NREL/TP-442-7812 • UC Category: 1213 • DE95009252

Guidelines for Reducing Dynamic Loads in Two-Bladed Teetering-Hub Downwind Wind Turbines

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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Task No. WE518210

June 1995

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GUIDELINES FOR REDUCING DYNAMIC LOADS IN TWO-BLADED TEETERING-HUB DOWNWIND WIND TURBINES

INTRODUCTION

A major goal of the federal Wind Energy Program is the rapid development and validation of structural models to determine loads and response for a wide variety of different wind turbine configurations operating under extreme conditions. Such codes are crucial to the successful design of future advanced wind turbines. In previous papers we described steps we took to develop a model of a two-bladed teetering-hub downwind wind turbine using ADAMS®[1] (Automatic Dynamic Analysis of Mechanical Systems), as well as comparison of model predictions to test data. In this paper we show the use of this analytical model to study the influence of various turbine parameters on predicted system loads. We concentrate our study on turbine response in the frequency range of six to ten times the rotor rotational frequency (6P to 10P). Our goal is to identify the most important parameters which influence the response of this type of machine in this frequency range and give turbine designers some general "design guidelines" for designing two-bladed teetering-hub machines to be less susceptible to vibration.

References 1 to 4 describe system modeling of two- and three-bladed wind turbines using the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) software. In those references we described specific modeling steps we used to develop system dynamics models of two-bladed teetering-hub and three-bladed rigid-hub wind turbines using ADAMS. In this paper we describe the application of one of these models for developing guidelines in reducing dynamic loads in two-bladed teetering-hub downwind wind turbines.

Some teetering-hub, horizontal-axis downwind wind turbines have shown an interaction at normal operating speed, involving blade symmetric edge-bending and nacelle and tower top tilt motion. In one machine this interaction was seen as a 7-per-revolution response in the blade root edgewise-bending moments, and as a 6- and 8-per-revolution response in the nacelle and tower. In cooperation with a wind industry partner, National Renewable Energy Laboratory (NREL) Wind Technology Division staff developed a full-system dynamics model of a prototype turbine which exhibits this response using ADAMS [2].

We developed an ADAMS model of the complete turbine, including blade flapwise, edgewise and torsional degrees of freedom, low-speed shaft bending and torsion degrees of freedom, tower fore-aft and lateral bending degrees of freedom, and rigid body nacelle yaw and rotor hub teeter degrees of freedom. We validated the model's mass and stiffness characteristics by comparing ADAMS predicted mode shapes and natural frequencies to modal test data, both for an isolated blade and for the complete nonrotating wind turbine. Identifying the important modes involved in this machine's response and validating the model with both modal test data and operating machine loads data greatly accelerated the development and validation of a systems dynamics model for this machine. We performed further validation of this model by comparing ADAMS predicted loads to measured loads, for various wind speed and operating conditions.

In this paper we use this validated model to show the effects of various turbine parameters on operating turbine loads. We study the effects of such parameters as blade edgewise and flapwise stiffness, tower top stiffness, blade tip-brake mass, low-speed shaft stiffness, nacelle mass moments of inertia, and rotor speed. We show which parameters can be varied in order to make the turbine less responsive to such atmospheric inputs as wind shear and tower shadow. We then give designers a set of "design guidelines" in order to show how these machines can be designed to be less responsive to these inputs.

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[1] ADAMS is a registered trademark of Mechanical Dynamics, Inc.

TURBINE DESCRIPTION

The machine under study is a free-yaw, downwind machine. The 12.1 m (39.7 ft) fixed-pitch blades have a 5.5° pretwist with a maximum chord of 1.2 m (3.8 ft). They use the NREL thick airfoil family (S809, S810, and S815[2]) designed for 12-m (40-ft) blades. The rotor diameter is 26.2 m (86 ft) with a 7° precone. It sits on top of a free-standing truss tower and the hub height is 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). Each blade has a tip brake, which weighs approximately 11.3 kg (25 lb).

REVIEW OF IMPORTANT MACHINE RESPONSES

We review observed machine response involving rotor symmetric lag and nacelle/tower tilt. Figure 1 shows a plot of the blade root edgewise-bending moment and nacelle vertical (or pitch) acceleration measured on an operating machine. We performed azimuthal averaging on a 10-minute section of test data, in order to obtain the turbine's steady-state response to such deterministic excitation sources as wind shear, tower shadow, and gravity. The plot shows the harmonic content of the azimuthally averaged blade root edgewise-bending moment and the nacelle's pitching acceleration. The root edgewise-bending moment shows strong harmonic content at 1X, 5X, and 7X the rotor rotational frequency (1P, 5P, and 7P), whereas the nacelle pitching acceleration shows strong response at 6X and 8X (6P and 8P) the rotational frequency. This shows that the rotor symmetric lag response, which occurs at 7P, is coupled with nacelle and tower top tilt, which occurs in the fixed frame at 6- and 8P. In addition, significant rotor flap response also occurs at 8P (not shown here).

