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Considerations for an Integrated Wind Turbine Controls Capability at the National Wind Technology Center: An Aileron Control Case Study for Power Regulation and Load Mitigation

Janet G. Stuart
Alan D. Wright
Charles P. Butterfield

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National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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CONSIDERATIONS FOR AN INTEGRATED WIND TURBINE CONTROLS CAPABILITY AT THE NATIONAL WIND TECHNOLOGY CENTER: AN AILERON CONTROL CASE STUDY FOR POWER REGULATION AND LOAD MITIGATION

Janet G. Stuart, Alan D. Wright, Charles P. Butterfield
National Renewable Energy Laboratory

ABSTRACT

Several structural dynamics codes have been developed at, and under contract to, the National Wind Technology Center (NWTC). These design codes capture knowledge and expertise that has accumulated over the years through federally funded research and wind industry operational experience. The codes can generate vital information required to successfully implement wind turbine active control. However, system information derived from the design codes does not necessarily produce a system description that is consistent with the one assumed by standard control design and analysis tools (e.g., MATLAB® and Matrix-X®). This paper presents a system identification-based method for extracting and utilizing high-fidelity dynamics information, derived from an existing wind turbine structural dynamics code (FAST), for use in active control design. A simple proportional-integral (PI) aileron control case study is then used to successfully demonstrate the method, and to investigate controller performance for gust and turbulence wind input conditions. Aileron control results show success in both power regulation and load mitigation.

INTRODUCTION

Virtually all economic analyses of wind energy point out the make-or-break necessity of the wind industry to reduce its *cost of energy* (COE) in order to compete with other energy options, and to ultimately survive in existing and foreseeable market environments. To make wind energy more cost-competitive, the federal wind program and the wind industry are pursuing critical wind turbine design objectives that enhance fatigue resistance, increase expected lifetimes and decrease costs. One way to achieve these design objectives is to mitigate the damaging loads and responses. Load mitigation can be accomplished through various means, one of which is the use of active control strategies. A few examples of load-mitigating active control strategies are aerodynamic device control, flexible wind turbine dynamics and control, and variable load control using power electronics (variable-speed turbines). These examples demonstrate the wide range of active control options for load mitigation, and imply that the use and selection of a particular active control strategy is highly dependent on wind turbine configuration.

Active control strategies for increasing wind turbine performance (and consequently decreasing the COE) have been proposed, some of which are currently in use. Active control of a dynamic system, however, complicates the system and sometimes destabilizes an otherwise stable, open-loop (i.e. uncontrolled) system. A logical and completely valid question is: why bother implementing active control in the first place? To make a case for continued research in active wind turbine control, one must look at the current performance of existing wind turbines, in terms of cost and design, and offer active control strategies that have a reasonable probability of impacting COE performance to a degree that is worth the effort.

One option for COE reduction is to mitigate the effects of damaging loads, and/or undesirable wind turbine responses, using active control of aerodynamic devices. The resulting control objectives include, but are not limited to, reducing excessive root-flap bending moments and regulating power output to minimize power spikes. It is assumed that minimizing excursions in power consequently reduces the loads caused by power spiking. Therefore, the general motivation for the research presented in this paper is COE reduction via load mitigation through the use of aerodynamic device control strategies.

The development of an integrated controls capability at the NWTC is a potential, long-term research objective currently under evaluation. Toward this end, control system engineers studying the wind turbine problem immediately identify the need for a reasonable dynamic model for use in control design. The body of knowledge existing within the NWTC, in terms of wind turbine structural dynamics design codes, provides valid, detailed dynamics information that can be used for control system dynamic model generation. Correspondingly, these codes must be updated to include control capability for evaluation of control's impact on performance. Therefore, the specific motivation for the research presented in this paper is to demonstrate the use of an existing NWTC structural dynamics design code, namely FAST, together with standard control system design tools, to design a simple aileron controller.

