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A COMPARISON OF RESULTS FROM DYNAMIC-RESPONSE FIELD TESTS

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ABSTRACT

The dynamic response of Howden's 330-kW horizontal-axis wind turbine (HAWT) and the Northern Power Systems 100-kW "North Wind 100" HAWT has been measured. The Howden machine incorporates a 26-m-diameter, upwind, three-bladed, wood/epoxy rotor that operates at 42 rpm and is a rigid-hub design. The North Wind 100 rotor has a diameter of 17.8 m, is upwind, two-bladed, and constructed of fiberglass, and has a teetered hub. The Northern Power turbine's blades are fully pitchable, while the Howden machine uses pitchable blade tips.

This paper will present the results from each of these test programs in an effort to compare the dynamic response of each turbine. The analysis will focus on rotor bending loads in terms of both time domain and frequency response. The FLAP code will be used to explore sensitivity to teeter stiffness and natural frequency placement to provide a better understanding of the differences in behavior caused by configuration alone.

The results are presented in the form of normalized azimuth-averaged plots of the deterministic loads, and spectral density plots of the stochastic responses. This presentation of the results will contrast major response differences due to design configurations.

INTRODUCTION

As part of the DOE Cooperative Field Test Program, SERI has conducted a series of tests on several wind turbines over the past few years. Two of the tests were performed on wind turbines located in the wind farm areas of California. Selected results from the dynamic-response testing of the Howden 330-kW wind turbine and the Northern Power Systems 100-kW wind turbine are presented in a normalized form so that conclusions can be drawn regarding relative design merits. Initial indications suggest that a compliant, teetered rotor produces much smaller rotor loads than does a stiff, rigid rotor.

TURBINE DESCRIPTIONS

The first test turbine, manufactured by James Howden and Company, is a three-bladed, upwind machine with a rigid hub and wood/epoxy blades. It is rated at 330 kW in a hub-height wind speed of 14.3 m/s and is designed to operate in cut-in and cut-out wind speeds of 6.0 and 28.0 m/s, respectively. The rotor diameter is 26 m, and the rotor speed is 42 rpm. The blades are tapered and twisted, with a maximum chord of 1.47 m and a maximum twist angle of 16°; the blade tapers to a 0.8-m chord and 0° twist at the blade tip. The blade airfoil section is a GA(W)-1, 17% thick. The rotor axis centerline above the ground is at 24.1 m, and the rotor coning angle (precone) is 0°. The tower diameter is 5.9 ft (1.8 m), and the distance from the yaw axis to the rotor plane is 11.5 ft (3.5 m).

The Northern Power Systems 100-kW North Wind 100 wind turbine employs a two-bladed, upwind, teetered rotor with an innovative rotor control system. The 17.8-m-diameter rotor is composed of two fiberglass blades and is located at a hub height of 25.6 m, atop a tapered steel tubular tower. The turbine was designed to maximize energy production over a wide range of wind regimes by employing a dual-speed, double generator configuration. Power production begins at a cut-in wind speed of 3.3 m/s, and rated power is reached at 14 m/s. The rotor control system uses a passive hydraulic system with full blade pitch control. This design concept uses the wind forces and the rotor inertial forces to automatically change the blade pitch to control turbine output power. A Flender two-stage, two-speed gearbox with a one-way sprag clutch produces high-speed, 1800-rpm output from the low-speed shaft inputs of 72 and 48 rpm. The electrical part of the drive train consists of two fully enclosed induction generators. The first generator is rated at 25 kW for the low-speed 48-rpm mode of operation, and the second generator is rated at 100 kW for the 72-rpm mode.

The major characteristics of the two turbines are summarized in Table 1.

TEST DESCRIPTION AND INSTRUMENTATION

The instrumentation for both of the tests was extensive. For this study, a subset of the nine channels listed in Table 2 was selected for analysis. However, the number of channels that were recorded in multiplexed form on analog tape was more comprehensive: a total of 44 channels were recorded for the Howden test, and 82 channels were recorded for the Northern Power test. The analog data were digitized at SERI using the Neff 720 system at rates of 42 Hz for the Howden data and 37 Hz for the Northern Power data.

The Howden tests were conducted in the Fall of 1986 at the Southern California Edison site near Palm Springs, California, while the Northern Power tests were held in the Fall of 1987 in Altamont Pass, California. Wind measurements were recorded using three levels of anemometers spanning the

Table 1. Comparison of the Designs for the Two Wind Turbines

Characteristic	Howden	Northern Power
Rotor Diameter (m)	26	17.8
Hub Height (m)	24.1	25.6
Rotor Speed (rpm)	42	48, 72
Rated Power (kW)	330	100
Rated Wind Speed (m/s)	14.5	14
Hub Attachment	Rigid	Teetered
Pitchable Blade Span	Tips	Full Span
Pitch Control	Active	Passive
Blade Precone	None	None
Rotor Orientation	Upwind	Upwind
Rotor Tilt (degrees)	0	3
Blade Material	Wood/Epoxy	Fiberglass

Table 2. Selected Channels for Comparison

Description	Howden Channel	Northern Power Channel
Blade Azimuth Position (degrees)	1	20
Root Flap Bending Moment (Nm)	2	1
Blade Pitch Angle (degrees)	9	5
Power Output (kW)	12	30
Tower Bending Moment (Nm)	42	22
Bottom Wind Speed (m/s)	20	27
Hub-Height Wind Speed (m/s)	34	26
Top Wind Speed (m/s)	29	25
Teeter Angle (degrees)	NA	6

rotor disk directly upwind of each turbine. Gill UVW anemometers were located 21 m upwind of the Howden wind turbine, and R.M. Young propvane anemometers were located 27 m upwind of the Northern Power machine. These anemometers provided the wind-speed data used for this study.

