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Individual pitch control of wind turbines using local inflow measurements

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Abstract: This paper describes a model based control approach for individually adjusting the pitch of wind turbine blades and thereby attenuating the effect of asymmetric wind loads. It is assumed that measurements of local inflow along each blade are available. This effectively provides an estimate of the load distribution along the blades. The load estimates are used in a predictive setup where inflow measured by one blade is used as basis for calculating future loads for the other blades. Simulations with a full stochastic wind field illustrate the effectiveness of the individual pitch controller as compared to controlling the pitch collectively.

1. INTRODUCTION

Wind turbines are subject to great attention due to their increasing importance in the energy production and their environmental properties. The demand for more and more power has set a trend for increasingly larger turbines. Increasing power efficiency and reducing mechanical and structural stress is therefore very important. One way to achieve this is through advanced model based control designs which explicitly take into account the challenging characteristics of wind turbines.

On the majority of modern wind turbines both the torque of the generator (variable speed control) and the pitch of the blades (pitch control) are used as control parameters for dealing with these challenges. In most documented research the pitch of the blades are controlled collectively applying a wide variety of methods. This ranges from linear methods such as LQ, LQG, and $\mathcal{H}_\infty$ (Bossanyi (2003b), Xin (1997), Grimble (1996)) to adaptive techniques (Johnson et al. (2006)) and nonlinear methods such as feedback linearization (Leith and Leithead (1997), Thomsen and Poulsen (2007)).

Collective pitch control has one major drawback: it is not possible to compensate for the asymmetric loads caused by the wind field. This can however be dealt with by using a strategy where the blades are pitched individually. Documented research on individual pitch control is more sparse. Most of the approaches assume that a collective pitch controller has been designed for the turbine and basically designs the individual pitch controllers as additional loops around the system (usually using classical control). This approach has eg. been taken in Bossanyi (2003a) and Larsen et al. (2005). However it is more natural to formulate the turbine control problem as a MIMO problem taking into account the inherent cross-couplings in the system. A step in this direction was taken in Stol et al. (2006) where the LQ method was used based on a periodic linear system description. The system description was obtained through numerical linearization of the aeroelastic code FAST. However, an analytical model suitable for model based individual pitch control has not been published.

The core contribution of this paper is the development of model elements for systematically designing individual pitch controllers. More specifically we derive a simplified model of the aerodynamics ie. a simplified description of the relation between the wind and the rotor loads which is suitable for individual pitch control. The wind is assumed to be measured through flow measurement devices along the blades. This knowledge can be used to gain information about future loads on the blades. It is shown how to use this as a model element suitable for controller design. Finally, it is illustrated how to combine these model elements (ie. model of aerodynamics and loads) together with a simple model of a wind turbine and formulate an optimal control problem. Simulations are used to illustrate the advantages as compared to collective pitch control.

2. METHOD

Wind turbines extract power from the wind by converting the wind to lift forces using aerodynamic blades. This gives rise to a torque at the roots of the blades which causes a drive shaft to rotate inside a generator. This in effect produces energy. The presence of the wind turbine cause the wind field to slow down and rotate as indicated in Fig. 1. This interaction between the blades and the wind is very complex. Highly accurate models of the interaction are therefore unsuitable for model based controller designs. This section describes the approach we have taken in order to deal with this complexity. More specifically the following is described:

- Simplified model of aerodynamics and wind field
- Prediction of future loads based on local inflow measurements

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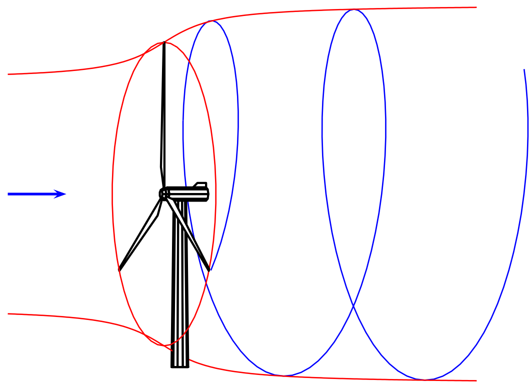

