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Full scale wind turbine test of vortex generators mounted on the entire blade

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Abstract. Measurements on a heavily instrumented pitch regulated variable speed Vestas V52 850 kW wind turbine situated at the DTU Risø Campus are carried out, where the effect of vortex generators mounted on almost the entire blade is tested with and without leading edge roughness. The measurements are compared to the predictions carried out by a developed design tool, where the effect of vortex generators and leading edge roughness is simulated using engineering models. The measurements showed that if vortex generators are mounted there is an increase in flapwise blade moments if the blades are clean, but also that the loads are almost neutral when vortex generators are installed if there is leading edge roughness on the blades. Finally, it was shown that there was a good agreement between the measurements and the predictions from the design tool.

1. Introduction

Vortex generators (VGs) have for many years been known as aerodynamic devices, that can delay separation and thereby increase the maximum lift for a wing. Already in the 1940s and 1950s this principle was investigated for airplanes, e.g. [1]. Later it was used for stall regulated wind turbines as early as in the 1980s on the MOD-2 wind turbine [2] and later in the 1990s for the commercially available stall regulated wind turbines to increase the rated power, e.g. [3,4]. In the process of changing control strategy from stall regulation to pitch regulation in the years around 2000 the industry lost the interest in VGs in a period after which they got a revival. Recently they have been used in retrofit to existing wind turbines. This was the reason to commence the PowerPack project in 2013, where retrofit of aerodynamic devices on existing wind turbines has been analyzed. Installation of VGs on both the inner and outer part of rotors has been investigated, where tools for prediction of performance have been used and also measurements have been carried out [5,6]. However, the measurements carried out so far in this project have been focused on the power performance and thereby on the annual energy production (AEP). In parallel to this, VG designs made in the developed PowerPack design tool has been tested on existing wind turbines and has shown improved AEP results in good agreement with the predictions.

In this paper measurements on a Vestas V52 850kW pitch regulated variable speed wind turbine are described. With these measurements it is the intention to answer the following questions: 1) What is the relation between power increase and load increase when VGs are mounted both in the case of clean blades and blades with leading edge roughness (LER)? 2) Can a few percent changes in load and



power due to the different blade configurations be detected in a full scale wind turbine test with inherently stochastic input? 3) How well can loads and power be predicted with the tools developed? 4) Depending on answers to 2) and 3) what are the practical implications with regards to structural integrity and certification, if any? To answer these questions both predictions and measurements will be presented.

2. Methods

This section describes the tools used to predict the performance and the setup of the measurements on the Vestas V52.

2.1. Prediction tool

The primary tools used in the project were engineering models used to predict the effect of the VG's and LER as described in [5] and [6]. These models are based on wind tunnel measurements of so-called 2-dimensional airfoils with relative thicknesses between 18% and 36% from mainly the Stuttgart laminar wind tunnel¹. The prediction tool also applies a model for three-dimensional effects [7], and the Blade Element Momentum (BEM) model with the same formulation as in the aeroelastic stability tool HAWCStab2 [8]. The present analysis was carried out in several steps, listed below:

1. The airfoil characteristics were predicted using the 2D panel code XFOIL [9]
2. The clean two dimensional airfoil characteristics were modified to emulate LER and VG's (0.5% or 1% high at suction side between $x/c=0.20$ and $x/c=0.60$) along the whole blade span.
3. The resulting polars, including also the clean (no LER) case, were modified to account for the three dimensional effects.
4. BEM computations were carried out to determine the aerodynamic rotor performance using each of the datasets from Step 2 along the whole blade span for all wind speeds in the turbine control scheme.
5. Weibull wind speed distribution was assumed with the scale and shape parameters at hub height according the Risø site, where the Vestas V52 is situated.
6. AEP between the different configurations are compared

These six steps are used for each configuration of the wind turbine. The configurations are described in the next section, *Measurement setup*.

