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Design of Controls to Attenuate Loads in the Controls Advanced Research Turbine

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DESIGN OF CONTROLS TO ATTENUATE LOADS IN THE CONTROLS ADVANCED RESEARCH TURBINE

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ABSTRACT

Designing wind turbines to maximize energy production and increase fatigue life is a major goal of the wind industry. To achieve this goal, we must design wind turbines to extract maximum energy and reduce component and system loads. This paper applies modern state-space control design methods to a two-bladed teetering-hub upwind machine located at the National Wind Technology Center[*]. The design objective is to regulate turbine speed in region 3 (above rated wind speed) and enhance damping in several low-damped flexible modes of the turbine. The controls approach is based on the Disturbance Accommodating Control (DAC) method and provides accountability for wind-speed disturbances. First, controls are designed using the single control input rotor collective pitch to stabilize the first drive-train torsion as well as the tower first fore-aft bending modes. Generator torque is then incorporated as an additional control input. This reduces some of the demand placed on the rotor collective pitch control system and enhances first drive train torsion mode damping. Individual blade pitch control is then used to attenuate wind disturbances having spatial variation over the rotor and effectively reduces blade flap deflections caused by wind shear.

INTRODUCTION

One of the main goals of wind turbine control is to increase power production and reduce loads using a minimum number of control inputs and required turbine measurements. Controls can often be designed to simultaneously satisfy more than one objective, i.e., regulate power and reduce loads. In the 1970s and 1980s, classical control design methods, such as proportional integral, were used to design controllers to regulate power while adding damping to the first drive train torsional mode of the turbine [1]. In Barton et al. [2], a power system stabilizer was included to add damping to the drive train mode.

Work has also been done in Europe using state-space methods for wind turbine control design. Mattson [3] designed a controller for regulation of power for a fixed-speed machine using blade pitch. In this work, rotor and generator rotation, drive train torsion, and tower fore-aft degrees of freedom (DOF) were modeled for use in control system design. Liebst [4] describes the use of individual blade periodic pitch control to reduce the loads on the Mod 0-A turbine caused by tower shadow, wind shear, and gravity. In Liebst, only blade DOF were modeled in the dynamics, using rigid blade/hinge models to represent the blade flap, lag, and pitch DOF.

In the United States, Stol et al. [5] worked on the use of state-space methods to design Disturbance Accommodating Controls (DACs). They developed a linear model of a turbine using a rigid blade/tower/hinge approach to model blade and tower flexibility. They developed DAC from a linear model containing only rotor rotation as the DOF. They then showed that this DAC adequately controlled a turbine, as modeled in their nonlinear simulator-SymDyn with only the rotor rotation DOF. This system became unstable when more DOF were turned on in SymDyn

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than included in the linear model for control design. In Wright and Balas [6], various flexible modes of a turbine were stabilized by appropriate control designs using rotor collective pitch.

In a recent study, Stol and Balas [7] designed controllers with periodic gains to regulate turbine speed and reduce loads for a two-bladed teetering-hub machine. Further work in designing periodic controls for wind turbine speed regulation and load reduction has been reported by Stol [8].

The controls approach used in this paper is based on DAC and provides accountability for wind-speed disturbances. First, controls are designed using the single control input rotor collective pitch to stabilize the first drive train torsion as well as the tower first fore-aft bending modes. Generator torque is then incorporated as an additional control input. This reduces some of the demand placed on the rotor collective pitch control system and enhances first drive train torsion mode damping. Individual blade pitch control is then used to attenuate wind disturbances having spatial variation over the rotor and effectively reduces blade flap deflections caused by wind shear.

We design controls based on linear models extracted from FAST [9]. After designing these controls, we test the closed-loop system through simulation using FAST. Finally, we draw conclusions and state future studies. We now review the turbine configuration.

CART CONFIGURATION

The Controls Advanced Research Turbine (CART), shown in Figure 1, is a two-bladed, teetered, upwind, active-yaw wind turbine. This machine is used as a test bed for studying a number of aspects of wind turbine controls technology on medium to large-scale machines (see Table 1).

The two bladed teetering upwind turbine operates variable speed with each blade capable of being independently pitched with its own electromechanical drive. Rated electrical power (600 kW at 42 RPM) is maintained in region 3 in a conventional variable speed approach. Power electronics are used to command constant torque from the generator and blade pitch controls the rotor speed. In region 2, the machine torque is varied to produce variable rotor speed in order to maintain optimum C_p.