An aileron control case study is used to demonstrate the process of bridging the gap between control system design and analysis software and existing structural dynamics codes, which is the primary objective. In addition, the paper discusses the development of an aileron control strategy for power regulation and load mitigation for a two-bladed, downwind, fixed-speed wind turbine. A FAST model of this turbine is used in conjunction with system identification techniques to characterize aileron power regulation effectiveness for mean wind speeds ranging from 8 to 20 meters/second.

Note that the intention here is *not* to design an "optimal" aileron controller, or even an advanced aileron controller. One can refer to Hinrichsen (1984) and Barton et al. (1979) for PI controllers with additional lead-lag and notch filters for maintaining a constant amount of produced energy and reducing loads, and to Bossanyi (1987, 1989) for an adaptive control scheme that takes into account that the gain from pitch angle to electrical power varies with wind velocity. In this paper, a very simple PI aileron controller is designed to regulate output power. The selected control design objective is to reduce the response time of an aileron-controlled wind turbine when subjected to step changes (i.e. gusts) in wind speed. A single controller design is selected for use over a range of wind speeds and wind input conditions.

DESCRIPTION OF THE FAST CODE AND THE WIND TURBINE EXAMPLE

Code Description. The wind turbine structural dynamics code, FAST (Fatigue, Aerodynamics, Structures, and Turbulence), which was developed at Oregon State University under subcontract to the National Renewable Energy Laboratory (NREL), uses equations of motion based on Kane dynamics (Wilson, 1995). Kane's method is used to set up equations of motion that can be solved by numerical integration. This method greatly simplifies the equations of motion by directly using the generalized coordinates and eliminating the need for separate constraint equations. These equations are easier to solve than those developed using methods of Newton or Lagrange and have fewer terms, thus reducing computation time. For more information on FAST code theory and formulation, see Harman (1995).

Aerodynamic forces are determined using blade element momentum theory. Lift and drag forces on the blades are determined by table look-up of the blade's lift and drag coefficients Cl and Cd. At NREL, there are two versions of FAST in use: a version with the original Oregon State University aerodynamic subroutines and a version with the University of Utah AeroDyn subroutines. The goal was to have the University of Utah develop a stand-alone aerodynamic subroutine package for inclusion into any wind turbine structural dynamics code (Hansen, 1995). This package includes the effects of dynamic stall, dynamic inflow, table look-up of Cl and Cd data, and input of 3-D turbulence (Hansen, 1995). The AeroDyn subroutines have been successfully incorporated into FAST2 and this version was used to generate the results presented in this paper.

In this first-order modeling effort, the effects of the deflected aileron on the blade's overall lift and drag properties, as a function of the degree of aileron deflection, are modeled. Changes in section mass and elastic properties, caused by a shift in the center of gravity of the blade section with the deflected aileron, are not modeled. The objective of this study is to include first order effects only, and then simulate the effects of the ailerons on the overall wind turbine behavior. To simulate this effect, it is necessary to include the modifications of the section lift and drag characteristics into the section airfoil tables at those blade spans employing ailerons. In the airfoil data tables used by the AeroDyn subroutines, multiple columns of Cl and Cd data are inserted corresponding to different discrete aileron angles (or deflections). For any given or prescribed aileron angle, the code interpolates between these columns of Cl and Cd data. These interpolated values of Cl and Cd will then be returned to the main aerodynamics subroutine for calculation of that section's final aerodynamic forces.

To include the PI aileron controller in FAST, one inputs the gains for this control law into the input data-set for the AeroDyn subroutines. The transfer function corresponding to this control law is transformed within this subroutine to a linear differential equation and the states of the controller are integrated along with the rest of the degrees of freedom contained in FAST. In this case, we are regulating power using ailerons, so the input to the aileron control transfer function is the error between the actual power and desired power. The output of the controller (or transfer function) is aileron angle. The calculated aileron angle is then passed to the aerodynamic subroutines, whence the section's lift and drag properties are determined via interpolation as described above.

