WIND ENERGY
*Wind Energ.* 2003; **6**:119–128 (DOI: 10.1002/we.76)

Research Article

# Individual Blade Pitch Control for Load Reduction

**E. A. Bossanyi*** Garrad Hassan and Partners Ltd, Silverthorne Lane, Bristol BS2 OQD, UK

**Key words:**
wind turbine; individual pitch control; loads; load reduction; fatigue; turbulence

*If a pitch-regulated wind turbine has individual pitch actuators for each blade, the possibility arises to send different pitch angle demands to each blade. The possibility of using this as a way of reducing loads has been suggested many times over the years, but the idea has yet to gain full commercial acceptance. There are a number of reasons why this situation may be set to change, and very significant load reductions can result. Copyright © 2002 John Wiley & Sons, Ltd.*

## Introduction

The possibility of using individual pitch control for load alleviation has been suggested many times over the years, and more recently by Caselitz *et al.*[1] Recent work demonstrates that some very significant reductions in loading can be achieved and that the control algorithms required for this may be relatively simple.

There are a number of reasons why the time may now be right to develop this idea commercially.

- As commercial turbines get larger, many of them now use individual pitch actuators anyway, since with careful design they can be considered as independent braking systems, obviating the need for a high-capacity shaft brake.
- The importance of load reduction becomes ever greater as turbines become larger and more flexible. Load reduction through 'intelligent' control systems becomes more attractive, compared with designing mechanical systems to cope with large loads, and processing power for control systems is no longer a limitation.
- The technique aims to reduce the asymmetric loads due to wind speed variations across the rotor disc, and these loads are becoming more significant as turbine rotors get larger with respect to the size of typical turbulent eddies in the wind.
- Through the use of the latest software tools, our understanding of the problem has increased and reliable methods for designing suitable control algorithms have been developed. The performance of these control algorithms can now be tested using very realistic simulations.
- The technique relies on sensors which can measure the asymmetric loads acting on the system, and load sensors with the necessary level of reliability are now becoming available. Various options for the positioning of load sensors are investigated in this article. It is also possible that other measurements could be used instead, such as accelerometers in each blade tip or lateral and vertical accelerometers in the nacelle.

## Understanding the Loads

As the turbine blade sweeps around the 'rotor disc', it experiences changes in wind speed and direction as a result of wind shear, tower shadow, yaw misalignment and turbulence. As rotor sizes increase with respect to the typical sizes of turbulent eddies, the importance of turbulent wind speed variations across the rotor disc becomes greater.

* Correspondence to: E. A. Bossanyi, Garrad Hassan and Partners Ltd, St Vincent's Works, Silverthorne Lane, Bristol BS2 OQD, UK. E-mail: bossanyi@garradhassan.co.uk

Published online 8 October 2002

*Received 13 May 2002*
*Revised 3 June 2002*
*Accepted 11 June 2002*

These variations result in a large once-per-revolution, or 1P, component in the blade loads, together with harmonics of this frequency, i.e. 2P, 3P, 4P and so on. With a three-bladed rotor, these load components will be 120° out of phase between the three blades, with the result that the hub and the rest of the structure will experience the harmonics at 3P, 6P, etc., but 1P and the other harmonics will tend to cancel out.

However, this cancellation relies on assumptions of stationarity and linearity, but as turbines become larger with respect to the length scales of the turbulence, these assumptions become less valid. For example, if blade 1 sees a gust as it passes top dead centre, the gust will have changed before blade 2 reaches the same position. This means that the asymmetric loads resulting from the 1P and other harmonics no longer cancel out, and load components at these frequencies can contribute very significantly to fatigue loads on the hub, shafts, yaw bearing, tower, etc.

The 1P load components are particularly significant on large turbines, and in principle it should be possible to reduce these by means of individual blade pitch action at the 1P frequency, 120° out of phase at the three blades. This forms the subject of this article.

## Analytical Tools

Recent developments in analytical tools have been instrumental in allowing the development of suitable control strategies. Several wind turbine simulation tools, of which the Garrad Hassan code Bladed is an example, are now capable of very detailed simulations of wind turbine operation in a realistic turbulent wind field, in which all three components of turbulence vary in space and time. Detailed predictions of the resulting loads on various components are available, and the effect of control actions on these loads can be evaluated in detail.