Table 1: CART Configuration

Turbine Type	Horizontal axis, upwind rotor, teetering hub
Number of Blades	2
Rotor Speed (region 3)	42 rpm
Power Regulation	Full-span blade pitch control
Yaw Configuration	Upwind rotor with active yaw drive
Rotor Diameter	43.3 m
Height	36.6-m hub height
Coning	0° pre-cone
Tilt	4°

CONTROL DESIGN AND SIMULATION

Linear Models

Because we based all of our control design on linear control theory, we needed linear turbine models. We extracted linear models of a turbine from the FAST code [10]. These linear models contain a subset of the DOF allowable in FAST.

These linear models can be expressed in state-space form as in Eq. (1).

$$\begin{aligned} \dot{\underline{x}} &= A\underline{x} + B\underline{u} + \Gamma\underline{u}_D \\ \underline{y} &= C\underline{x} \end{aligned} \qquad (1)$$

where $\underline{x}$ is the state vector, $\underline{u}$ is the control input, $\underline{u_D}$ is the disturbance input, $\underline{y}$ is the measured output, A is the state matrix, B is the control input distribution matrix, Γ is the disturbance input distribution matrix, and C relates the measured output $\underline{y}$ to the turbine states. These vectors and matrices varied in size depending on the number of states and control inputs in the linear model.

An example linear model used for control design includes generator speed as well as the first drive train torsion mode [10] and can be expressed as in Eq. (2).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{(\gamma - C_d)}{I_{rot}} & \frac{-1}{I_{rot}} & \frac{C_d}{I_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{I_{gen}} & \frac{1}{I_{gen}} & \frac{-C_d}{I_{gen}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{\zeta}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \delta\beta + \begin{bmatrix} \frac{\alpha}{I_{rot}} \\ 0 \\ 0 \end{bmatrix} \delta w$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}. \qquad (2)$$

where,

$x_1 = \delta\dot{q}_4$, perturbed rotor speed,

$x_2 = K_d(\delta q_4 - \delta q_{15})$, perturbed drive train torsional spring force,

$x_3 = \delta\dot{q}_{15}$, perturbed generator speed.

In this equation, the control input is $\underline{u} = \delta\beta$ -perturbed rotor collective pitch, while the disturbance input is $\underline{u_D} = \delta w$ -perturbed wind disturbance (the uniform component over the rotor disk). The pitch input distribution matrix is $B = \begin{bmatrix} \frac{\zeta}{I_{rot}} \\ 0 \\ 0 \end{bmatrix}$, while the disturbance input distribution matrix is $\Gamma = \begin{bmatrix} \frac{\alpha}{I_{rot}} \\ 0 \\ 0 \end{bmatrix}$. Here, ζ is the partial derivative of rotor aerodynamic torque with respect to rotor collective pitch angle, and α represents the partial derivative of rotor aerodynamic torque with respect to wind speed. In addition, in Eq. (2), K_d is the drive train torsional spring constant, while C_d is the torsional damping constant. I_{rot} and I_{gen} represent the rotational inertia of the rotor and generator about the spin axis, respectively. The torsional spring/damper connects the rotor to the generator modeled as lumped mass rotational inertia.

The coefficients in this model may vary with turbine rotor speed, pitch angle, and wind speed. Figure 2 shows the variation of aerodynamic torque with pitch angle for various wind speeds. For control design purposes, the linear model is evaluated at a particular turbine operating point called the control design point. The control system designed at a certain design point may perform poorly for other turbine operating points. It is important to test the designed control system through simulation for a variety of turbine operating points. One method of doing this is to input step winds into the turbine simulator, allowing the wind speed to vary above and below the control design point wind speed as shown in Figure 3.

Disturbance Accommodating Control

We use DAC for the control designs shown in this paper. Disturbance accommodating control allows us to regulate turbine rotor speed while accounting for wind-speed disturbances and placing plant poles through full-state feedback [11]. It also allows us to use state estimation to provide the controller with values for those states that are not measured. This is important when limited turbine measurements are available. For the studies included in this paper, the only allowed turbine measurements are generator speed, tower-top fore-aft bending displacement, and blade-tip flap displacement.