Turbine Description. A two-bladed, teetering hub, free-yaw, downwind machine was simulated for this study. The 12.1-m (39.7-ft) fixed-pitch blades have a 5.5° pre-twist with a maximum chord of 1.2 m (3.8 ft). They use the NREL thick airfoil family (S809, S810, and S815)[1] designed for 12-m (40-ft) blades. The rotor diameter is 26.2 m (86 ft) with a 7° pre-cone. It sits on top of a free-standing truss tower, with a hub height of 24.4 m (80 ft). The turbine rotates at 57.5 revolutions per minute (RPM) (0.958 Hz) and generates 275 kW of power at rated wind speed (18 m/s, 40 mph). The ailerons are assumed to be attached to the outer 30% of the blade span. Unfortunately, there is no accurate wind tunnel airfoil data for the S810, or any other S8 series airfoil, tested with ailerons. Therefore, airfoil data for other airfoils fitted with ailerons was examined and the general trends of Cl and Cd data for different aileron deflections were followed. The accuracy of the results is obviously affected by this extrapolation. However, it is assumed that the general trends and conclusions that are reached will not be greatly affected by this approximation.

[1] S809, S810, and S815 are trademarks of the National Renewable Energy Laboratory.

OVERVIEW OF AILERON CONTROL STRATEGY AND MODEL REQUIREMENTS

Aileron control is used to regulate power output according to the block diagram shown in Figure 1. The control block, **C**, defines the aileron controller in terms of its transfer function description. The plant model, **P**, characterizes the wind turbine system's output power response to changes in commanded input aileron angle for a given wind speed and corresponding reference power, **Pref**.

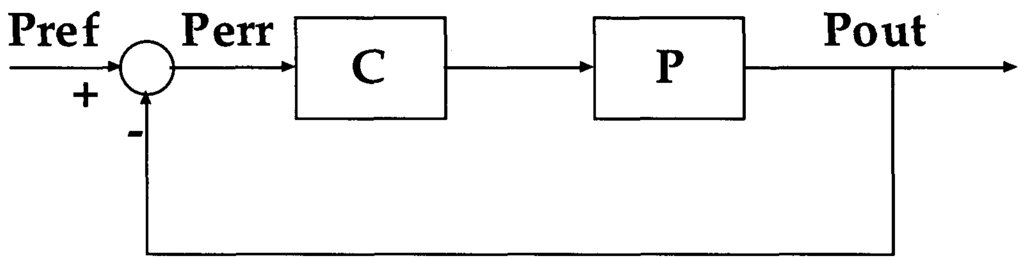

FIGURE 1. AILERON CONTROL BLOCK DIAGRAM FOR POWER REGULATION

The equations describing the conversion of wind energy to electrical energy are non-linear and complex, in that they involve interactions between system elements. Most of the wind turbine active control work, to date, is based on linear control theory. Thus, a linearization about an operating point is required. Operating points, in this case, correspond to various wind speed inputs, and associated turbine power outputs.

Reference power, plant dynamics and possibly controller design, in the case of adaptive control, change as a function of wind speed. Reference power, **Pref**, as a function of wind speed, can be obtained from turbine design specification and/or performance verification. Controller characterization, in **C**, is specified by the control design engineer, and is therefore known. The linearized description of the plant, **P**, as a function of wind speed, however, is more difficult to define. As discussed by Bongers and van Baars (1994), the linear model can be derived in two different ways:

- Given the non-linear model of the wind turbine system, a linearization is performed in one operating condition, resulting in a linear model.
- Using data, measured at a wind turbine, system identification techniques can be applied to obtain a linear description.

For the purposes of integrating active wind turbine control capability into an existing NWTC dynamics code, the system identification option permits the quick generation of a plant model using input and output data generated by the code. Linearization of the code about an operating point is a workable option. However, the magnitude of the work associated with this option, based on the structure of the existing codes and the modifications required to yield the linearization, is significantly greater than the system identification option. (The linearization option is currently being pursued in related research at the NWTC).