The design of control algorithms for calculating appropriate control actions as a function of measured loads is a specialized task. A prerequisite for such design work is a linearized model representing the dynamics of the turbine to a sufficient level of detail. For this task the model must be sufficiently detailed to represent not only the rotational dynamics and aerodynamics of the turbine in a uniform wind field, which is relatively straightforward, but also the effect of asymmetric wind speed variations and individual pitch actions on the various loads, which is much more difficult. However, a recent extension to the Bladed package now allows suitable linearized models to be generated automatically from the standard turbine description, by numerical analysis of the effect of small input and state perturbations. Furthermore, the resulting linear state space model can be read directly into Matlab, which is a software tool very widely used by control system designers throughout industry.

## Control Algorithms

Using models created with this Bladed model linearization tool, a range of different algorithms has been developed for controlling the 1P loads using individual pitch control.

Since this is a multivariable control problem, in which several inputs (including measured loads) are simultaneously processed to generate three pitch actuator demands, initial work concentrated on the use of so-called ‘LQG’ or linear–quadratic–gaussian control design techniques as described below, these being among the simplest of the ‘modern’ control design methods which are directly applicable to multivariable problems. This has led to some very successful results being demonstrated in detailed simulations.[2] However, the development of complex multivariable controllers in this way is far from straightforward, and the resulting algorithms can be of very high order, requiring a large amount of processing on each controller time step. It is also difficult to guarantee robustness: the controller must still be able to perform satisfactorily if the real turbine differs somewhat from the model used for the control design, or if measured signals are contaminated with noise, etc.

Subsequent work has been very successful in refining the design techniques to the point where excellent performance has been obtained with greatly reduced model orders. Furthermore, simulations have been used to demonstrate that the performance is not unduly degraded by imperfections in the turbine model or by signal noise.

The best results have been obtained by decoupling the collective from the differential or 1P pitch action. The collective pitch action, which is the same for all three blades, is calculated from the measured rotational speed using a standard classical PI-based controller, and a zero-mean 1P differential pitch action is superimposed on this to reduce the 1P loads. The differential pitch action requires a multivariable controller with at least two inputs (measurements) and two outputs. Although there are three blades, the three pitch demands can be considered to consist of a collective pitch demand and two independent differential demands. A useful approach is the d–q axis representation borrowed from three-phase electrical machine theory,[3] in which three blade root load signals are transformed into a mean value and variations about two orthogonal axes (the ‘direct’ and ‘quadrature’ axes), which could represent the vertical and lateral directions for example. Differential pitch ‘outputs’ in the d- and q-axes are then calculated and a reverse transformation provides the differential demands for the three blades. An LQG controller of relatively low order can generate the d–q axis pitch demands from the d–q axis loads.

More recently, however, it has been shown that it is possible to treat the d- and q-axes as being almost independent. This means that conventional classical design techniques can be applied to generate a single-input, single-output controller which can be applied separately to the d-axis and the q-axis. A conventional PI controller in series with a simple filter provides very satisfactory control action. In practice there is some interaction between the two axes, but this can be accounted for by introducing a simple azimuthal phase shift into the d–q axis transformation, i.e. adding a constant offset to the rotor azimuth angle used in the transformation.

This approach has yielded results comparable with the LQG approach. Some loads are reduced slightly less, while others are reduced somewhat more. The resulting pitch activity is very similar. Furthermore, it has been shown that it is possible to use a variety of different sensors with equal effectiveness. Results are presented in this article using load sensors at the blade roots, on the hub or low-speed shaft, or at the yaw bearing. With the PI approach it is particularly straightforward to switch from one set of sensors to another—all that is required is a slight change in gain—and the resulting performance is very similar in each case.

## *The d–q Axis Transformation*

The d–q axis transformation can be expressed as follows.

(1) Transformations from three rotating blades to direct and quadrature axes:

$$\begin{pmatrix} \beta_d \\ \beta_q \end{pmatrix} = \begin{pmatrix} \frac{2}{3} \end{pmatrix} \begin{pmatrix} \cos(\theta) & \cos(\theta + 2\pi/3) & \cos(\theta + 4\pi/3) \\ \sin(\theta) & \sin(\theta + 2\pi/3) & \sin(\theta + 4\pi/3) \end{pmatrix} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix}$$

where $\beta_1$–$\beta_3$ are quantities referred to blades 1–3 respectively, $\beta_d$ and $\beta_q$ are referred to the direct and quadrature axes respectively and $\theta$ is the angle between blade 1 and the direct axis direction.

