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Modelling and Analysis of Aeroelastic Tailoring Blade Wind Turbine Systems

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Abstract: Modelling and performance analysis of wind turbine control systems with aeroelastic tailoring blades (ATBs) are investigated. An industrial scale horizontal axis wind turbine (HAWT) model with rigid blades is firstly developed as the baseline model using the blade element momentum (BEM) theory. Designed twist angle variation distributions along blades are then introduced to the baseline model to characterise the ATB nature. The developed ATB wind turbine models are analysed by employing a baseline control system. The performances of the ATB wind turbine systems are compared with that of the baseline turbine using both nonlinear models and linearised models at selected wind speeds. The impacts of ATB design can be clearly observed from the simulation studies. Preliminary results suggest that with ATB design in wind turbines, the blade fatigue loads and the pitching activities can be reduced for large turbines without compromising the energy capture performance.

Keywords: Wind turbine control, aeroelastic tailoring blade (ATB), twist angle distribution, performance analysis, fatigue load reduction.

1. INTRODUCTION

Wind power generation is the most popular renewable energy resource that has been evolving tremendously over the decades (McKenna et al., 2016). There has been a move to larger size wind turbines (WTs) so as to achieve higher energy capture efficiency with lower cost. As the blade size increases, the unbalanced loads increase and the frequency of the spectral peaks decrease accordingly, hence the loads have increasing impacts for bigger turbines. New design technologies are being investigated to create the next generation WTs to produce more energy, at lower operation and maintenance cost, with aero-electro-mechanical systems.

Aeroelasticity is the interaction between aerodynamics, dynamics and elasticity (Holierhoek, 2013b) that exists in many structures. The aeroelastic tailoring blade (ATB) adopts the basic concept of aeroelasticity in a blade structure. It has been introduced and studied in aircraft technology (Cornette et al., 2015). ATB is a new approach in WT systems where the blades are built up with composite materials in contrast to conventional rigid blades. The use of composite materials contribute to blade behaviours such as flexibility and flutter control (Jensen et al., 2006). The trailing edge is designed to be a lot more flexible compared to the normal rigid blade (also called baseline blade in this paper). The shape of the ATB is designed with a bend-and-twist coupling structure, which ideally, is stated to have independent pitching mechanism for the blade to feather in reaction to the incoming wind.

In WT applications, the studies on ATB are mainly focused on the blade structure design. The objective is to alleviate the loading effects on the blades, and at the same time, not to jeopardise the WT power production performance. Conventionally, the design of a baseline blade has already taken into account the blade ability to withstand aeroelasticity in high altitude and also during high wind speeds. ATB in WTs is an improved version of the baseline blade. It is designed by adopting the natural behaviour of plants that have bending leaves capable to deform and return to its initial formation in response to imposed forces. This capability is also known as the adaptive behaviour. For a large scale WT, a blade with such adaptive behaviour towards incoming wind speed is believed to have lower loading effects compared to a rigid blade (Capuzzi et al., 2014a,b).

To apply ATB to large WTs, various technical problems need to be investigated on fluid dynamics, aerodynamics, control system development and others. In (Malcolm and Laird, 2003), the aeroelastic blade characteristics was modelled as equivalent beams, and the aeroelastic modelling was approximated by including information such as the elastic axes location and warping effects in the beam stiffness matrices of the structural information. The bi-

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stable laminated composite structures for morphing an airfoil section were investigated in (Diaconu et al., 2008). The bi-stable structures were introduced because they are capable to sustain at its natural equilibrium state after the occurrence of shape changes in the structures. The bi-stability behaviour is driven by temperature where it operates at colder temperature and will be lost when temperature exceeds a certain level. This characteristic suits wind energy systems since the air temperature is low at higher altitude. Morphing is another ATB concept where the blade shape can be changed in response to imposed forces and the structural integrity can be maintained (Lachenal et al., 2013).

