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ABSTRACT

Accurately predicting wind turbine blade loads and response is important for the design of future wind turbines. The need to include turbulent wind inputs in structural dynamics models is widely recognized.

In this paper, the Force and Loads Analysis Program (FLAP) code will be used to predict turbulence-induced bending moments for the SERI Combined Experiment rotor blade and the Howden 330-kW blade. FLAP code predictions will be compared to the power spectra of measured blade-bending moments.

Two methods will be used to generate turbulent wind inputs to FLAP:

1. A theoretical simulation: the Pacific Northwest Laboratories (PNL) Simulation Theory (1)
2. Measured wind-speed data taken from an array of anemometers upwind of the turbine.

Turbulent wind-speed time series are input to FLAP for both methods outlined above. Power spectra of predicted flap-bending moments are compared to measured results for different wind conditions.

Conclusions are also drawn as to the ability of the turbulence simulation models to provide accurate wind input to FLAP and to FLAP's ability to accurately simulate blade response to turbulence. Finally, suggestions are made as to needed improvements in the theoretical model.

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NOMENCLATURE

a_0, a_1, a_2	Coefficients in wind expansion, Eq. (1)
D	Rotor diameter
Hz	Hertz
kW	Kilowatts
L_x	Integral scale of turbulence in the flow (or "along wind") direction
L_y	Integral scale of turbulence in the crosswind direction
m	Meters
N-m	Newton-meters
P	Cycles per revolution
r	Blade radial station
rpm	revolutions per minute
s	seconds
TI	Turbulence intensity
v	Mean wind speed (meters/second)
Ψ	Blade azimuth angle
σ	Standard deviation

INTRODUCTION

Past comparisons of wind turbine blade load predictions with test results have indicated large discrepancies. These discrepancies are thought to be caused by turbulent wind fluctuations, which have not been properly accounted for in structural dynamics models.

The need to include turbulent wind effects in structural dynamics models is now widely recognized. The subject of stochastic loads for wind turbines remained largely unreported until the early 1980s. The 1981 Wind Turbine Dynamics Workshop was held in Cleveland, Ohio, and saw the first of a number of papers and presentations concerning the simulation of atmospheric turbulence and the prediction of turbulence-induced blade loads. Previously (2), a simplified treatment of turbulence was developed to predict the response characteristics of horizontal-axis wind turbines (HAWTs) to turbulence. The filtered noise model described in (2) has been further refined for use in structural dynamics models (3).

Recently, turbulence-induced blade loads for the Howden 330-kW turbine have been reported 3,4,5). In (5), a model was presented that accounted for the dominant vibration mode of the blade and used the experimentally determined wind spectra and coherence functions at a fixed point in space. This model works in the frequency domain, and results for the flap-bending moments were compared to measured results. The results agreed well with measured data, especially below rated wind speeds. Recently, a method for performing a three-dimensional wind simulation has also been reported (6).

Reference (3) described the filtered noise model (2) that was incorporated into the FLAP dynamics code. Predicted blade-bending moments were compared to measured results for different cases for the Howden 330-kW field test turbine in Palm Springs, California. Inputs to the code included parameters such as the mean wind speed, turbulence intensity, and integral scale.

In Reference (4), wind-speed data were taken from an array of nine anemometers, located 0.8 rotor diameters (D) upwind of the Howden 330-kW turbine; the data were then used as turbulence excitation in FLAP. Data from the array of anemometers were used in a least-squares curve-fitting routine to obtain a series expansion of the turbulent wind profile over the rotor disk. The coefficients of this expansion were computed for each measurement interval of recorded wind data. The time series of coefficients were then input to the FLAP code. Then, blade flapwise bending moments were computed for the stochastic portion of blade response by setting deterministic excitations to zero in FLAP. The deterministic portion of blade response was subtracted from the test data by the process of azimuth averaging. The blade load comparisons for this machine were then reported (4).

Recently, three turbulence simulation methods have been compared and evaluated. Blade-tip rotational wind simulations were made with different simulation methods. Results were compared to rotational wind data taken from the Howden 330-kW HAWT (7). The models were evaluated for result quality, ease of use, compatibility with loads codes, and computational speed.

This paper will show the FLAP code predictions of stochastic loads. In one method, the PNL Simulation Theory (1) will be used to input turbulent velocity fluctuations into the structural code. In the second method, actual anemometer time-series data will be input to FLAP. The data are taken from an array of anemometers upwind of the SERI Combined Experiment turbine. Resulting FLAP code-predicted bending loads will then be compared to measured results for the SERI machine for two data cases.