(2) Transformations from direct and quadrature axes back to three rotating blades:

$$\begin{pmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) \\ \cos(\theta + 4\pi/3) & \sin(\theta + 4\pi/3) \end{pmatrix} \begin{pmatrix} \beta_d \\ \beta_q \end{pmatrix}$$

It is useful to use the vertical and lateral directions for the direct and quadrature axes, since this gives an axis system which is fixed in space. Wind speed variations in this co-ordinate system are of low frequency, unaffected by rotational sampling. $\theta$ is then the rotor azimuth angle.

If blade loads are measured, the forward transformation (1) is used to convert the measured loads into d–q axes. If rotating hub or shaft loads are used, a simple rotational transformation through the azimuth angle is

 

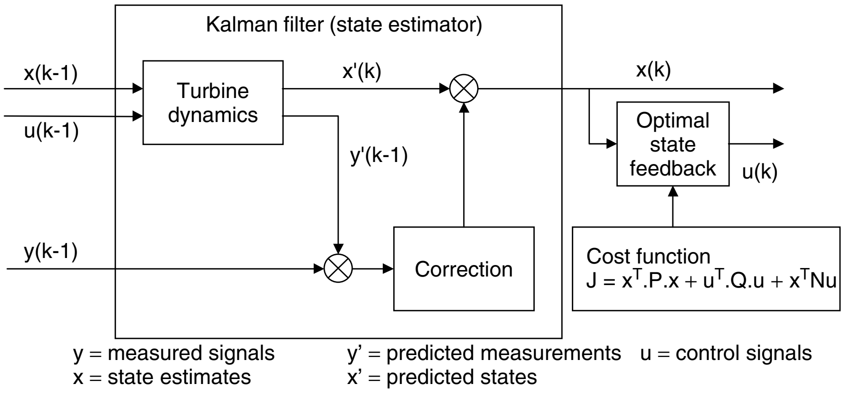


*Figure 1. Structure of an LQG controller*

Table I. Key turbine parameters

| | |
|---|---|
| Rotor diameter | 75 m |
| Hub height | 65 m above surface |
| Water depth | 15 m |
| Control | Variable speed, full-span pitch |
| Gearbox ratio | 84·15 |
| First tower mode | 0·4 Hz |
| Rated power | 2000 kW |
| Speed range | 850–1500 rpm (generator) |
| | 10·1–17·825 rpm (rotor) |
| Rotational frequency (1P) | 0·297 Hz (at rated speed) |

all that is required. Loads measured on a stationary part of the turbine, such as the main bearing housing or the yaw bearing, can be considered to be in the d–q axis co-ordinate system already.

The reverse transformation (2) is used to generate the individual pitch demand increments for the three blades from the d–q axis pitch demands generated by the LQG or PI algorithm.

## *The LQG Controller*

The LQG design process requires a *linear* model of the plant, uses a *quadratic* cost function to define the controller objectives, and assumes *Gaussian* disturbances. These aspects are described below.

The linear model of the turbine dynamics can be represented by means of a state space model:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \qquad \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

Here $\mathbf{x}$ is a vector consisting of the 'states' of the system. These are a set of variables which can be used to describe the system dynamics, which are embodied in the state space matrix $\mathbf{A}$. The vector $\mathbf{u}$ represents external inputs to the system, such as stochastic wind speed variations or control signals. The inputs affect the state dynamics through the matrix $\mathbf{B}$. Then $\mathbf{y}$ is a vector of output variables, which are any variables of interest which can be constructed from the states and the inputs through matrices $\mathbf{C}$ and $\mathbf{D}$. For a discrete time step controller this model may be discretized as follows:

$$\mathbf{x}_{k+1} = \overline{\mathbf{A}}\mathbf{x}_k + \overline{\mathbf{B}}\mathbf{u}_k, \qquad \mathbf{y}_k = \overline{\mathbf{C}}\mathbf{x}_k + \overline{\mathbf{D}}\mathbf{u}_k$$

Figure 1 illustrates the structure of an LQG controller. The Kalman filter is a state estimator, which makes estimates of the states of the system from the measured signals $\mathbf{y}$. The inputs $\mathbf{u}$ are the control signals, e.g.