Fig. 1. Sketch of a horizontal axis wind turbine

2.1 Simplified model of aerodynamics and wind field

Simplified models of both the aerodynamics and the wind field are usually used when designing collective pitch controllers for wind turbines (See eg. Xin (1997), Thomsen and Poulsen (2007)). These models do not carry enough spatial information such that individual pitch controllers can be designed. However, the same general ideas used in collective pitch control can be extended to individual pitch control. In the following we explain how.

With blade element momentum theory (BEM) it is possible to calculate how much torque that is delivered at the blade root owing to the wind field (See eg. Hansen (2000)). This is in general an iterative procedure which cannot be used as a model element in a model based control design. Assuming a uniform wind field one can, however, calculate static relations from the wind speed v, rotational speed ω_r and pitch angles θ_1, $\theta_2, \ldots,$ θ_b (where b denotes the number of blades) to the root moments normal T_{N_i} and tangential T_{T_i} to the rotor disk ie.

$$T_{N_i} = g_N(v, \omega_r, \theta_i), \quad T_{T_i} = g_T(v, \omega_r, \theta_i) \tag{1}$$

where $i = 1, 2, \ldots, b$. It is important to note that induction is implicitly included in these relations. Hence v is the wind speed *without* induction. Induction is the phenomena that the presence of the rotor decreases the wind speed in the axial direction (axial induction) and cause the wind field to rotate (tangential induction). In Fig. 2 this is illustrated for a cross-section element (airfoil) of a wind turbine blade rotating with angular velocity ω_r. The local radius is r. a and a' are called the axial and tangential induction factors respectively. v_r is the actual wind speed experienced by the blade element which has the angle of attack α. These two quantities, v_r and α, constitutes the so called local inflow measurements.

The total tangential torque $T_T = \sum_{i=1}^{b} T_{T_i}$ with T_{T_i} given in (1) is widely used when designing collective pitch controllers. Since the wind field is nonuniform in real life the wind field is usually approximated with a single scalar that describes it as a whole. This is denoted the effective wind speed. Motivated by this approach we individually assign effective wind speeds for each blade to obtain spatial resolution. We will denote these effective winds by $\bar{v}_1$, $\bar{v}_2$, $\ldots$, $\bar{v}_b$. The definition of effective wind speed which has been found suitable in this work is based on the definition in Sørensen et al. (2002). The definition is extended to comply with our specific needs.

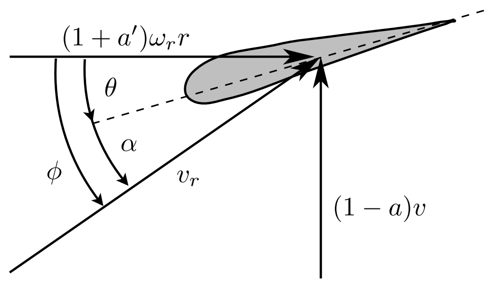

Fig. 2. Wind interaction with a cross-sectional element (airfoil) of a wind turbine blade.

To derive the effective wind speeds we linearize the blade root moment with respect to the wind along the span of the blade.

$$T_{N_i} = T_{N_i,0} + \int_{r_0}^{R} W_{N_i}(r)(v_i(r) - V_0)dr \tag{2}$$

$$T_{T_i} = T_{T_i,0} + \int_{r_0}^{R} W_{T_i}(r)(v_i(r) - V_0)dr, \tag{3}$$

where

$$W_{N_i}(r) = \frac{\partial T_{N_i}}{\partial v_i(r)} \quad W_{T_i}(r) = \frac{\partial T_{N_i}}{\partial v_i(r)}, \ i = 1, 2, \ldots, b \tag{4}$$

and $i = 1, 2, \ldots, b$. V_0 is the mean wind speed of the wind field. r_0 is the hub radius and R is the rotor radius. $W_{T_i}(\cdot)$ and $W_{N_i}(\cdot)$ can be regarded as influence or weight coefficient.

