Load validation using nacelle-mounted lidars: progress and challenges

Nikolay Dimitrov[1,2], **Anand Natarajan**[1], **Rozenn Wagner**[1]

[1] Technical University of Denmark, Department of Wind Energy, Frederiksborgvej 399, 4000 Roskilde, Denmark

[2] E-mail: nkdi@dtu.dk

Abstract. Aeroelastic load simulations on a Siemens 2.3MW wind turbine have been validated using load measurements from the turbine and wind inflow measurements from a Nacelle based Lidar. A detailed survey of industrial usage of Nacelle mounted Lidars has also been conducted to extrapolate the findings from the present study to a broader framework.. Based on this information we assess the current technology status and recommend future focus areas.

1. Introduction

Nacelle-mounted lidars have high potential as tools for wind turbine load validation due to beneficial features such as scanning multiple points, and always scanning directly upwind of the rotor. However, there are also technical challenges in achieving a quality load validation. Due to the specific technology involved, using lidars requires data processing different from the one used for mast-based measurements, and the estimated wind field may be subject to additional uncertainties. Solutions to these challenges are pursued in earlier studies as e.g. [1],[2],[3]. In the present paper, we utilize information from a load measurement campaign from a wind farm in Denmark, a survey among lidar users in wind energy industry, and from numerical models. Based on this information we assess the current status of the nacelle-mounted lidars as tools for load validations, and recommend future focus areas.

2. Approach

The most essential environmental inputs for load simulations consist of 10-minute average wind statistics: mean wind speed, turbulence, and wind shear – with yaw angle and veer affecting the results to a lesser extent. In addition, the turbulence spectrum is of interest as it is used to define the properties of the turbulence realizations used in the simulations. Aiming at demonstrating how the load-relevant environmental variables can be determined reliably using nacelle-mounted lidars, a load measurement campaign was carried out at the Nørrekær Enge (NKE) wind farm in Northern Denmark. A ZephIR continuous-wave and an Avent 5-beam pulsed lidar [4] were mounted on the nacelle of a Siemens 2.3MW turbine equipped with load sensors. The lidars were calibrated following the procedure defined in [4]. A met mast at 2.5 rotor diameters distance was available as supplemental data source. Wind conditions were measured and fed as inputs to aeroelastic simulations, followed by a comparison with the measured loads. The aim of the analysis is to test whether a procedure using solely lidar-based wind inputs to load simulations could match or even improve the level of load prediction accuracy achievable with mast-based data.

The mean wind conditions are reconstructed from lidar line-of-sight measurements using least-squares fits of 10-minute mean values, estimating simultaneously the effect of wind shear, veer, yaw misalignment, and rotor induction, a procedure similar to the one defined in [3]. The turbulence is estimated from the residuals of the mean wind field fits, accounting for the effect of volume averaging and beam line-of-sight angles. The effect of volume averaging on measured turbulence is estimated by considering the lidar as a low-pass filter, where the amount of filtering depends on the turbulence spectral properties [2]. The averaged turbulence spectrum in the longitudinal direction is estimated using the forward-pointing beam of the 5-beam lidar. The measured variance of the residuals is then corrected by increasing the values with an amount equal to the expected attenuation due to the volume-averaging effect.

The results obtained in [1] suggest that carrying out constrained simulations (incorporating measured high-frequency wind time series in load simulations) could lead to reduction in the load estimation uncertainty. Constrained simulations are also considered in the present work, using the measured time series from both the continuous-wave lidar and the 5-beam pulsed lidar, and applying the methods described in [1].

Since the present study focused on a single nacelle mounted Lidar on a particular wind farm, an online survey was made whereby various wind turbine manufacturers, wind farm owners and Lidar manufacturers were requested to provide their inputs on the type of nacelle mounted Lidar measurements that have been made on different wind farms and turbines. In all 18 respondents were surveyed.

3. Main body

In the following, we present the results of our studies, beginning with the ones from the survey among industry. Figure 1 depicts the type of terrain that the wind turbine from survey respondents is installed in, with the vast amount of usage of nacelle based Lidars (~66%) limited to flat terrain low roughness sites. Figure 2 details the wind quantities of interest, where like in Nørrekær Enge, the main quantities measured were the 10-minute mean wind speed, direction, std. deviation, shear and the rotor effective mean wind speed. While turbulence spectra and upflow were seldom quantified, other inferred quantities included such factors as induction.

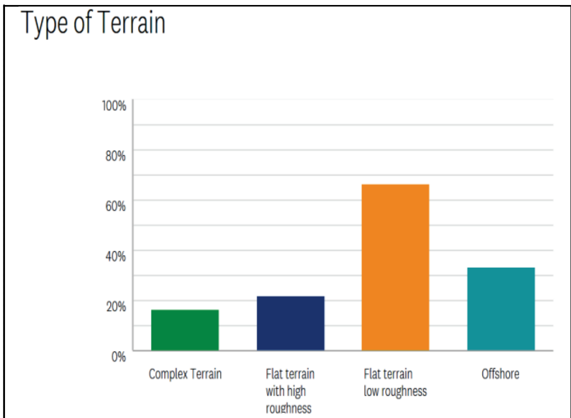

Figure 1. Variation of the usage of nacelle mounted Lidars over different wind farm terrains.