Various ATB designs have been proposed and investigated for WTs. In (Capuzzi et al., 2014b), the distribution target of an elastic twist was defined as the difference between the target curve of a single blade and the blade root structural constraint. The use of the distribution target is to obtain the passive structural behaviour. Bending and twisting deformation is coupled in the spar cap with unbalanced laminates. In (Capuzzi et al., 2015), adaptive spar cap was designed to satisfy the adaptive behaviour of the blade structure. In their preliminary studies, the tests were implemented for a single blade structure only not for the complete rotor structure. Also the load reduction due to aeroelastic tailoring was not examined. More recently, similar research was conducted for a 10MW machine (Zahle et al., 2016), where the tool of HaWTOpt2 was used for the aerostructural design. The main parameters, such as the chord, twist, relative thickness and airfoil information in the 10MW WT, are generally comparable to 5MW ATB WTs.

New control laws need to be developed for WTs with the new aeroelastically-coupled adaptive blades. Pitch control at high wind speeds could become difficult for ATB WTs since flutter occurs in aeroelastic structures due to external forces. For this reason, ATB is designed to operate at a safe region where flutter instability will not occur. Moreover, the pitching activities must be taken into consideration carefully because they are sources of external forces. The gesture of the pitch actuator will excite the blade motion and if not fairly controlled, it will result in flutter instability. Unlike the rigid blade, where flutter is not a problem, ATB will face critical instability problem if the pitching is not properly controlled. This motivates our work in this paper. The remaining of the paper is organised as follows. In Section 2, the general idea of ATB modelling is explained by considering fundamental theory of aeroelasticity and aerodynamics. In Section 3, the ATB WT models are established via introducing three sets of twist angle distribution data into a baseline 5MW WT model. The performances of the ATB WTs are analysed in Section 4 with comparisons to the baseline WT. Both nonlinear WT models and linearised models are used to examine the ATB WT performances. Conclusions are made in Section 5.

2. WIND TURBINE ATB MODELLING

2.1 Aeroelastic Model of Airfoil

Aeroelasticity characteristics in a WT blade can be modelled following similar modelling of helicopter airfoil blades. The main feature of an ATB in aerodynamics context is the bend and twist coupling. Also the unknown elastic centers at each section of the blade and the changes of its position when the wind speed varies need to be considered. WT blades are built with a set of different airfoil profiles. Fig. 1 depicts an aeroelasticity model of an airfoil that represents one section of a blade where U is the wind speed. The spring with stiffness k_h represents the plunge and h is the up and down movement of the spring. The pitch angle is denoted by β. The left hand point, *c.g.*, is the center of gravity; the middle point is the elastic centre by which k_α denotes the stiffness in pitch; L is the lift force, M is the blade moment. x_a is the distance between the elastic center and the gravity centre, b_s is the blade semi-chord, and a is the position of elastic axis relative to the semi-chord (nondimensional). When a force is applied to the airfoil, pitch and plunge move simultaneously giving new output response. The movement also affects the flap deflection, σ, at the trailing edge. This aeroelasticity model is modified to comply with aerodynamic properties of ATB.

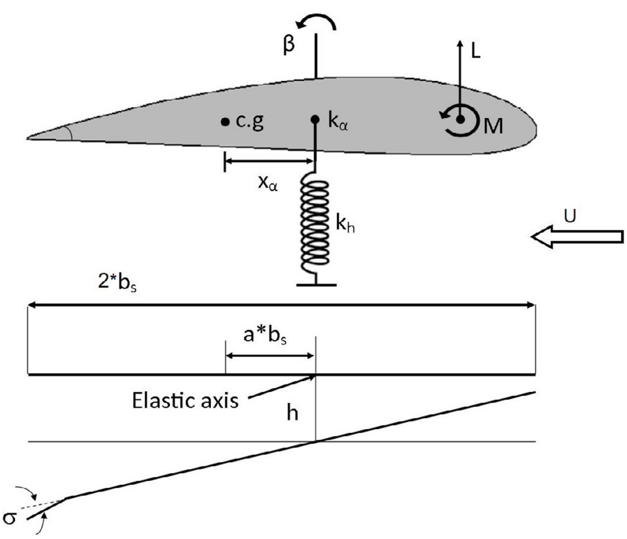

Fig. 1. Aeroelastic model of airfoil

The flexible behaviour of ATB is owing to the use of composite materials in the structure. Technically the spar cap position contributes to aeroelastic tailored features since the elastic centre is actually determined by the position of the spar cap. Composite materials also enable ATB to deform and return to its initial shape. The power production performance of ATB WTs can be examined though the C_p - λ curve, where C_p is the power coefficient and λ is the tip-speed ratio. The C_p input into the ATB power generation model can be handled similarly as to a baseline model Capuzzi et al. (2014a).