The effective wind speeds are now introduced as the constant quantities $\bar{v}_{N_i}$ and $\bar{v}_{T_i}$ that results in the same moments when substituting $v_i(r)$ in the equations (2)-(3):

$$T_{N_i} = T_{N_i,0} + \int_{r_0}^{R} W_{N_i}(r)(\bar{v}_{N_i} - V_0)dr \tag{5}$$

$$T_{T_i} = T_{T_i,0} + \int_{r_0}^{R} W_{T_i}(r)(\bar{v}_{T_i} - V_0)dr \tag{6}$$

where $i = 1, 2, \ldots, b$. Equating (2)-(3) with (5)-(6) leads to the following expression for the effective wind speed.

$$\bar{v}_{N_i} = \frac{\int_{r_0}^{R} W_{N_i}(r) v_i(r) dr}{\int_{r_0}^{R} W_{N_i}(r)} \tag{7}$$

$$\bar{v}_{T_i} = \frac{\int_{r_0}^{R} W_{T_i}(r) v_i(r) dr}{\int_{r_0}^{R} W_{T_i}(r)}, \ i = 1, 2, \ldots, b \tag{8}$$

What needs to be determined are the functions $W_{N_i}(\cdot)$ and $W_{T_i}(\cdot)$. Calculating these "exactly" (using BEM) involves total knowledge of the entire wind field swept by the blades. However, as stated in Sørensen et al. (2002) a typical load distribution will be approximately proportional to r eg. $W_{N_i} = K \cdot r$ where K is some constant. It is easily verified that this results in $\bar{v}_{N_i} = \bar{v}_{T_i}$. Better weights may be attained using knowledge of the blade elements, but either way we will be dealing with an approximation. In connection to real-time control this simple weight is also more suitable from a computational point of view. In the following we assume that:

$$\bar{v}_{N_i} = \bar{v}_{T_i} = \bar{v}_i \tag{9}$$

Using these effective wind speeds in the relations (1) we have directly a simplified model of the aerodynamics suitable for model based individual pitch control:

$$T_{N_i} = g_N(\bar{v}_i, \omega_r, \theta_i), \quad T_{T_i} = g_T(\bar{v}_i, \omega_r, \theta_i) \tag{10}$$

We have now established a simplified relation between the velocities (without induction) along the blades $v_i(r)$ and the root moments by relating $v_i(r)$ with $\bar{v}_i$. Knowing $v_i(r)$ we can therefore take this relation into consideration in a model based controller. However, we cannot measure $v_i(r)$ since this is the wind as it would look *without* axial induced speeds caused by the presence of the rotor. What we can measure is the local inflow along the blade ie. α and v_r as seen in Fig. 2. Therefore, in order to attain $v_i(r)$ it is necessary to calculate the axial induction factor a. Using basic BEM theory (See Hansen (2000)) we can approximate a by:

$$a = \frac{1}{\frac{4\sin(\phi)^2}{s \cdot c_N} + 1}, \quad s = \frac{c \cdot b}{2\pi r} \tag{11}$$

where c is the local cord length and c_N is a blade coefficient.

In summary, by measuring the angle of attack and the relative velocity it is possible to estimate the effective wind speed for each blade and use these in the controller design. The total algorithm for attaining estimates of the root moments based on inflow measurements is summarized in table 1.

Table 1. Algorithm for attaining root moments based on inflow measurements

	Action
1	Measure α and v_r along the blade
2	Use BEM theory to attain $v_i(r)$
3	Use a suitable weight to calculate the effective wind speeds
4	Calculate moments based the simplified aerodynamics

Remark 1. It is possible to measure the inflow using flow measurement devices such as pitot tubes (See Larsen et al. (2005) and references therein). These measurements will in practice be of varying reliability, however this issue is beyond the scope of this work.