Another basic idea in DAC is that the wind disturbance gain is chosen to cancel or minimize the effect of wind-speed disturbances. A variety of wind-speed disturbances can be modeled using DAC. To begin, we show control designs to accommodate wind-speed disturbances uniform over the rotor disk (have no spatial variation). For these disturbances, we can use the single control input rotor collective pitch, because these disturbances do not vary spatially over the rotor disk, and the pitch of each blade can be identical. Figure 4 shows a diagram of DAC for turbine speed regulation using rotor collective pitch.

Rotor Collective Pitch Control

Rotor collective pitch control is used to regulate turbine speed in region 3 and enhance damping in the first drive train torsion mode as well as the tower first fore-aft bending mode [10] [12]. These modes are excited by wind disturbances uniform over the rotor disk. DAC is used to accommodate these wind-speed disturbances by modeling these disturbances as step functions [5] [11]. For most of the controls designed using rotor collective pitch, only generator speed is measured and state estimation is used to estimate plant states.

Using DAC, plant poles can be placed using full-state feedback. Figure 5 shows the effect on regulated generator speed of placing plant poles to give high and low damping in the first drive train torsion mode, using the linear model shown in Eq. (2). The goal is to control generator speed to a 42-RPM set point. For the low-damped case, oscillations in generator speed can be seen, corresponding to the first drive train torsion mode. These oscillations would cause an increase in fatigue loads in the drive train.

Additional flexible modes of the turbine can be damped using rotor collective pitch if appropriate states are included in the linear model to describe these modes. One penalty of adding complexity to the linear model used for control design is that when more flexible modes are included in the model, the speed regulation becomes less robust in terms of performance. Figure 6 compares speed regulation using two different controllers, one designed from a 3-state model and the other from a 7-state model (which includes the tower first fore-aft mode). In this figure, the turbine was excited with step changes in wind speed. The DAC design based on a linear model having only 3 states results in robust speed regulation to the 42-RPM set point over the full range of tested wind speeds. When additional flexible modes are included in the linear model for control design, the speed regulation becomes less robust.

Figure 7 shows the benefit of including the tower first fore-aft mode in the linear control design model. When the model is excited by turbulent wind inflow, a dramatic reduction in tower-top fore-aft motion can be seen using the controller designed from the 7-state model, allowing significant damping to be added to the tower first fore-aft mode by the controller. These results are compared to a controller designed from a model neglecting this mode (the 5-state model, which includes rotor and generator speed, drive train torsion, and rotor first symmetric flap displacement and velocity). For the controller designed from the 7-state model (which includes the states in the 5-state model plus tower-top fore-aft deflection and velocity), a tower-top fore-aft displacement or acceleration measurement is needed. When only generator speed was measured, poor simulation results were obtained because of weak observability of the tower first fore-aft mode in the generator speed signal.

An additional consideration is actuator duty, quantified in terms of blade pitch rates. Figure 8 shows simulated pitch actuator rates, using the controller designed from the 7-state linear model, when excited by turbulent wind inflow. These pitch rates sometimes exceed an actual limit of 18°/second set in the CART. This shows that the demand on the pitch control system is too high. We are performing several control objectives here: regulation of generator speed, enhanced damping of the first drive-train torsion mode, and enhanced damping of the tower first fore-aft mode. A consideration is whether additional control actuators can be used to perform the same function as the rotor collective pitch control system, thereby relieving some of the duty imposed on the pitch actuators.

Generator torque is a possible control actuator. Perhaps generator torque control can be used to add damping to the drive train torsion mode, thus relieving some of the duty imposed on the pitch control system.

Addition of Generator Torque Control

The primary goal in region 3 is to maintain rated power. This is done by maintaining constant generator torque (by commanding constant generator torque through the power electronics) and using rotor collective pitch to regulate aerodynamic torque, which regulates speed.

If generator torque is now allowed to vary, there will be increased variation of generator power. Only small variations of generator torque can be allowed. The only function of the proposed generator torque control will be to add damping to the first drive train torsion mode, which should result in only small perturbations of generator torque about a mean value. Generator torque will not be used to regulate speed or perform any other function, as the generator torque excursions would then become too high for acceptable power regulation.