SYSTEM DESCRIPTION USING SYSTEM IDENTIFICATION TECHNIQUES

The selection of system identification for this problem necessitates the use of modeling tools, in this case, MATLAB® and its system identification toolbox. The theoretical basis for system identification is thoroughly developed by Ljung (1987), and the application of the technique, using the MATLAB® system identification tool box, is also developed by Ljung (1995). MATLAB® control design tools are based on standard definitions, derived from basic principles, and, therefore, require standard inputs. In contrast, wind turbine structural dynamics models have evolved to efficiently handle the complex, non-linear problem, specific to wind turbine dynamics. Extracting the standard inputs required for control system design from the existing codes is greatly simplified by using the system identification capability available in MATLAB® in conjunction with input and output data generated using the FAST code. This method was used to generate linear plant models corresponding to linearizations about four operating points. The operating points selected correspond to wind speeds of 8 m/s, 12 m/s, 16 m/s and 20 m/s.

The plant model description for each operating point was based on input data corresponding to a sine-sweep of aileron input angle, and output data corresponding to the resulting change in power output. The dynamic models produced by system identification analyses of the input-output data were fourth-order for all of the operating points. The plant behavior does indeed vary as a function of wind speed, as seen by the comparison of the open-loop system eigenvalues for the four wind speed cases, shown in Table 1. The open-loop systems are quite stable, as characterized by the eigenvalue with the smallest, negative real value. In the next section, PI control gains are selected to move the negative real values of the closed-loop system further to the left, resulting in a faster system response.

TABLE 1. OPEN-LOOP SYSTEM EIGENVALUE COMPARISON

Wind Speed = 8 m/s		
Eigenvalue	Damping	Freq. (rad/sec)
-4.8894 ± 51.8535i	0.0939	52.0835
-7.4623 ± 18.0724i	0.3817	19.5525
	12 m/s	
Eigenvalue	Damping	Freq. (rad/sec)
-4.7123 ± 19.6746i	0.2329	20.2311
-7.0414 ± 60.4978i	0.1156	60.9062
	16 m/s	
Eigenvalue	Damping	Freq. (rad/sec)
-5.2675 ± 18.6609i	0.2717	19.3901
-6.9171 ± 61.8496i	0.1111	62.2352
	20 m/s	
Eigenvalue	Damping	Freq. (rad/sec)
-1.5580 ± 13.6879i	0.1131	13.7763
-5.1719 ± 54.5658i	0.0944	54.8103

AILERON CONTROL DESIGN AND SIMULATION

Design. As mentioned previously, this case study focuses on the design of an aileron controller for power regulation. A simple PI controller is designed and the associated gains are selected to meet the control objective of minimizing the aileron-controlled wind turbine's response time when subjected to a step input. The performance of an *initial* aileron controller was the motivation for the design of this simple controller and for the selection of the control objective when simulations of the initial controller showed that it was taking several seconds for the ailerons to respond to gust inputs. The performance of the initial and new controllers are compared in the next section.

Typically, control system performance is characterized by the closed-loop system response to a given input. Impulse and step responses are commonly used to evaluate controller performance. The step input is also a reasonable approximation of a gust input, and was, therefore, selected for the evaluation of PI controller designs. A step/gust wind input profile for use in FAST was created to emulate the standard step input so that MATLAB® and FAST output could be compared. For this FAST input file, a 4 m/s step increase in wind speed occurred over a 0.25 second time period about the mean wind speeds for the four wind input cases.

Controller gains were varied to produce a closed-loop system response that meets the stated objective for the various wind speed operating points. The controller design selected for this case study is specified by the transfer function,

$$\mathbf{C} = \frac{0.1\,s + 10}{s}$$

and the resulting closed-loop systems for the wind speeds of 8, 12, 16, and 20 meters/second are characterized by the eigenvalues shown in Table 2. (Compare with $\mathbf{C} = [0.2s^2+0.5s+2]/[s^2+3s]$ for the *initial* aileron controller). Note that the closed-loop system's stability and response are enhanced through the selection of PI control gains. The smallest negative real values of the closed-loop system (see Table 2.) are further to the left of those for the open-loop system (see Table 1.), resulting in a faster system response.

