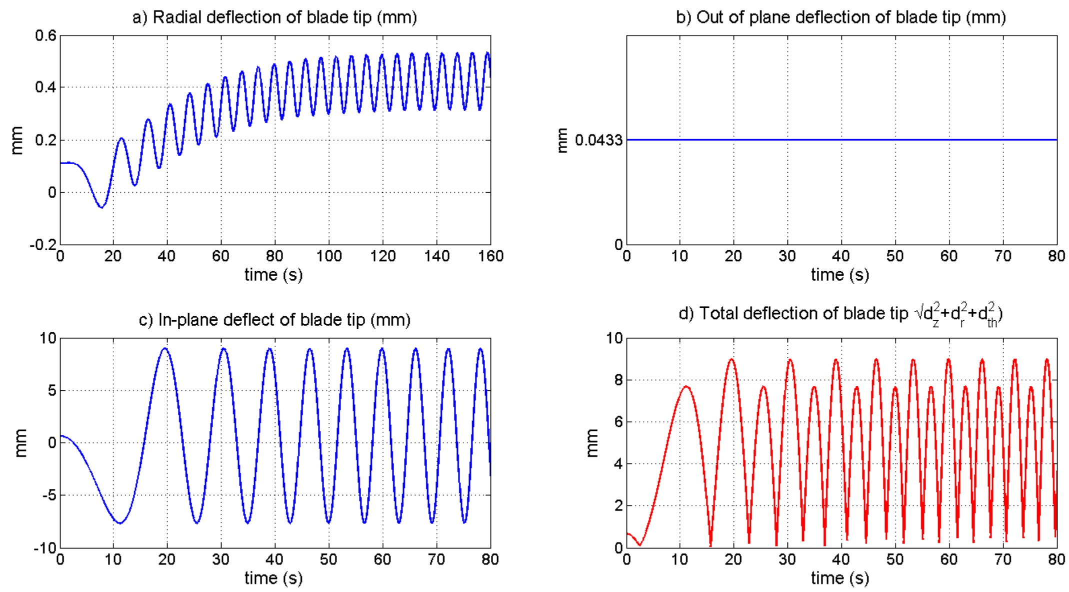

Figure 8: Deterministic solutions of deflection of blade tip

The constant value of wind speed with Eqs. (8) and (10) make the out of plane deflection independent of time and this is shown in Figure 8-b. Also the assumption of constant wind speed causes initial value for the lift force in Eq. (2) at $t = 0$ and, therefore, we see an initial value for the inplane deflection of the tip in Figure 8-c.

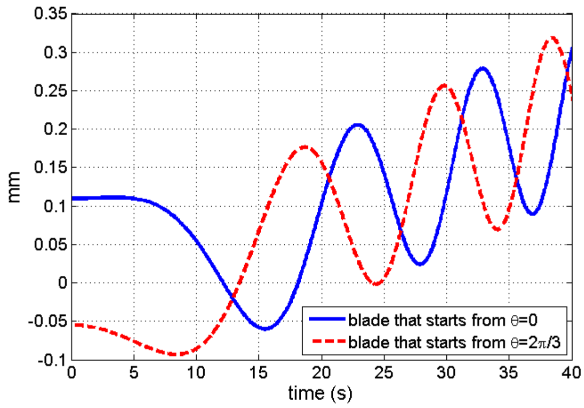

Figure 9: Comparison of the radial deflection of two different blades of wind turbine

In Figure 8 we see that most important deflection is the In-plane deflection that is because of the large dimensions of turbine and the effect of the gravity and the centrifugal forces and also small amount of the moment I.

5.2 MSC.ADAMS results versus MATLAB

Using Msc.ADAMS software, we modeled the system of our wind turbine. Because of small deformations, the rotor dynamics is not influenced by the deflections of the blade, therefore, in this model, two of blades are assumed to be rigid and the third one is modeled using multi-body beam elements. A model of this configuration with 15 elements for flexible blade is shown in Figure 10.