2.2 ATB Modelling

The blade element momentum (BEM) theory is applied to model a baseline wind turbine rotor. The blade is analysed individually by dividing it into sections and each section might have different airfoil profiles. The force that was caused by the wind will generally create the torque which is proportional to the power production by a factor of the blade length. As shown in Fig. 2 (Burton et al., 2001), the

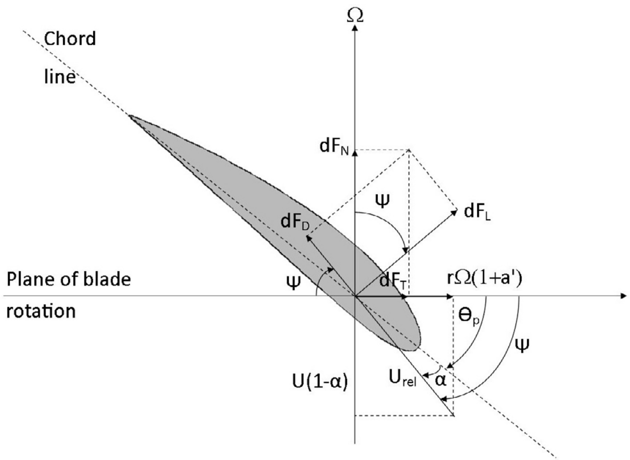

Fig. 2. Blade element velocities and forces (Burton et al., 2001)

lift force and the drag force on a span wise length of dr of each blade, normal to the wind direction, are given by

$$dF_L = \frac{1}{2}\rho U_{rel}^2 \cdot c \cdot C_L dr \quad (1)$$

$$dF_D = \frac{1}{2}\rho U_{rel}^2 \cdot c \cdot C_D dr \quad (2)$$

where ρ is the density of the air, U_{rel} is the relative wind speed, c is the chord length, C_L and C_D are the lift and drag coefficients, and dr is the span wise length.

As shown in Fig. 2, the component of aerodynamic force on each blade element in the axial direction is given by

$$dL = dF_L sin(\psi) - dF_D cos(\psi) \quad (3)$$

where ψ is the twist angle, α is the angle of attack, θ_p is the pitch angle, dF_N is the normal force on a span wise length, dF_D is the drag force on a span wise length, dF_T is the thrust force on a span wise length, dF_L is the lift force on a span wise length, U is the incoming wind speed and Ω is the generator speed.

Theoretically, an ATB can be modelled following the mechanisms in Fig. 1 and Fig. 2. As discussed earlier, an ATB is built up with composite materials and it is designed with constraints to ensure that it will operate in its stability regions. The ATB feature is introduced by altering the elastic center position of each airfoil and this will effect the deflection at the trailing edge. The response can be integrated with the BEM theory for all blade sections. The aerodynamic force and the moment for each section, as given in (4) and (5), will provide the lift force and the moment for the entire blade (Bichiou, Abdelkefi, and Hajj, 2014).

$$dL = \rho U_{rel}^2 b_s C_{L\alpha}(\alpha_{eff} - c_s\alpha_{eff}^3)dr \quad (4)$$

$$M = \rho U_{rel}^2 {b_s}^2 C_{M\alpha}(\alpha_{eff} - c_s\alpha_{eff}^3) \quad (5)$$

Here the effective angle of attack, α_{eff}, is defined by

$$\alpha_{eff} = \alpha + \frac{\dot{h}}{U_{rel}} + (\frac{1}{2} - a)\frac{b}{U_{rel}}\dot{\alpha} \quad (6)$$

where $C_{L\alpha}$ is the aeroelastic lift coefficient, $C_{M\alpha}$ is the aeroelastic moment coefficient, and c_s is a nonlinear coefficient.

3. MODELLING OF AN INDUSTRIAL SCALE ATB WIND TURBINE

The ATB WT model in this work is developed from a 5MW Supergen HAWT model with rigid blade structure, which is referred as the baseline model (Leithead and Rogers, 1996a,b). The main parameters for the baseline model are tabulated in Table 1.