Simulation. Control design using system identification-based dynamic models was done "off-line" in the MATLAB® environment. The resulting controller design was then put in its transfer function form and integrated into the FAST code as discussed previously. FAST simulations of the controller were used to validate the system identification-based model, and to evaluate performance for the step/gust inputs at the four wind speeds, and for a gust input based on the IEC '88 gust model (IEC, 1994). Simulations of the uncontrolled system's response to these inputs were also conducted for comparison. Simulation output for selected gust input cases are shown in Figures 2, 3, and 4. These figures show power and root flap bending moment as a function of time for controlled and uncontrolled cases. Figure 2 shows power output for both the initial and new aileron controllers for a step/gust input, whereas Figures 3 and 4 show only the new aileron controller's performance when subjected to the IEC '88 gust input. Note that the set-point power for a step gust about a mean wind speed of 8 m/s, as shown in Figure 2, is 58.01 kW for this turbine example. The set-point power for the IEC '88 gust is 241.51 kW, as shown in Figure 3.

Simulations for rough and smooth turbulence inputs, at wind speeds of 14 m/s and 18 m/s, were performed for the controlled and uncontrolled systems. The output for selected turbulence input cases are shown in Figures 5 and 6. Again, these figures show power and root flap bending moment as a function of time for controlled and uncontrolled cases. The simulation results are discussed in greater detail in the next section.

TABLE 2. CLOSED-LOOP SYSTEM EIGENVALUE COMPARISON

Eigenvalue	Damping	Freq. (rad/sec)
Wind Speed = 8 m/s		
-6.3196	1.0000	6.3196
-7.0448 ± 33.5172i	0.2057	34.2495
-7.5454 ± 53.4511i	0.1398	53.9811
12 m/s		
-5.9778 ± 61.0319i	0.0975	61.3240
-6.0129 ± 30.0832i	0.1960	30.6782
-8.4841	1.0000	8.4841
16 m/s		
-5.2644 ± 29.5953i	0.1751	30.0598
-5.9033 ± 62.7378i	0.0937	63.0149
-7.5853	1.0000	7.5853
20 m/s		
-2.0861	1.0000	2.0861
-3.0453 ± 25.1213i	0.1203	25.3052
-4.8039 ± 54.5519i	0.0877	54.7630

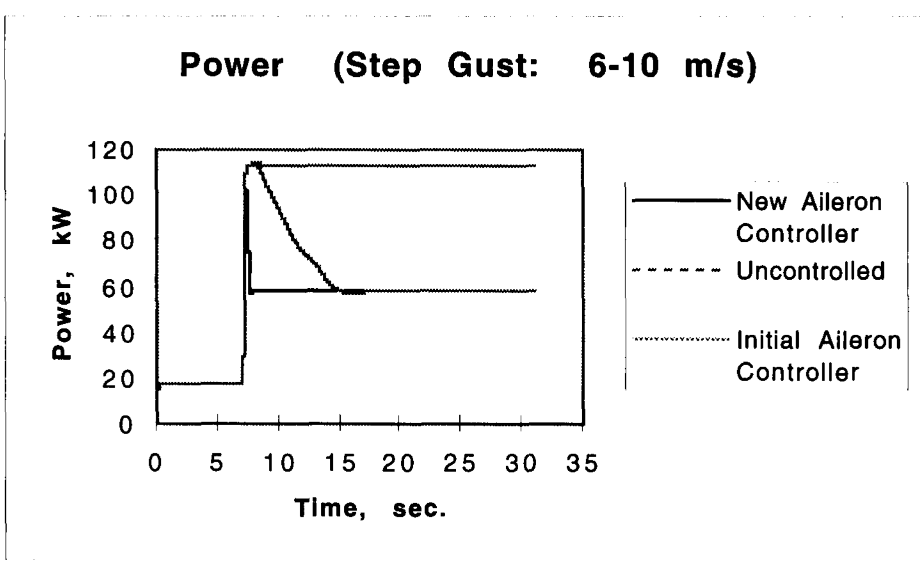

FIGURE 2. SIMULATION OUTPUT FOR STEP INPUT (CONTROLLED AND UNCONTROLLED CASES)