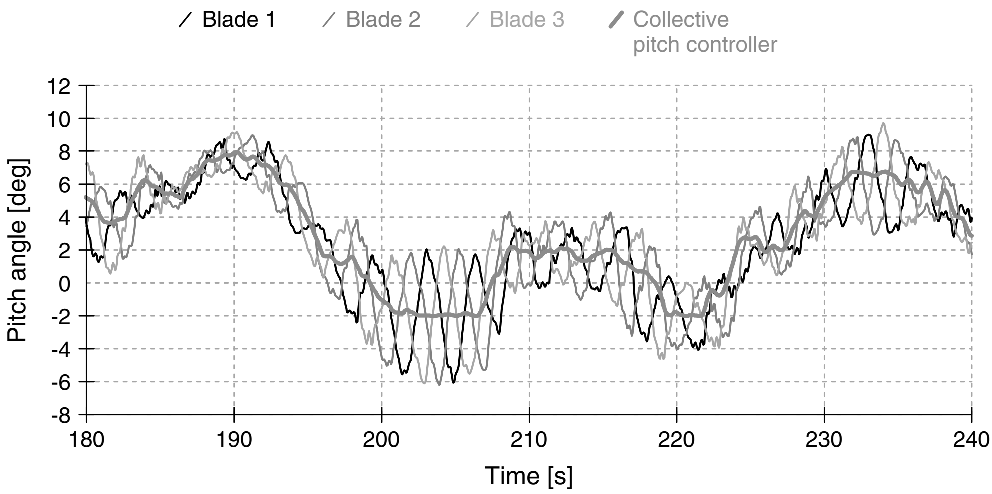


*Figure 2. Typical pitch angle variations close to rated wind speed*

pitch demands. The Kalman filter consists of a block representing the turbine dynamics, represented simply by the matrices $\overline{\mathbf{A}}$ and $\overline{\mathbf{B}}$, which make a one-step-ahead prediction of the states, and $\overline{\mathbf{C}}$ and $\overline{\mathbf{D}}$, which estimate what the measured outputs would be. There is then a correction which updates the state estimates, taking into account the prediction errors, i.e. the difference between the measured signals $\mathbf{y}$ and the predictions $\mathbf{y}'$:

$$\mathbf{x}_{k+1} = \mathbf{x}'_{k+1} + \mathbf{M}(\mathbf{y}'_k - \mathbf{y}_k)$$

The matrix $\mathbf{M}$ can be calculated from the system dynamics and a representation of the stochastic disturbances acting on the system, as long as these can be assumed Gaussian. It is calculated such that the expected sum of squares of the prediction errors $(\mathbf{y}'_k - \mathbf{y}_k)$ is minimized.

A similar calculation yields the optimal state feedback matrix $\mathbf{K}$, such that the control law

$$\mathbf{u}_{k+1} = -\mathbf{K}\mathbf{x}_{k+1}$$

minimizes the expected value of a chosen cost function $\mathbf{J}$, which is a quadratic function of the states and control actions:

$$J = \mathbf{x}^{\mathrm{T}}\mathbf{P}\mathbf{x} + \mathbf{u}^{\mathrm{T}}\mathbf{Q}\mathbf{u} + \mathbf{x}^{\mathrm{T}}\mathbf{N}\mathbf{u}$$

A straightforward transformation allows the cost function to be re-expressed in terms of outputs $\mathbf{y}$:

$$J = \mathbf{y}^{\mathrm{T}}\mathbf{P}'\mathbf{y} + \mathbf{u}^{\mathrm{T}}\mathbf{Q}'\mathbf{u} + \mathbf{y}^{\mathrm{T}}\mathbf{N}'\mathbf{u}$$

This is a more convenient formulation, since output variables can be selected which are more meaningful than the system states.

This cost function approach means that the trade-off between a number of partially competing objectives is explicitly defined, by selecting suitable weights for the terms of the cost function. For the present application, $\mathbf{u}$ represents the d–q axis pitch contributions, $\mathbf{y}$ represents the measured d- and q-axis loads, and the cost function must include the integrated d- and q-axis loads, since these are to be minimized. It can also include bandpass or highpass filtered d- and q-axis pitch rates to prevent unnecessary action at high frequencies. Of course, the LQG controller could simultaneously generate the collective pitch action, using measured generator speed as a measured signal, but this seems to offer no benefit over a PI controller for the collective pitch action.