The objectives of the pitch control system will be to regulate generator speed and enhance damping in the tower first fore-aft mode. We will remove the requirement of enhancing damping in the first drive train torsion mode from the rotor collective pitch control system as the generator torque control system now performs this function.

Two separate controllers will be designed; the generator torque controller and the rotor collective pitch controller. The generator torque controller will be designed based on a reduced state-space model containing only the states needed to describe the first drive train torsion mode. This model can be expressed as in Eq. (3).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} \frac{(\gamma - C_d)}{I_{rot}} & \frac{-1}{I_{rot}} & \frac{C_d}{I_{rot}} \\ K_d & 0 & -K_d \\ \frac{C_d}{I_{gen}} & \frac{1}{I_{gen}} & \frac{-C_d}{I_{gen}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{I_{gen}} \end{bmatrix} \delta T_{gen}$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} . \qquad (3)$$

This system is much like the 3-state model shown in Eq. (2) with exactly the same states, except the control input is now δT_{gen}. Notice the control input gain $\frac{-1}{I_{gen}}$ in the 3rd row of B. This gain is constant (I_{gen} is constant) and does not change with wind speed or pitch. This means that controllability does not vary with wind speed and pitch as it does when rotor collective pitch control is used. Again, we measure only generator speed.

The generator torque controller is designed from this state-space model. The poles are placed to add significant damping to the first drive train torsion mode, because the system is controllable. In addition, state estimation is made using generator speed as the only measurement, because the system is observable.

The rotor collective pitch control system is designed from the linear models used previously, except that now the poles corresponding to the first drive train torsion mode are placed close to the open-loop values. This means that the rotor collective pitch control system does not add damping to this mode (this is now performed by the generator torque controller). The rotor collective pitch system is designed to regulate speed and accommodate wind disturbances using DAC. For collective pitch control designed from the 7-state model, tower-top fore-aft displacement or acceleration must also be measured.

Figure 9 shows regulated speed from this controller as excited by turbulent wind inflow. A benefit is reduced pitch rates, as observed in Figure 10, when excited with turbulent wind inflow, using generator torque control versus pitch control to add drive train damping. Use of generator torque control removes the task of enhancing damping in the drive train mode from the pitch control system, thus reducing pitch rates. Figure 11 shows electrical power, showing higher excursions for the case of using generator torque control. A trade-off must be performed between the amount of damping added to the drive train from the generator torque control and the electrical power excursions. As the amount of damping is increased through pole placement, these excursions will increase.

All of the controls designed so far have only accommodated wind disturbances uniform over the rotor disk. We now show control designs for attenuation of the effects of wind shear, using independent blade pitch control.

Individual Blade Pitch Control

Rotor collective pitch control was adequate for accommodating uniform disturbances over the rotor disk. Control of the flap displacement of individual blades is not necessary in that case, because uniform wind inputs to the rotor excite only symmetric rotor modes, which can be controlled using rotor collective pitch. As soon as we allow wind disturbance components having spatial variation over the rotor disk, we need to control each blade independently. The goal of independent blade pitch control is to regulate turbine speed and reduce blade flap response in the presence of both uniform and spatially varying wind disturbances.

An issue in independent blade pitch control is observability. When designing controls using only rotor collective pitch, we found that successful controls could be designed by only measuring generator speed (when tower fore-aft motion is ignored). The linear models used for control design contained the rotor symmetric flap mode, which is observable in the generator speed signal. Now that we are designing controls from linear models that contain the flap mode of each individual blade, the system is not observable when measuring only generator speed. Additional measurements are needed, such as the flap displacement of each blade. The best results are obtained when the flap displacement of each blade is measured and transformed into the rotor first *asymmetric* flap mode [10]. The improved control results are due to improved observability when directly measuring rotor first asymmetric flap.

Another issue is the disturbances modeled with DAC. Before, when designing controls using rotor collective pitch, only uniform wind disturbances over the rotor disk were modeled. Now, when the wind is assumed to vary spatially over the rotor disk, a new disturbance term is needed. This disturbance term models the dominant component of wind shear, the once per revolution (1P) component that has spatial variation over the rotor disk [10]. This new term has the form of Eq. (4).

$$V_{hub}\ (\frac{mr}{h}\ \sin\Psi)\ . \tag{4}$$

where r is the radial position along the blade from the center of the hub, V_{hub} is the wind speed at hub height h, m is the power law wind shear coefficient, and Ψ is the blade azimuth angle [10].