STUDY DATA CASES

Three 10-minute data records were chosen from each test to represent a range of operating conditions. Table 3 summarizes the six selected data sets. The data sets beginning with an "H" represent Howden data, while those beginning with "NP" represent Northern Power data. In general, the data sets represent a low-wind-speed case, a below-rated-wind-speed case, and one at or just above rated wind speed. Data sets H12-7 and NP6 represent low wind speed with high turbulence intensity, while data sets H17-1 and NP4 represent high wind speed and lower turbulence.

The turbulence intensity is defined as the standard deviation of the wind speed for the 10-minute data set divided by the mean. Vertical wind shear is simply the difference in wind speeds between the top and the bottom of the rotor. As shown in Figure 1, the vertical wind shear for the Howden data is relatively well behaved; that is, wind speed increases with height above the ground. However, the Northern Power wind profile is rather unpredictable; in fact, data set NP6 has a large negative shear. This is because the turbine and the meteorological tower are located near the top of a steep rise, which influences the flow. The terrain surrounding the Howden test turbine was relatively flat, with hills several miles upwind.

DATA ANALYSIS

Three different data reduction schemes were used. First, the mean turbine responses were computed using the method of bins as described in (1). Second, azimuth averaging (2) was

Table 3. Operating Conditions for the 10-Minute Data Sets

Data Set	Disk Averaged Wind Speed (m/s)	Turbulence Intensity (%)	Vertical Wind Shear (m/s)	Power Output (k)
H1-5	12.9	12	2.5	240
H12-7	10.3	18	2.5	170
H17-1	16.4	12	2.5	300
NP4	14.5	11	.5	95
NP5	13.1	12	0	80
NP6	7.2	20	-1.5	25

used to isolate the deterministic portion of the time-series turbine responses. Finally, the means were removed from the blade-bending loads and spectral analysis was used to examine the frequency characteristics of the loads. To better understand the effects of design changes, the FLAP code was used to predict rotor loads for various design variations on the Howden wind turbine. Because of the unique design features of the Northern Power machine, we were unable to achieve good agreement between the predicted rotor loads and the test data; therefore, those results are not presented here.

Mean Turbine Responses

The per-revolution averaged turbine responses of blade-bending moments, power, teeter, and pitch angles were binned or sorted as a function of disk averaged wind speed. Preaveraging over the time period of one rotor revolution was used to eliminate the higher harmonic responses. The disk averaged wind speed was the mean of the three anemometers, preaveraged over a period of one rotor revolution. The turbine responses were binned into 0.5-m/s bins, and bins containing less than ten data points were discarded. No density correction or pressure adjustments were made to the data. The data have also been normalized to allow for direct comparison between the two machines.

Figures 2 through 5 present the mean turbine responses using this method-of-bins computation. In each of these figures, the independent variable represents the disk averaged wind speed divided by the rated wind speed for each machine. In other words, a value of 1 on the x axis represents the rated wind speed for the wind turbine of interest, either 14.5 m/s for the Howden or 14.0 m/s for Northern Power.