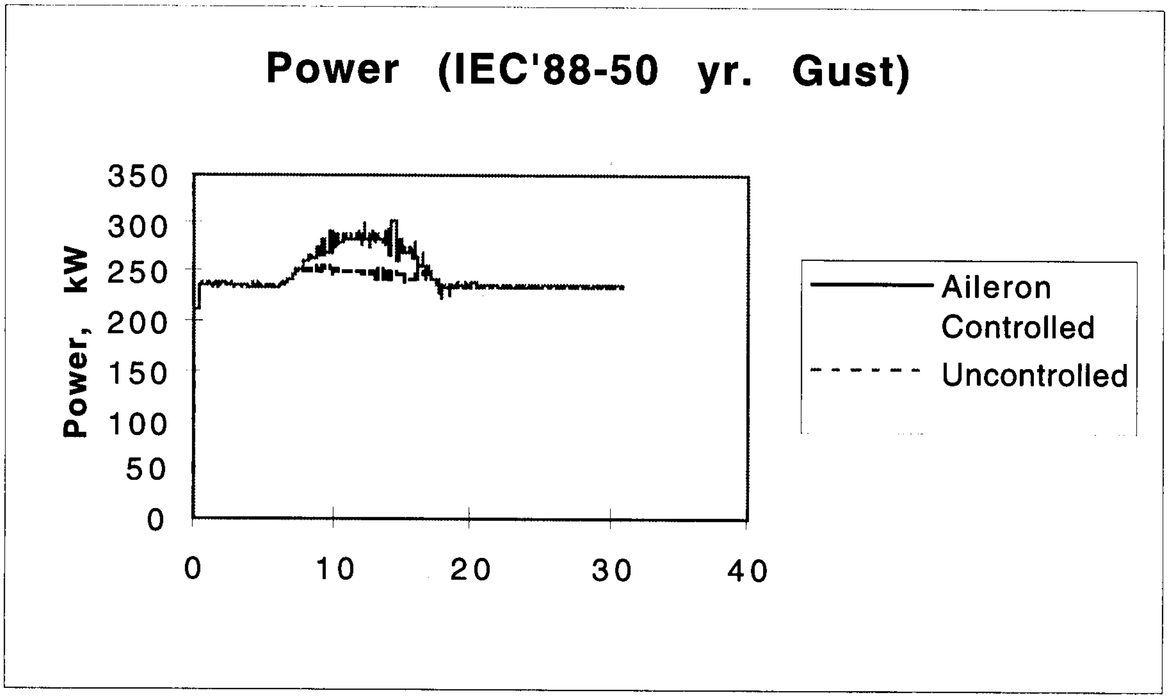

FIGURE 3. SIMULATION OUTPUT FOR IEC '88 GUST INPUT
(CONTROLLED AND UNCONTROLLED CASES)