Table 1. 5MW Supergen Baseline Parameters

Parameter	Value
Rated Power	5MW
Blade Length	61.63975m
Blade Sections	19
Airfoil Types	8
Rotor Radius	63m
Control Strategy	variable speed pitch regulated

To establish the ATB model using the baseline model, modifications are made mainly in the rotor dynamic part. Aeroelasticity relevant factors such as the blade shape and the airfoil design will be included in the modelling. The aeroelastic behaviour of airfoil can be ignored since the blade size is large compared with each element. Since the aeroelastic axis of the WT blade is relatively very small, it can be disregarded and the behaviour of the blade is observed based on its bending moment of the principal axes and the root axes(Holierhoek, 2013a).

Table 2. Aerodynamic twist distribution along the blade for ATB design (Degree)

Blade Section	Baseline	Model A	Model B	Model C
1	13.31	0.00	0.00	0.00
2	13.31	-0.15	-0.01	-0.01
3	13.31	-0.54	-0.09	-0.09
4	13.31	-1.01	-0.20	-0.20
5	13.31	-1.83	-0.46	-0.50
6	11.48	-2.93	-0.90	-1.02
7	10.16	-4.02	-1.49	-1.65
8	9.01	-5.21	-2.33	-2.62
9	7.80	-6.34	-3.42	-3.91
10	6.54	-6.95	-4.47	-5.10
11	5.36	-7.20	-5.00	-5.70
12	4.19	-6.82	-4.95	-5.65
13	3.13	-6.16	-4.68	-5.38
14	2.32	-5.18	-3.60	-4.31
15	1.53	-4.20	-2.56	-3.10
16	0.86	-3.51	-1.81	-2.21
17	0.37	-3.15	-1.41	-1.82
18	0.11	-2.88	-1.10	-1.55
19	0.00	-2.80	-1.00	-1.50

Extracting the twist angle distribution data, along the length of blade, from a recent study on ATB (Capuzzi et al., 2015), the new blade data are used as an input into the GL Bladed for modelling of ATB HAWT. The extracted data are altered to comply with the 61m blade of the 5MW Supergen HAWT (see Table 2). As presented in (Capuzzi et al., 2014a,b), there are three sets of data used in this study corresponding to Models A, B and C, respectively, in the following discussions. Model A is the blade design with target twist angle distribution at the rated wind speed. Models B and C are the blade design with similar concept as model A but further enhanced with finite element linear and nonlinear approaches, respectively. The distance along the blade is normalised to fit into the interpolated data. Applying the data in GL Bladed, the blade geometry is altered to follow the ATB behaviour. The twist angles in the blade geometry sections, are modified by interpolating the literature data in (Capuzzi et al., 2015) to fit into these sections of the case study machine.

4. PERFORMANCE ANALYSIS OF ATB WT SYSTEM

4.1 Performance Analysis with Nonlinear Models

Power coefficient values generated from GL Bladed are used to indicate efficiency of the WT systems. Fig. 3 illustrates the power coefficient profiles without a controller. Fig. 4 shows the results with the baseline controller developed by the Wind Energy research group from Strathclyde University.

It can be seen that, compared with the system without control, a better power efficiency performance is achieved for all the blade data sets with the baseline controller. Under the baseline control, it can also be observed that in the above-rated region, the power efficiency with ATB are higher than that of the baseline WT. The peak values in the C_p - λ curves, i.e. C_p^{max}, from the three ATB models can be observed to be lower than the baseline peak value, but the neighbouring regions of ATB models around C_p^{max} are wider. This suggests that ATB WTs have wider operation regions for high efficiency power production.

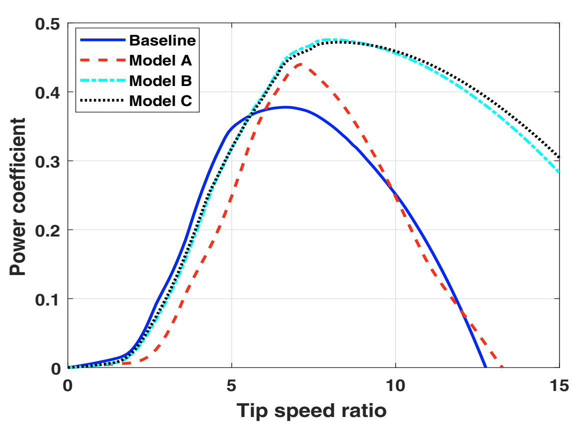

Fig. 3. Power coefficient profiles without control

Fig. 5 and Fig. 6 show the effects of different models on rated speeds and pitch activities with and without control. It is apparent that the rated wind speed and the pitching are affected by ATB characteristics. The rated wind speed for all models are varied in the range of 10 m/s to 12 m/s.