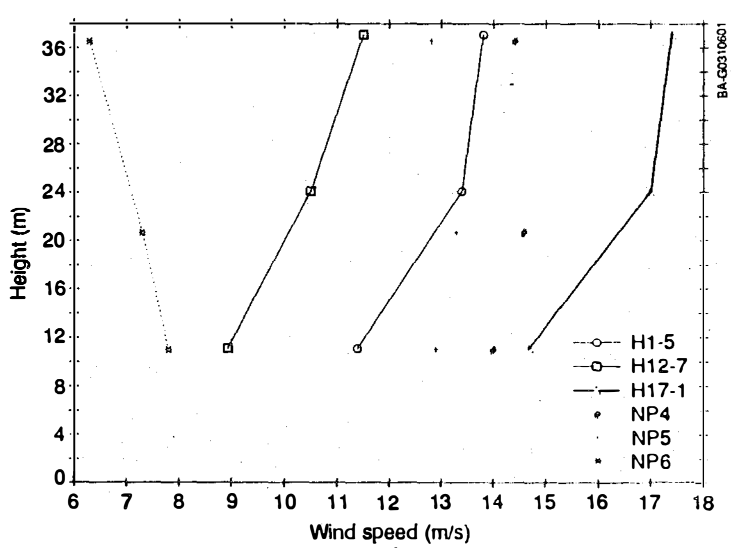

Fig. 1. Wind shear profiles

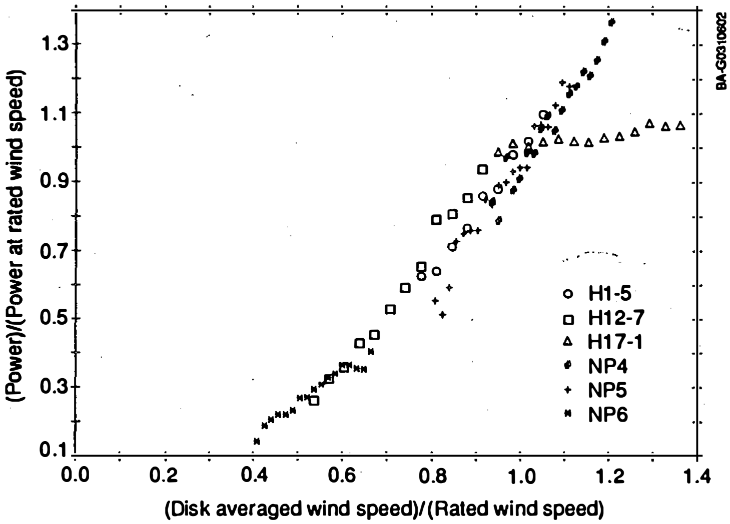

Fig. 2. Normalized power output

Figure 2 presents the normalized mean power as a function of the wind-speed ratio. The power is shown as the fraction of mean power output to the power output at the rated wind speed. For these data sets, the power measured at rated wind speed was 300 kW for Howden and 90 kW for Northern Power. The trends depicted in Figure 2 show that both turbines have similar power output characteristics below rated wind speeds. For these data sets, the Howden machine, with its active pitch control, holds the power level constant above rated wind speed; the Northern Power wind turbine shows increasing power above rated wind speed. The Northern Power machine was undergoing refinements of the passive pitch control system during the test to improve this power control response; it was not regulating properly when these data were taken.

Figure 3 presents the mean blade root flapwise bending moments as a fraction of the bending moment at rated wind speed for the six cases. Here, the bending moments at rated wind speed were 89,500 N-m for Howden and 28,500 N-m for Northern Power. Once again, the normalized loads compare very well, showing the same relationship to the normalized wind speed. The loads above rated wind speed show a lower slope for the Howden data, which is again attributable to the

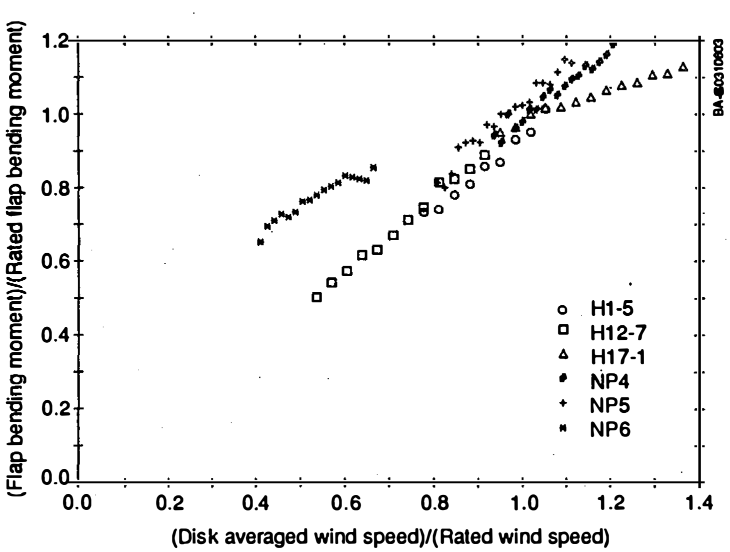

Fig. 3. Normalized mean root flap bending moments

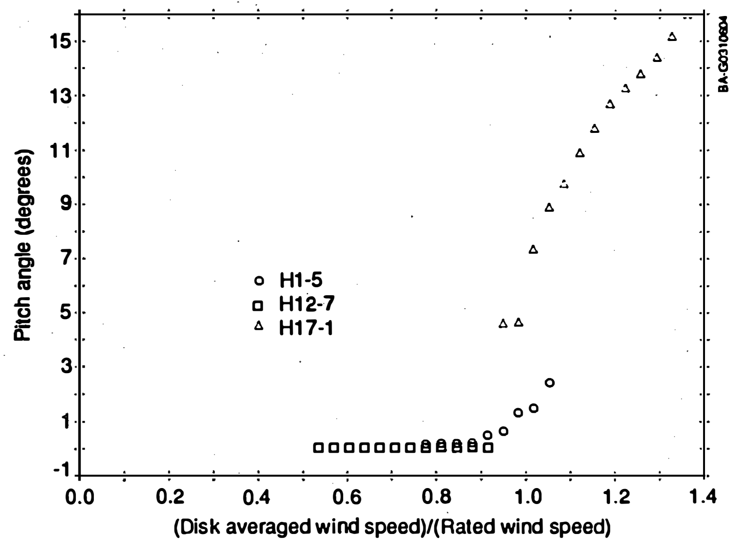

Fig. 4. Mean pitch angle for the Howden data sets

different pitch control conditions for the Northern Power machine. Data set NP6 stands out from the rest because, for this low wind speed, the rotor is spinning at the low rate of 48 rpm, as opposed to 72 rpm for the other cases.

The mean pitch angles for each of the three data sets for Howden and Northern Power are shown in Figures 4 and 5, respectively. These plots simply show how the pitch angle increases with the wind-speed ratio, and they help us understand the other turbine responses. The active pitch control of the Howden provides a more precise variation of pitch angle with wind speed as compared to the Northern Power pitch response curves.