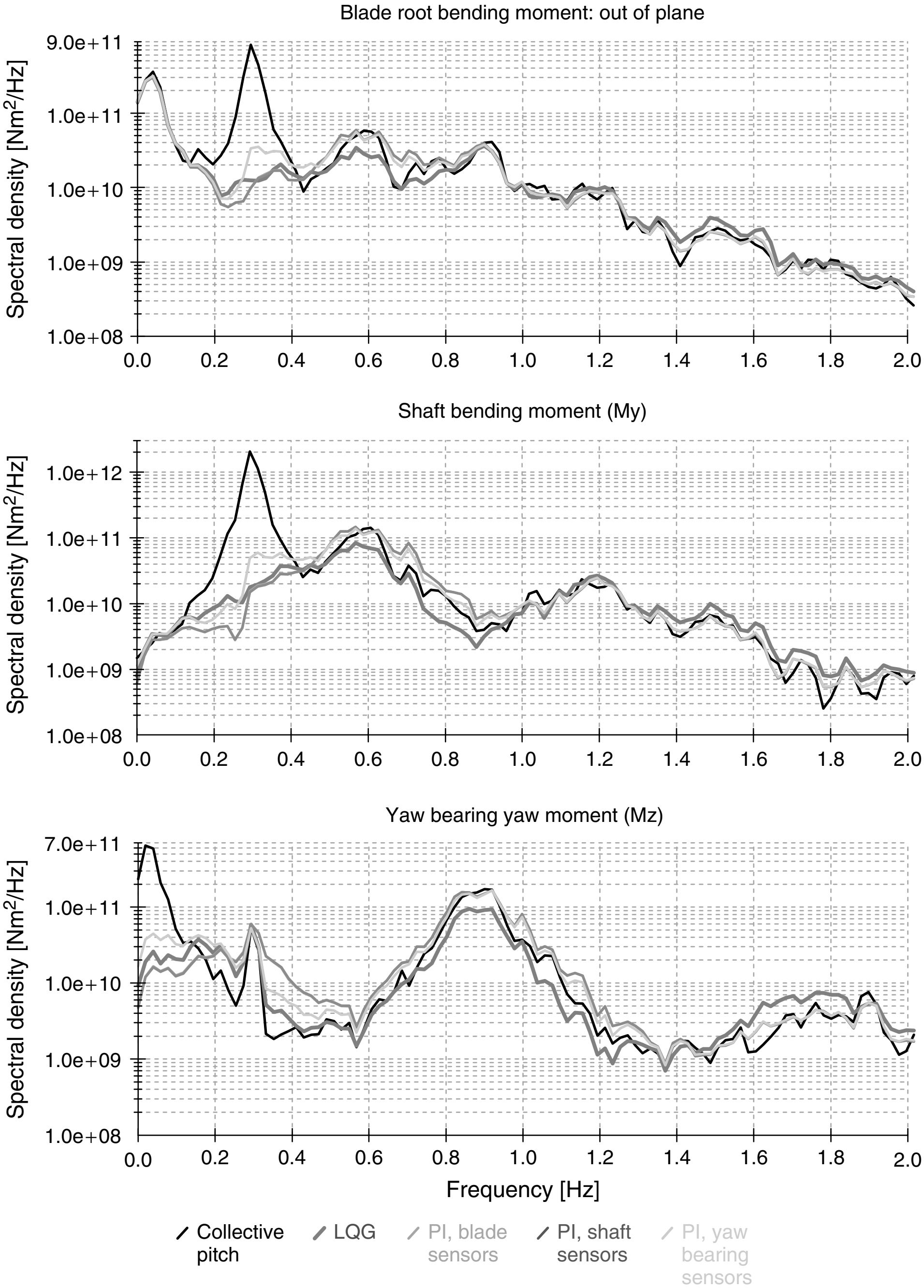


*Figure 3. Load spectra*

The LQG control design method should be straightforward and intuitive, but in practice this is rarely the case. The method can also produce rather high-order controllers. Model order reduction techniques have been used successfully in this application and have resulted in little if any loss of performance. However, the computational requirements per time step are still one or two orders of magnitude greater than for the PI controller described below.