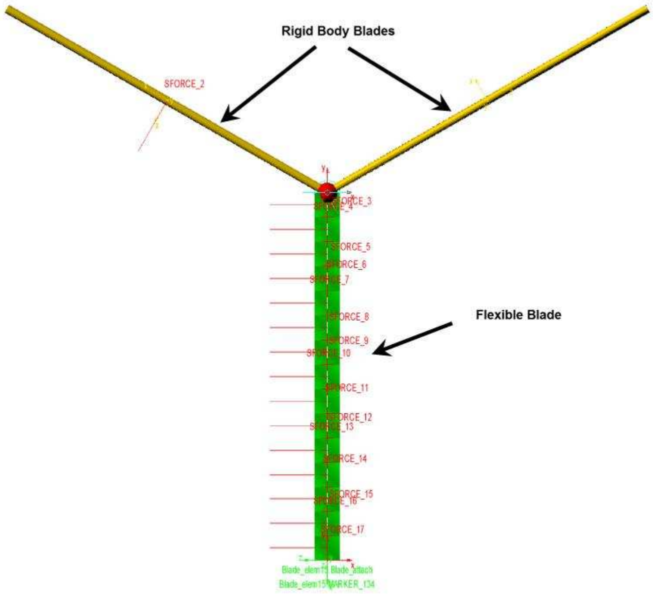

Figure 10: multi-body model of sample wind turbine in MSC.ADAMS

Here we model and simulate the sample turbine one time with 15 beam elements and the second time with 50 elements. Figure 11, Shows the comparison of angular velocity of turbine from Matlab Code, the multi-body blade ADAMS model with 15 elements and the multi-body ADAMS blade with 50 elements. It is seen that results for angular velocity are the same.

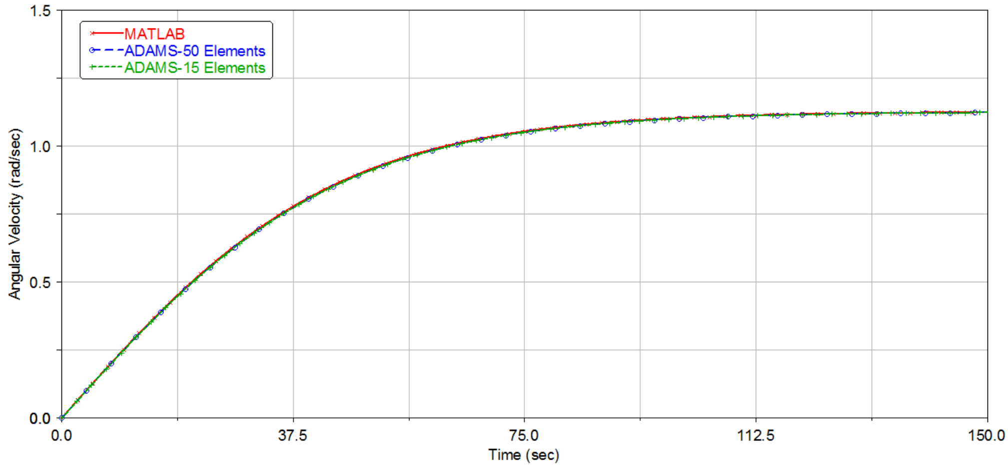

Figure 11: Comparison, angular velocity obtained from different approaches

In Figure 12, it is shown that when the number of elements in multi-body blade increases, the error of results of the radial deflection of the blade tip obtained from MATLAB and MSC.ADAMS, is negligible.

In Figure 13, it is shown that, when the number of elements in multi-body blade increases, the error of results of the In-plane deflection of the blade tip obtained from MATLAB and MSC.ADAMS is negligible too.

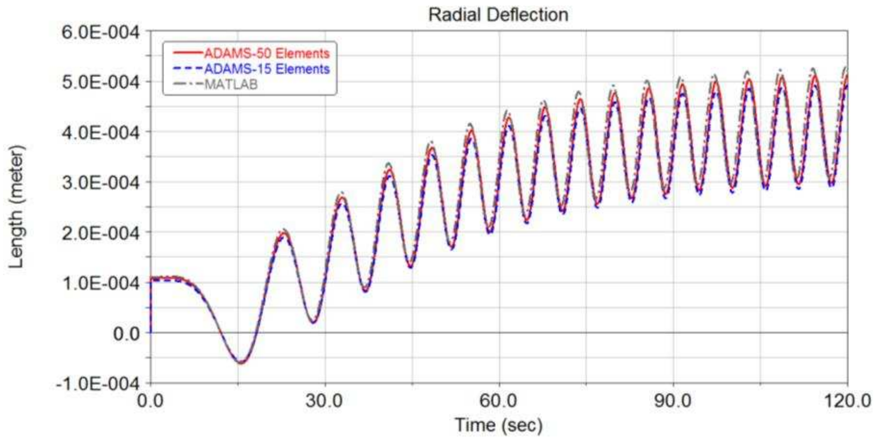

Figure 12: Comparison, Radial deflection of blade tip obtained from different approaches