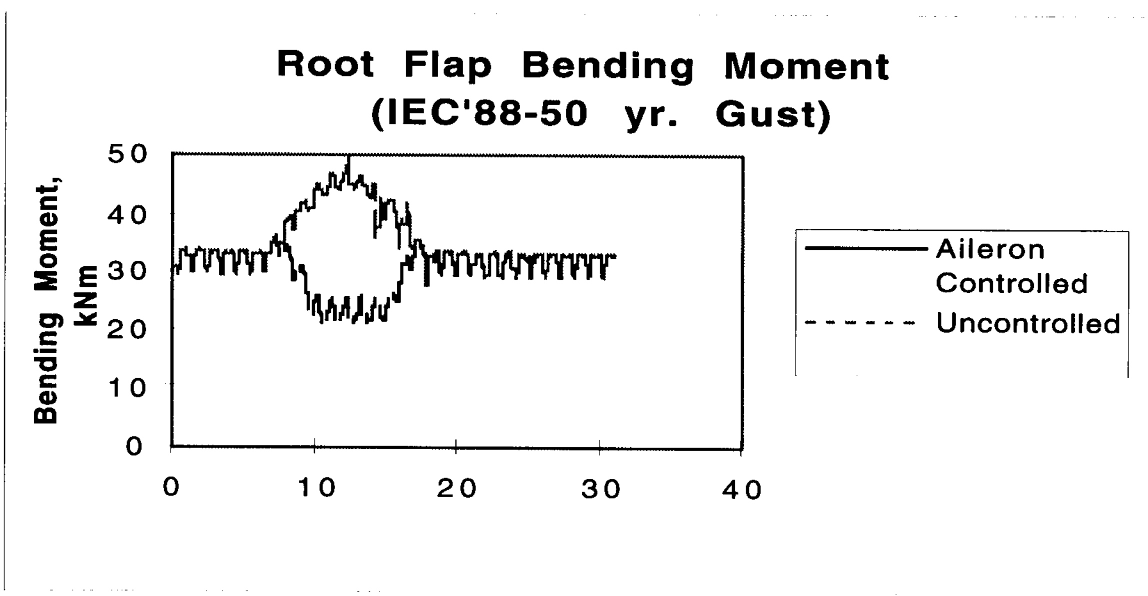

FIGURE 4. SIMULATION OUTPUT FOR IEC '88 GUST INPUT
(CONTROLLED AND UNCONTROLLED CASES)

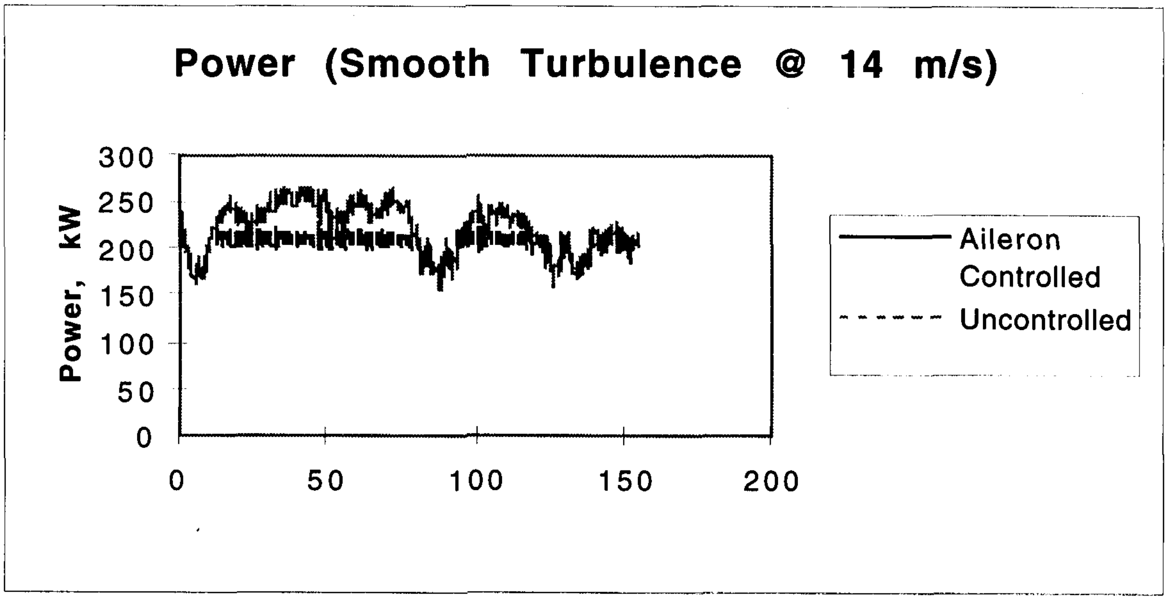

FIGURE 5. SIMULATION OUTPUT FOR TURBULENCE INPUT @ 14 m/s
(CONTROLLED AND UNCONTROLLED CASES)