Predicted loads from FLAP will also be shown for the Howden 330-kW blade using PNL Simulation Theory turbulence inputs. It is important to show results using PNL simulation inputs for a three-bladed machine of intermediate size. The Combined Experiment rotor is only 10 m in diameter, whereas the Howden rotor is 26 m in diameter.

The SERI blade is relatively stiff compared to the Howden blade. The first flapwise bending frequency of the SERI blade is very close to 4 per revolution (P), whereas the frequency of the Howden blade is approximately 2 P.

The turbulent wind input methods of previous studies (4) and (3) provided a frequency input only up to 2 P because of truncation of the series expansion above 2 P (4). It is important for the SERI blade to choose a turbulence simulation scheme that provides wind inputs with higher frequency content, especially at 4 P, because the blade natural frequency lies in this range.

For this reason, the PNL Simulation Theory and actual anemometer array data inputs are chosen as the two types of turbulence input to FLAP. Flap-bending moment predictions of the FLAP code will be compared to measured results for the SERI Combined Experiment and Howden 330-kW machines.

Conclusions will be drawn concerning the accuracy of theoretical predictions and needed improvements in the models. Future work will also be outlined.

TURBINE AND INSTRUMENTATION

The Combined Experiment wind turbine, shown in Figure 1, is a three-bladed, downwind machine with relatively stiff blades. The rotor diameter is 10.1 m, and the machine sits on top of a 16.8-m tower. The rotor speed is 72 rpm. The blades have no pretwist, and the airfoil is an S809 series. The rotor precone angle is approximately 3°. Figure 2 shows the blade. For more information on the test setup and experimental results see (8).

In correctly modeling the dynamic response of the blade, the distributed weight and stiffness of the blade are important input parameters. To obtain good predictive capabilities with any

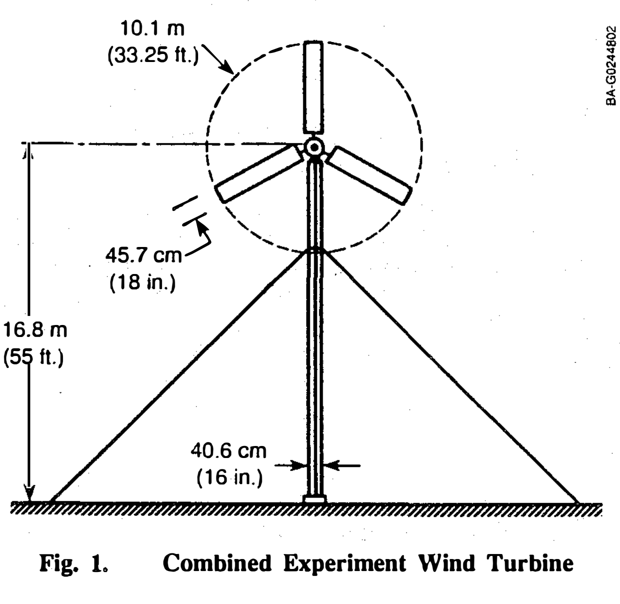

Fig. 1. Combined Experiment Wind Turbine

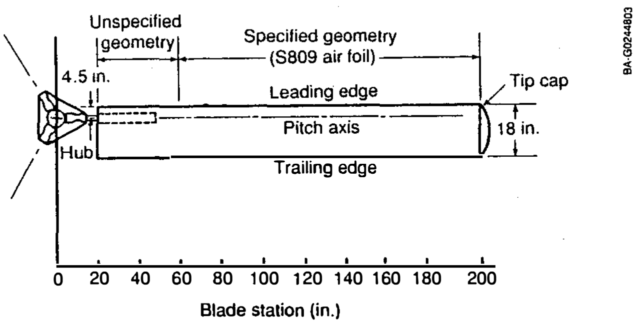

Fig. 2 Combined Experiment Blade

type of dynamic model, the natural frequencies of the model must faithfully reproduce those of the turbine.

The dominant mode of vibration for this machine is the blade's first flap-bending mode. The exact value for the rotating blade frequency for this case is unknown but is close to 4 P. The mass and stiffness inputs are only approximate and are used as starting approximations, resulting in a predicted frequency slightly above 4 P. The resulting FLAP code stiffness matrix is then modified to set the rotating blade natural frequency at exactly 4 P. This approximation then causes the blade to be excited by turbulent wind excitations in a resonance (worst case) condition.

