Impact of the Low-Level Jets Negative Wind Shear on the Wind Turbine's Blades

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Abstract*– Nocturnal Low Level Jets (LLJs) are defined as relative maxima in the vertical profile of the horizontal wind speed at the top of the stable boundary layer. Such peaks constitute major power resources, since they are observed at altitudes within the heights of commercial-size wind turbines. However, a wind speed maximum implies a transition from a positive wind shear below the maximum height to a negative one above. The effect that such transition inflicts on the wind turbine's blade has not been thoroughly studied. Using actual atmospheric LLJ data of high frequency as input for the NREL aeroelastic simulator FAST, different scenarios were created varying the LLJ maximum height with respect to the wind turbine hub height. We found that most of the time, the blade was bended near maximum values across the plane of rotation, with transient relapses to zero deflection. Within the plane of rotation, the blade was bended 85% of the time in the direction opposing the rotor motion. The values of these deflections were proportional to the strength of the LLJ, but they were also slightly reduced if negative wind shears were present within the turbine's sweeping area. There were also strong centrifugal forces at the root of the blade. The shear forces and the bending moments were moderate, with transient relapses to near zero values. The amplitude of oscillation of these moments and forces were attenuated by the negative wind shears.

Keywords-- low level jet, wind energy, wind turbine.

I. INTRODUCTION

Nocturnal Low Level Jets (LLJs) are defined as relative maxima in the vertical profile of the horizontal wind speed. They are the result of the stable stratification in the lower atmosphere and the inversion of potential temperature that occurs mainly at night. LLJs occur in many regions of the world and are especially important in the Great Plains of the United States for their role in the formation of the climate and their impacts on the production of wind energy. Wilczak et al. [1] determined that LLJs drive the wind farm' capacity factors to over 60 % during the nocturnal hours.

The most distinctive feature of a LLJ is a peak of wind velocity that is observable in the vertical profile of the horizontal wind speed at some height above the ground level, usually between 100m and 700m [2]. They seem to exert a noticeable impact at altitudes as low as z=40m which indeed results in a direct influence over the performance of the wind turbines [3]. The existence of the velocity peak implies that the wind speed shear, defined as the variation of the wind speed with the height above the ground level, is positive below the jet peak and negative above.

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II. MOTIVATION

Due to the increase in wind speed, LLJs are significant contributors of wind energy, with an increase in wind power density in the order of 10-15 times the values in the diurnal unstable conditions. On the other hand, studies have demonstrated that there is an increase in mechanical loads and fatigue loads with the occurrence of LLJs [5].

As wind turbines grow taller, the get deeper and deeper into the atmospheric region of influence of LLJs, [3] and this transition from positive wind shear below the peak of the jet to negative wind shear above the peak will be more frequently found near, inside or even below the turbine's sweeping area. The effect that such transition inflicts on wind turbines has not been thoroughly studied.

A key objective of this research is to compare the resulting deflections and loads in the blades of a wind turbine when the peak of a LLJ impacts above, within or below the turbine's sweeping area. The blades are especially vulnerable parts of the turbine, due to their slim geometry and their rotation within a variable wind speed field.

III. EXPERIMENTAL DATA AND ANALYSIS

The bulk of the experimental data was collected from the measurement system of the West Texas Mesonet 200 meters' meteorological tower [7], located at 33°36'27.32" N, 102°02'45.50" W and at elevation 1021m. Sensors were installed at 10 heights in the tower: 0.91m, 2.44m, 3.96m, 10.06m, 16.76m, 47.24m, 74.68m, 116.43m, 158.19m and 199.95m. Gill R3-50 sonic anemometers [8] at each height were used to obtain the measurements of the three components u, v, and w of the instantaneous velocity. The horizontal wind, which was directed normal to the plane of the wind turbine blades at the height of the turbine hub, was obtained as the vector sum: $\vec{U}_{xy} = \bar{u} + \bar{v}$. The modulus of the horizontal velocity was calculated as $U_{xy} = \sqrt{u^2 + v^2}$

At each height, Young 41382VF sensors [9] provided measurements of temperature T and relative humidity RH, while Young 61302V barometers [10] provided measurements of atmospheric pressure P. Values of potential temperature were then calculated as in (1),

$$\theta = \left(\frac{P_0}{P}\right)^{\frac{R}{c_p}}. \tag{1}$$

where P_0 is a pressure reference, R is the gas constant of air, and c_p is the specific heat capacity at constant pressure. Values of virtual potential temperature were obtained as $\theta_v = \theta(1 + 0.61r)$ for unsaturated air, where the mixing ratio r was obtained from the relative humidity [11]. All tower measurements and dependent parameters were obtained at a frequency of 50 Hz.