We begin design of independent pitch control by using a linear model that describes just the flap displacement of each blade as well as rotor speed (5-state model), neglecting drive train torsion and tower fore-aft motion. These controls are tested using step changes in mean wind speed with a vertical wind shear profile superimposed. The coefficient m is assigned the value 0.4, which represents a large variation in wind speed over the rotor disk. Figure 12 shows speed regulation and blade pitch using the new DAC. The pitch time series shows significant periodic behavior, demonstrating that the blade pitches to reduce the effects of wind shear. This is due to including the new disturbance term in the model. Figure 13 shows the flap deflection in response to the wind shear variation over the rotor disk. In the old DAC, the disturbance term shown in Eq. (4) has been ignored, while in the new DAC, this term has been included. The dramatic reduction in flap displacement when using the new DAC is very evident. The blade root flapwise bending moments are also significantly reduced using this new DAC, because these moments are directly related to the flap displacements. In these simulations, the drive train and tower were assumed to be rigid.

We now add these DOF. We use a 9-state model, which includes the flap displacement and velocity of each blade, drive train torsion, generator and rotor speed, and tower first fore-aft mode displacement and velocity [10]. In addition, generator torque is used as a control actuator to enhance damping in the first drive train torsion mode. This DAC design will be shown to meet several control objectives simultaneously: regulation of turbine speed, enhanced damping and stabilization of several flexible modes such as the flap mode of each blade, the first drive train torsion mode, and tower first fore-aft mode. It will also successfully attenuate the 1P component of wind shear.

This control algorithm is tested using turbulent wind inflow, with Figure 14 showing speed regulation at the 42-RPM set point. In this controller, gains have been selected to place plant poles to give high damping in the drive train torsion and tower fore-aft bending modes. The gains corresponding to the wind-speed disturbances have been selected to give maximum attenuation of both the uniform and 1P components. We compare results from this controller to a controller designed with reduced gains, giving lower amounts of mode damping and disturbance attenuating effects. We compute power spectral densities (PSDs) of various outputs, including tower-top fore-aft deflection and blade-tip flap deflection.

Figures 15, 16, and 17 show PSDs of the tower-top fore-aft displacement, blade-tip flap displacement, and shaft torque. The PSDs show peaks at frequencies corresponding to the tower first fore-aft bending mode, rotor rotational speed, and first drive train torsion mode. The higher gains result in reduced response at these frequencies, while the lower gains result in increased response. The load alleviating capability of the controller with high gains is very evident.

Figure 18 shows the effect of high and low gains on blade pitch actuator rates. For the high-gain case, some of the pitch rates exceed the 18°/s limit imposed in the CART and must be reduced. A trade-off must be performed between allowable pitch rates and the amount of damping added to various flexible modes and amount of disturbance attenuation achieved by the controller.

CONCLUSIONS

In this paper, rotor collective pitch control based on DAC was used to regulate turbine speed in region 3 and add damping to important flexible modes of the turbine. We concluded that it was possible to stabilize the first drive train torsional mode and the tower first fore-aft bending mode using only rotor collective pitch as the control input for the CART for these cases. By measuring only generator rotational speed, it was possible to use state estimation for the unmeasured states of the model containing the generator and rotor rotational speeds, drive train torsion, and rotor first symmetric flap DOF. When the tower first fore-aft mode was added, we needed an additional measurement: tower-top fore-aft deflection.

Generator torque control was then added to add damping to the first drive train torsion mode. This reduced some of the demand on the rotor collective pitch control system, resulting in a modest reduction in pitch rates. Using generator torque to control the first drive train torsion mode results in excursions in electrical power. A trade-off must be performed between allowable power excursions and the amount of damping added to the drive train mode by the controller.

Finally, independent blade pitch control was introduced to regulate turbine speed and attenuate the effects of spatial variations of wind speed over the rotor disk (such as wind shear). A new disturbance was added to the DAC model to describe the dominant component of wind shear, the 1P component that has spatial variation over the rotor disk. A large reduction in blade-tip flap deflections was shown using this method. In addition, these control inputs stabilized the first flap mode of each blade, the first drive train torsion mode, and the tower first fore-aft mode.