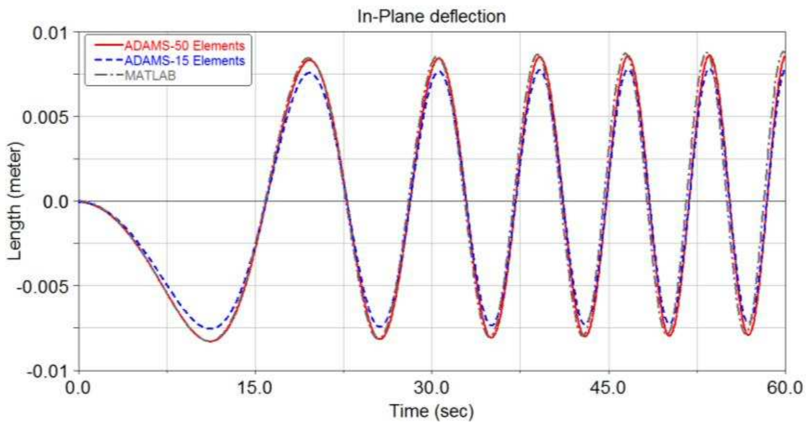

Figure 13: Comparison, In-plane deflection obtained from different approaches

6 STOCHASTIC ANALYSIS

Comparison between MATLAB and MSC.ADAMS in our wind turbine model shows that the simplified model has negligible error, but with the same accuracy, MATLAB takes 3 seconds to give the deterministic results and MSC.ADAMS takes 26 seconds. Therefore, we use simplified equations with MATLAB to analyze the stochastic model of wind turbine.

6.1 Stochastic analysis with one random variable

First we will consider only the uncertainties related to the wind speed. We assume a random distribution for wind speed with the mean value equal to its nominal value from Table 1, which is 12m/s, and the 90% confidence limits of standard deviations given, $\pm$ 10%. This means that with a probability of 90%, the wind speed will be in the interval of $[10.8\ ,13.2]\ m/s$. To compute the statistics of the response, 1000 Monte Carlo simulations were made. Figure 14, shows the mean value inside the 90% confidence limit for the angular velocity of the rotor. With these results we see that with the probability of 90%, the final value of the angular velocity of wind turbine will be within the interval, $[9.7\ ,11.8]\ rpm$, which is equal to $\pm$ 10% change of the mean value of $10.7\ rpm$.

The coefficient of variation (CV), which is defined as the standard deviation over the mean, is now analyzed at each time of simulation. Although, Figure 14-a shows that the standard deviation increases with time (larger statistical envelope), Figure 14-b shows that the CV always decreases, which is not evident from Figure 14-a. This result is due to the increasing of the mean value of the velocity.

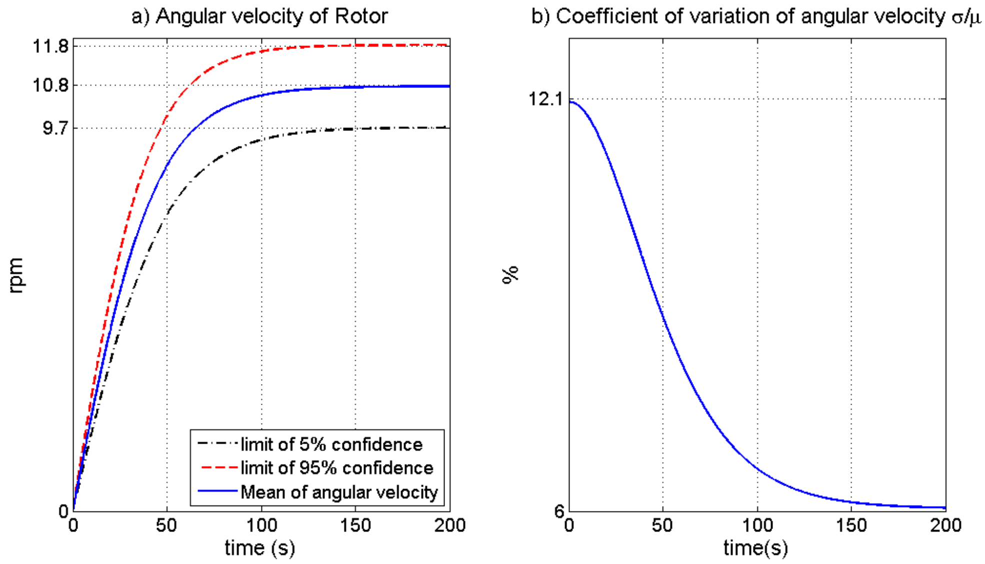

Figure 14: Stochastic analysis results for the angular velocity with wind as random variable