2.2. Measurement setup

Measurements are carried out on the Vestas V52 850 kW pitch regulated variable speed wind turbine at the DTU Risø Campus, Table 1. The wind turbine including the blades is new (installed summer 2015) and the blades are clean and have only experienced a marginal degradation in aerodynamic performance due to leading edge roughness.

Table 1 Data for the Vestas V52 wind turbine.

| Technical data for the Vestas V52-850kW | | |
|---|---------------------------|---------------------------------|
| Rotor | Power regulation | Variable speed / variable pitch |
| | Number of blades | 3 |
| | Rotor diameter | 52 [m] |
| | Hub height | 44 [m] |
| | Rotor rated speed (range) | 26 rpm (14.0 – 31.4 rpm) |
| Blade | Length | 25.3 [m] |
| | Chord blade root / tip | 2.3 [m] (max) / 0.33 [m] |

The wind turbine is heavily instrumented, but the main sensors used in this test are:

¹ Measurements are carried out in the Stuttgart Laminar Wind Tunnel on FFA-W3-301, FFA-W3-360 and NACA63418 airfoils with and without VGs.

- Blade root moment in flapwise and edgewise direction for all three blades
- Rotational speed
- Pitch
- Electrical power and shaft torque
- Tower bottom moment
- Wind speed and direction from met mast

Also, a meteorology mast is placed west of the turbine (corresponding to a wind direction of 270 degrees) where wind speeds in several heights are sampled, however in this test only the wind speed in hub height is used.

Signals are sampled at 35 Hz, but in the process of analyzing, only 10-min average values are used. Since predictions assuming a moderate LER in general show a loss of AEP of approx. 5 % and a regain of AEP of approx. 3% due to VGs, the measurements need to reveal these small changes. Experience has shown that such small changes can be challenging to detect if the measurements are separated in time due to the stochastic input. This was the reason that a test with the following four configurations of the blades was prepared:

1. **Baseline:** All three blades are clean with no LER or VGs mounted. This configuration will work as a reference to the remaining configurations
2. **VGs:** Two blades are mounted with VGs and one blade remain clean and work as a reference. The layout of the VGs is made so that a clear load increase will be seen i.e. an ‘aggressive’ VG design approach is used to amplify the investigated effects.
3. **VGs and LER:** Two blades are mounted with VGs and LER and one blade remain clean and work as a reference
4. **LER:** Two blades are mounted with LER and one blade remain clean and work as a reference

By configuring two blades and maintaining one blade as a reference, the changed blade configurations can be compared to the reference without separating the measurements in time. Thus, the intention was to filter out as much as possible of the stochastic effects. Furthermore, because two blades are configured, the changes may not only be detected on the blade level in terms of e.g. the blade root moments, but also detected on the integral level such as power or thrust. Due to delays in the measurement campaign, the fourth configuration, LER, was not finalized for this paper.

The VGs are between 0.5% and 1% in height compared to the chord length and positioned in different chordwise positions between 20% and 60% chord lengths. The VGs are mounted both in the root part of the blade (between $r=4.0\text{m}$ and $r=10.0\text{m}$) and on the outer part of the blade (between $r=15.0\text{m}$ and $r=25.0\text{m}$). The LER is represented by zigzag tape as used in numerous wind tunnel tests and with a height of $h=0.4\text{mm}$ corresponding to a relative roughness height between $h/c=1.2\text{‰}$ and $h/c=0.17\text{‰}$ depending on the radial position of the tape. Because the measurements are going to reveal small changes a somewhat ‘aggressive’ VG layout was made so that changes were detectable.

Note that the given VG layout was therefore not comparable to a common retrofit of VGs on an existing wind turbine, but to validate the design tool.

2.3. Data handling

Measurements are carried out in such a period of time so that the maximum root flap moment can be detected. Thus, wind speeds up to approximately 15m/s are needed. A result of the measurements are 10 min values based on 35 Hz time series. For each 10 min series values for mean, minimum, maximum and standard deviation are available. To investigate the changes in performance between the different configurations comparisons of mean and standard deviations are carried out. This requires a certain amount of data points and for each bin of root moments a minimum of 40 10-min values are required.