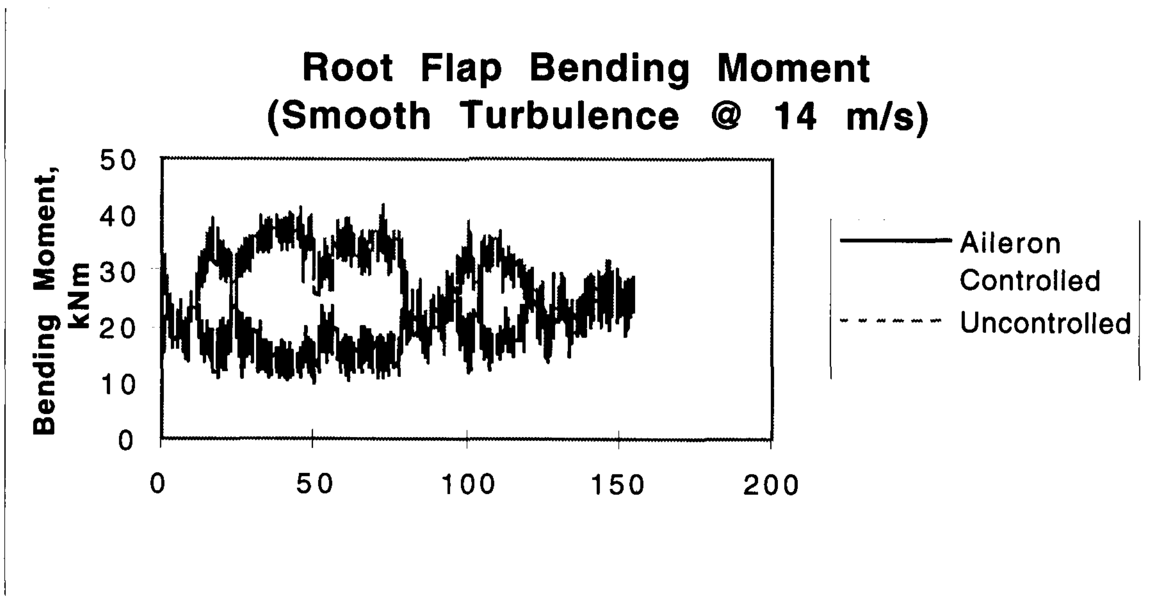

FIGURE 6. SIMULATION OUTPUT FOR SMOOTH TURBULENCE INPUT @ 14 m/s
(CONTROLLED AND UNCONTROLLED CASES)

SUMMARY OF SIMULATION RESULTS

A comparison of the performance of the initial and new aileron controllers, as seen in Figure 2., shows that the new controller reduces the response time to a step-gust input by several seconds, thus achieving the selected control objective. This response to the step-gust input validates the aileron controller from a controls perspective. Aileron controller performance, when subjected to the IEC '88 50-year gust, is shown in Figures 3 (power) and 4 (loads).

Power regulation at 250 kW is quite good, especially when compared to the uncontrolled case. The root flap bending moment is also reduced through aileron control. The IEC '88 gust case, therefore, validates the aileron controller from more of a wind industry perspective. The performance of the same aileron controller, when subjected to a smooth turbulence wind input at 14 m/s, is shown in Figures 5 (power) and 6 (loads). Power regulation at the reference power for this wind speed is excellent, and once again, loads are reduced when compared to the uncontrolled case. Note that smooth and rough turbulence at wind speeds of 14 and 18 m/s were also simulated, with similar results, but are not presented here.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The control objectives for this research were met, namely that the design code, FAST, was successfully used for control system design and analysis using standard control system design tools, and correspondingly, that simple P-I aileron control was successfully implemented in the FAST code. The primary control performance objective was met, i.e. that a new aileron controller was designed to reduce the response time for a step-gust wind input. This simple controller then yielded reasonable performance for a range of wind speeds and input conditions.

The research presented here also served to scope the problems associated with defining a linear system description for use in control system design, and it led to the use of the system identification technique as a viable option worthy of more detailed, future investigation. Background research in aileron control identified the need for the inclusion of actuator dynamics and associated bandwidth limitations in future research. Also, the exciting possibilities of other aerodynamic device control strategies, such as full-span pitch control, both differential and collective, were clearly identified as high-payoff control opportunities. And finally, the utilization of control schemes more sophisticated than PI, and perhaps more appropriate for the challenging wind problem, is another promising control opportunity being evaluated at the NWTC.

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