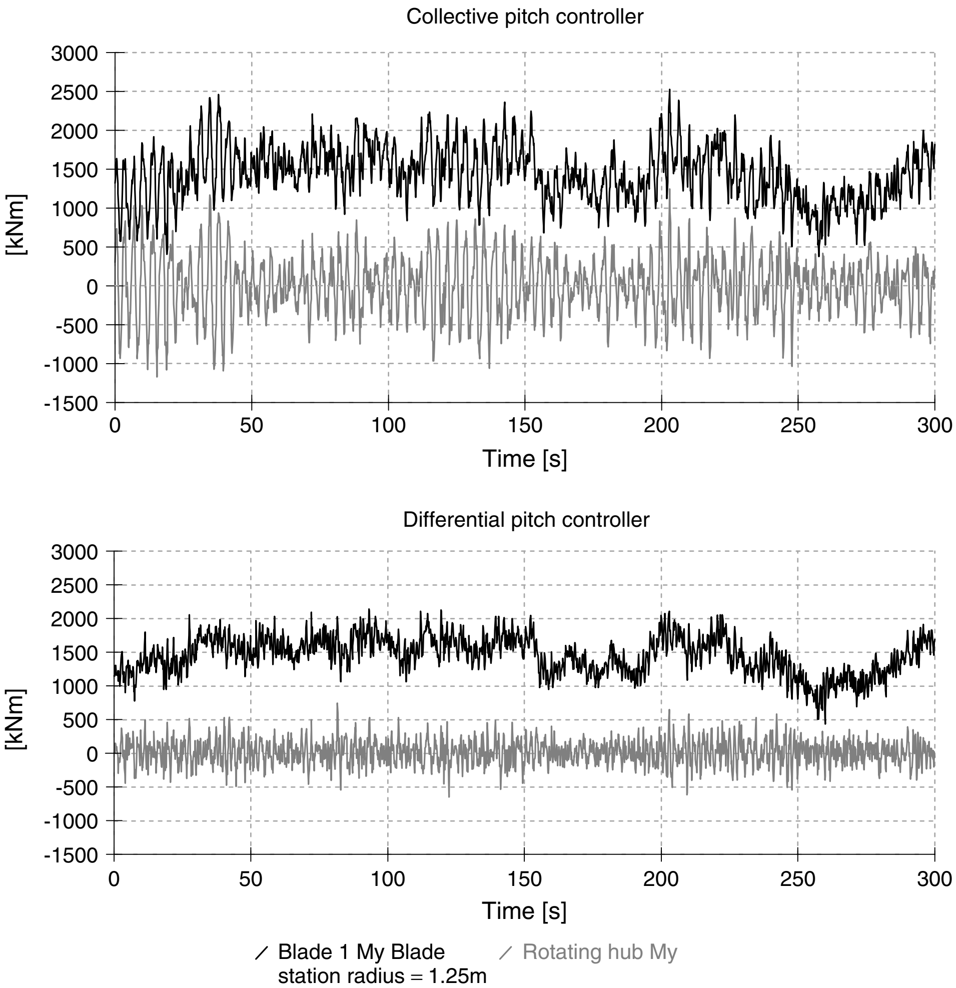


*Figure 4(a). Sample time histories of rotating loads: blade root out-of-plane moment (upper trace) and shaft moment (lower trace)*

## PI Differential Pitch Controller

The PI approach to differential pitch control treats the d- and q-axes independently of each other. A PI controller generates a d-axis pitch demand from the measured d-axis load, and the same for the q-axis. Some filtering of the d- and q-axis loads is necessary to prevent unnecessary high-frequency activity. The integral term ensures that the d- and q-axis loads are zero on average.

## Simulation Results

The results presented in this article are based on a generic 2 MW offshore variable-speed turbine developed as part of a CEC-funded project concerned with design recommendations for offshore wind turbines (RECOFF, contract number ENK5-CT-2000-00322). Some of the key turbine parameters are shown in Table I.

Each simulation covered a 10 min period, using the same three-component turbulent wind field in each case to drive the simulation. The mean wind speed was 13 m $s^{-1}$ and the turbulence intensity was 18·9% in the longitudinal direction, 14·8% laterally and 10·6% vertically. The sample time histories shown below are excerpts from these simulations, while the spectra and fatigue loads are calculated from the full 10 min.