Remark 2. The inflow can be measured at discrete points along the blades. Therefore, when applying the method all the integrals will be substituted by finite sums.

2.2 Model for future disturbances

The setup presented so far illustrates that it is possible to take into account the presence of an asymmetric wind field in a model with a complexity suitable for model based control. However, if our model does not describe the future evolution of the loads this puts heavy restrictions on the controller design.

The effective wind speeds $\bar{v}_i$ are independent of the induction caused by the presence of the rotor. Consequently it can be seen as a measure of the power in the wind which is independent of the presence of the rotor. It is therefore natural to setup a model of the evolution of $\bar{v}_i$.

In model based collective pitch control a common approach is to setup a stochastic model of the effective wind (See eg. Xin (1997)) and incorporate this model in the controller design. We will apply a more simple approach which is made possible through the local inflow measurements. When a blade passes through an area on the rotor disk we estimate the effective wind speed for this blade as described earlier. The slowly varying trends in the wind (such as wind shear) are likely to be present from the time that one blade passes an area to the next blade does. This estimate can therefore be used as an assessment of the future wind speed experienced by the next blade to pass through the area. Fig. 3 illustrates the idea

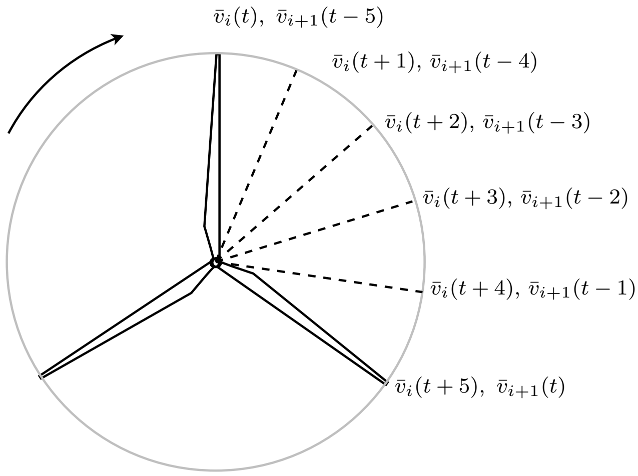

Fig. 3. The blades enter the same spatial regions. Winds experienced by one blade are therefore correlated with winds experienced by the next blade.

This just needs to be formulated systematically such that it can be included in a controller design. The following discrete time model can be used to tell our control design that we know the wind evolution H_d time steps into the future.

$$w_i(k+1) = \underbrace{\begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}}_{F_i} w_i(k) \tag{12}$$

$$d_i(k) = \underbrace{[1\ 0\ \cdots\ 0]}_{M_i} w_i(k), \ i = 1, 2, \ldots, b \tag{13}$$

where the state vector is

$$w_i(k) = [\Delta\bar{v}_i(k)\ \Delta\bar{v}_i(k+1)\ \cdots\ \Delta\bar{v}_i(k+H_d)]^T \tag{14}$$

ie. it contains our knowledge of the wind H_d time steps into the future. The total effective wind speed is

$$\bar{v}_i(k) = d_i(k) + V_0 \tag{15}$$

where V_0 is the mean wind speed. The total wind model for all blades becomes:

$$w(k+1) = Fw(k) \tag{16}$$

$$d(k) = Mw(k) \tag{17}$$

where $w(k) = \left[w_1^T(k)\ w_2^T(k)\ \cdots\ w_b^T(k)\right]^T$. F and M are block diagonal matrices eg. $F = \mathrm{diag}(F_1,\ F_2, \ldots, F_b)$.