The main objective of this research was to compare the impacts on turbines of the negative wind speed shears above the peak of the jet, in relation with the positive shears below the peak. This task presented the preliminary question of how to account for “more” or “less” negative shears. The response to this problem was to create some parameter that could be associated with: a) vertical closeness between jet and turbine, b) proportion of the turbine sweeping area covered by negative wind shears, and c) relative position (above or below) between jet and turbine. To that purpose, we defined the following parameter,

$$\xi = \frac{z_t - z_p}{R}. \qquad (2)$$

where ξ is the turbine-jet relative distance, z_t is the height above the ground level of the turbine hub, z_p is the height above the ground level of the peak of the jet, and R is the turbine’s rotor radius. Characteristics values of the parameter ξ are represented in Fig. 1.

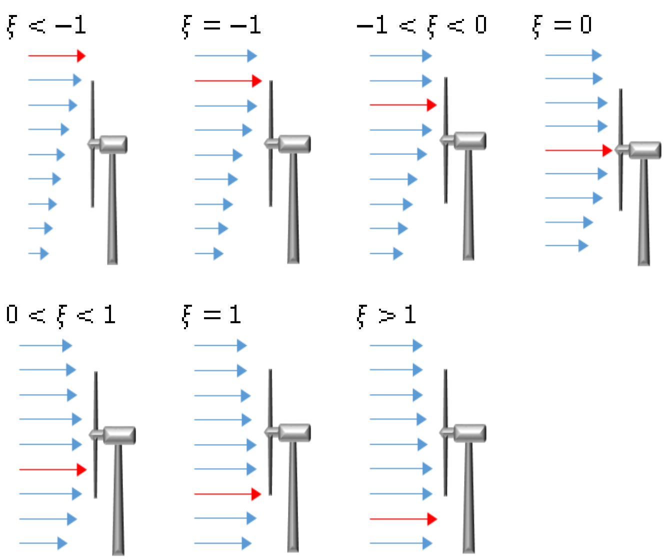


Fig. 1 Characteristic values of the turbine-jet relative distance ξ. The LLJ, represented with the blue lines, impacts the turbine at different vertical positions. The red line represents the peak of the jet.

To evaluate the impact of the negative shears above the jet peak in relation to the positive shears below the peak, calculations of the mechanical responses of the blades were performed at multiple values of the parameter ξ. These mechanical responses included: deflections, velocities, accelerations, forces and moments on the blades.

Each calculation was performed by plugging in wind speed data grids into the FAST (Fatigue, Aerodynamics, Structures, and Turbulence) simulation code developed by NREL [6]. The FAST code is a comprehensive aero elastic simulator and is capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines (HAWTs). The turbine model selected for the simulations was the NREL WindPACT 1.5-MW Wind Turbine [13].

IV. Results

The way the mechanical responses vary with modifications of the parameter ξ is well visualized by looking at plots of probability density function (pdf) for each response. The pdf for any turbine response r at a given value of ξ is defined as the function $f_{(r,\xi)}$ that satisfy the following expression,

$$Pr[a \leq T \leq b] = \int_a^b f_{(r,\xi)} dr, \quad \xi = const. \qquad (2)$$

where $Pr[a \leq T \leq b]$ is the probability of a response value T of being within the interval defined by *a* and *b*.

The figures in this section (Fig. 2-7) represent the pdf variation with ξ of several blades' responses. In each figure, the parameter ξ is represented in the vertical axes, from wind speed shear totally positive at the bottom (where ξ=-1) to wind speed shear totally negative at the top (where ξ=1). The background color is deeper where values are more concentrated. The red line and the dark red line connect the mean and the median values respectively. The green lines and the dark green lines delimit the zones with 95% and 68% of the values respectively.

A. *Blade tip deflections*

The variations of the pdf corresponding to the three components of the blade tip deflection are represented in Fig. 2-4. Fig. 2 shows the component of the deflection across the plane of rotation of the blade; it reveals that most of the time, the blade was bended near maximum values, with transient relapses to zero deflection. No variation in magnitude was observed with modification in the proportion of negative shears impacting the turbine's sweeping area. On the other hand, the component within the plane of rotation, in Fig. 3, shows that 85% of the time the blade was bended opposite to the rotation, compared to 15% of the time in the direction of the rotation. Deflections opposed to the rotation tended to be slightly reduced if more negative shears were present within the turbine's sweeping area. Finally, Fig. 4, shows that the radial component of the deflection oscillated around a reduced length, with transient relapses to zero. This length was slightly less affected if more proportion of negative shears were present.