4.2 Performance Analysis with Linearised Models

In the above discussions, nonlinear models produced from GL Bladed were used in simulation studies. For WT control systems, linearised models are often used for controller development. For both the the baseline model and the ATB models, their linearised versions are generated at selected wind speeds using the embedded linearisation tools in GL Bladed. The results are examined in frequency domain using Bode plots, which are convenient for checking

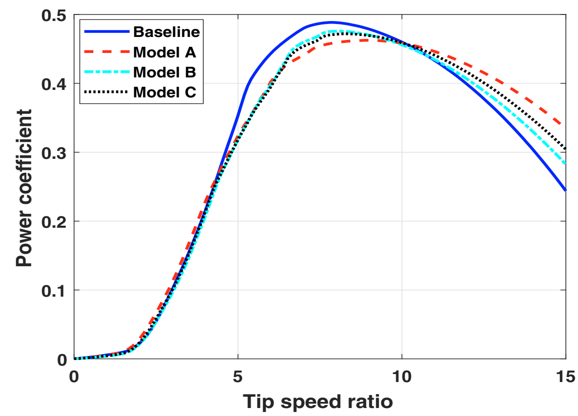

Fig. 4. Power coefficient profiles with baseline control

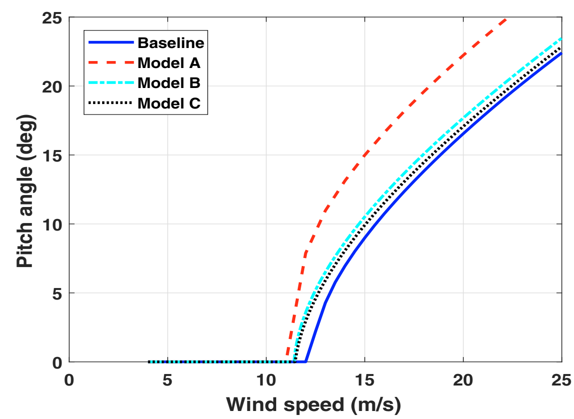

Fig. 5. Pitch angle without control

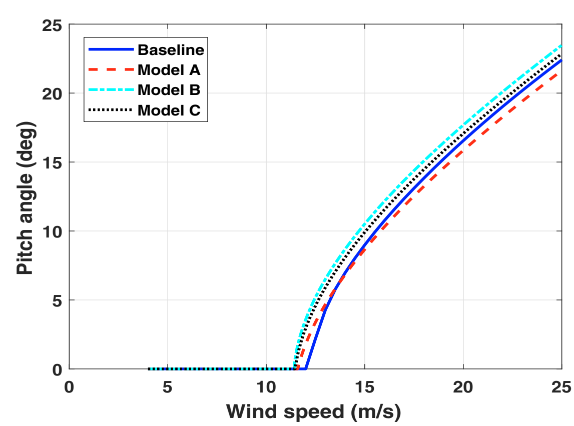

Fig. 6. Pitch angle with baseline control

the blade and tower frequencies. Bode plots are also helpful for WT controller development where the gain cross-over frequency is expected to be at 1 rad/s to match with the wind speed characteristics.

The linearised model is a simplification of the nonlinear model. Although the performance of a linearised WT model may not be as accurate as the nonlinear WT model, the output generated from the linearised model is comparable to the nonlinear model for this case study WT. In this simulation, the models are linearised at 22 operating points of wind speed from 4 m/s to 25 m/s. Due to the space limitation, only the results at 15 m/s mean wind speed are used for discussions.