Typical modes of the nonrotating turbine which have natural frequencies in the 6P to 8P range are shown in Figures 2 to 4. The frequency of some of these modes depends upon rotor orientation (whether the rotor is parked horizontally or vertically). Figure 2 shows the rotor's symmetric lag mode when the rotor is parked horizontally. This mode shows considerable rotor symmetric edgewise bending, low-speed shaft- and tower top-bending, and tower top-nacelle tilt participation. When the blade tips move up, the hub end of the nacelle moves down, 180° out of phase with the blade tips. When the rotor is parked vertically, the frequency of this mode changes, because of involvement of the nacelle's yaw motion, shown in Figure 3. Figure 4 shows the rotor's second symmetric flap mode, which is the same whether the rotor is parked vertically or horizontally. We found very little tower or nacelle participation in this mode. There is also a mode involving rotor symmetric lag in phase with nacelle tilt motion at about 4 Hz (not listed) and a first symmetric flap mode at about 2.4 Hz (also not listed). These modes are not expected to significantly affect response in the 6-10 Hz range.

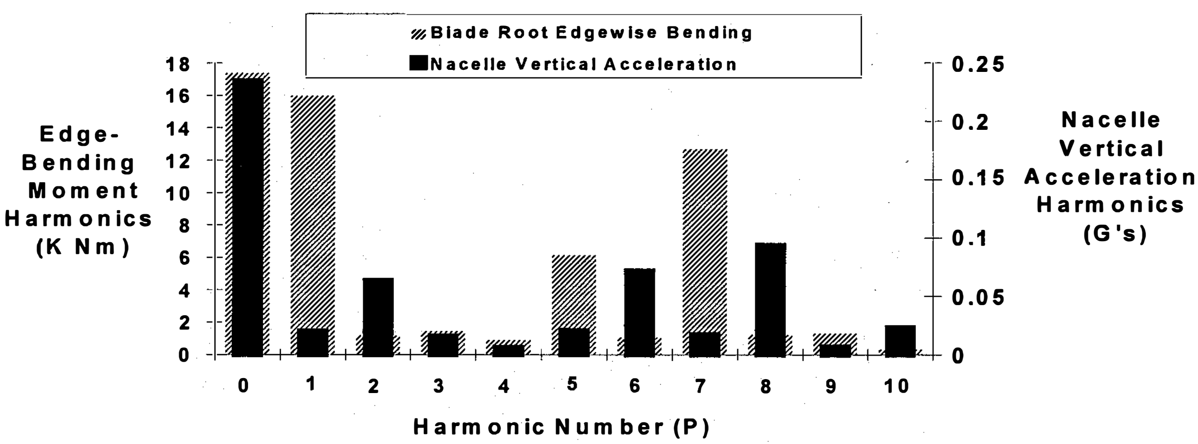

Figure 1. Blade root edgewise bending moment and nacelle vertical acceleration harmonics

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

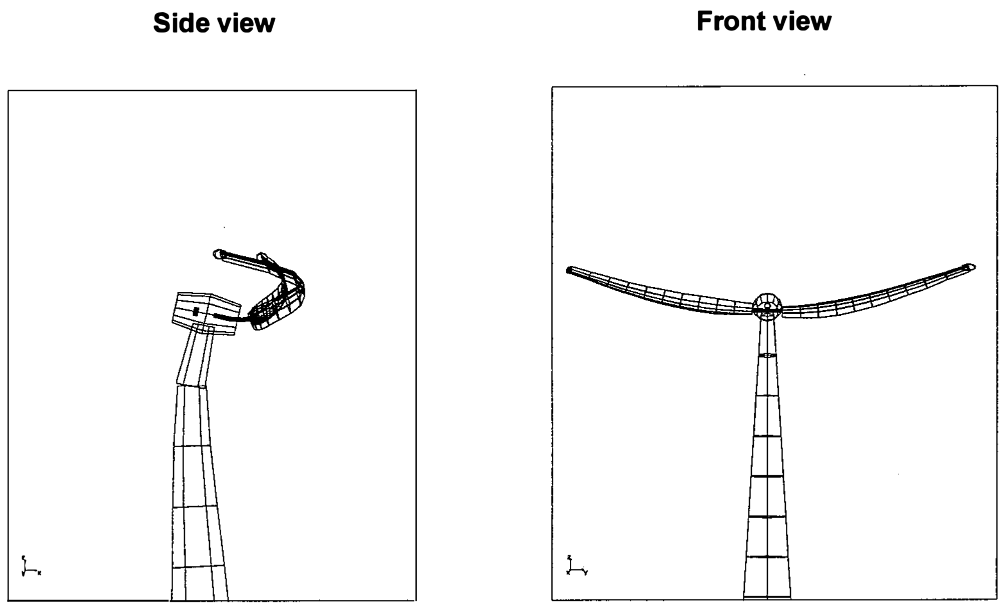

Figure 2. Rotor symmetric lag mode, rotor parked horizontally, frequency = 7.15 Hz