Independent blade pitch control required the rotor first asymmetric flap mode displacement to be measured. For the controls designed using rotor collective pitch control, blade flap displacement was not needed because the rotor first symmetric flap mode was observable in the generator speed measurement. When blade independent pitch is used, the rotor first asymmetric mode is contained in the linear model for control design. It was found that this mode is not observable by measuring only generator speed. The best controller performance occurred when the flap deflection of both blades was measured and transformed to obtain a measurement of the rotor first asymmetric mode. The improved control results were due to improved observability when measuring rotor 1st first asymmetric flap.

FUTURE WORK

Directions for future work include the implementation and field-testing of these controls in the CART. Important issues may include effects of measurement noise and the need to convert these control algorithms into digital form. The effects of turbine property uncertainties must also be accounted for.

Further studies need to be conducted to investigate controls for very flexible machines. As machines become much more flexible than the CART, periodic control design methods probably will be important. Other important issues include the attenuation of more complex turbulent wind inflow structures, which may require additional model complexity as well as turbine measurements.

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Figure 1. The Controls Advanced Research Turbine (CART).

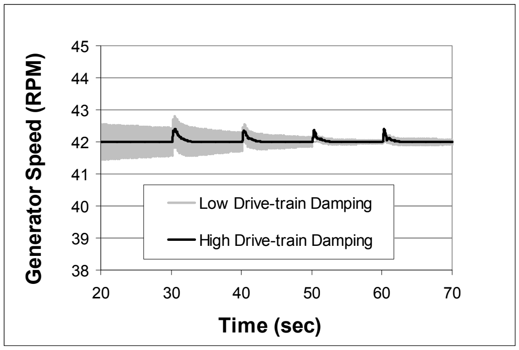

Figure 5. Plot of FAST simulated CART generator speed using DAC controller designed from 3-state model for different pole locations.

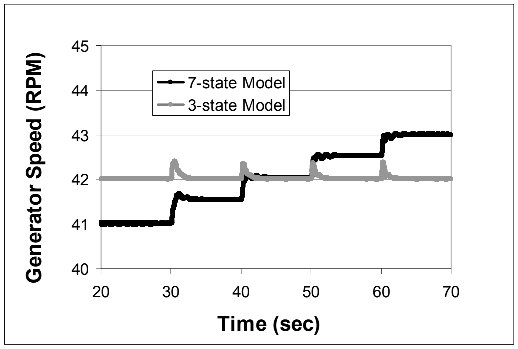

Figure 6. Plot of FAST simulated CART generator speed using DAC controller designed from 3-state model for different pole locations.

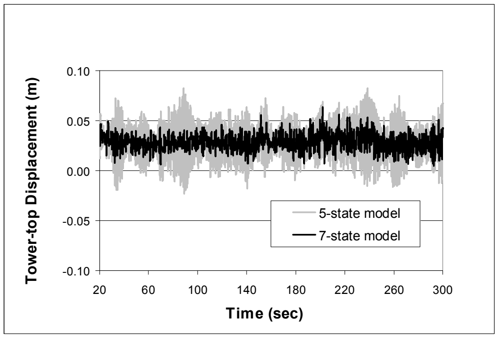

Figure 7. FAST simulated CART tower-top fore-aft deflection with turbulent inflow using DAC control designed from 5-state and 7-state models.

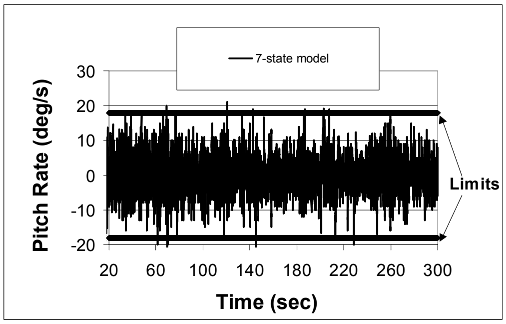

Figure 8. FAST-simulated pitch rates using DAC control designed from 7-state model with turbulent inflow.