For the SERI Combined Experiment rotor, an array of anemometers located 2 D upwind of the turbine provided turbulence inputs to FLAP (i.e., the second method). The array contained eight prop-vane anemometers on an outer ring spaced in 45° increments (see Figure 3). Although the array contained anemometers on an inner ring, data from these were not used. Data from a center anemometer (#9, also a prop-vane) were also

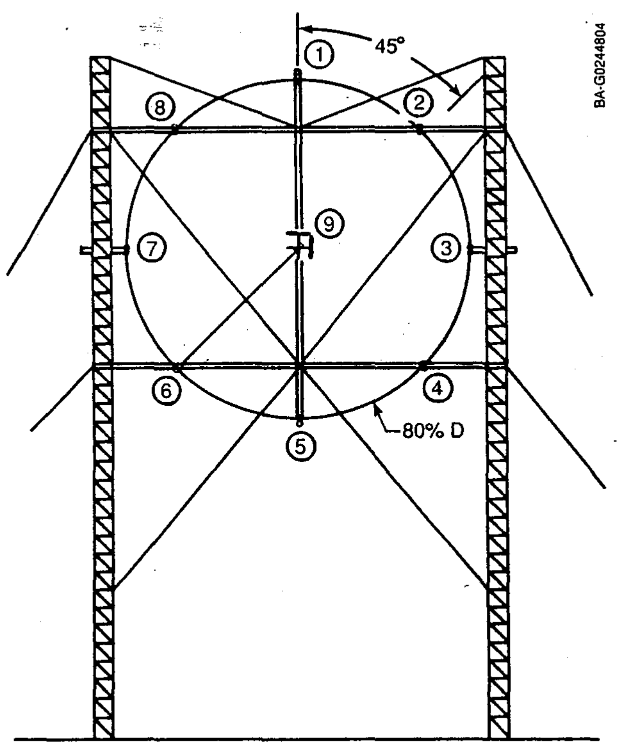

Fig. 3 Anemometer Array Configuration

used in the analysis. The method of curve-fitting anemometer array data for input to FLAP will be described in the following section.

The blade was instrumented with several flap-bending strain gages along the blade from root to tip. In this paper, comparisons are made only at the blade root.

The Howden 330-kW turbine and instrumentation setup were previously reported in (4) and (3). Modeling blade stiffness and mass distribution was also important for this machine, in which the blade fundamental flapwise frequency was close to 2 P. Turbulent wind excitations, at or close to 2 P, excited this blade at its natural frequency.

The Howden turbine has a larger rotor diameter (26 m) than that of the Combined Experiment turbine; it is included in this paper to show load predictions using PNL theory wind inputs for a larger rotor than that of the Combined Experiment turbine. FLAP code predictions using anemometer array inputs were previously reported in (4) and will not be shown here for the Howden rotor.

TURBULENCE INPUT METHODS

Two methods were used to input turbulent wind-speed fluctuations to the FLAP code for analysis of the Combined Experiment rotor. Method 1 was the PNL Simulation Theory and Method 2 was the use of actual anemometer data as input to FLAP. In both methods, the simulation or curve-fitting routines were run first to provide a file of turbulent wind times series for FLAP to read later. Neither of these methods have been incorporated within FLAP.

Because the FLAP code is a time-domain model, the resulting predicted loads consisted of a time series. From this time series, a power spectral density (PSD) was omputed and compared to the power spectra of the measured loads.

The first method used to produce a file of turbulent wind time series for FLAP was the PNL Simulation Theory. It was developed by Powell and Connell in 1987 (1) and is based on an autocorrelation function for wind on a single rotating point. Gaussian white noise is used to randomly select harmonics. An inverse Fourier transform is used to create a turbulence time series for one point of a rotating blade. The program is executable on any IBM PC-compatible computer, and it is written in Fortran 77.

Inputs to the code include turbine characteristics such as rotor angular velocity and hub height, mean wind speed, standard deviation of wind speed, turbulence integral length scale, surface roughness, and a starting seed (9). The code produces a rotational time series of velocities normal to the rotor disk at one rotating point on one blade.