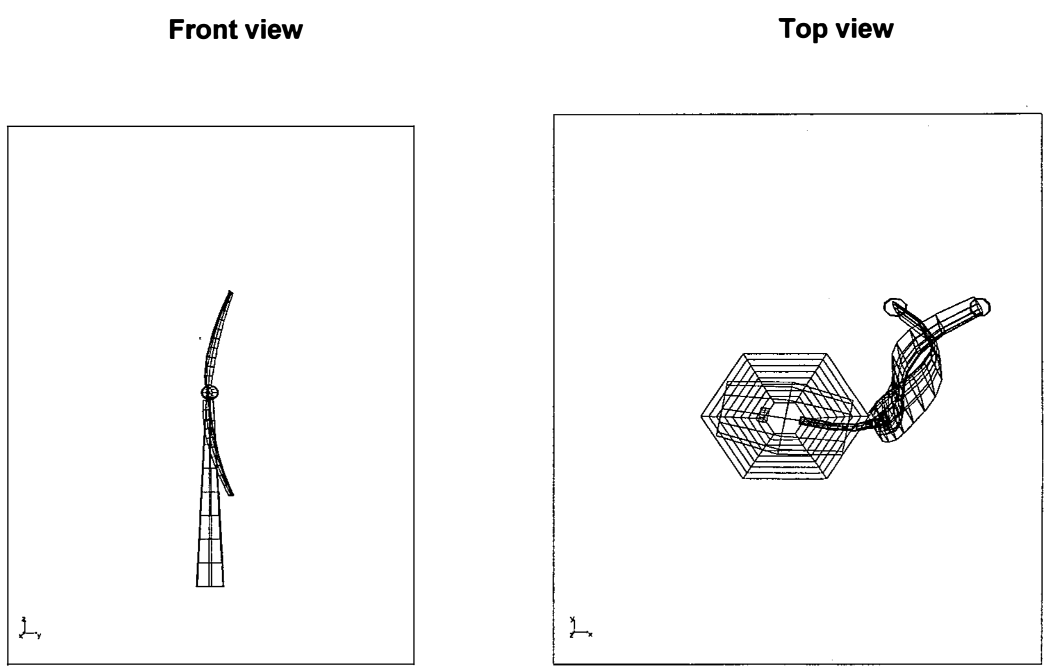

Figure 3. Rotor symmetric lag mode, rotor parked vertically, frequency = 6.81 Hz

Reference 1 describes some of the difficulty we experienced in predicting an accurate value for the symmetric lag mode with the rotor parked horizontally, as compared to a real turbine's measured modal results. This mode involves extensive nacelle tilt response and is therefore particularly sensitive to any errors we might have made in estimating or knowing the tower top, nacelle bedplate, and low-speed shaft stiffness. We had to soften the last two tower top stiffness elements by approximately 50% in order make the predicted results agree with the machine's measured nonrotating frequency. Somewhere in the real system there exists extra compliance for which we were not able to account, even with our most careful review of the machine drawings and estimated nacelle bedplate and tower top stiffnesses. It is possible that this extra compliance could be added at other locations and similiar results obtained. "Tuning" the ADAMS model to get good agreement for this mode was particuliarly important to realistically predict the blade's root edgewise-bending moments. We still have not found the cause of this discrepancy.

PARAMETRIC STUDIES

We used the ADAMS model to predict the turbine's operating loads, such as blade root flapwise and edgewise bending moments. We studied the effects of key turbine input parameters on predicted loads, using our "tuned" ADAMS model as a basis. We ran the ADAMS code using the University of Utah AeroDyn package [8] to supply aerodynamic forces to the model. We ran the aerodynamics package using steady winds as inputs, with dynamic stall and dynamic inflow included, as well as tower shadow having a 50% velocity deficit in a rectangular shaped region and also a small amount of vertical wind shear (.05 power law wind shear coefficient). The wind speed for these cases was approximately 12 m/s. We simulated the machine's steady-state response to such input by running the code until a sufficient number of machine revolutions were completed in order to obtain a representative steady-state response (approximately 25 revolutions). Then we performed azimuth averaging on the predicted loads in order to average out any numerical noise. We then made parametric changes in certain machine parameters and studied their effects on predicted blade root loads. Our objective was to study the changes in the harmonic content of the blade root loads as these parameters were varied. The harmonic content of the blade's root edgewise and flapwise bending moments was obtained by fitting a Fourier Series to the azimuthally averaged root loads and then determining the magnitude of each harmonic, using the General Purpose Postprocessor Program (GPP) developed at NREL [7].

From examination of the mode shapes involving rotor symmetric lag motion, shown in Figures 2 and 3, we see that several parameters may affect the rotor's symmetric lag mode. With the rotor parked horizontally, this mode involves bending of the blades (mostly in edgewise bending), low-speed shaft bending, and tower top bending. When the rotor is parked vertically, this mode involves blade bending, low-speed shaft bending, and nacelle yaw motion. The features of these modes give us a clue as to the most important turbine parameters that can be adjusted to affect these modes, which in turn affect the rotor's symmetric lag response to atmospheric inputs. We show that by moving the frequency of these modes closer to or away from certain harmonics of the rotor speed, the rotor response is increased or decreased.

Figures 5-7 show the effects of variations in these parameters: 1) blade edgewise stiffness distribution, 2) blade tip brake mass, and 3) tower top stiffness. In each case we have started with the baseline value, shown as solid black in each figure. We then varied each parameter from the baseline value, reran the code, and computed and plotted the predicted content in each harmonic of the edgewise-bending moments. We must emphasize that we are studying only the rotor's response to the steady atmospheric effects such as wind shear and tower shadow; we have not input any turbulent wind speed fluctuations. We believe, however, that decreasing the machine's response to these inputs is the first step in reducing overall machine response.

In order to make parametric changes to the blade's stiffness distribution, we changed the distribution uniformly along the blade. We did not make changes to the actual shape of distribution. In order to make parametric changes to the tower top stiffness, we changed the stiffness values of the last two tower top elements by equal amounts. We did not change the tower's stiffness uniformly along the tower, because we felt that changing the tower top stiffness was most important.