 

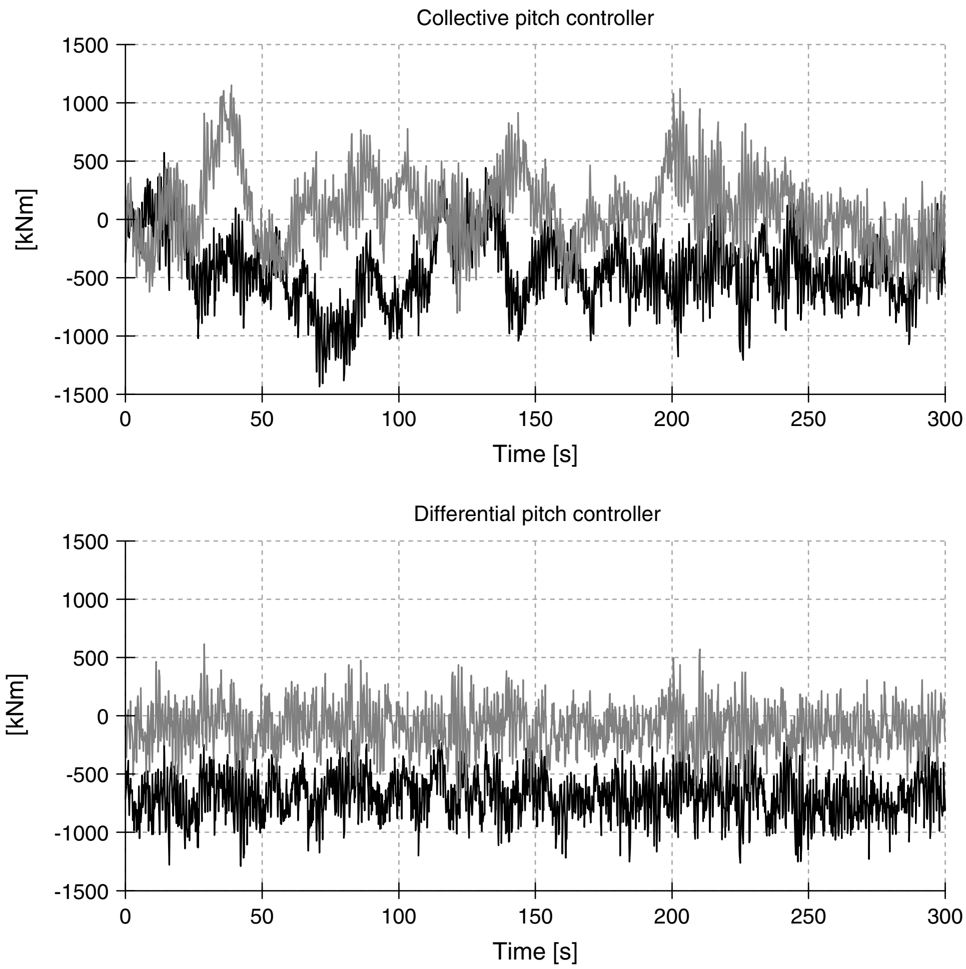


*Figure 4(b). Sample time histories of yaw bearing loads: yaw moment (upper trace) and nodding moment (lower trace)*

Figure 2 illustrates the typical magnitude of the 1P pitch action which is required during operation around rated wind speed. Clearly this represents a considerable increase in pitch actuator duty compared with a conventional controller, particularly as some differential pitch action continues to be useful even in below-rated winds, where significant load reductions may still occur without any significant loss of energy. However, apart from a possible increase in wear and the need to take account of heat dissipation in the actuators, this is unlikely to require major changes in the design of pitch actuators.

Figure 3 shows spectra of some of the key bending moment loads: at the blade root in the out-of-plane direction, on the shaft and at the yaw bearing. Several differential pitch controllers are shown, namely LQG with blade root load sensors and PI with each of blade root, shaft or yaw bearing load sensors. The different differential pitch controllers give very similar results; in fact, for the blade root and shaft sensors the results are nearly indistinguishable. The results are taken from 10 min simulations with the same three-component turbulent wind in each case, around rated wind speed. For the blade and rotating shaft loads the large 1P peak in the conventional case is virtually eliminated by differential pitch control. The yaw bearing loads are in a co-ordinate system which is not rotating with the blades and are therefore dominated by a low-frequency peak, representing the asymmetry in the wind field which is the cause of the 1P loading on the rotating components. The effect of the differential pitch control therefore is to cut out this low-frequency peak.