Even though the sensors are calibrated, the values from the strain gauges are normalized. The blade root flap moment is normalized so that the maximum mean load in the baseline case is 1 (unity).

Since the important result from this work is relative comparisons between the baseline case and another configuration, this normalization gives sufficient information.

2.4. Analysis

To reduce the influence from the stochastic behavior of the atmospheric wind it is needed to increase the correlation between the different analyzed sensors. This is done by using one blade as an anemometer (the reference/clean blade). Even though the nacelle anemometer is close to the blades it was chosen not to use this mainly because the blade root flap moment integrates the loading over the rotor disk which corresponds to a mean flow speed through the rotor disk.

3. Results

In the following, the results from three different configurations of the Vestas V52 wind turbine are presented. The measurement campaign started out November 2015 and, due to delays, it was not completely finalized by the end of August 2016. Therefore, the measurements with the ‘LER’ case were not completed. Furthermore, predictions of the performance of the wind turbine are shown.

3.1. The baseline case

One of the critical issues in the measurements was how well the measurements between the blades were correlated. In Figure 1 the blade root flap moments of the configured blades *B* and *C* are plotted against blade root moments of the reference blade *A* for configuration 1 (reference/clean). It is seen that the coefficients of determination, R^2 of the regression lines, are very close to 1 (unity). Analysing all moments, the values are between 0.9973 and 0.9981, i.e. between 1.9‰ and 2.7‰. This indicates that the blades experience almost identical loading and that even rather small changes of a few percent can be detected. It also indicates that variations between the different configurations below approx. 2 ‰ cannot be detected.