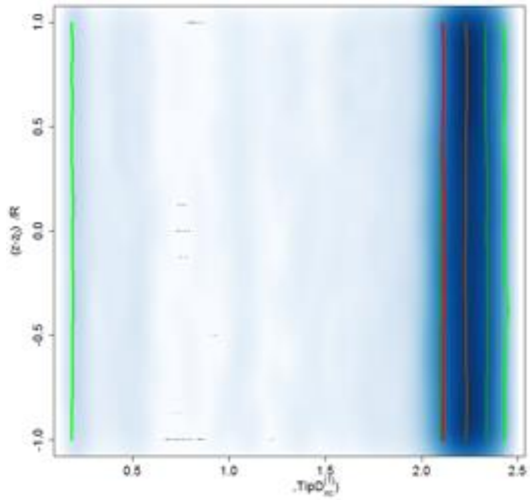
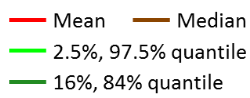


Fig. 2 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade tip deflection, out of the plane of rotation.



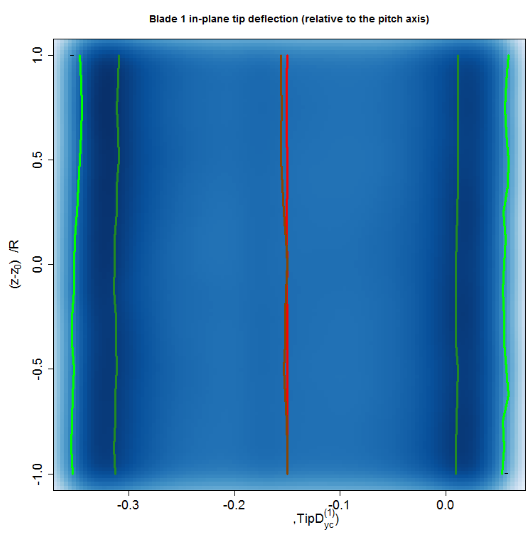
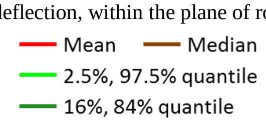


Fig. 3 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade tip deflection, within the plane of rotation.



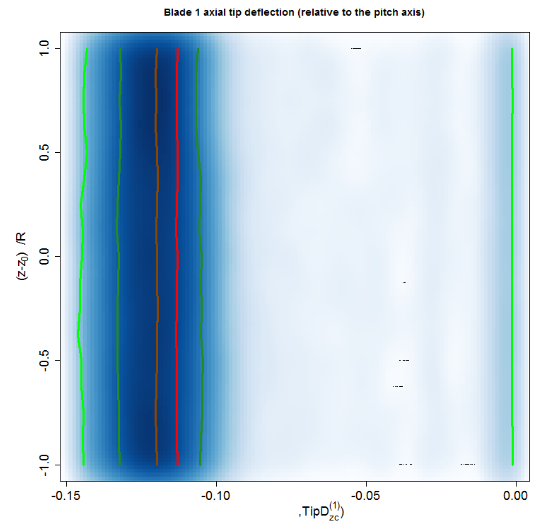
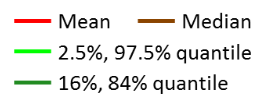


Fig. 4 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade tip deflection, in the radial direction.



B. Blade root forces

The variations of the pdf corresponding to the three components of the blade root forces are represented in Fig. 5-7. Fig. 5 shows that moderate values of the shear force occurred across the plane of rotation, with transient relapses to near zero values. This force implied a bending moment in the direction of the wind. The figure also reveals that more negative shears within the turbine's sweeping area reduced the magnitude of the force. On the other hand, the shear force within the plane of rotation, in Fig. 6, oscillated between favoring and opposing the rotation. Values opposed to the rotation tended to be slightly reduced if more negative shears were present within the turbine's sweeping area. Finally, Fig. 7, shows the occurrence of a strong centrifugal force that was slightly reduced when more proportion of negative wind shears were present.