Fig. 7 shows the Bode plots for the transfer function model from the generator torque to the generator speed obtained at 15 m/s mean wind speed, from which it can be seen that at lower frequencies, the baseline model and the ATB models have similar responses. At higher frequencies, the tower frequency is shifted from the baseline's 10.7 rad/s to the ATB's 14.2 rad/s. The changes in the physical twist angle distribution contributes to the shifting of the tower frequency value. In the setting within GL Bladed, the blade mode is chosen to be 1 instead of 2 for the purpose of reducing spectra peaks of the blades at high frequencies. It is shown in Fig.7 that the peak presents at 25 rad/s in the baseline model does not occur in those ATB models. Removing spectra peaks shows improvement in load reduction since these feature peaks are related to the structure modes of a WT.

Fig. 8 presents the Bode plots of the transfer function between the pitch angle to the generator speed. At higher frequencies, similar peak shifting phenomenons were observed as in Fig. 7. It can also be observed from Fig. 8 that the phase angle of the ATB models drops 360^o compared to the baseline model. In both Figs. 7 and 8, the peak magnitudes of the ATB models are slightly reduced compared to the baseline model's peak. This again suggests that improved fatigue load reduction performance can be achieved through ATB WT design.

Another important metric is the blade root bending moment at above rated wind speeds. The flap-wise root bending moment of the blade (M_y) can be used to evaluate the effects of fatigue loading on blades. Conceptually, altering physical twist angle distribution of the blade will change its root bending moment. The results in Fig. 9 are calculated from the transfer function between the pitch angle to the blade root bending moment. It can be seen that at higher frequencies the peaks are noticeably trimmed off for the ATB models compared to the baseline model. This indicates the potential of reducing blade fatigue loads through ATB design.

Simulations have been conducted in time domain to examine the power production and the pitching activities above rated under the baseline control. It can be seen from Fig. 10 that the ATB turbines produce the same rated power around 5MW as the baseline WT. The pitch angles of the ATB WT models appear to be lower than that of the baseline model, which is an expected improvement since the ATB turbines have adaptive behaviour in blades.

5. CONCLUSIONS

In this paper, the preliminary studies on modelling and control of industrial-scale ATB wind turbines are reported. Since the ATB design in wind turbines are still in its early exploration stage, as far as we know, there are no models available nor real industrial data to reveal the aeroelastic nature of such machines. Most of the ATB modelling is carried out using computational fluid dynamics (CFD) simulation, which is computationally demanding for control purpose. Our modelling have been conducted by using aeroelastic blade data extracted from literature (also in early stage investigation) and we expand and interpolate the data to case study baseline model.

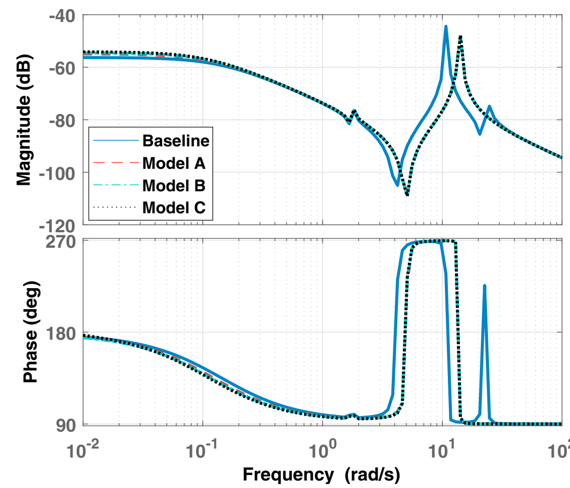

Fig. 7. From generator torque to generator speed at 15 m/s

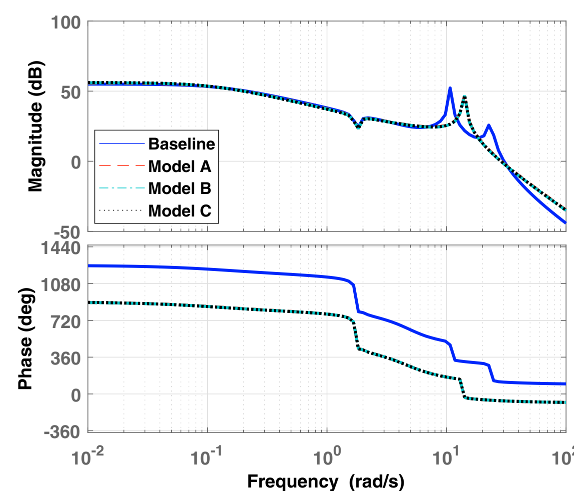

Fig. 8. From pitch angle to generator speed at 15 m/s

Both nonlinear models and linearised models at selected wind speeds are used in the simulation studies. The preliminary results show the impact of altering the twist angle distribution along the blade on various turbine performances such as power coefficient, rated speed, spectrum peaks, pitching activities, etc. Compared with the baseline WT model, at above-rated operation region, improvement in fatigue load reduction and reducing pitching activities can be observed from the ATB WTs without compromising the power production at above rated.