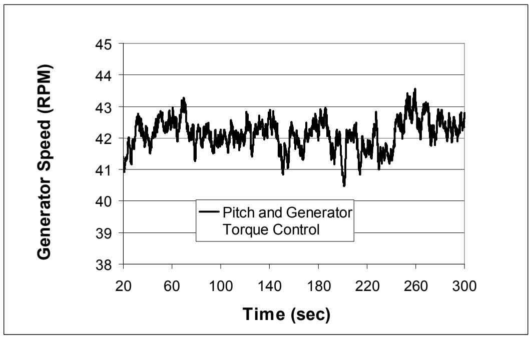

Figure 9. Plot of FAST simulated CART generator speed when generator torque control is used to add drive-train damping.

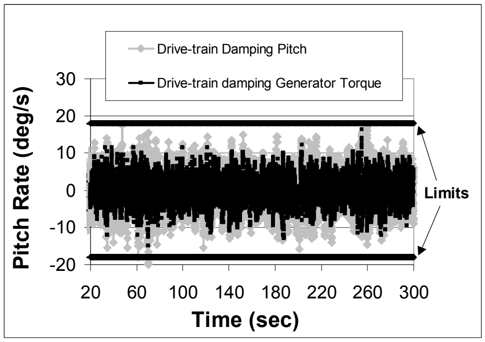

Figure 10. Plot of FAST simulated CART pitch rates, showing reduced pitch rates when generator torque control is used to add drive-train damping.

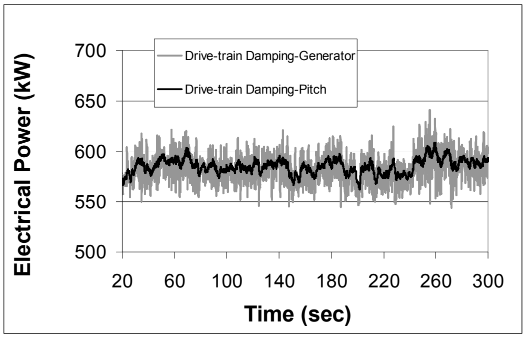

Figure 11. Plot of FAST simulated CART electrical power, showing effects of using generator torque control.

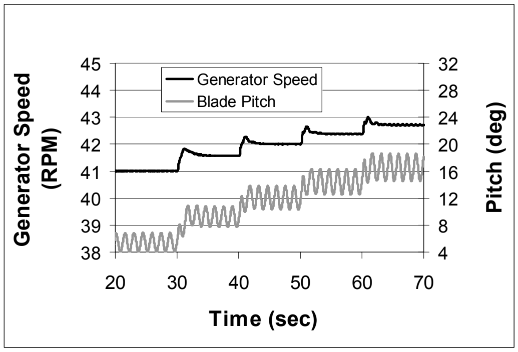

Figure 12. FAST simulated generator speed and blade pitch, using DAC designed from 5-state model.

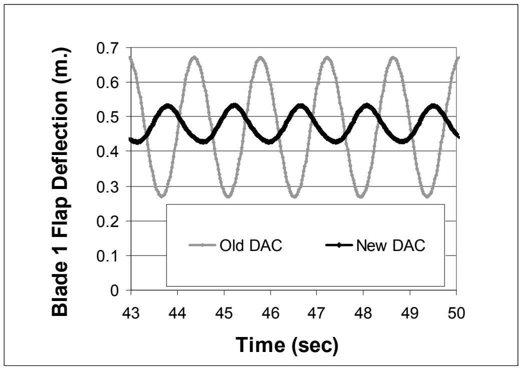

Figure 13. FAST simulated blade flap displacement excited by wind shear for old and new DAC designed from 5-state model.

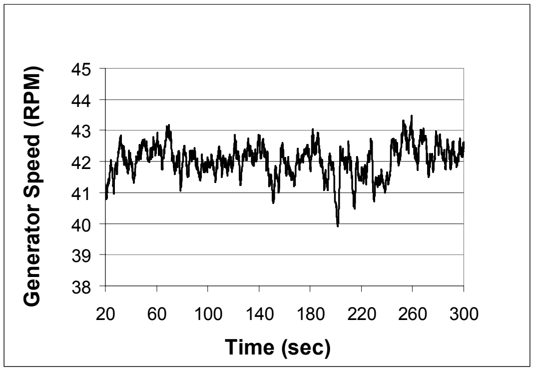

Figure 14. FAST simulated generator speed, using DAC designed from 9-state model, excited by turbulence.