Because the PNL Simulation Theory produces a rotational time series for only one point at a time, the code was run twice for each data case. The first run was for a point located at the root of the blade (at the center of rotor rotation). The second case was for a point at the tip of the blade, using the same seed to start the process (1). The resulting turbulent wind input file had two columns of data; the first column was for the root of the blade and the second was at the blade tip. Linear interpolation between these two points was then used to obtain wind velocity inputs for intermediate blade radial stations.

There is a certain amount of correlation between actual turbulence values at different blade radial locations. The PNL Simulation Theory assumes perfect correlation when run separately for different blade stations using the same starting seed. Still, as we will see, the method seems to give adequate results for small to intermediate-sized rotors, where blade load measurements are only being calculated or compared to test data on one blade of the rotor. This method might be inadequate for determining loads for a two-bladed, teetering rotor, where one blade is coupled through the teeter pin to the other. It might also be inadequate for calculations of loads for large rotors, where wind-speed inputs must be simulated for more than one point on the blade.

Reference (5) documents direct comparisons of blade-tip rotational time series with rotational wind data obtained from a row of anemometers for the Howden 330-kW turbine. Such comparisons are not shown in this paper; instead, we show the comparisons of blade-load predictions to measured loads using the PNL simulation method as input to FLAP.

In the second method, a curve-fitting routine was used to transform stationary-frame, digitized anemometer array data into the rotating frame as needed by FLAP. This was performed by breaking the rotor disk into eight pie-shaped (45°) sectors, as shown in Figure 4. Each sector is bracketed by three anemometers (such as anemometer numbers 1, 2, and 9 for sector #1, anemometer numbers 8, 1, and 9 for sector 8, etc.).

Along with data from each anemometer, the blade azimuth position was also recorded. Depending upon which sector the blade azimuth position corresponded to, only the three anemometers corresponding to that sector were used in a curve-fitting process. The simple form

$$V(r,\Psi) = a_0 + a_1 r\cos\Psi + a_2 r\sin\Psi \qquad (1)$$

was used as the polynomial in the curve-fitting process, where r is blade station and Ψ is the azimuth angle. The coefficients for this equation were recalculated for each line of digitized anemometer data at a sample rate of approximately 26 Hz. These coefficients (a_0, a_1, and a_2) were then input to FLAP in a time-iteration process. The wind velocity field was then expanded within FLAP in Eq. 1 at each instant of time. This procedure differs from the method of (4), in which a polynomial in r and Ψ was calculated over the entire rotor disk at every time step. In that process, all anemometers of the array were used at once. That method gave a turbulent wind frequency input only up to 2 P.

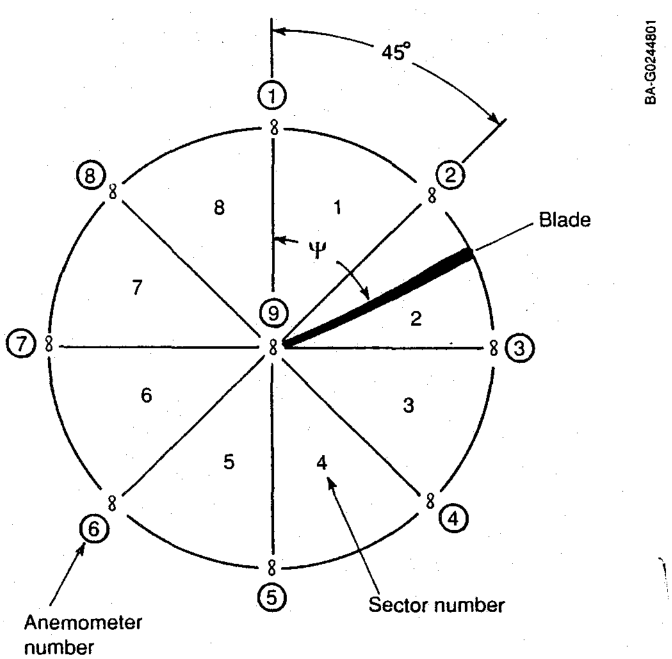

Fig. 4 Sectors for Curve-Fitting Anemometer Data

Because FLAP does not advance blade azimuth positions in equal azimuth step sizes (due to the Euler Predictor-Corrector scheme), linear interpolation of equation coefficients (a_0, a_1, and a_2) was used. This provided the correct curve-fitting equation for blade positions lying between measurement intervals.