We see that decreasing the stiffness from its baseline value dramatically changes the 7P harmonic of the blade's root edgewise bending. The effect of changing this parameter is to effectively change the frequency of the rotor symmetric lag mode. At the baseline value, the machine's nonrotating rotor symmetric lag frequency is at 7.1 Hz, which is slightly above 7P. For the operating machine, this frequency will be even higher, because of the effects of centrifugal stiffening. When we increase the blade's edgewise stiffness by 30%, the machine's nonrotating rotor symmetric lag mode increases to 7.8P, and decreases to 6.6P with a 15% decrease from the baseline value. We see the resonant behavior of this response, as the symmetric lag frequency changes from its highest value of 7.8P (at the baseline +30% stiffness) to 6.6P for the lowest value of stiffness (baseline -30% stiffness).

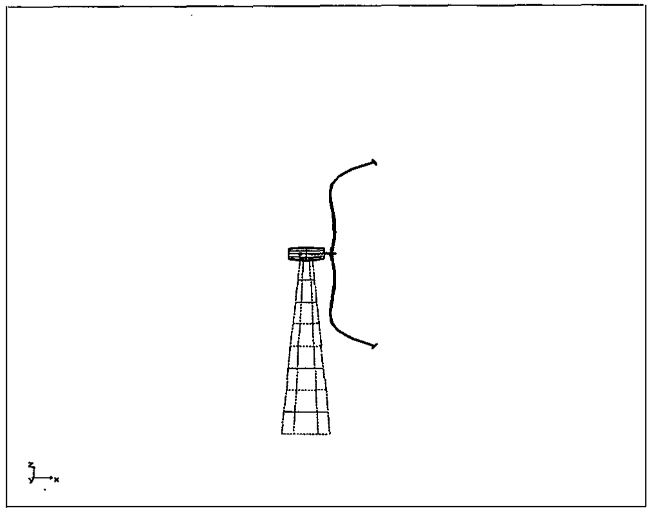

Figure 4. Rotor second symmetric flap mode, frequency = 7.3 Hz

We saw very similiar behavior when we varied the blade's tip-brake mass. Again, the 7P response shows a resonant character because changing the blade's tip-brake mass affects the rotor's symmetric lag natural frequency. Increased tip mass lowers the frequency of this mode and vice versa. We see that increasing the mass from its baseline value first causes an increase in the 7P root edgewise-bending moment harmonic and then a decrease.

Figure 7 shows the effects of variations in the tower's top stiffness on predicted bending moments. We changed the tower's stiffness incrementally from its baseline value. This parameter has a dramatic effect on the frequency of the rotor symmetric lag mode, decreasing it when the tower top stiffness is decreased. The amplitude of the 7P harmonic response increases as we lower the tower top stiffness. Again, we can see the resonant behavior of the rotor symmetric lag response, as the symmetric lag frequency decreases and moves through 7P.

We studied other parameters that affect the frequency of the rotor's symmetric lag mode and the results are very similiar to the results we have just shown. Decreasing the low-speed shaft stiffness causes the frequency of the symmetric lag mode to decrease, in much the same way as the tower top stiffness. Increasing the nacelle mass moments of inertia can increase or decrease this mode depending upon which values of inertia are changed. If the nacelle mass moment of inertia about the nacelle pitching axis is increased, the symmetric lag frequency will decrease relative to the baseline value when the rotor is horizontal. If the nacelle mass moment of inertia component about the nacelle yaw axis is increased, the symmetric lag frequency with the rotor vertical will decrease. The blade's pretwist also has an effect upon the predicted response, because it changes the blade's fundamental lag and second flap natural frequencies, thereby affecting the total system lag response in a manner similiar to the effects of these other parameters, but to a smaller degree.

Examination of the modes involving rotor symmetric flap response show very little tower or nacelle participation. These modes show dominant blade response. We would not expect changes in such parameters as tower top stiffness, low-speed shaft stiffness, or nacelle mass moments of inertia to have a great effect on this type of response. The main parameters we could change to affect this response are blade flapwise stiffness, blade mass distribution, or blade tip-brake mass. We chose blade flapwise stiffness and tip-brake mass for this study. We did not change the blade's mass distribution, because that would also affect the rotor lag response, and we wanted to keep that fixed. It should be noted that changes made to the blade's flapwise or edgewise stiffness distribution would affect the blade's mass distribution in a way consistent with the type of production method chosen.

Figure 8 shows the effects of variations in the blade's flapwise stiffness on predicted blade root flap-bending moments. The ADAMS code has been used to simulate the steady-state response of the rotor to steady wind inputs, including the effects of wind shear and tower shadow. We changed the blade's flapwise stiffness distribution incrementally from its

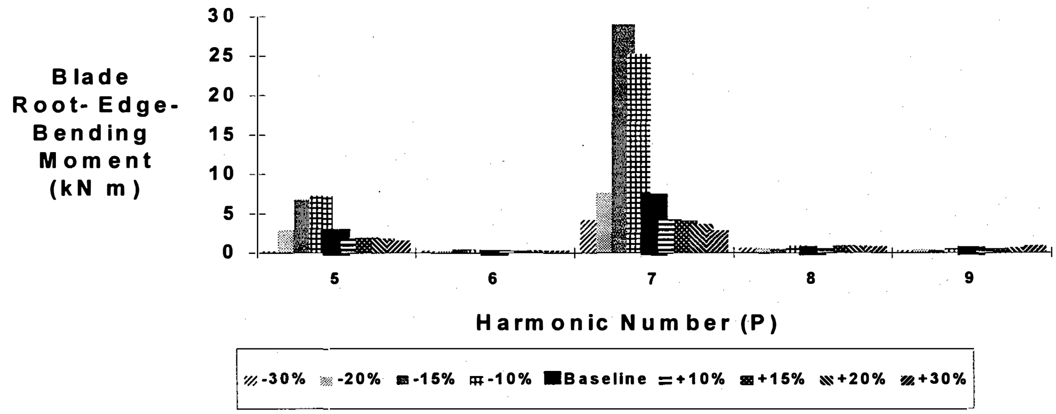

Figure 5. Effects of variations in blade edgewise stiffness on predicted blade root edgewise bending moments