Deterministic Turbine Responses

It is assumed that for stationary operating conditions the deterministic and stochastic loads can be separated by the azimuth averaging. Azimuth averaging sorts the measured forces with respect to the azimuth angle of the rotor blade for a large number of rotor cycles. The results of this averaging process are signals that are periodic with rotor angle and provide an estimate of the deterministic forces acting over the

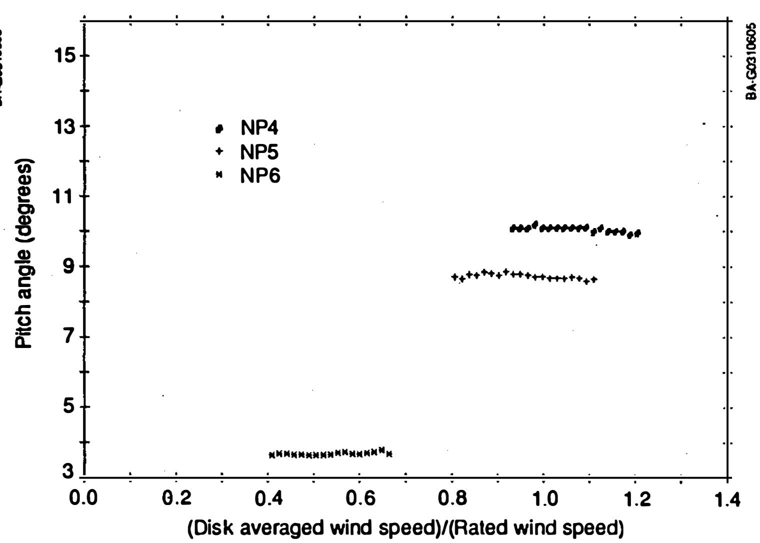

Fig. 5. Mean pitch angle for the Northern Power data sets

averaging time. The stochastic forces are obtained by subtracting the azimuth-averaged signals from the original signals.

The time-series root flapwise bending moments were binned on blade azimuth signal for each 10-minute data case to produce the normalized azimuth-averaged plots shown in Figure 6. As shown in Figure 6, all three cases for each wind turbine have the same characteristic waveform, with only a change in the mean levels. A blade position of 0° represents the blade pointing straight up, so 180° corresponds to the blade pointing straight down.

The wave forms for the Howden data sets are very similar and change shape only slightly with increasing mean level (wind speed), except for Case H1-5. The azimuth averaging clearly shows the strong one-per-revolution (1P) bending-moment content for this 14° yaw case.

As expected, the bending loads peak near 90° (blades horizontal) for the Northern Power machine, which is typical of a teetered rotor. In this position, the teetering acceleration is a maximum and produces higher bending moments due to inertial loads. The teetering motion is excited by the wind shear and a gravity moment for nonzero blade pitch angles. To enhance upwind yaw stability, teeter springs were used to provide a stronger wind-following moment from the rotor. This accounts for the dominant 1P bending-moment fluctuation seen in Figure 6, rather than the expected 2P response for a freely teetering rotor. Case NP6 has a strong negative wind shear; this causes a lower-amplitude cyclic bending moment, as the azimuth-averaged plot shows.

The harmonic content of the deterministic root flapwise bending moment is shown in Figures 7 and 8 for the Howden and Northern Power data sets. Both figures represent the ratio of the harmonic content to the mean load for each data set. Thus, the values have been normalized to allow for direct comparison. It is immediately obvious that the relative values of the deterministic root flapwise bending moments are much lower for the Northern Power machine. This is especially true for the 1P loads. This reduction of about one-half is attributable mainly to the teetered rotor of the Northern Power wind turbine.

The azimuth-averaged teeter signal for the three Northern Power cases is shown in Figure 9. The teeter angle oscillates between ±1° for data set NP4, which has the highest positive wind shear, and between ±0.4° for case NP6, with the negative wind shear. The teeter action is also influenced by mass imbalances and aerodynamic load imbalances, such as different pitch settings or twist distributions on the blades, and by rotor pretilt and yaw errors. The bar chart in Figure 10 that shows the harmonic content of the teeter angle is not surprising: the largest percentage of the signal content is in the first harmonic mode.

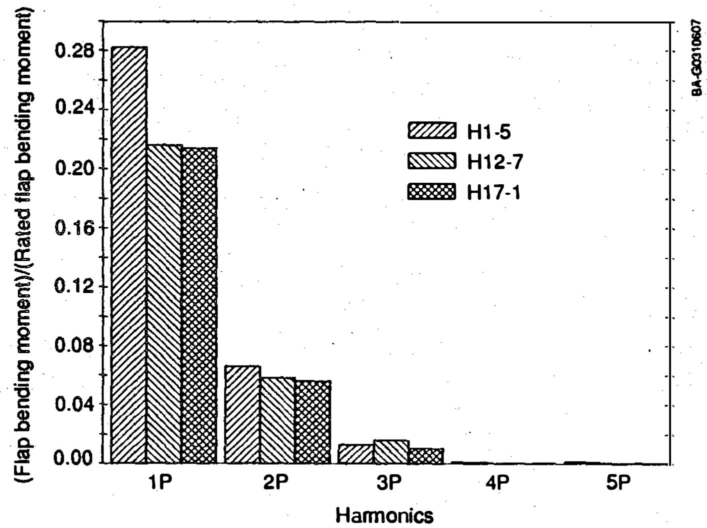

Fig. 7. Harmonics of the deterministic portion of the normalized root flapwise bending moment for the Howden data sets