All load comparisons to be shown are only for the stochastic portion of blade flapwise bending moments. Azimuth averaging has been used to separate the stochastic portion of measured blade loads from the deterministic part of blade-measured test loads. We therefore compare "stochastic load predictions" to "stochastic loads test data" instead of comparing "apples" to "oranges." For details on the theoretical bases of the FLAP code loads calculations, see (10).

Stochastic blade flap-bending moment predictions were then output from FLAP at time steps corresponding to measured loads. Power spectra of predicted flap-bending moments were then compared to those of measured data using time series with the same number of points.

Usually, these time series consisted of 8192 points, corresponding to approximately 300 seconds of data (26.05 Hz sample rate). Two spectra of 4096 point length were then computed and averaged together. This procedure was followed for both predicted time series and measured time series, so that proper comparisons could be made.

LOADS COMPARISON AND DISCUSSIONS

The results of this discussion show predictions for two cases of the SERI Combined Experiment rotor and one case for the Howden machine. Table 1 shows the mean wind speed (v), standard deviation (σ), longitudinal and lateral integral scales for input to the PNL Simulation Theory (L_x, L_y), turbulence intensity (TI, σ/v), and pitch angle for the two SERI cases (I and II). Also shown are rotor diameter (D) and hub height. Case III represents the Howden machine.

Table 1. Parameters for the Three Data Cases (PNL simulation inputs)

	Case		
Parameter	I*	II*	III**
v (m/s)	11.7	14.4	10.5
σ (m/s)	2.26	3.01	1.89
L_x (m)	140	170	119
L_y (m)	56	68	48
TI	0.19	0.21	0.18
Pitch (deg.)	14	14	0.5 (tip)
D (m)	10	10	26
Hub height (m)	16.7	16.7	24.1

*Combined Experiment rotor.
**Howden rotor.

Some of the parameters outlined in the table were determined by analyzing hub-height anemometer data. The longitudinal and lateral integral length scales were determined by curve fitting the Von Karman Spectrum formula to hub-height anemometer data, allowing the integral scale in that formula to be a variable (3). A least-squares curve-fitting routine was used to determine the integral scale parameter.

First, we will show FLAP load predictions using the PNL simulation turbulence inputs for all three data cases. Figures 5, 6, and 7 show these results at the blade root. First, the difference in load signatures between the SERI cases (I & II) and the Howden case (III) should be noted. The magnitude of the PSD for the Howden case drops off immediately after 2 P, whereas the SERI Combined Experiment case shows a drop-off after 1 P (1.2 Hz) and then an increase in magnitude at 4 P (4.8 Hz). The rotor speeds for the SERI and Howden machines are 1.2 Hz (72 rpm) and 0.7 Hz (42 rpm), respectively. Recall that

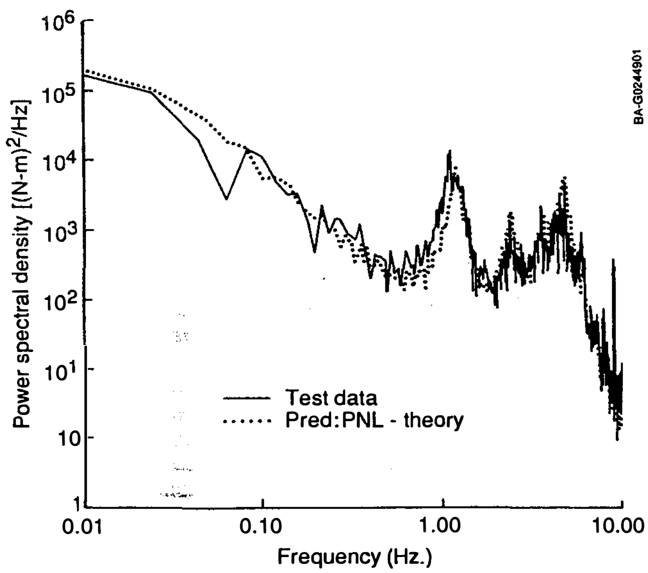

Fig. 5 Spectra of Root Flap-Bending (Case I, Combined Experiment turbine)