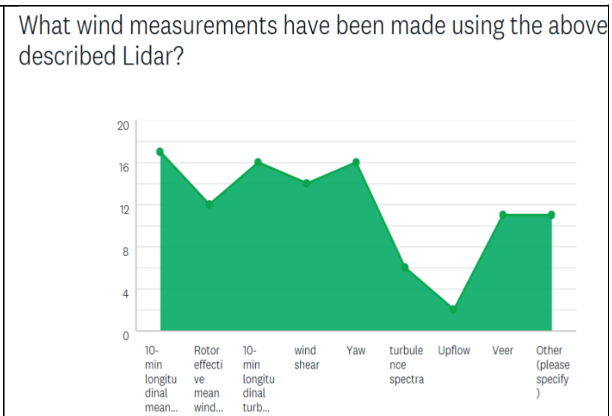

Figure 2. Type of measurements made using nacelle mounted Lidars

Figure 3 shows an example comparison of the statistics of measured and simulated blade root flapwise bending moment for the turbine at NKE. The 5-beam Avent lidar was used to derive wind statistics for the simulations shown. As seen from Figure 3, there is good agreement between the model and the measurements for all wind speeds, indicating that the wind conditions derived from the lidar data and used in simulations are sufficiently representative. The model performance (the bias in predictions and the uncertainty) obtained using lidar-based input data was very similar to what was obtained using mast-based input data. The chosen wind direction sector ($102.9° \pm 5°$) points exactly towards the mast, meaning that this is the sector most favorable for obtaining representative data from mast-based instruments. One of the biggest advantages of the nacelle-mounted lidars over a met mast is the ability to follow the turbine wind direction, thus always pointing upwind. This is illustrated in Figure 4 where the tower base fore-aft moment predictions are compared over wind direction sectors with different width. While the uncertainty in mast- and lidar-based load predictions is very similar for a narrow sector centered at the mast direction (top left and right plots in the figure), for a wider sector the mast-based load predictions have bigger uncertainty than the lidar-based predictions (lower left and right plots respectively).

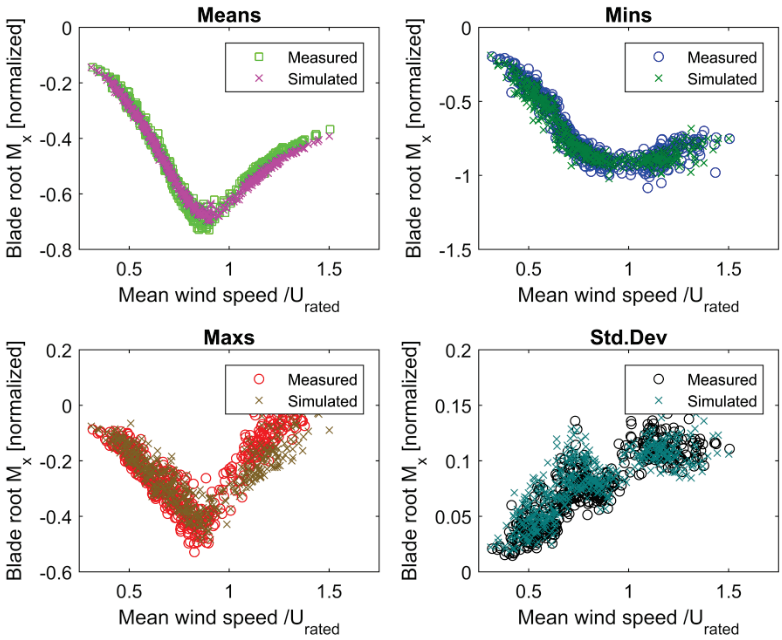

Figure 3. Comparison between measured and simulated blade root flapwise load statistics for a narrow wind direction sector ($\mathbf{102.9° \pm 5°}$) at Nørrekær Enge. Simulation inputs are derived using a 5-beam nacelle-mounted lidar.

While the lidar-based load validations from the NKE measurement campaign showed promising results, a few issues were observed which currently pose uncertainty on whether the present hardware and analysis procedures can be universally applied to a wider range of sites. These include:

- The quality of the load predictions is very sensitive to the applied turbulence levels. Since obtaining second-order statistics such as wind speed variance (turbulence) and turbulence spectrum by a lidar is relatively challenging, this may increase the uncertainty in the load predictions, especially for sites with high turbulence.
- A full load validation as prescribed by the IEC standards 61400-1 [5] and 61400-13 [6] requires covering a number of load cases under various environmental conditions. As the majority of load measurement campaigns have been taking place in flat, low-turbulence sites, the current experience with lidar-based load validation does not cover the full range of load cases.

We consider the above points as important challenges to be solved in order to enable the full potential of nacelle-mounted lidars as load validation tools, and therefore recommend them as focus of future research efforts.