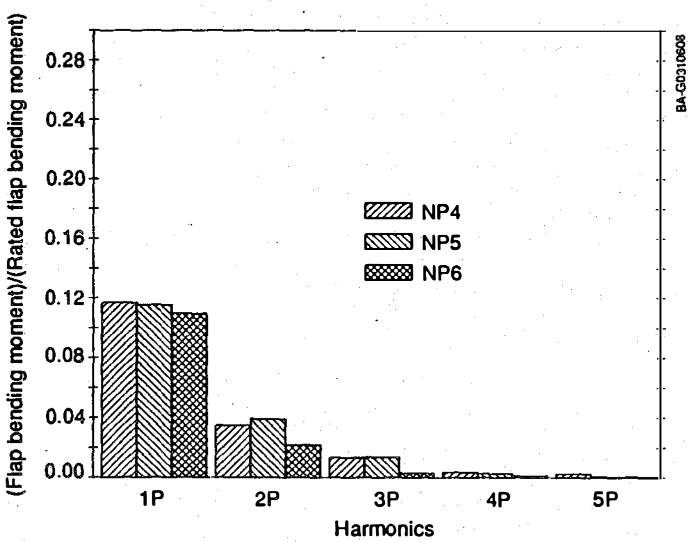

Fig. 8. Harmonics of the deterministic portion of the normalized root flapwise bending moment for the Northern Power data sets

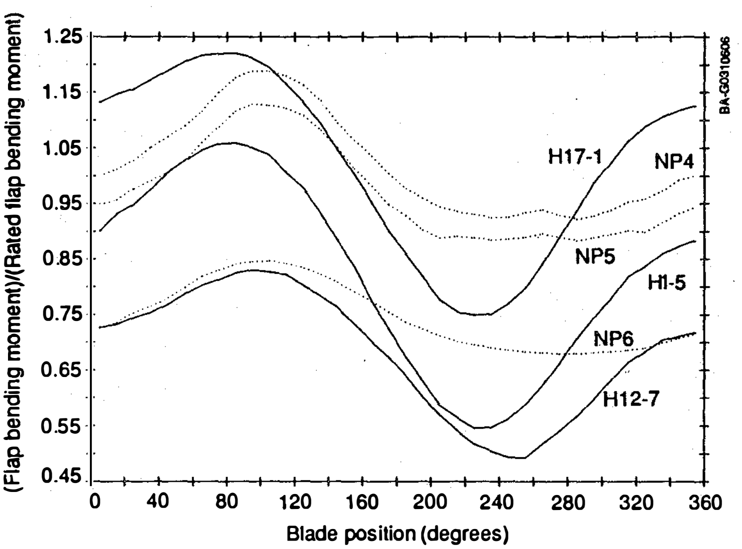

Fig. 6. Normalized azimuth-averaged root flap bending moments

Stochastic Turbine Responses

The stochastic rotor loads were obtained by subtracting the azimuth-averaged signal from the original time series. These residual time series were then analyzed to determine the response as a function of frequency. To compare the system dynamic responses to the wind inflow, it is first necessary to compare the inflow conditions. Figures 11 and 12 show the power spectral density plots for the hub-height wind speeds for both tests. The linear trends were first removed from the wind-speed signals to remove the influence of the mean wind speed.

The spectral plots shown in Figures 11 and 12 are truncated at 1 Hz because the Howden wind-speed data were filtered at 1.2 Hz, and the anemometers begin to lose responsiveness at about 1 Hz in low winds. It appears that the frequency

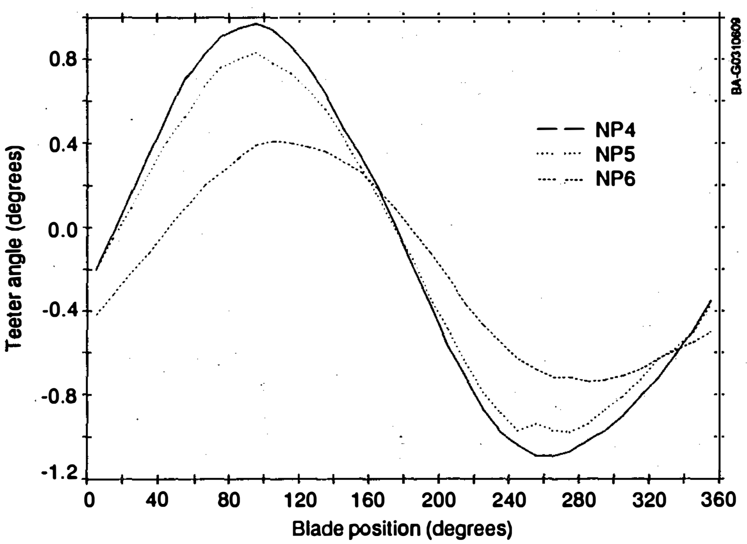

Fig. 9. Azimuth-averaged teeter angle for the Northern Power data sets

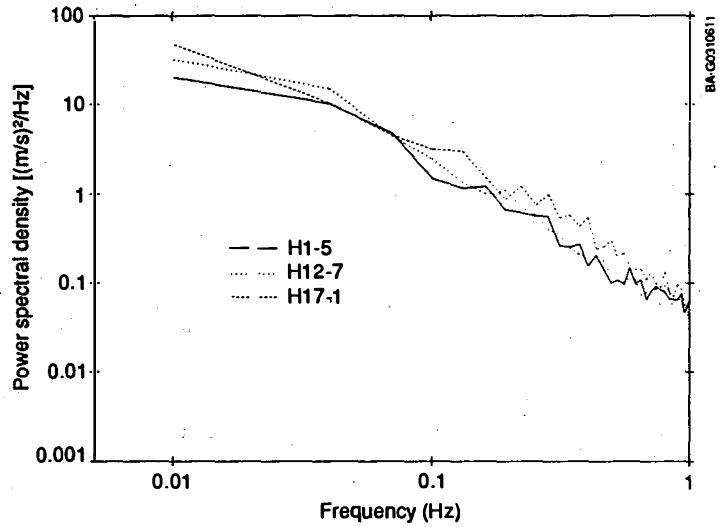

Fig. 11. Power spectral density of the detrended hub-height wind speed for the Howden data sets