In Figure 15, we see that if the probability that the wind speed has the value within the interval $[9.8\,,13.2]m/s$ be 90%, then with probability of 90%, the value of the radial deflection of the blade tip is within the interval, $[0.35\,,0.55]mm$; But because of the oscillations, the interval limits are not precise. Using the CV we see that the ratio of the standard deviation of the radial deflection of the blade tip 21.6% is two times the CV of the angular velocity.

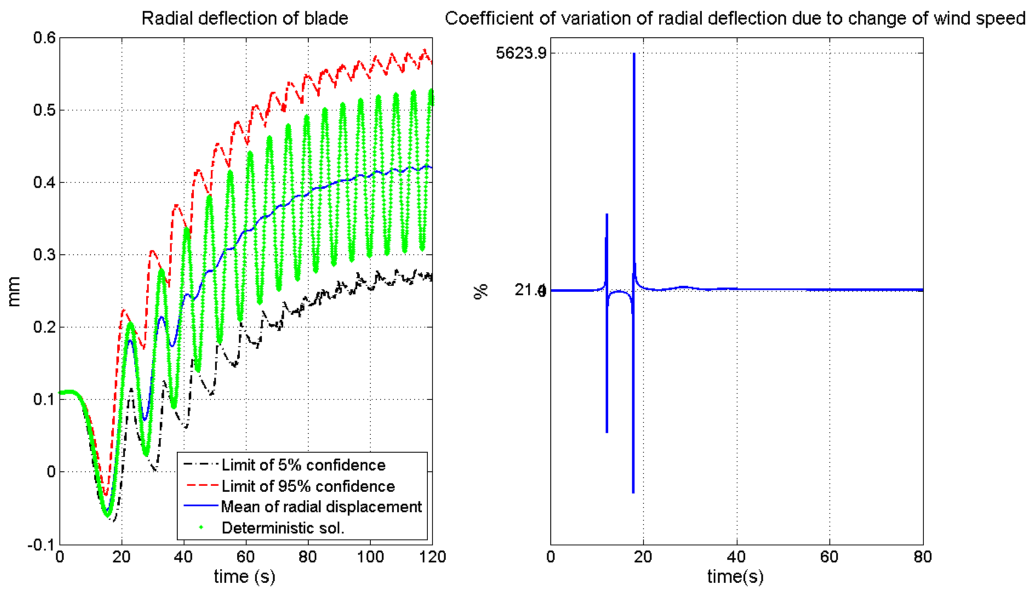

Figure 15: Stochastic analysis of the radial deflection of blade tip with wind speed as random variable

When the value of wind speed is not exact, the radial deflection is more sensitive to changes of wind speed than the angular velocity of wind turbine. Note that extreme peaks in the graph of CV belong to times that mean value has zero value.

Figure 16 shows that with the same probability distribution for wind speed, the probability that the value of the inplane deflection of blade tip be in the interval $[-7.5\,,9]mm$ is 90%. Again from the graph of the CV it is clear that the sensitivity of the inplane deflection to the changes of the wind speed, in comparison with the radial deflection, is very high. Since the mean value passes zero many times, this graph has many extreme peaks.