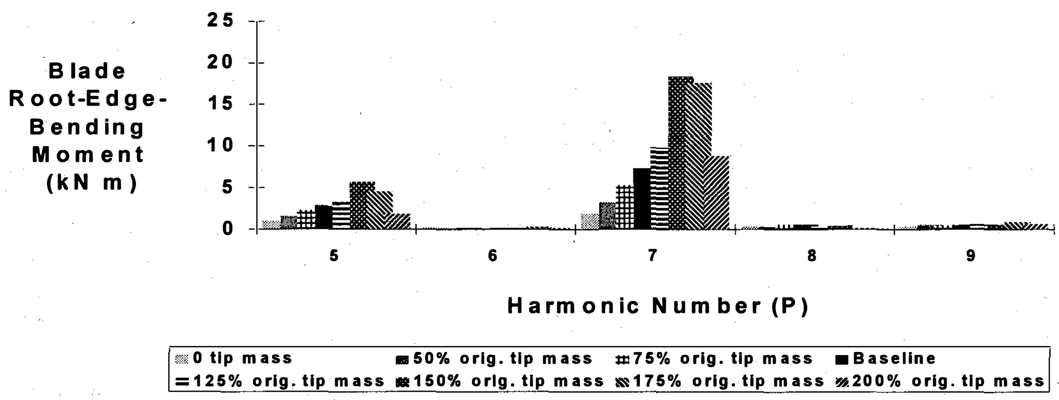

Figure 6. Effects of changes in blade tip brake mass on predicted blade root edgewise bending moments

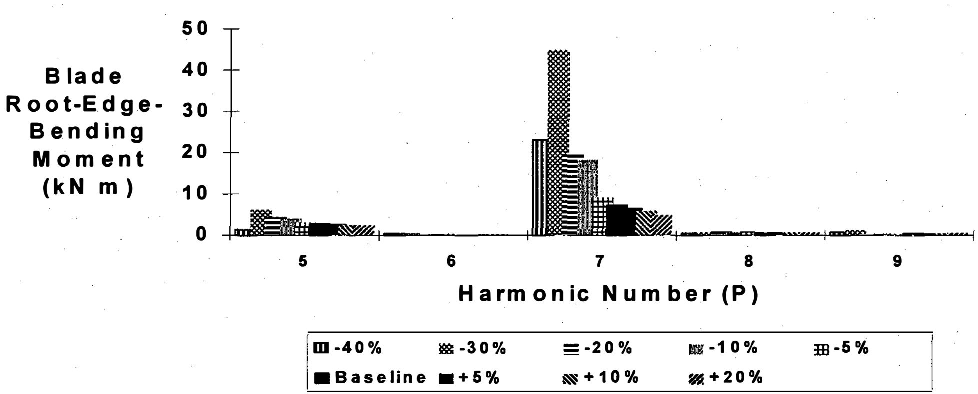

Figure 7. Effects of changes in tower top stiffness on predicted blade root edgewise bending moments

baseline value. We see that increasing or decreasing the stiffness from its baseline value decreases the 8P root flapwise-bending moment harmonic. The effect of changing this parameter is to change the frequency of the rotor second symmetric flap mode, regardless of rotor orientation. At the baseline stiffness value, this mode lies very close to the 8P harmonic when the rotor is rotating (because of centrifugal stiffening). Changing the blade's flapwise stiffness moves the frequency away from this harmonic, which lowers the response of the rotor in this mode. We found that changing the blade's flapwise stiffness distribution did not greatly affect the blade's harmonic content of the root edgewise bending moments, even though the isolated blade's first lag mode and second flap modes were highly coupled, because of the blade's structural pretwist. The dominant parameters that affected the rotor lag response were the parameters we studied, such as blade edgewise stiffness, tower top stiffness, blade tip mass, etc.

Similiar results can be seen in Figure 9 in which we have changed the blade's tip-brake mass incrementally from its baseline value. The effect of changing this parameter is to effectively change the frequency of the rotor second symmetric flap mode, regardless of rotor orientation. At the baseline stiffness value, this mode lies very close to the 8P harmonic when the rotor is rotating (because of centrifugal stiffening). Changing the blade's tip-brake mass moves the frequency away from this harmonic, which lowers the response of the rotor in this mode.

DESIGN GUIDELINES

We showed the effect of various parameters on predicted blade root bending moments in the last section. We saw that the response at various harmonics of the rotor speed increased as the rotor's symmetric lag mode approached 7P or the symmetric flap mode approached 8P. We wanted to see if the harmonic content of these root moments increased as these modes approach other harmonics of the rotor speed. Instead of changing the model properties to the extent required to change natural frequencies by a large amount, we simply used the rotor speed as a parameter to be varied, thereby bringing the frequency of these modes close to other odd and even harmonics of interest. We realize that using rotor speed as a parameter to be varied may present a difficulty: the aerodynamic damping of the rotor blade may quite possibly change with rotor speed. We have not quantified this effect. The results here show the combined effect of changing rotor speed and quite possibly changing aerodynamic damping because of the change in aerodynamic loading with rotor speed. We will attempt to separate these effects in later studies.