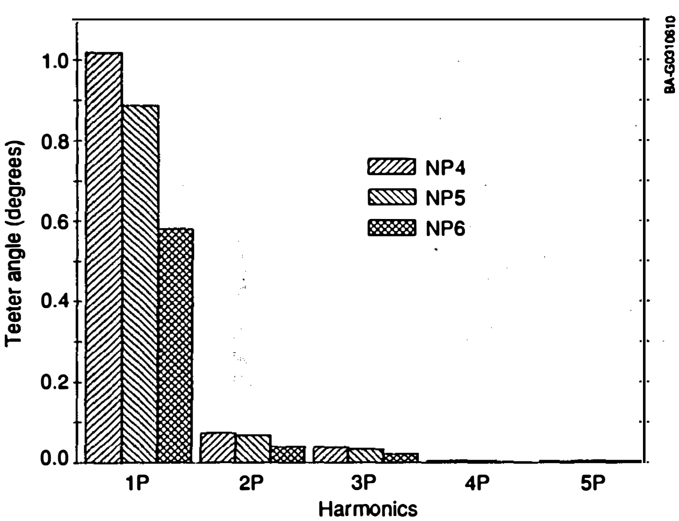

Fig. 10. Harmonics of the deterministic portion of the teeter angle for the Northern Power data sets

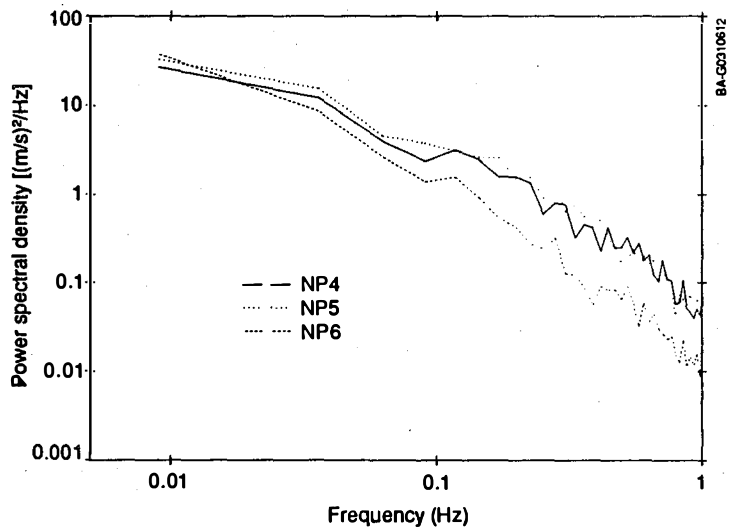

Fig. 12. Power spectral density of the detrended hub-height wind speed for the Northern Power data sets

content of the incident wind at the two test sites is similar for the cases considered in the frequency range of interest.

Figures 13 and 14 are reduced normalized spectral plots of the stochastic portion of the blade root bending moments for the Howden and Northern Power data sets. These plots show the spectral amplitude $S(\omega/\Omega)$ multiplied by the frequency ω and normalized by the total variance σ^2 in each signal

$$\left[\frac{\omega S(\omega/\Omega)}{\sigma^2}\right]$$

where Ω is the rotor rotation rate. The total area under each curve is therefore constant, allowing direct comparison of the energy contribution to the variance over the entire frequency range. The total variance σ^2 for each case is indicated on the plots. In general, the variance of the Howden random blade root bending moments is an order of magnitude higher than the Northern Power variance. What is of particular interest here is the relative heights of the individual signals: the 1P and 2P spikes for the Howden loads are several times as high as the Northern Power 1P and 2P spikes. A large portion of the stochastic energy is contained in the 1P and 2P bands for the Howden machine, while the majority of the stochastic energy for the Northern Power machine is contained in the low-frequency band, below 1P.

It is also useful to consider the natural frequencies for each turbine. The Howden rotor has a cluster of closely spaced flapping modes at about 2P. For the Northern Power wind turbine, the first flapwise mode is at a frequency of 2.7P. These natural frequencies affect the broader peaks shown on the figures. The placement of the Howden natural frequencies close to 2P also influences the height of the 2P spike.

For both rotors, but especially for the Northern Power rotor, the energy content in the low-frequency part of the flapwise bending moments is significant compared to the higher-frequency contributions. This low-frequency part of the spectrum could probably be better controlled through optimized rotor designs and control strategies.