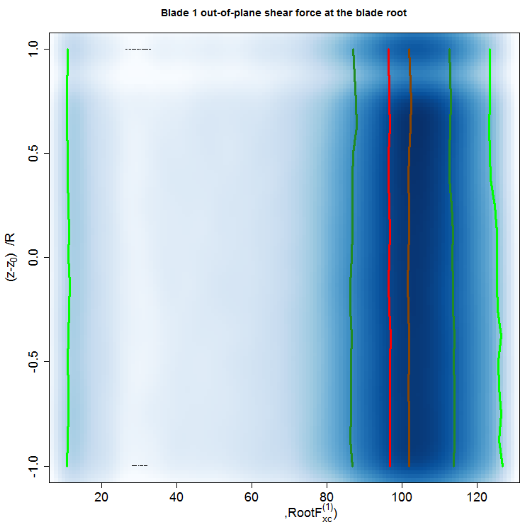


Fig. 5 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade root shear force, out of the plane of rotation.

Mean Median
2.5%, 97.5% quantile
16%, 84% quantile

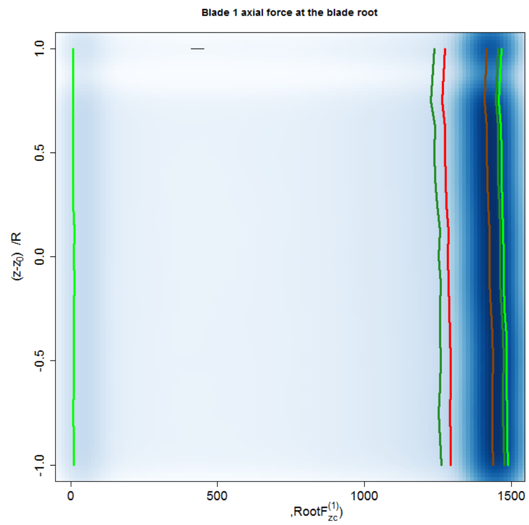


Fig. 7 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade root force, in the radial direction.

Mean Median
2.5%, 97.5% quantile
16%, 84% quantile

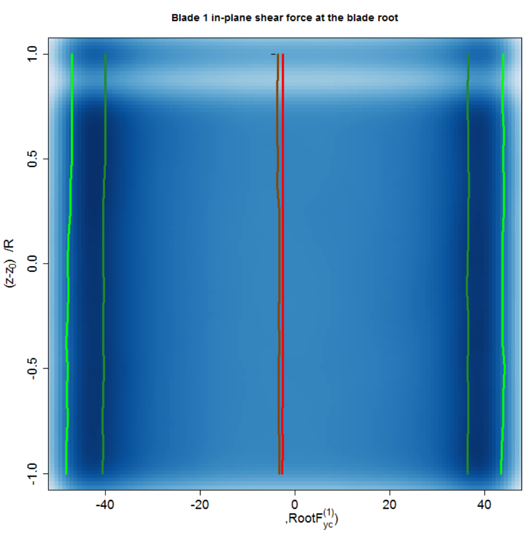


Fig. 6 Variation of the pdf (in the x-axis) with ξ (in the y-axis) of the blade root shear force, within the plane of rotation.

Mean Median
2.5%, 97.5% quantile
16%, 84% quantile

V. Conclusions

In this research, we have determined the mechanical impacts that the LLJ negative wind shears have over the blades of commercial size wind turbines, as they continue to reach deeper into the atmospheric region of influence of LLJs. It has been determined that the wind shear is a feature of the jet that correlates with the values of loads at the turbine's blades.

A non-dimensional parameter ξ was created to evaluate the impact of more proportion of negative wind speed shears reaching the wind turbine's sweeping area. Calculations were performed by correlating the deflections and loads in several parts of the wind turbine with variations of the parameter ξ.

Results show that the transition from positive to negative wind speed shears had a weak-to-moderate influence over the amplitude of oscillations of several mechanical responses of the turbine's blades.

The increment of negative wind shears within the turbine's sweeping area resulted in slight reductions in the deflection of the blade tip within the plane of rotation. Moderate decreases were also observed in the shear forces, bending moments and centrifugal forces at the blade root.

In summary, the negative wind shears, when present within the turbine's sweeping area, had a slight positive impact on the mechanical regime of the turbine's blade as they tended to alleviate the loads on it. Nevertheless, this conclusion cannot be extended to other parts of the wind turbine, such as the tower or the nacelle, as their situation is different in terms of design conditions and motions.

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