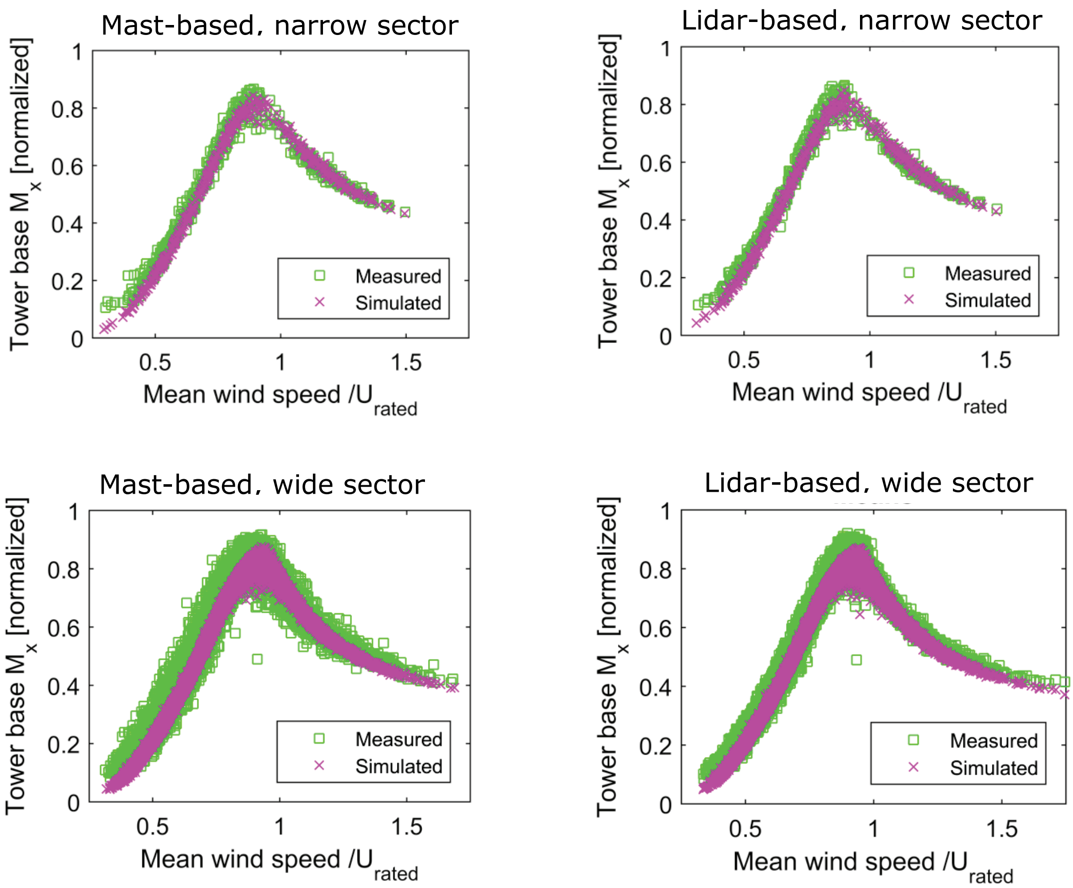

Figure 4. Comparison between measured and simulated mean tower base bending moment at Nørrekær Enge. Top left and right: comparison for narrow wind direction sector ($\mathbf{102.9^\circ \pm 5^\circ}$) for mast-derived and lidar-derived statistics respectively. Bottom left and right: comparison for wide wind direction sector ($\mathbf{96^\circ - 225^\circ}$). Left: using statistics from mast data, right: using lidar-derived statistics.

4. Conclusions

Based on our experiences and the analysis presented, we conclude the following:

- Nacelle-mounted lidars using current-day technology are generally capable of providing sufficiently good input for load validation at sites with flat terrain or offshore where ambient turbulence is not a critical factor.
- In some cases nacelle-mounted lidars may perform better than masts since the lidars follow the turbine orientation and are thus constantly measuring exactly upwind of the wind turbine.
- Due to the technical challenges imposed by the volume-averaging effect of lidars, and due to the measurements only consisting of a single line-of-sight component, obtaining second-order wind statistics such as standard deviations and spectrum is difficult.

The conclusions above were found to be consistent with the results obtained from the survey reporting industrial experience with nacelle-mounted lidars.

In addition to what is presented in this abstract, the full paper will elaborate on the following:

- A sensitivity study on the effect of including lidar-derived shear/veer in the load simulation input
- the extent of industrial usage of nacelle-based lidars for load measurements
- Provide a more extensive, quantitative description of the measurement campaign results

5. Learning objectives

By attending our presentation, the listener will learn the following:

- How nacelle-mounted lidars can be used for load validation in some cases
- That nacelle-mounted lidars provide reliable mean wind speed and wind shear measurements for load validation
- Why estimating the standard deviation of wind speed with lidars requires assumptions or detailed information for the turbulence spectrum
- What is the current level of adopting lidar technology for load validation in the industry.
- What are the main challenges and suggested focus for future research in lidar-based load validation

References

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