The tower loads were analyzed following the same procedure as the blade loads. Figure 15 shows the deterministic portion of the tower base bending moments (fore to aft) for both turbines. The loads have been normalized by the mean load over each 10-minute data set. It is clear that the harmonic amplitudes of the deterministic part of the signal are relatively low and consist mostly of 1P and 2P loads. There are also significant 3P loads for the Howden tower, as would be expected

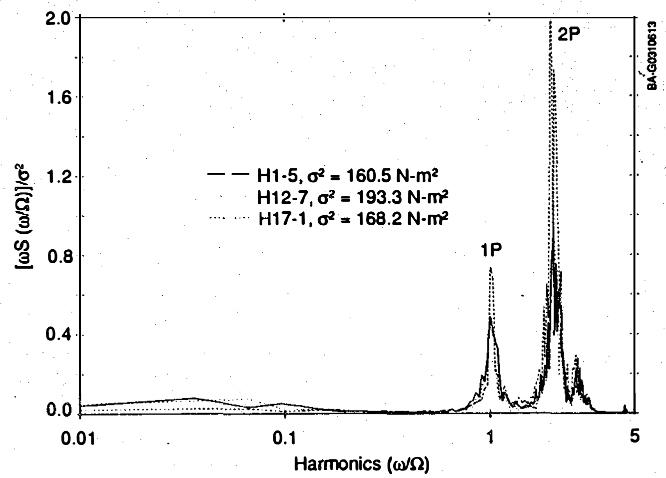

Fig. 13. Reduced normalized spectra of the stochastic root flapwise bending moments for the Howden data sets

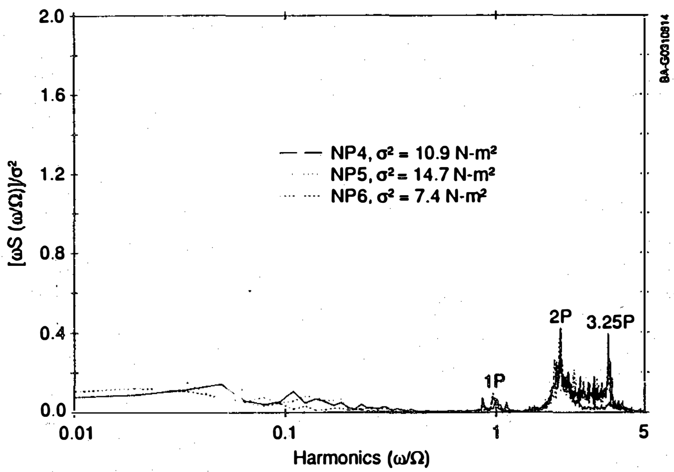

Fig. 14. Reduced normalized spectra of the stochastic root flapwise bending moments for the Northern Power data sets

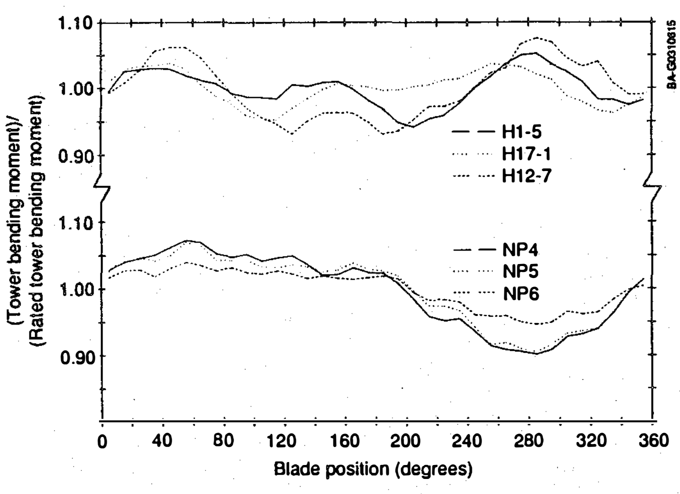

Fig. 15. Normalized azimuth-averaged tower bending moments for the Howden and Northern Power data sets

for a three-bladed rotor. Figures 16 and 17 show the results of the reduced normalized spectral plots for the stochastic portion of the tower bending loads for the two turbines. The total variance σ^2 for the tower loads is not available in terms of engineering units, so it is not presented on these plots. However, once again the relative energy content (seen as the areas under the curves) in the stochastic loads at high frequencies is lower for the Northern Power machine. The Howden machine exhibits a broad peak around 2P to 3P, which probably represents the tower's natural frequency. The Northern Power tower's natural frequency, at 1.3P, is clearly evident in Figure 17.

FLAP Code Predictions

The Force and Loads Analysis Program (FLAP) code was used to predict the stochastic blade responses for the Howden rotor using measured wind-speed data. Data from an array of anemometers, located 0.8 rotor diameters upwind of the rotor, were used as the turbulence excitation for the FLAP code. A least-squares curve fitting routine was used to fit a polynomial to the turbulence field at each time step of digitized data. The time series of coefficients in the polynomial expansion was input to the FLAP code for a particular 10-minute data case. Power spectra of predicted flap bending moments were then compared to measured results.

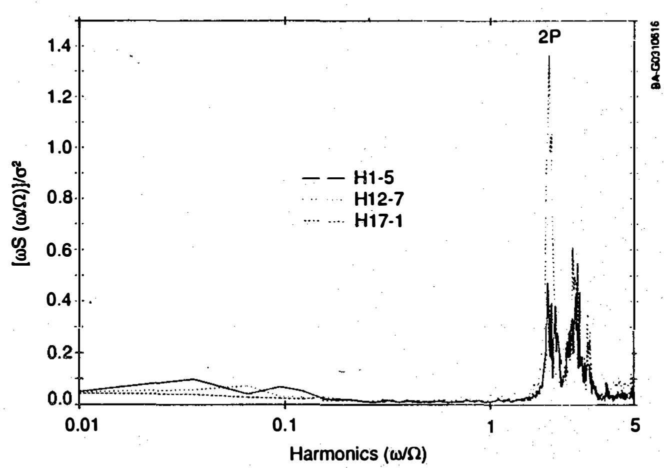

Fig. 16. Reduced normalized spectra of the stochastic tower bending moments for the Howden data sets