 

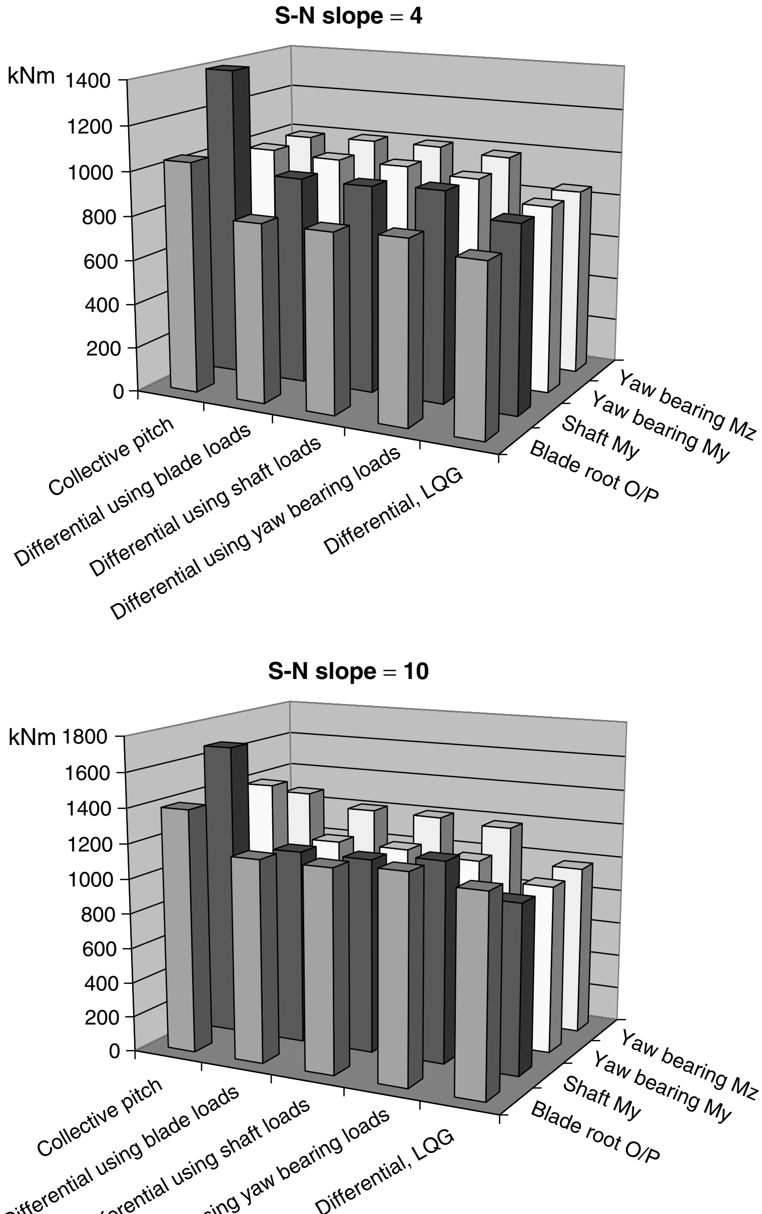


*Figure 5. Reduction in fatigue loads*

Figure 4 presents some typical time histories of these loads (only the LQG case is shown, but others are similar), while Figure 5 shows the damage equivalent loads, which are a measure of the equivalent fatigue damage caused by each load taking into account the fatigue properties of the material. S–N slopes of 4 and 10 have been used, which are typical for steel and composite materials respectively. The differential pitch control produces a dramatic reduction in fatigue loading for the blades and shaft. For the yaw bearing it is only the low-frequency loads which are reduced, so the effect on fatigue is more modest, since only a relatively small number of large cycles are affected.

## Conclusions

The work presented in this article demonstrates that a very significant reduction in operational loading can be achieved by means of individual pitch action, provided a suitable measurement of the asymmetric loading is available. A number of alternative measures of asymmetric loading have all been found to work satisfactorily. The sensors used for this task must be very reliable, and suitable sensors are now becoming available.

To design the necessary control algorithms, a linear model of the turbine which embodies the asymmetric loading and the effect of individual pitch action is required, and a convenient method for generating such models is now available.

Since a multivariable controller is required, i.e. to calculate several control actions from several measured signals, initial work was based on 'LQG' control design methods, which are well suited to this situation. Although this has been shown to yield good results, the design process is not straightforward and the resulting algorithm is somewhat cumbersome. Later work has shown that is possible to transform the problem into two decoupled single-input, single-output control loops. The resulting algorithm is much easier to design, using classical techniques, is much more straightforward to implement, and achieves comparable results.

Detailed simulations have been used to demonstrate that very significant reductions in operational loading can be achieved without compromising energy capture. The pitch actuators will clearly experience greater activity and must be designed with this in view, but the additional duty is not prohibitively large.

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