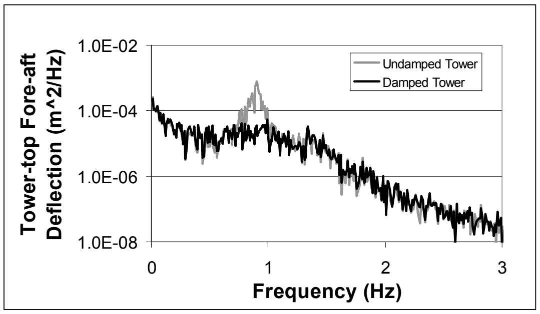

Figure 15. Power spectral density of FAST simulated tower-top fore-aft displacement, using DAC designed from 9-state model excited by turbulence.

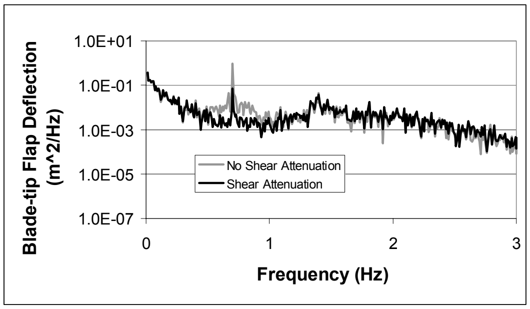

Figure 16. Power spectral density of FAST simulated blade-tip flap Displacement, Using DAC designed from 9-state model excited by turbulence.

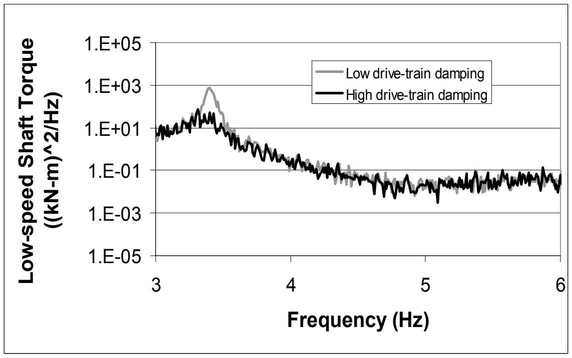

Figure 17. Power Spectral Density of FAST simulated Shaft Torque, Using DAC Designed from 9-state Model Excited by Turbulence.

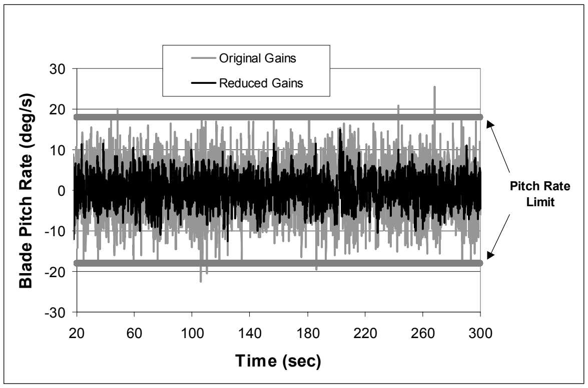

Figure 18. Blade Pitch Rates for Original Gains and Reduced Gains Cases Using DAC Designed from 9-state Model.

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13. ABSTRACT *(Maximum 200 words)*

Designing wind turbines to maximize energy production and increase fatigue life is a major goal of the wind industry. To achieve this goal, we must design wind turbines to extract maximum energy and reduce component and system loads. This paper applies modern state-space control design methods to a two-bladed teetering-hub upwind machine located at the National Wind Technology Center∗. The design objective is to regulate turbine speed in region 3 (above rated wind speed) and enhance damping in several low-damped flexible modes of the turbine. The controls approach is based on the Disturbance Accommodating Control (DAC) method and provides accountability for wind-speed disturbances. First, controls are designed using the single control input rotor collective pitch to stabilize the first drive-train torsion as well as the tower first fore-aft bending modes. Generator torque is then incorporated as an additional control input. This reduces some of the demand placed on the rotor collective pitch control system and enhances first drive train torsion mode damping. Individual blade pitch control is then used to attenuate wind disturbances having spatial variation over the rotor and effectively reduces blade flap deflections caused by wind shear.

14. SUBJECT TERMS
wind turbine design methods; wind turbine control; wind turbine speed regulation

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