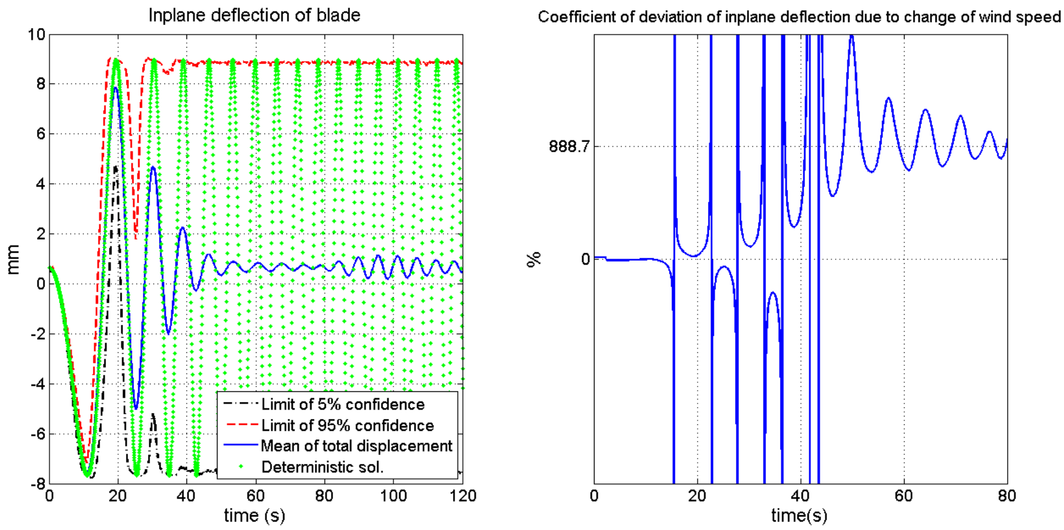

Figure 16: Stochastic process of total deflection of blade tip with wind speed as random variable

6.2 Stochastic analysis with more than one parameter as random variable

Now to bring uncertainty of other parameters of the system into account, giving a uniform random distribution to parameters of the simple model with 10% changes with respect their exact values, including $I, \rho_{air}, C_L, C_D, \rho_b, E$. We see that if each uncertain parameter of the system, with 90% probability be in the interval $[0.9\mu\,, 1.1\mu]$, the final value of the angular velocity of wind turbine will be within the interval $[9.5, 12]rpm$ with confidence of 90%.

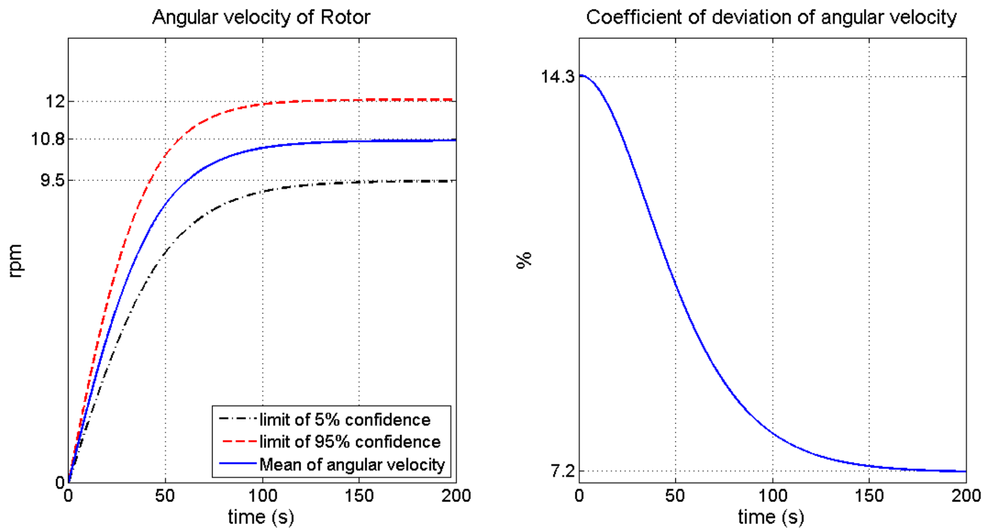

Figure 17: Stochastic process of angular velocity with all parameters as random variables, 1000 observations

In Figure 17 we can see that, taking into the account many sources of uncertainty, confidence limits of the angular velocity only have about 3% of increase in comparison to the system with only the wind as the only source of uncertainty. Because, the deflections of the blade tip, are functions of the wind speed, and comparing Figure 17 to Figure 14, we can say that our model of wind turbine is more sensitive to the changes of wind speed than other parameters.

7 CONCLUSIONS

A simple model for a three bladed wind turbine with a fixed support is introduced in this paper and then compared to a combination of flexible beam elements with multi-body model in MSC.ADAMS. With this simplified model, results of stochastic analysis show that, the role of wind speed as a random variable is the most important term in the response of the dynamical system of the blades. This model is a basic model to understand the behavior of a wind turbine to bring more details into account for more studies on the offshore wind turbine that has a big role to use renewable energy sources within next few years.

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