Figure 10 shows a Campbell (fan) plot of the model turbine's operating frequencies. In this figure, L2 is the symmetric lag mode and F2 is the symmetric flap mode. We have taken the average of the frequency of the symmetric lag mode when the rotor is horizontal and when it is vertical (6.98 Hz). We do not have the complete tools in place to predict the

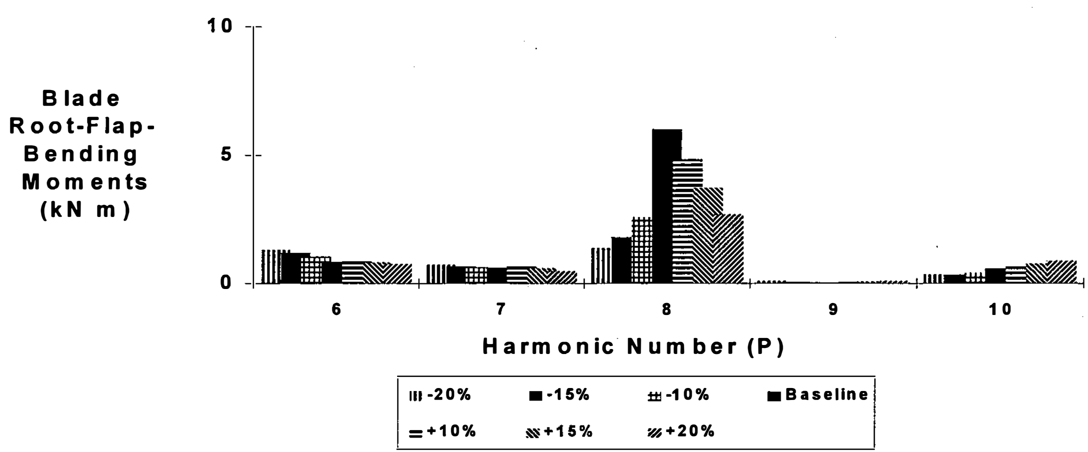

Figure 8. Effects of changes in blade flapwise stiffness on predicted blade root flapwise bending moments

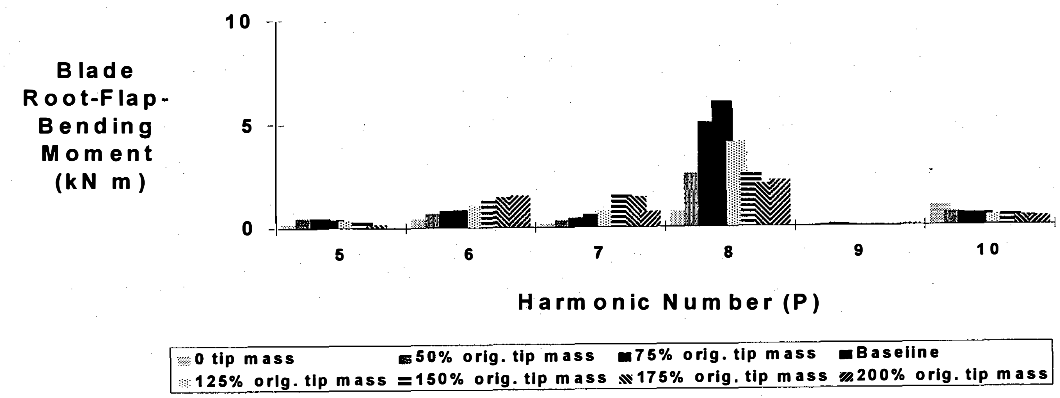

Figure 9. Effects of changes in tip brake mass on predicted blade root flapwise bending moments

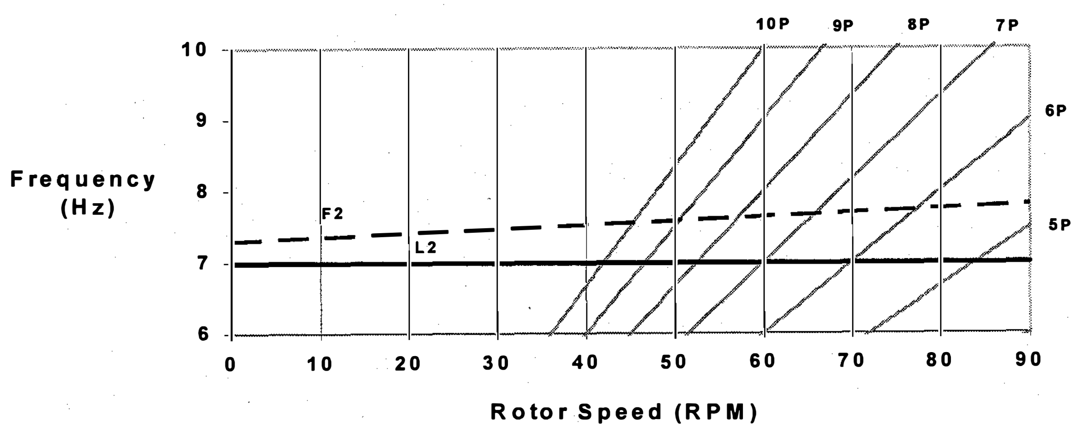

Figure 10. System Campbell plot

operating turbine's natural frequencies nor to perform a Floquet Analysis. We believe that looking at the average frequency is a good starting point for the conclusions we reach here.