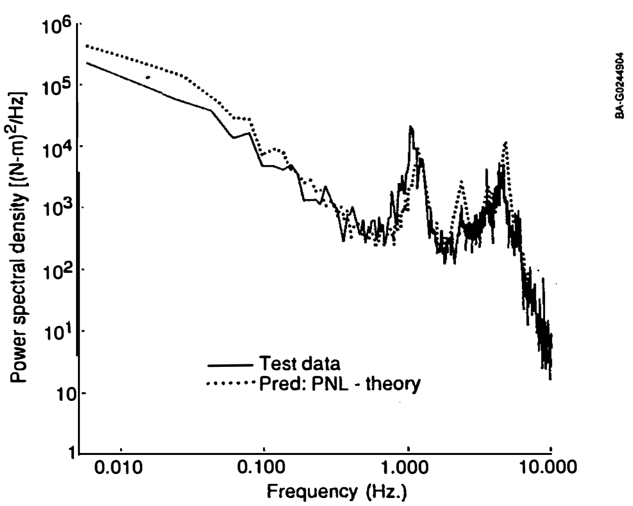

Fig. 6 Spectra of Root Flap-Bending (Case II, Combined Experiment turbine)

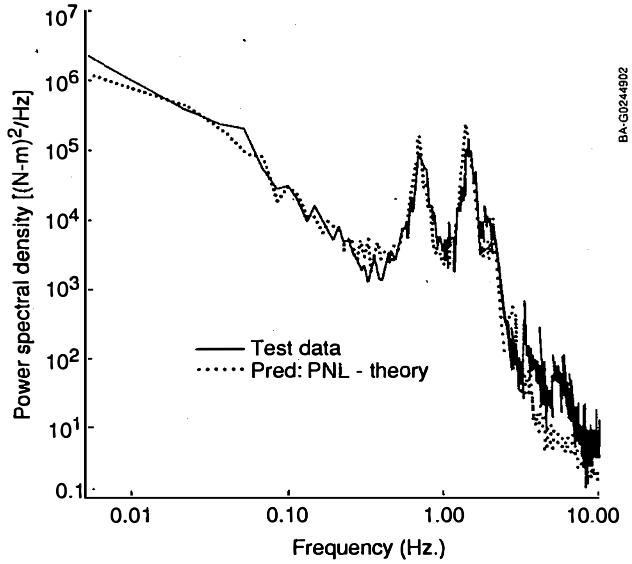

Fig. 7 Spectra of Root Flap-Bending (Case III, Howden turbine)

the first flapwise blade natural frequency is 4 P (4.8 Hz) and 2 P (1.4 Hz) for the SERI and Howden machines, respectively. These frequencies are being excited by turbulent wind inputs.

Using the PNL Simulation Theory to input turbulence provides the frequency content for loads simulation at harmonics of the rotor speed (1 P, 2 P, ..., 4 P). This is especially important for the SERI blade, with its natural frequency at 4 P.

The FLAP loads predictions show reasonable agreement with measured results for Cases I and II, using PNL inputs. The magnitude of the 1-P harmonic is slightly underpredicted and slightly shifted in phase, for reasons not exactly known. Still, the method gives the correct general trend of the loads PSD, even for Case II (which has a higher mean wind speed and turbulence intensity. The 2-P and 4-P harmonics for Case II (Figure 6) are slightly overpredicted.

The magnitude of FLAP-predicted stochastic loads is sensitive to the damping used in the code, especially near resonant peaks. The damping used in FLAP is only aerodynamic damping from the flapping of the blade; it is not "structural" damping.

There is some overprediction of blade loads in the very low frequency range of 0.01-0.1 Hz for Cases I and II. This discrepancy may be due to errors in blade input properties to the FLAP code, resulting in overprediction of blade root bending moments. The mean loads are sensitive to such blade inputs as mass and stiffness, lift and drag data, etc.

FLAP predictions using PNL inputs for Case III also show the applicability of this method for a larger rotor. The PNL Simulation Theory was used by simply simulating time series for one or two points on this blade. The magnitudes of the harmonics for this case are slightly overpredicted. This discrepancy could possibly be because the PNL-simulated time series for every point of this blade are all in phase (1), or perfectly correlated; this is probably not the case for this rotor and instead causes an overprediction of the blade response. Still,