At below rated wind speeds, experimental results on ATB WTs reveal that the torque control may not assure tracking of the C_p^{max} curve as expected for rigid-blade machines. For ATB WTs at below rated, one alternative option is to control the operation in a nearby region of the C_p^{max} profile instead of controlling it to a single value of C_p^{max} for each wind speed.

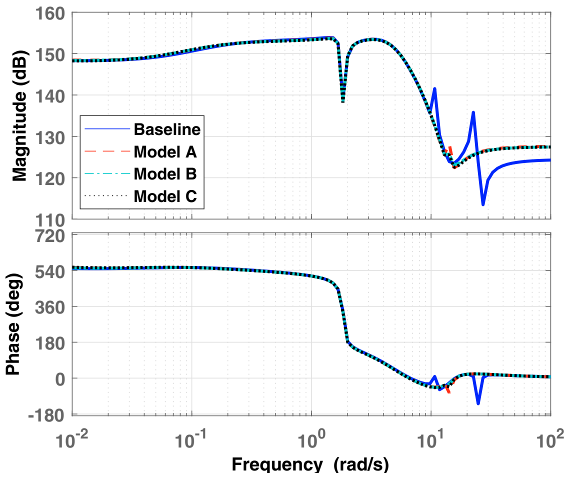

Fig. 9. From pitch angle to blade root bending moment at 15 m/s

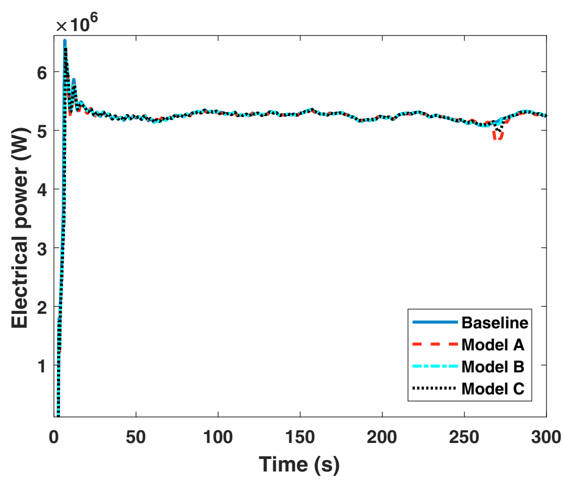

Fig. 10. Power output at 15 m/s

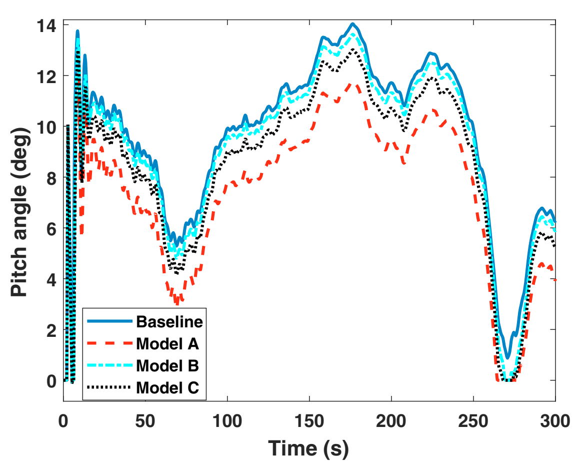

Fig. 11. Pitch angle at 15 m/s

A baseline controller is applied to all models for the simulation studies. The results show that the baseline controller works mostly well. However, there will be rooms for improving controller design by taking into account ATB WTs' adaptive properties. Potentially, WTs with ATBs can be controlled by reduced pitch activities, while perform to power standards comparable to current rigid blade turbines, which will help to reduce complexity, cost and maintenance of wind turbines.

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