Figure 11 shows the effects of changes in rotor speed on the odd harmonics of the blade's root edgewise-bending moment. We see the amplification of the odd harmonics at certain rotor speeds corresponding to those values at which the rotor symmetric lag mode crosses odd harmonics of the rotor speed. Figure 12 shows that the even harmonics do not get amplified significantly.

Figures 13 and 14 show the blade's root flapwise moment harmonics versus rotor speed. We see the amplification of the even harmonics, as the rotor's second symmetric flap mode crosses even harmonics of the rotor speed. The odd harmonics do not get amplified.

We can formulate two guidelines from this study. The first guideline is to design the machine so that the rotor's symmetric lag modes do not coincide with odd harmonics of the rotor speed. The second is to place the rotor's symmetric flap modes away from even harmonics of the rotor speed. The designer has various parameters at his/her control in order to carefully place these frequencies away from these harmonics. In order to affect the rotor's symmetric lag frequency, he/she can vary the blade's edgewise stiffness distribution, tip-brake mass, low-speed shaft stiffness, tower top stiffness, nacelle mass moment of inertia, and rotor speed. In order to place the second symmetric flap mode away from even harmonics of the rotor speed, the designer can adjust the blade's flapwise stiffness, mass distribution, or tip-brake mass.

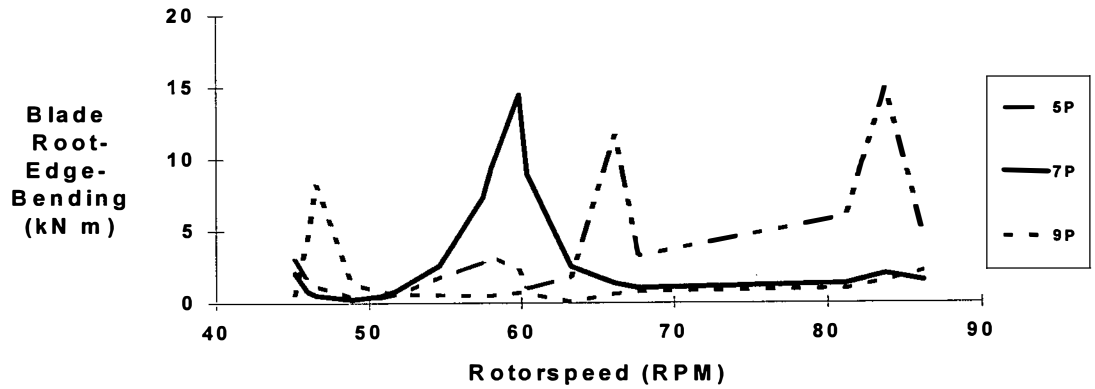

Figure 11. Odd harmonics of the blade's root edgewise bending moments as a function of rotor speed

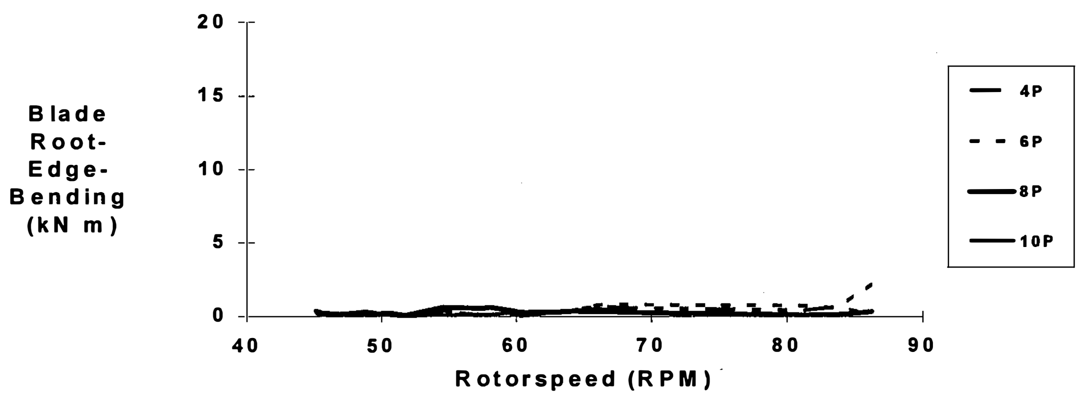

Figure 12. Even harmonics of the blade's root edgewise bending moments as a function of rotor speed

Following these guidelines should greatly help in decreasing the response of this type of machine in this frequency range to the deterministic inputs such as tower shadow and wind shear. It will also reduce the response to atmospheric turbulence inputs, as the machine will not be operating in a resonance condition.

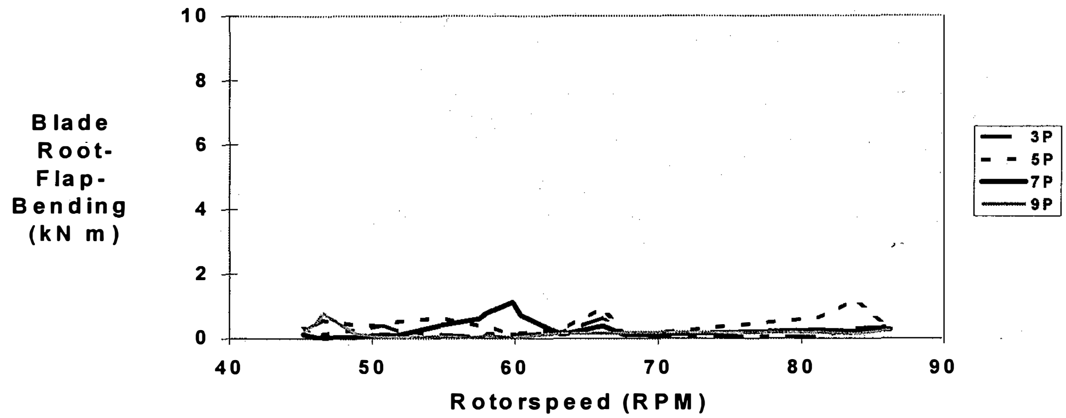

Figure 13. Odd harmonics of the blade's root flapwise bending moments as a function of rotor speed