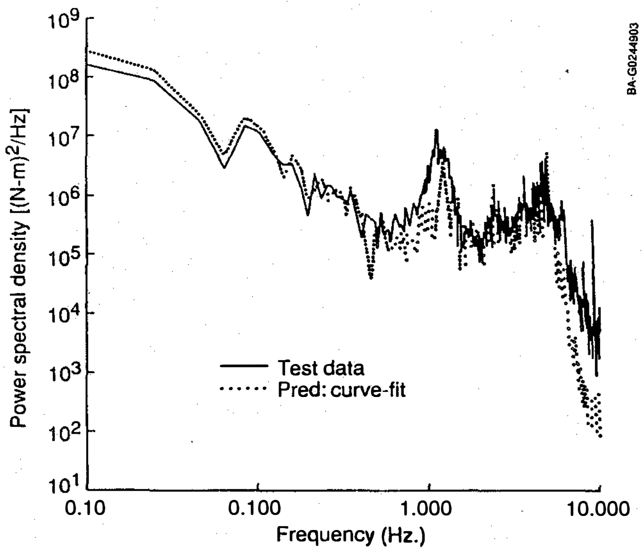

Fig. 8 Spectra of Root Flap-Bending (Case I, Combined Experiment turbine)

the predictions give reasonable results when compared to measured loads.

To show the validity of Method 2 turbulence input, we will show FLAP load predictions using anemometer array data input for only one case. Figure 8 shows the comparison of FLAP predictions to test data for Case I. This case also shows some load overprediction in the low frequency range. The general character of load response is displayed at the harmonics of the rotor speed, especially near the 4-P natural frequency. The magnitude of the 1-P frequency harmonic is somewhat underpredicted, for reasons not yet known. Perhaps there is a structural mode near the 1-P frequency, such as a coupled rotor tower mode. With the FLAP code, we are only modeling a single blade flap-bending mode.

Although the anemometer data are digitized at 26 Hz and fed into the FLAP code at this rate, the frequency content of the wind inputs drops off after 4 P using this curve-fitting method. This is caused by the spacing of the anemometers in the array. With eight anemometers located in 45° increments on the outer ring (shown in Figure 3), we can only obtain a rotational wind input up to 4 P (half the number of anemometers); this is adequate to excite this blade's fundamental frequency but then shows a drop-off above that frequency (see Figure 8).

CONCLUSIONS

In this paper, FLAP predicted stochastic blade loads were compared to measured loads for two three-bladed rotors. In one method, the PNL Simulation Theory (1) was used to input turbulence to FLAP. In the second method, data from an array of nine anemometers upwind of the turbine were used as input. Blade-root flap-bending moments were compared to two test cases for the SERI Combined Experiment rotor and one test case for the Howden 330-kW rotor.

The relatively stiff blade of the Combined Experiment rotor has a high natural frequency, close to 4 P. The turbulence input methods of this paper were shown to provide high enough frequency content to properly excite the blade at its natural frequency. Some turbulence methods of previous investigations (3,4) provide frequency inputs only up to 2 P.

It was shown that the PNL Simulation Theory gave comparable results to the second method. In the second method, data from an entire array of nine anemometers were used as turbulence input. With the PNL simulation method, data from only one anemometer would be needed to determine inputs such as mean wind speed, standard deviation, and integral length scale for inputs to the simulation. The need for an expensive array of anemometers would be alleviated. Another attractive feature of the PNL simulation method is that it is fully operational on an IBM PC-compatible computer and can be run in just a few minutes.

In a similar loads comparison (11), researchers found differences in the PNL simulated wind time series PSD when using different starting seeds for the same wind case (i.e., except for the starting seed, all inputs were held constant). Theoretically, the statistics of two simulated time series for a given set of inputs should be the same, even if two different starting seeds were used.

We are currently investigating the causes of this discrepancy and its effects. At this time, we believe that the simulation method must be run for a long enough period of time (5 minutes or more) to model the low-frequency wind fluctuations. The discrepancies encountered using different starting seeds may be enhanced when the simulation run is too short.

More comparisons will be made using this method to investigate its validity for different rotor sizes and different hub configurations. Currently, the PNL Simulation Theory provides simulated wind time series for only one rotating point. The next step in model improvement might be to expand its capabilities to provide simulations for more points, such as a point on each blade of a teetering rotor, or a point on each blade of a three-bladed rotor, or for more than one point on a single blade.

As shown, progress is now being made in the turbulence load prediction for three-bladed, rigid-hub wind turbines. The next step in model development is to expand these capabilities to include proper analyses for other rotor types (such as two-bladed teetering rotors and rotors with flexible blades). These analyses will become important for load predictions of advanced machine designs. The good news is that we finally have some means of predicting turbulence loads using desktop computers. More investigations will soon be performed to expand these capabilities.

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