3. CONTROL DESIGN

In this section we combine the simplified aerodynamic model derived in the previous section with a dynamic model of the wind turbine. The model is linearized, discretized and augmented with the predictive wind model (12)-(13). We then design a controller using the linear quadratic method. The controller is designed for operation at high wind speeds where the rotational speed and the produced power should to be stabilized at nominal values.

3.1 Nonlinear design model

The wind turbine model used in this work models the following dominant characteristics: Aerodynamics, mechanics, actuators and a variable speed generator. The interconnection of the model parts is shown in Fig. 4.

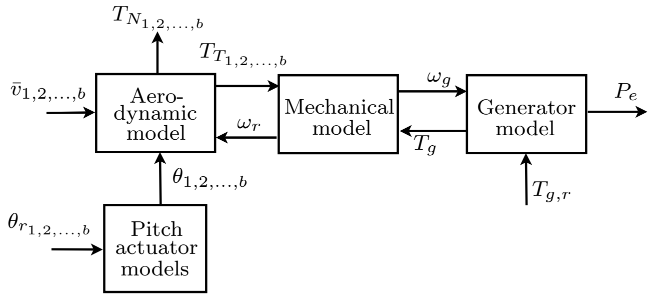

Fig. 4. Diagram showing the interconnection between the model parts

The aerodynamics is simply described by the relations (10) and the pitch actuator systems are approximated by first order systems ie.:

$$\dot{\theta}_i = -\frac{1}{\tau_\theta}\theta_i + \frac{1}{\tau_\theta}\theta_{r,i},\ i = 1, 2, \ldots, b \tag{18}$$

A schematic of the mechanics is shown in Fig. 5. The

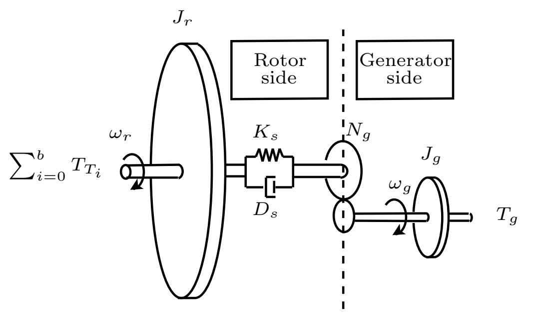

Fig. 5. Schematic of mechanics

leftmost and rightmost disks represent the inertia on the rotor side J_r and the generator side J_g of the transmission respectively. The small disks in the middle represents the gear ratio N_g in the transmission. The flexibility of the shaft connected to the blades is represented by an equivalent spring constant and damping. The dynamic equations for the mechanics are:

$$\dot{\omega}_r = \frac{\sum_{i=1}^{b} T_{T_i}}{J_r} - \frac{\omega_r D_s}{J_r} + \frac{\omega_g D_s}{J_r N_g} - \frac{\delta K_s}{J_r} \tag{19}$$

$$\dot{\omega}_g = \frac{\omega_r D_s}{J_g N_g} - \frac{\omega_g D_s}{N_g^2 J_g} + \frac{\delta K_s}{N_g J_g} - \frac{T_g}{J_g} \tag{20}$$

$$\dot{\delta} = \omega_r - \frac{\omega_g}{N_g} \tag{21}$$

where δ is the torsional deflection of the flexible drive shaft.

The power produced by the generator is given as (assuming a lossless generator):

$$P_e = \omega_g T_g \tag{22}$$

where the generator torque T_g can be varied. The torque demand $T_{g,r}$ versus the actual torque T_g is related through a first order response:

$$\dot{T}_g = -\frac{1}{\tau_T} T_g + \frac{1}{\tau_T} T_{g,r} \tag{23}$$

Combining all differential equations the result is a $(4+b)$th order nonlinear state space system

$$\dot{x} = f(x, u, d) \tag{24}$$

where the state x, input u and disturbance vector d are

$$x = [\omega_r\ \omega_g\ \delta\ \theta_1\ \theta_2\ \cdots\ \theta_b\ T_g]^T \tag{25}$$

$$u = [\theta_{r,1}\ \theta_{r,2}\ \cdots\ \theta_{r,b}\ T_{g,r}]^T \tag{26}$$

$$d = [\bar{v}_1\ \bar{v}_2\ \cdots\ \bar{v}_b]^T \tag{27}$$

The physical output of the wind turbine is naturally P_e. However with control in mind it is natural to specify an output vector with the variables which we want to control. As mentioned earlier these are first and foremost the rotational speed and the generator power. Additionally we also want to attenuate the asymmetric loads. This leads to the following output vector:

$$y = h(x, d) \tag{28}$$

$$= \left[\Delta\omega_g\ \Delta P_e\ \Delta T_{N_{1,2}}\ \Delta T_{N_{2,3}}\ \cdots\ \Delta T_{N_{b-1,b}}\right]^T \tag{29}$$

Where Δ denotes deviations away from nominal values and $\Delta T_{N_{i,j}} = T_{N_i} - T_{N_j}$ ie. the difference between the root moments normal to the rotor disk for blade i and j. If we stabilize these differences at zero the loads will be perfectly symmetric.

3.2 Linear design model including wind model

The system equation (25) and the output equation (28) are linearized at conditions corresponding to a given mean wind speed. Furthermore, the model is discretized. The resulting model is:

$$x(k+1) = Ax(k) + Bu(k) + D_1 d(k) \tag{30}$$

$$y(k) = Cx(k) + D_2 d(k) \tag{31}$$

where x, u, y and d here denotes deviations from the point of linearization rather than absolute values. To include the predictive model of the wind in the design we augment the model with the wind model. Furthermore, to attain zero steady state error we add integral states corresponding to the vector y. The integral state vector is denoted y_I. The total augmented system becomes.

$$\begin{bmatrix} x(k+1) \\ y_I(k+1) \\ w(k+1) \end{bmatrix} = \begin{bmatrix} A & 0 & D_1M \\ C & I & D_2M \\ 0 & 0 & F \end{bmatrix} \begin{bmatrix} x(k) \\ y_I(k) \\ w(k) \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} u(k) \quad (32)$$

$$y(k) = [C \;\; 0 \;\; D_2M] \begin{bmatrix} x(k) \\ y_I(k) \\ w(k) \end{bmatrix} \quad (33)$$

3.3 Linear controller

Having set up the linear design model the controller is designed using the standard LQ algorithm that gives a feedback law which minimizes the infinite horizon cost:

$$V = \sum_{k=0}^{\infty} \left|\left| \begin{matrix} y(k) \\ y_I(k) \end{matrix} \right|\right|_Q^2 + ||u(k)||_R^2 \quad (34)$$

where $||q||_W^2 = q^T W q$. The result is the linear feedback law

$$u(k) = -K \begin{bmatrix} x(k) \\ y_I(k) \\ w(k) \end{bmatrix} \quad (35)$$

In this design procedure we indirectly tell the design algorithm that we know the evolution H_d time steps into the future.

Remark 3. Solving for the feedback gain K will naturally be computationally extensive when H_d is large. However, this is an offline calculation and will have no influence when doing real time control.

4. SIMULATIONS

In this section results from simulations with the described controller design is presented. The parameters for the model (except the aerodynamics) are seen in table 2.

Table 2. Parameters for simulation model

Parameter	Value
b	3
N_g	87.97
K_s	$5.6 \cdot 10^9$ N/rad
D_s	$1 \cdot 10^7$ N/rad·s
J_g	53 kg·m^2
J_r	$2.956 \cdot 10^6$ kg·m^2
R	36.75 m
τ_θ	0.15 s
τ_T	0.1 s

The nominal speed of the turbine is $\omega_g = 185$ rad/s and the nominal power is $P_e = 1.5$ MW. The parameter values are adopted from a wind turbine model (WindPACT 1.5 MW) included in the distribution of the aeroelastic code `FAST`. `FAST` is developed by the National Renewable Energy Laboratory (NREL) in USA. To simulate realistic wind turbine aerodynamics a BEM algorithm is used to calculate the loads on the blades. The code `TurbSim` developed by NREL is used for generating a stochastic wind field. The wind time-series which is generated by `TurbSim` is a 10×10 grid of correlated point winds evolving in time. The mean wind speed for the times series is $V_0 = 16$m/s and an exponential shear is superimposed on the wind field. As basis for comparison the individual controller is compared to a collective pitch controller designed using the LQ method. The collective and individual controller designs are equivalent where possible. A sample time of $T_s = 0.01$s is used for the controllers and a prediction horizon of $H_d = 40$ is used in the individual pitch controller design.

Fig. 6 shows the moments normal to the rotor disk for each blade when the turbine is controlled by both controllers. It

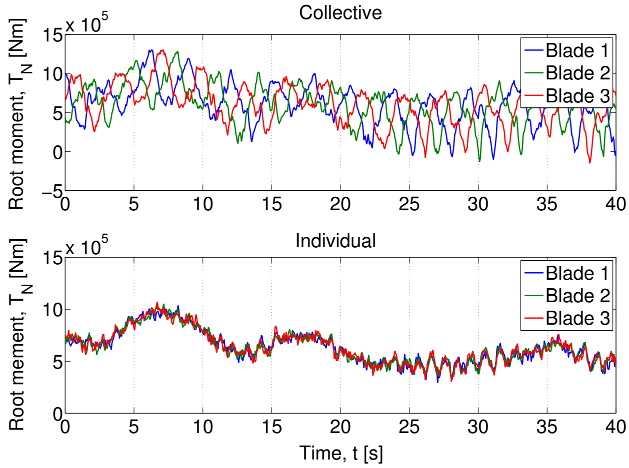

Fig. 6. Blade root moments normal to the rotor plane. Top: wind turbine controlled by collective controller. Bottom: wind turbine controlled by individual controller

is seen that the blade moments for the collective controller exhibit the same periodic trend (due to shear) but with different phase. It is readily seen that this periodic trend is heavily attenuated in the simulation with the individual pitch controller. Fig. 7 shows the associated control signals for both controllers. The periodic trend seen in the loads

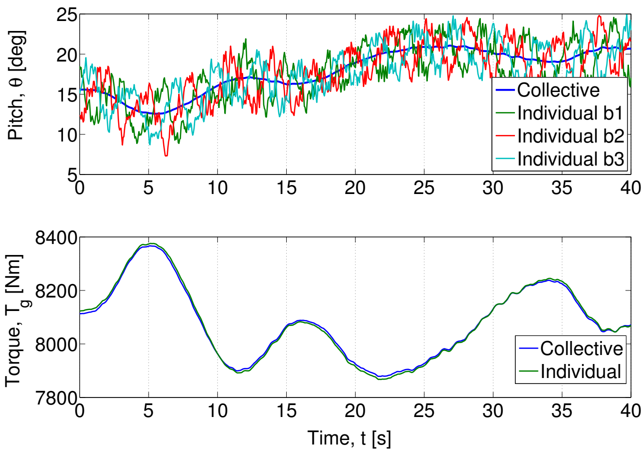

Fig. 7. Control signals for collective and individual pitch controller

associated with the collective pitch controller is naturally reflected in the control signals for the individual pitch controller.