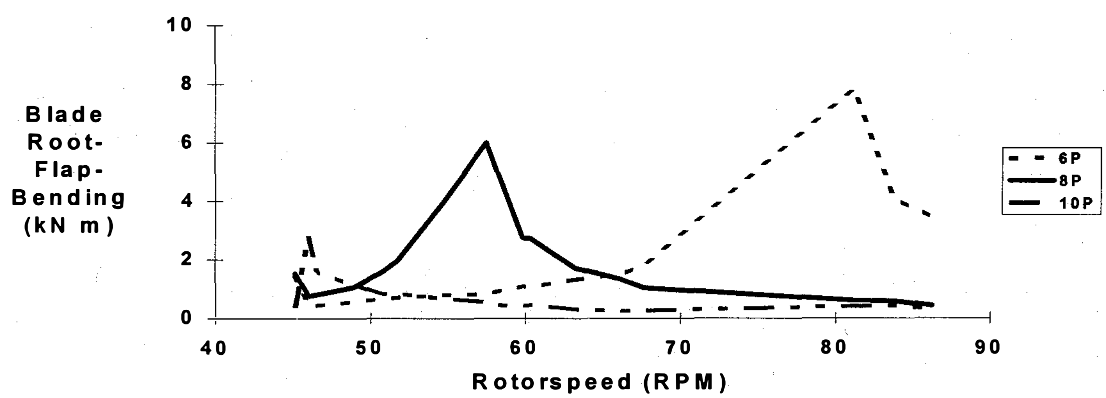

Figure 14. Even harmonics of the blade's root flapwise bending moments as a function of rotor speed

CONCLUSIONS

In previous papers we have shown the steps we took to develop a system dynamics model for this machine using ADAMS. Here we have shown the effects of various turbine parameters on predicted loads, especially those responses involving rotor symmetric lag motion and rotor symmetric flap motion. We have also given a couple of design guidelines for designing two-bladed teetering-hub wind turbines to be less responsive to atmospheric inputs and tower shadow, and less susceptible to vibration. With careful selection of such turbine parameters as blade flapwise and edgewise stiffness, tip-brake mass, low-speed-shaft and tower stiffness, and nacelle mass moment of inertia, a designer of this type of machine should be able to place turbine natural frequencies to avoid system resonance conditions.

FUTURE WORK

We plan to develop a similiar set of guidelines for three-bladed rigid hub turbines. In addition, we plan to obtain a turbine's operating mode shapes, natural frequencies, and damping, both through analysis of turbine operating data and specialized modal tests. We also plan to expand our code predictive capabilities to obtain the machine's operating modes and to perform Floquet Analysis to predict a periodic system's natural modes and stability characteristics. Such analyses will become more important as the wind industry moves to softer rotors, in which the effects of centrifugal stiffening and other rotating frame effects become very important.

ACKNOWLEDGMENTS

We thank Dr. Craig Hansen and his students at the University of Utah for their work on the aerodynamics model. We thank Mr. Timothy McCoy of Advanced Wind Turbines, Incorporated, for preparing the turbine's operating test data in such a manner as to make comparisons to predictions much easier. Finally, we thank the managers at NREL and the U.S. Department of Energy for encouraging us and approving the time and tools we needed to complete this modeling effort. This work has been supported by the U.S. Department of Energy under contract number DE-AC36-83CH10093.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1.

2. REPORT DATE
July 1995

3. REPORT TYPE AND DATES COVERED
Technical Report

4. TITLE AND SUBTITLE
Guidelines for Reducing Dynamic Loads in Two-Bladed Teetering-Hub Downwind Wind Turbines

5. FUNDING NUMBERS
C:
TA: WE518210

6. AUTHOR(S)
A.D Wright, G.S. Bir, C.D. Butterfield

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TP-442-7812
DE95009252

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE
UC-1213

13. ABSTRACT *(Maximum 200 words)*

A major goal of the federal Wind Energy Program is the rapid development and validation of structural models to determine loads and response for a wide variety of different wind turbine configurations operating under extreme conditions. Such codes are crucial to the successful design of future advanced wind turbines. In previous papers, we described steps we took to develop a model of a two-bladed teetering-hub downwind wind turbine using ADAMS® (Automatic Dynamic Analysis of Mechanical Systems), as well as comparison of model predictions to test data. In this paper, we show the use of this analytical model to study the influence of various turbine parameters on predicted system loads. We concentrate our study on turbine response in the frequency range of six to ten times the rotor rotational frequency (6P to 10P). Our goal is to identify the most important parameters which influence the response of this type of machine in this frequency range and give turbine designers some general "design guidelines" for designing two-bladed teetering-hub machines to be less susceptible to vibration.

14. SUBJECT TERMS
wind turbine design, two-bladed

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL