Wind Shear and Turbulence Effects on Rotor Fatigue and Loads Control

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The effects of wind shear and turbulence on rotor fatigue and loads control are explored for a large horizontal axis wind turbine in variable speed operation at wind speeds from 4 to 20 m/s. Two- and three-blade rigid rotors are considered over a range of wind shear exponents up to 1.25 and a range of turbulence intensities up to 17%. RMS blade root flatwise moments are predicted to be very substantially increased at higher wind shear, and resultant fatigue damage is increased by many orders of magnitude. Smaller but similar trends occur with increasing turbulence levels. In-plane fatigue damage is driven by 1P gravity loads and exacerbated by turbulence level at higher wind speeds. This damage is higher by one to two orders of magnitude at the roots of the three-blade rotor compared with the two-blade rotor. Individual blade pitch control of fluctuating flatwise moments markedly reduces flatwise fatigue damage due to this source, and, to a lesser degree, the in-plane damage due to turbulence. The same is true of fluctuating rotor torque moments driven by turbulence and transmitted to the drive train. Blade root moments out of the plane of rotation aggregate to create rotor pitching and yawing moments transmitted to the turbine structure through the drive train to the yaw drive system and the tower. These moments are predicted to be relatively insensitive to turbulence level and essentially proportional to the wind shear exponent for the two-blade rotor. Fluctuating moments are substantially reduced with individual blade pitch control, and addition of a teeter degree-of-freedom should further contribute to this end. Fluctuating pitching and yawing moments of the three-blade rotor are substantially less sensitive to wind shear, more sensitive to turbulence level, and substantially lower than those for the two-blade rotor. Mean rotor torque and, hence, power are essentially the same for both rotors, independent of wind shear, and are somewhat reduced with individual blade pitch control of fluctuating flatwise moments. The same is true of mean rotor thrust; however fluctuations in rotor thrust are substantially reduced with individual blade pitch control.

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Introduction and Background

Much attention has been devoted to the fatigue design of larger horizontal axis wind turbines (HAWTs) operating in turbulent winds with a moderate vertical shear exponent in the range of 0.14 to 0.20. Opportunities for reducing fluctuating structural loads and resulting fatigue damage using active closed-loop control of blade pitch angle have been explored in turbulent winds with rapidly varying mean wind speed and 17% turbulence intensity [1,2]. Studies indicate that wind shear characterized by a moderate exponent is of secondary importance compared with wind turbulence characterized by 17% intensity in determining rotor blade fatigue life.

These levels of wind shear and turbulence are not generally characteristic of the wind resources in the Midwest and Southwest regions of the United States. This is illustrated by recently published results of three ongoing Electric Power Research Institute (EPRI)-sponsored Turbine Verification Program (TVP) projects involving larger scale HAWTs mounted on relatively tall towers [3–5]. At the diverse locations of these projects the wind characteristics were essentially as follows. Mean monthly wind speeds and average diurnal wind speeds ranged from about 6 to 9 m/s, and wind speed varied relatively slowly with time. Distributions of these variations can be approximated with Rayleigh or Weibull statistical models. The average turbulence intensity varied from about 9 to 12%, which is low compared with the above noted assumption for earlier studies, and the average wind shear exponent varied from about 0.20 to 0.40, which is high. There is a consistent pattern of higher wind shears occurring at night, when it is cooler, and lower wind shears occurring during the day, when it is warmer and mixing would be expected to increase. High-wind shears were a matter of particular concern to the Big Spring Project where it was concluded that: ‘‘The effects of wind shear should be analyzed in detail to determine if shear-induced loads are contributing to drive train component failures’’ [5]. There was also concern about failures in yaw drive systems under conditions of high wind shear–e.g., with exponents up to 0.75 based on wind speed measurements for a considerable period of time. It has been more recently reported [6] that findings made at a Colorado wind site indicate shear exponents as high as 1.25 occur at tall tower heights for significant periods of time (up to two hours) at night.

Based on the above-noted experimental data, an exploratory study was undertaken of the effects of wind shear and turbulence on rotor fatigue and loads control for a large HAWT on a tall tower with wind shear exponent varied from 0 to 1.25, and turbulence intensity varied from 0% to 17%. The results of this study are the subject of this paper. It proceeds from a description of the wind and rotor models to a discussion of blade moments and fatigue predictions, followed by a discussion of rotor moments and thrust predictions and conclusions.

Wind and Rotor Models

These models are simplified as follows. The wind is assumed to have a constant turbulence intensity over the rotor disk and nonuniform mean speed, varying vertically according to the shear exponent. The resultant wind is thus vertically nonuniform in both

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mean wind speed and the magnitude of turbulent fluctuations of wind speed about the mean. Turbulence at each mean wind speed is assumed to behave in accordance with the modified von Karman spectrum employed in previous studies [1,2]. This study focused on winds with mean speed invariant with time. This isolates the effects of shear exponent and turbulence intensity from those due to varying mean wind speeds with time [1,2]. The wind shear and turbulence effects were examined over a range of hub height wind speeds from 4 to 20 m/s in two-hour time segments. An example of the normalized turbulent fluctuations of wind speed about the mean is shown in Fig. 1 for 17% turbulence intensity. Combining these normalized fluctuations with the wind shear variation of mean wind speed yields the vertical variation of total horizontal wind speed with time over the rotor disk. Vertical and lateral winds are assumed to be zero in the study.

The rotor was chosen from the spectrum of those previously studied [2]. It had a diameter of 70 m with rated power near 1.5 MW occurring at a rated wind speed of 10.9 m/s. Rotor speed increased up to this wind speed to maximize energy capture, and it remained constant at higher wind speeds, with increased blade pitch into the wind to hold mean power near rated. Tower height was taken to be 84 m. Two- and three-rigid blade configurations of the rotor were studied with the constraints that they have the same solidity, the same control systems, and operate at the same tip speeds in the same winds. With the added constraint of geometrical similarity of blade shape (including taper and twist), rotor power should be the same, independent of the number of blades [2]. Assuming thin walled construction of the same material for each blade, these constraints indicate that individual blade weight should be the same if all blades are to experience the same fatigue damage due to mean and fluctuating flatwise moments induced by the same turbulent winds. Based on previous studies in open-loop control operation, this weight was taken to be 8,365 kg (18,440 lb.), assuming unidirectional fiberglass materials of construction for the blades [2]. All blade and rotor loads (mean and cyclic) were determined from the two-hour time simulations, and blade root fatigue damage was estimated using rain flow counting, linear damage theory and Miner's rule for the fraction of fatigue life lost ($\Delta N/N$). All time-series results were generated using SIMULINK [7]. Blade loads aggregate, of course, to yield rotor loads, including pitching, yawing and torque moments, and thrust. In the presence of wind shear and turbulence, these loads depend on both blade azimuth angles and time, and they must be accounted for in both open and closed-loop operation of the control system.

Figure 2 shows a schematic of the blade open-loop power control system employed in this study. Based on the prescribed hub height mean wind speed V_{mh}, rotor speed Ω_c and blade pitch angle δ_c are fixed to control mean torque and, hence, power. In addition, depending on the point in time in each two-hour segment, blade azimuth angles θ are known in the nonuniform wind. This information is input to the nonlinear maps/look-up tables to yield the power, thrust, torque and root flatwise moment outputs for each of the blades in the rotor, depending on the wind speed distributions to which they are exposed. These outputs were determined using the YawDyn/Aerodyn code [8] and they provide the core of open-loop information required in this study. Note that V in Fig. 2 is hub height wind speed determined at 0.05 s intervals in the time series simulations. For the closed-loop simulations, individual rather than collective blade pitch control was employed to improve effectiveness in reducing fluctuating blade flatwise moments in the presence of wind shear and turbulence. The closed loop control system is based on sensing blade root flatwise moments, and it combines with the open-loop power control system as shown in Fig. 3. A simple PI control law K(s) was employed in this study with first-order actuator lag $1/(\tau s+1)$ where s is the LaPlace operator and τ is the characteristic time constant of the system. The system is constrained to be critically damped to minimize peaking in the output, and the transfer function from open- to closed-loop operation is given by:

$$\frac{M-M_{mean}}{M_o-M_{mean}}=\frac{\tau s(\tau s+1)}{(\tau s+m)^2} \tag{1}$$

where M_{mean} is fixed by V_{mh}, and M_o is the open-loop moment. A value of $m=1$ was chosen for this study, corresponding to unit gains in the P and I control terms, and τ was taken to be 0.1 s. Obviously increasing m and/or reducing τ would increase control system bandwidth and effectiveness.

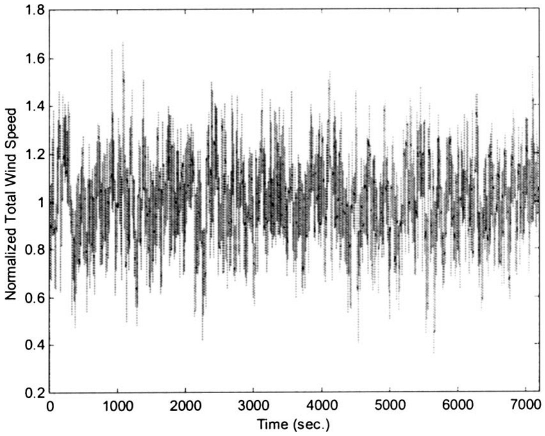

Fig. 1 Normalized fluctuations of wind speed

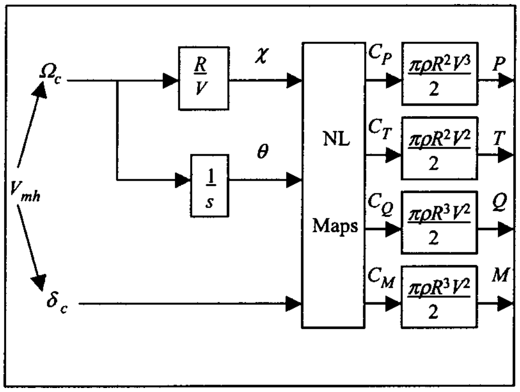

Fig. 2 Schematic of blade open-loop power control system

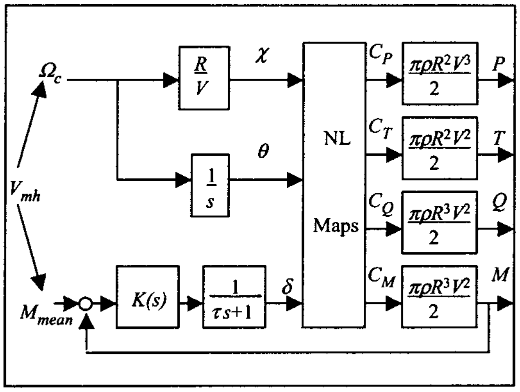

Fig. 3 Schematic of blade open-loop power control and closed-loop moment control system

Blade Moments and Fatigue

Predicted blade root RMS flatwise bending moments (fluctuations about the mean) are shown in Fig. 4 for the two-blade rotor operating over the full range of mean hub height wind speeds in winds with a shear exponent (SE) of 0.75 and turbulence intensities (TI) of 0, 10 and 17%. These predictions result from the two-hour time series for each mean wind speed, and the results for the three-blade rotor are two thirds the magnitude of those shown in Fig. 4. The resulting blade root flatwise fatigue damage fractions ΔN/N should be the same, independent of the number of blades, each of the same weight, in the rotor, and Fig. 5 indicates that this is the case, to the accuracy of the calculations. Comparison of Figs. 4 and 5 shows, as expected, that reductions in RMS moments in going from the open-loop (OL) to the closed-loop (CL) control mode cause greatly amplified reductions of fatigue damage fractions. The predicted effect of wind shear on flatwise fatigue damage fraction at the roots of the two- and three-blade rotors is shown over the range of turbulence intensities in Figs. 6 and 7 for open- and closed-loop control at a mean wind speed of 12 m/s. The effect decreases with increasing turbulence intensity, but it remains substantial at the highest turbulence level of 17%. At the intermediate level of 10%, increasing the shear exponent from 0.14 up to 1.25 increases ΔN/N by near 10^4 in open-loop control, and more in the closed-loop control mode. The increase appears to be roughly in proportion to the shear exponent, and, at higher values of the exponent, the increase would portend significant reductions in blade fatigue life. Figures 8 and 9 show the predicted blade root in-plane fatigue damage fractions for the two- and three-blade rotors due to 1P gravity and fluctuating aerodynamic torque loads over the operating range of wind speeds. The wind shear exponent is 0.75, and the effect of turbulence intensity

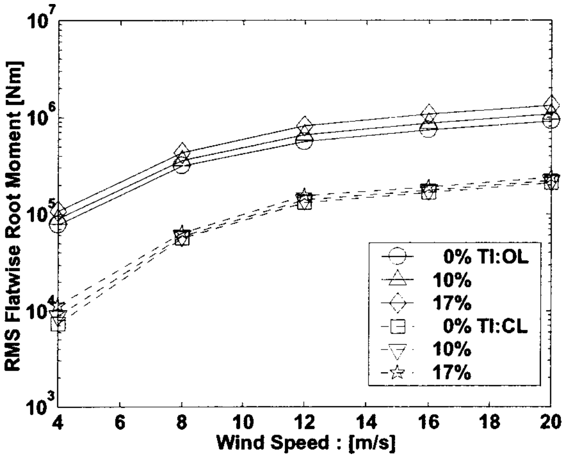

Fig. 4 RMS Flatwise Root Moments, Shear Exponent=0.75, 2 Blades

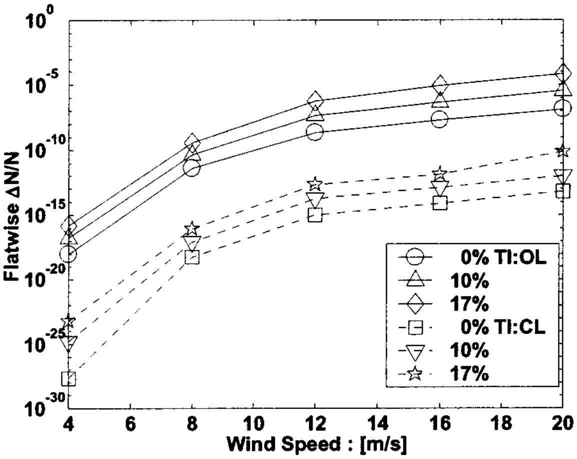

Fig. 5 Flatwise Fatigue Damage, Shear Exponent=0.75, 2 and 3 Blades

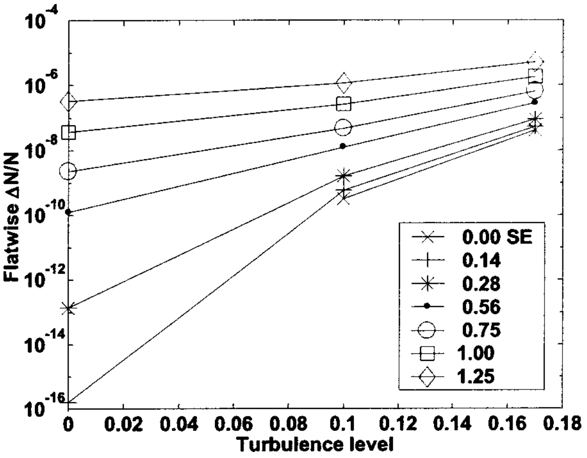

Fig. 6 Flatwise Fatigue Damage, 12 m/s, Open Loop, 2 and 3 Blades

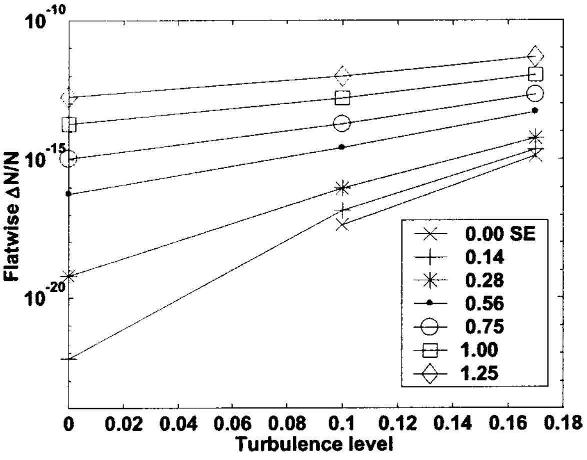

Fig. 7 Flatwise Fatigue Damage, 12 m/s, Closed Loop, 2 and 3 Blades

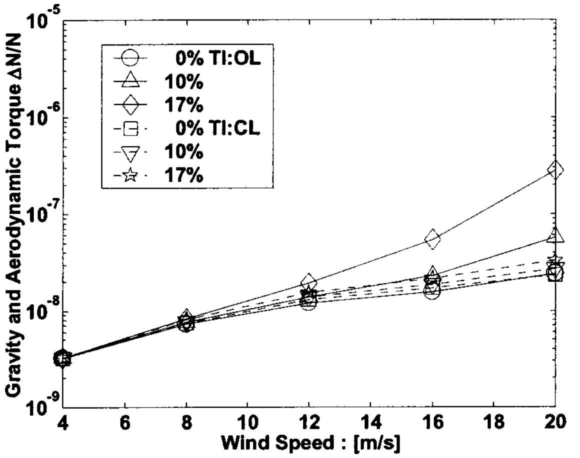

Fig. 8 In-plane Fatigue Damage, Shear Exponent=0.75, 2 Blades

is included as in Figs. 4 and 5. It is clear from Figs. 8 and 9 that in-plane fatigue damage is dominated by 1P gravity loads up to rated wind speed (10.9 m/s), and increased turbulence intensity exacerbates this damage at higher wind speeds. Closed-loop control is effective in reducing this damage only at higher wind speeds. Not surprisingly, this damage due to 1P gravity loads is much lower with the two-blade rotor than with the three-blade rotor [2]. It is found that wind shear generally plays a minor role in in-plane fatigue damage.

Rotor Moments and Thrust

Predicted RMS and mean rotor pitching moments over the full range of wind shear exponents are shown in Figs. 10 and 11 for a mean hub height wind speed of 12 m/s with the two-blade rotor. These moments are taken about the horizontal axis of the rotor disk. These results show that these moments are relatively independent of turbulence intensity, and they increase essentially in proportion to the shear exponent. These results are in line with the findings of elementary analysis. Substantial reductions in both moments are obtained in the closed-loop control mode. These moments are, of course, sources of fatigue damage to the wind turbine structure, just as blade moments are to its structure. Note that increasing shear exponent from 0.14 to 1.25 increases these moments by an order of magnitude, and as noted with the blades, such an increase can greatly magnify damage rates in fatigue critical areas. This possibility requires additional study. Corresponding RMS and mean rotor yawing moments are shown in Figs. 12 and 13. These moments are about the vertical axis of the rotor disk. Note that RMS yawing moments (Fig. 12) behave much like the pitching moments (Fig. 10), whereas the mean yawing moments (Fig. 13) are much smaller than the mean pitching moments (Fig. 11). This behavior was observed over the operating range of wind

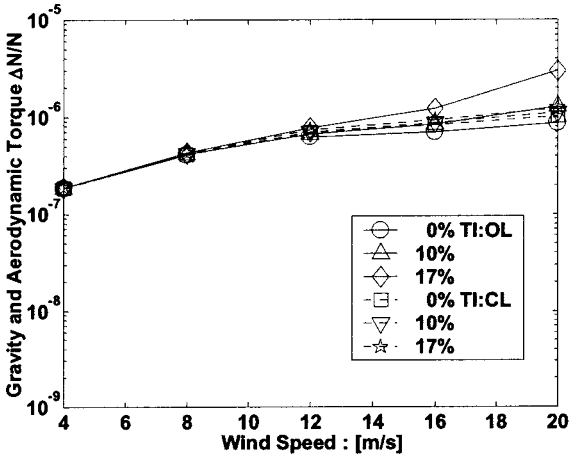

Fig. 9 In-plane Fatigue Damage, Shear Exponent=0.75, 3 Blades

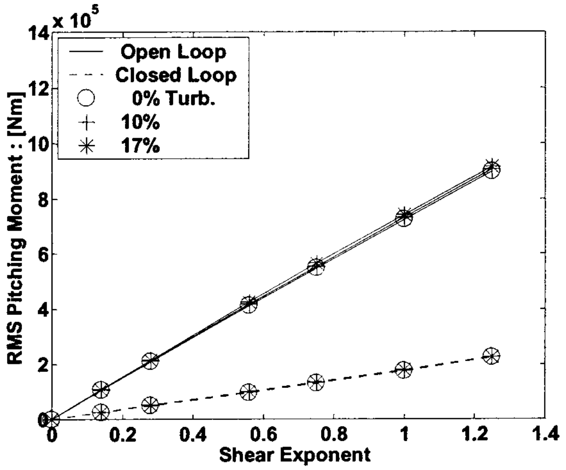

Fig. 10 RMS Pitching Moment, Wind Speed=12 m/s, 2 Blades

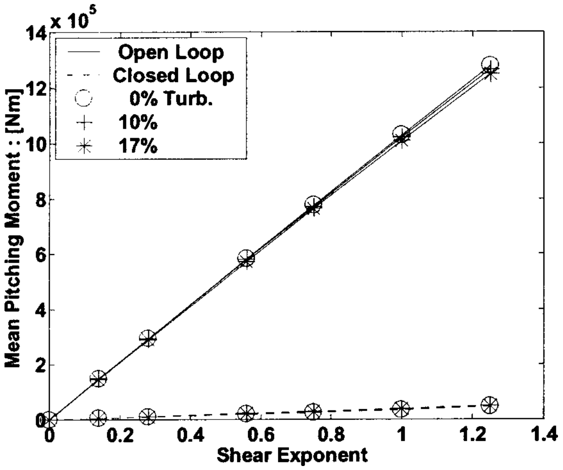

Fig. 11 Mean Pitching Moment, Wind Speed=12 m/s, 2 Blades

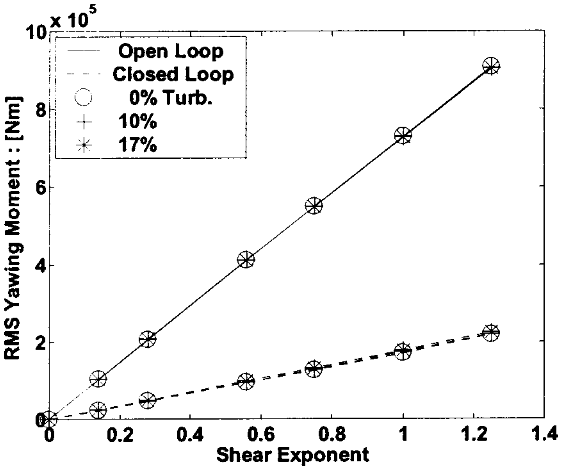

Fig. 12 RMS Yawing Moment, Wind Speed=12 m/s, 2 Blades

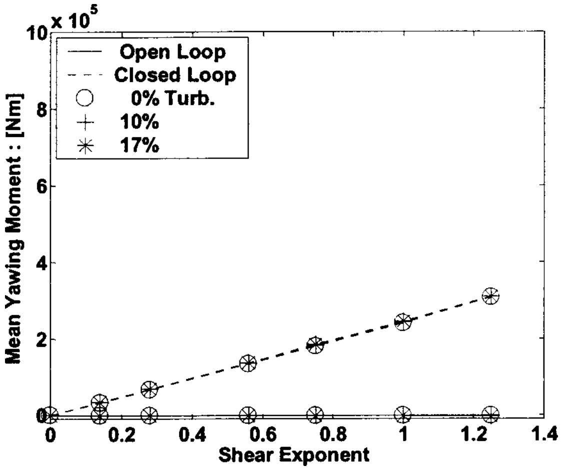

Fig. 13 Mean Yawing Moment, Wind Speed=12 m/s, 2 Blades

speeds. The same was true of the curious prediction that mean yawing moment is increased in the closed-loop control mode. This result prompted a closer look at the resolution of out-of-plane blade root moments into rotor pitching and yawing moments. Figure 14 shows the open and closed loop 1P blade root moments over one revolution of one blade in a 12 m/s wind with zero turbulence and a wind shear exponent of 0.28. Note that the closed-loop moment has smaller amplitude but much the same mean as the open-loop moment. Both of these results are governed by the closed-loop control logic. When these results are

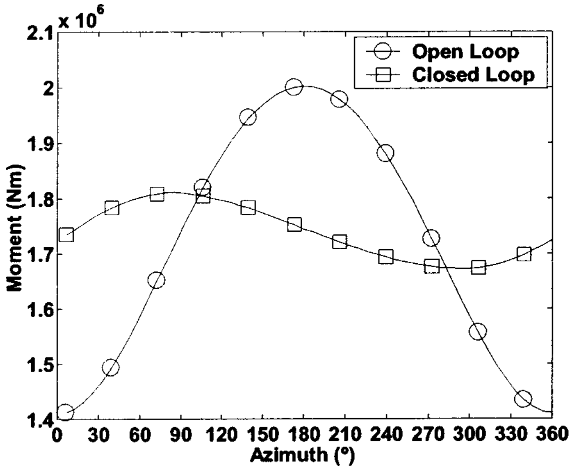

Fig. 14 Blade Out-of-plane Moments, 12 m/s, Shear Exponent =0.28, Turbulence=0%, 2 Blades

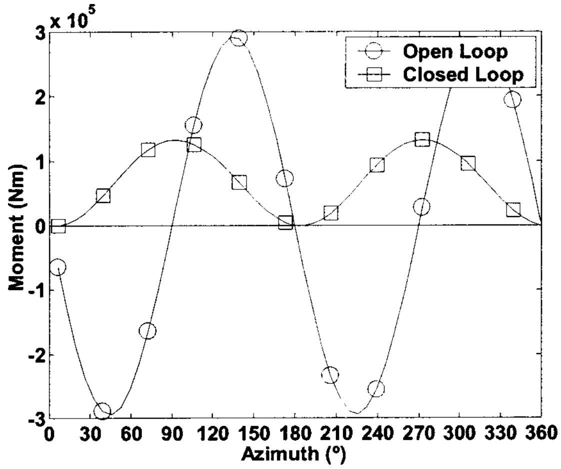

Fig. 15 Rotor Yawing Moments, 12 m/s, Shear Exponent =0.28, Turbulence=0%, 2 Blades

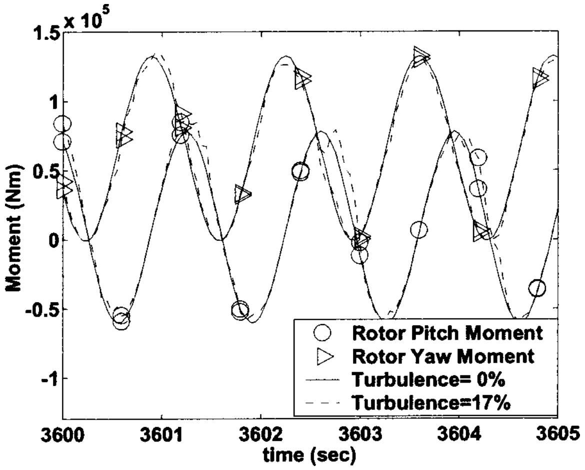

Fig. 16 Rotor Pitching and Yawing Moments, 12m/s, Shear Exponent=0.28, Closed Loop, 2 Blades

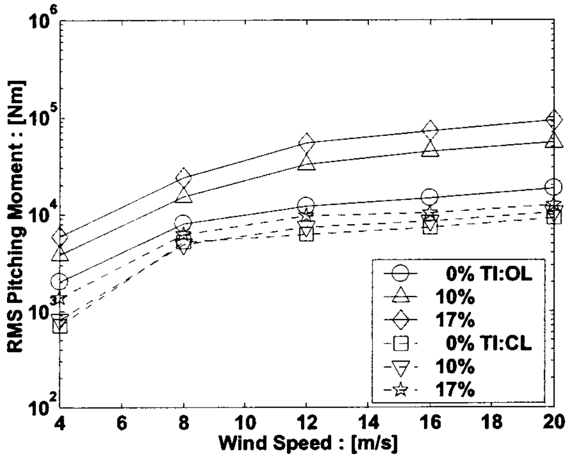

Fig. 17 RMS Pitching Moment, Shear Exponent=0.28, 3 Blades

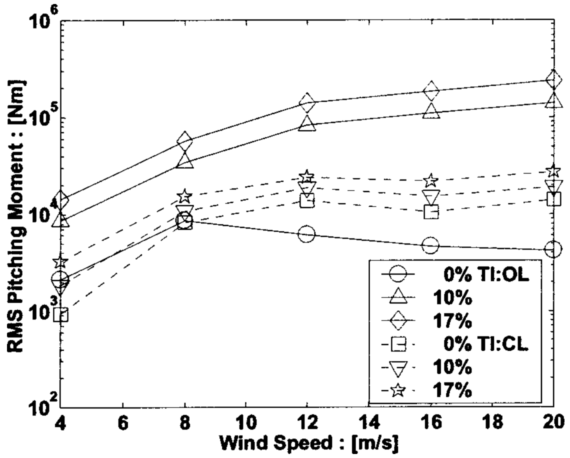

Fig. 18 RMS Pitching Moment, Shear Exponent=0.75, 3 Blades

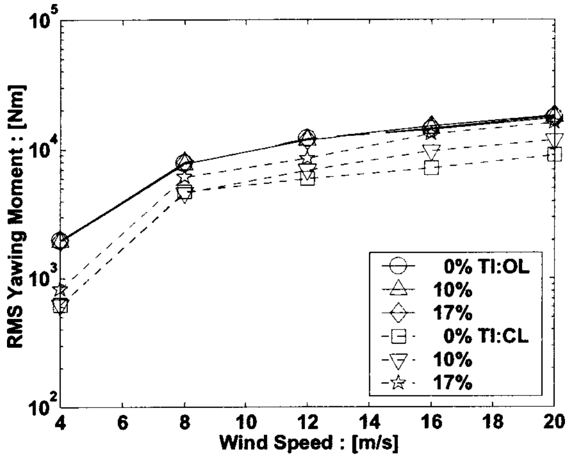

Fig. 19 RMS Yawing Moment, Shear Exponent=0.28, 3 Blades

resolved and combined for both blades into 2P rotor yawing moments, the latter are as shown in Fig. 15. While the mean of the open-loop moment is zero, it is clearly positive for the closed-loop moment; there is nothing in the closed-loop control logic to cause the latter to be zero. Figure 16 shows the rotor 2P pitching and yawing moments as a function of time in closed-loop operation in the same wind for the cases of 0% and 17% turbulence intensity. Note that the mean of pitching moments is near zero. Note again that turbulence has relatively little effect on either pitching or yawing moments, compared with the effect of wind shear. Obviously, the relative effect of turbulence would be expected to increase if the wind shear effect were reduced.

Predicted RMS pitching moments for the three-blade rotor are shown in Figs. 17 and 18 for wind shear exponents of 0.28 and

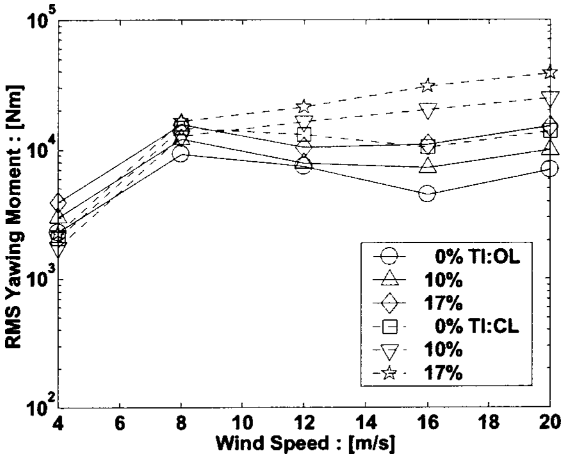

Fig. 20 RMS Yawing Moment, Shear Exponent = 0.75, 3 Blades

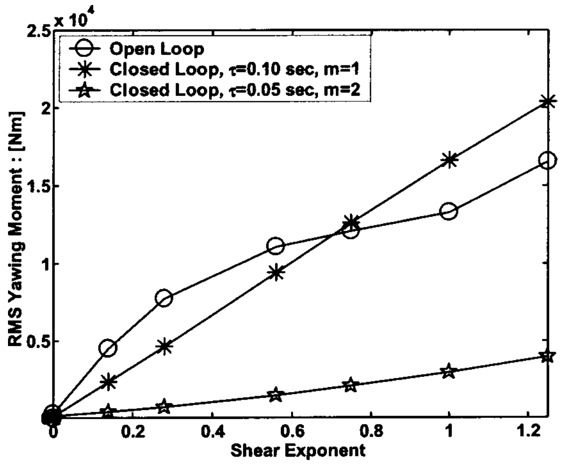

Fig. 21 RMS Yawing Moment, 8 m/s, 3 Blades, 10% Turbulence

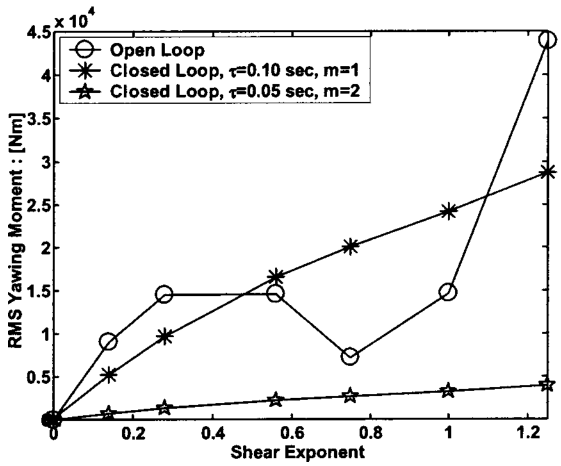

Fig. 22 RMS Yawing Moment, 16 m/s, 3 Blades, 10% Turbulence

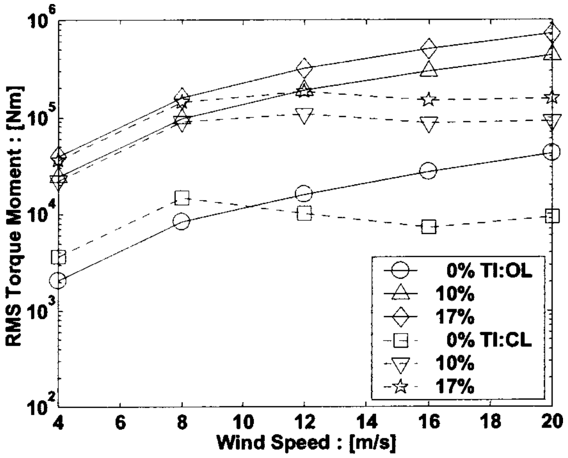

Fig. 23 RMS Torque Moment, Shear Exponent = 0.75, 2 Blades

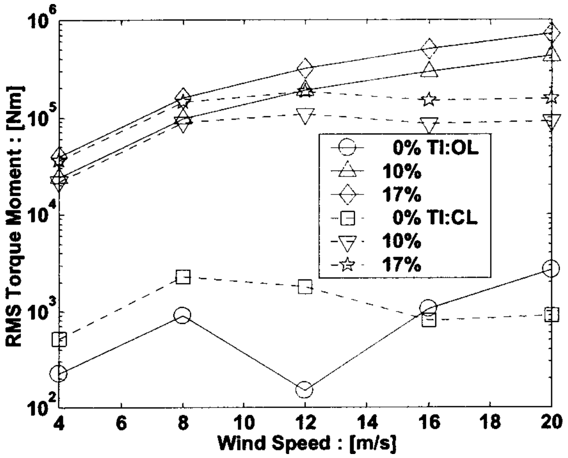

Fig. 24 RMS Torque Moment, Shear Exponent = 0.75, 3 Blades

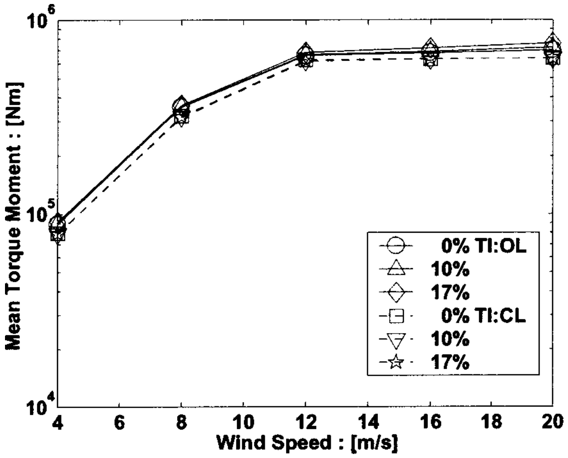

Fig. 25 Mean Torque Moment, Shear Exponent = 0.75, 2 Blades

0.75. Comparison of these predictions with those for the two-blade rotor at 12 m/s wind speed (Fig. 10) indicates, as expected, that RMS pitching moments are substantially lower for the three-blade rotor. This trend persists over the operating range of wind speeds. Not surprisingly, these lower pitching moments are noticeably sensitive to turbulence intensity. The substantial increases in RMS pitching moments with increased turbulence intensity noted in Figs. 17 and 18 are driven by the vertical gradient in turbulent fluctuations in wind speed. This gradient is determined by the mean wind shear gradient, which increases with the shear exponent (compare Figs. 17 and 18). The RMS yawing moments of the three-blade rotor are shown in Figs. 19 and 20 for shear exponents of 0.28 and 0.75. Again, they are much lower than those for the two-blade rotor (see Fig. 12). Note the curious trends predicted for these moments at the higher shear exponent of 0.75 and wind speeds above rated (Fig. 20); to wit, open-loop moments decrease at wind speeds above rated, and closed-loop moments are increased above the open-loop values. The latter result is reversed by increasing the bandwidth of the closed-loop control system, as noted in Figs. 21 and 22. The decrease in open loop moments may be traced to the fine balance between the 1P out-of-plane blade root moments that are resolved to yield the 3P rotor yawing moments. This phenomenon persists at higher wind shears and requires further study.

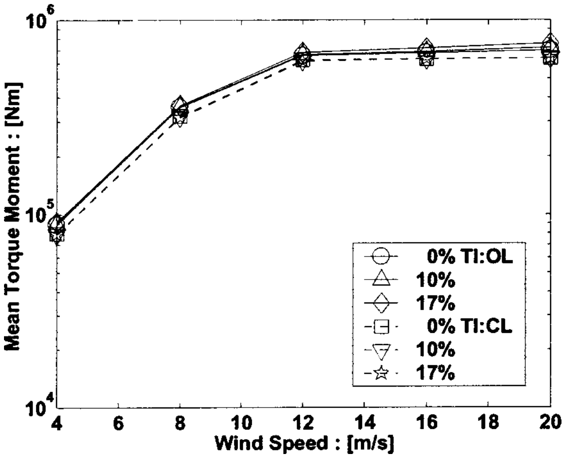

Fig. 26 Mean Torque Moment, Shear Exponent=0.75, 3 Blades

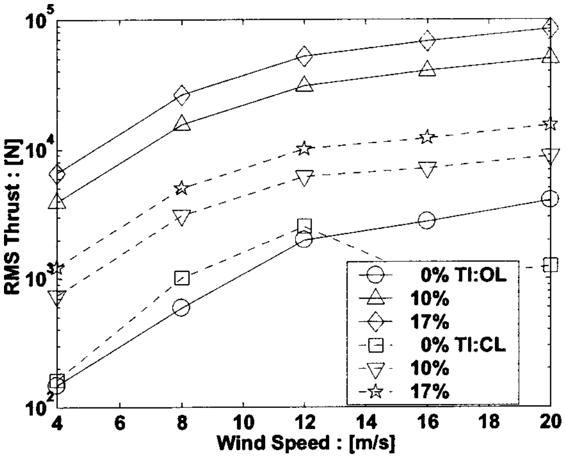

Fig. 27 RMS Thrust, Shear Exponent=1.25, 2 Blades

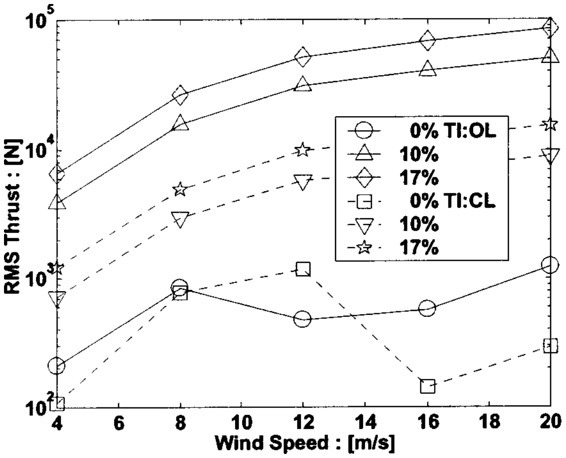

Fig. 28 RMS Thrust, Shear Exponent=1.25, 3 Blades

Figures 23 and 24 compare predicted RMS rotor torque for the two- and three-blade rotors operating over the wind speed range with a shear exponent of 0.75. These results show that this torque is strongly affected by turbulence, that wind shear plays a minor role in this torque, and that there is little effect of the number of rotor blades. Further increase in the shear exponent does not appear to significantly alter this result. This is not surprising, since rotor torque is the sum of the blade torques. Figs. 25 and 26 show the corresponding predictions for mean rotor torque and, thus, average power. These results show that increased turbulence somewhat increases mean torque and, as expected, closed-loop operation somewhat decreases it. Again, there is no significant effect of the number of blades. Figs. 27 and 28 show predicted RMS rotor thrust at the highest shear exponent of 1.25, and it is clear that just as with RMS torque, turbulence dominates the result. Here again, there is no significant effect of the number of blades, and the same result applies to mean thrust. As a general rule, predicted mean loads are the same for the two- and three-blade rotors.

There are, of course, lateral and vertical in-plane forces exerted on the two- and three-blade rotors in the presence of wind shear. The RMS forces are, as are rotor RMS moments, much smaller for the three blade than the two-blade rotor. More study is required to determine if either the lateral or vertical forces may be a source of structural loads that could seriously influence wind turbine design. Early indications are that RMS lateral forces will be of less importance than rotor RMS yawing moments in their potential influence on yaw drive design.

Conclusions

This exploratory study indicates that increased wind shear will substantially increase blade flatwise fatigue damage in turbulent winds as a result of increased fluctuations in flatwise moments. These moments are the prime drivers of blade out-of-plane moments, and these out-of-plane moments are the origin of rotor pitching and yawing moments. As a result, the rotor pitching and yawing moments can be substantially increased by increased wind shear, more so with two-blade than three-blade rotors. Teetering a two-blade rotor should alleviate these moments, but teetering can cause other problems requiring further study. Closed-loop control of blade fluctuating flatwise moments can substantially alleviate these moments and the resulting rotor pitching and yawing moments, providing the control system has sufficient bandwidth. Turbulence is the prime driver of fluctuating rotor torque and thrust. These fluctuations can also be alleviated with closed-loop control of blade fluctuating flatwise moments.

Much work remains to be done in the study of wind shear and turbulence effects on rotor fatigue and loads control. Enlarging the body of reliable test data [6] on high wind shear and associated turbulence characteristics will be invaluable to improved modeling of the effects of these phenomena on rotor and resultant turbine loads and fatigue life. This will, in turn, help sharpen the tradeoff analyses required of alternative turbine configurations and control systems to reliably deal with these phenomena in long life operation.

Acknowledgment

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