Transforming the local moments to the yaw and tilt axis of the wind turbine, the effect of the individual controller becomes very apparent. This is seen in Fig. 8 and 9 respectively. The effect of the asymmetric wind field is

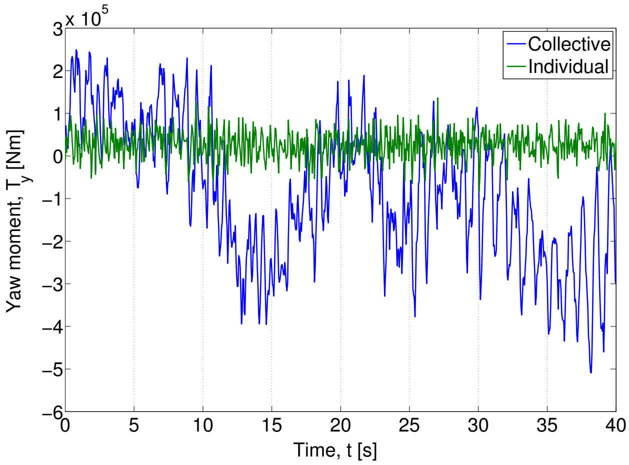

Fig. 8. Yaw moment when controlled by collective and individual pitch controller

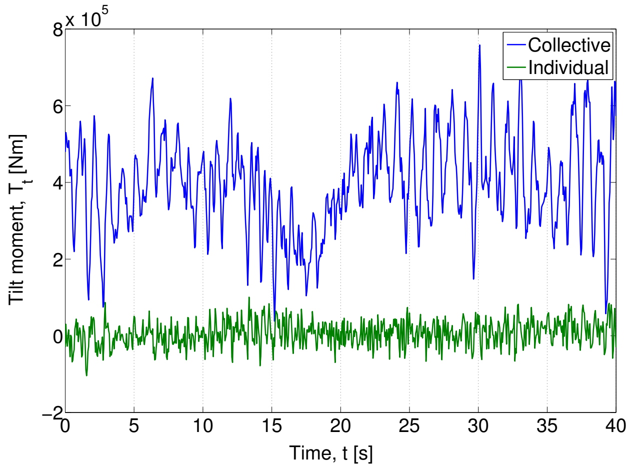

Fig. 9. Tilt moment when controlled by collective and individual pitch controller

attenuated to a high degree with the individual pitch controller.

Fig. 10 shows the rotational speed w_g and the power P_e which were both objectives in the controller designs. Although the individual pitch controller has the additional objective to minimize asymmetric loads it gives approximately the same response for ω_g and P_e as the collective pitch controller.

5. CONCLUSION

A framework for individual pitch control has been described in this paper. The framework relies on the notion of effective wind speed for each wind turbine blade. Knowing these effective wind speeds it is possible to attain estimates of the future blade root moments. It has been demonstrated how to derive the effective wind speeds based on local blade flow measurements along the blade. Furthermore, we have suggested to use the wind speeds experienced by advancing blades as future measurements for the other blades. The combined framework allows for systematically designing model based individual pitch controller in combination with variable speed control. Finally, it has been illustrated how to design a model based controller based on the framework and it is shown that a significant reduction of the asymmetric loads can be achieved.

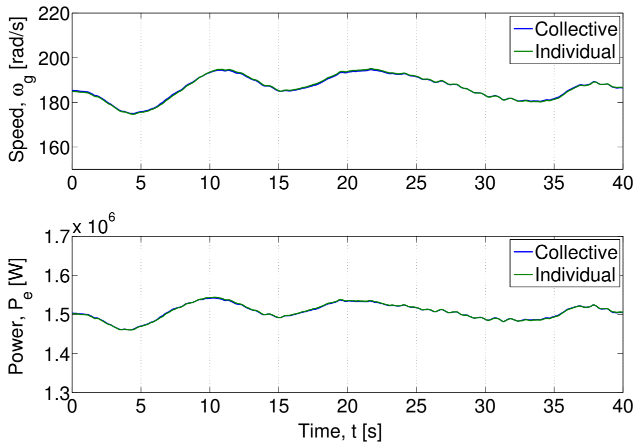

Fig. 10. Rotational speed ω_g and power P_e when controlled by collective and individual pitch controller

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