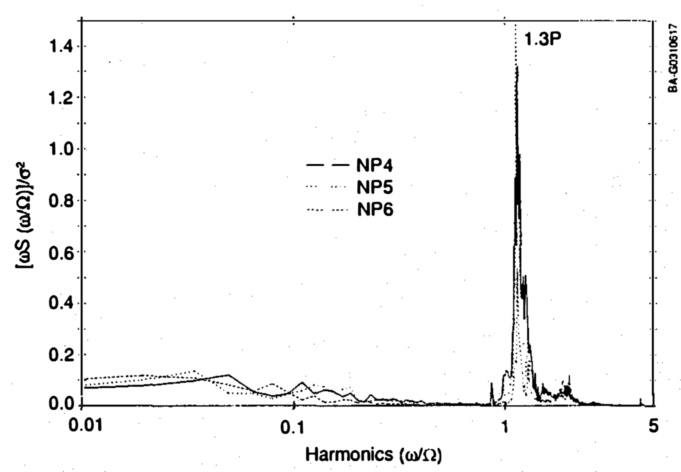

Fig. 17. Reduced normalized spectra of the stochastic tower bending moments for the Northern Power data sets

To investigate how the FLAP-predicted load harmonics change for different hub configurations, the code was run for the Howden machine as a three-bladed rigid hub and a two-bladed teetering hub. Figure 18 shows these results. The rigid-hub case was run with the first flapwise blade frequency set at 2P (1.40 Hz). The predicted results show very strong 1P and 2P contributions. The teetering-hub case was run with zero teeter spring stiffness (free teeter) and a positive teeter spring stiffness (stiff teeter). The free-teeter case shows a significant decrease in the 1P harmonic as compared to the rigid-hub case. The stiff teeter case shows an increase in the 1P contribution as compared to the free-teeter case.

Other comparisons were made by adjusting the symmetric flap bending frequency to 1.5P to eliminate the blade resonance condition at 2P. First, the rigid-hub case was run with an adjusted first flapwise bending frequency of 1.5P. Then, the teetering-hub case was run with an adjusted first symmetric flap frequency of 1.5P. The results are displayed in Figure 19. In both cases, the magnitude of the 2P harmonic has

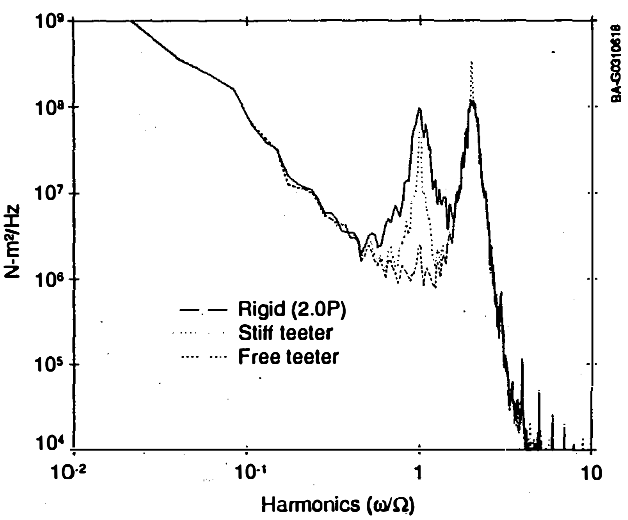

Fig. 18. FLAP code prediction of the stochastic portion of the root flap moment for Howden data set 12-7, showing the effects of teeter stiffness

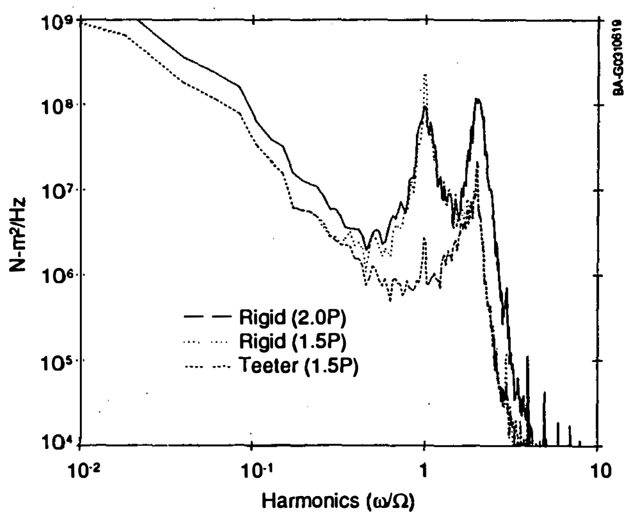

Fig. 19. FLAP code prediction of the stochastic portion of the root flap moment for Howden data set 12-7, showing the effects of blade stiffness and a teetering rotor

been substantially reduced, as compared to the original rigid-hub condition (with f = 2.0P). A possible benefit might be realized by designing the rotor as a teetering-hub configuration and designing the blade so that the first symmetric flap frequency is about 1.5P. In this case, the magnitude of the first and second harmonics would be greatly reduced.

CONCLUSIONS

This analysis of data from the Howden and Northern Power wind turbines has provided a comparison between two very different designs. The results indicate that the teetered rotor design of the Northern Power machine produces lower dynamic flapping moments. This conclusion has been reinforced by the FLAP code's simulations of the Howden machine. The FLAP code's results also show the importance of designing the rotor blades to produce natural frequencies that are not coincident with rotor passage frequencies.

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