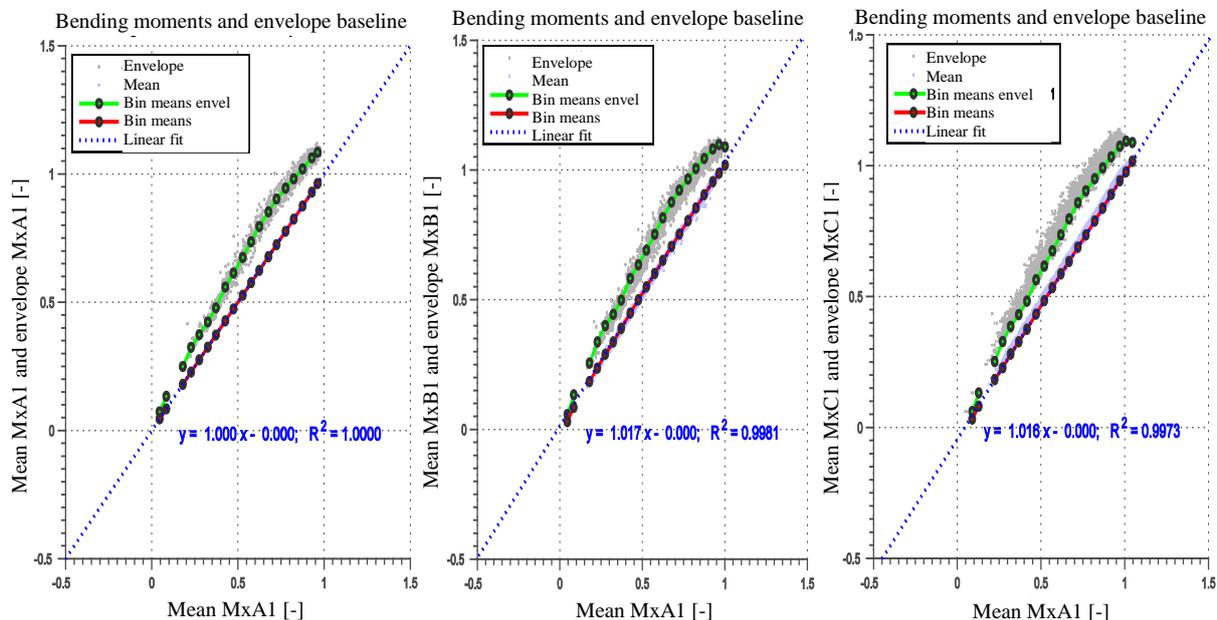


Figure 1 Blade root flap moments of blade *A*, *B* and *C* plotted against blade root moments of blade *A*. Left: M_{xA1} versus M_{xA1} . Mid: M_{xB1} versus M_{xA1} , Right: M_{xC1} versus M_{xA1}

Figure 2 shows the same values that are binned, but on the same plot. What can be observed is that the measured loading from each blade is not exactly the same. Thus, the slope of Blade *B* as a function of blade *A* is 1.017 and for blade *C* it is 1.016. Considering the fluctuations in load due to turbulence, the standard deviation is investigated. Therefore, values where the standard deviations (std) are added

are shown. The maximum values of blades B and C compared to blade A in this case relate to each other as $MxB1_max/MxA1_max= 1.002$ and $MxC1_max/MxA1_max= 1.014$. Since these ratios are close to the ratios for the mean values this indicates that the increase in standard deviations are proportional to the increase in mean loading.

Analyzing the edgewise moments the coefficients of determination, R^2 of the regression lines are between 0.9918 and 0.9979 showing a high correlation between the loading on the different blades. These are however not shown here.

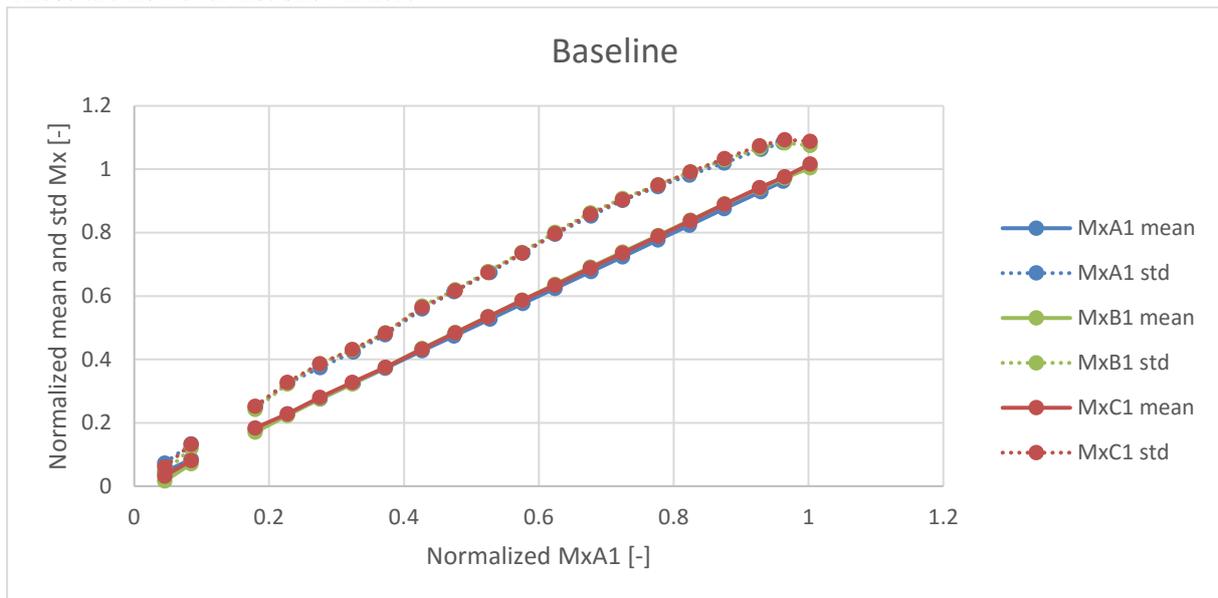


Figure 2 Mean blade root flap moments of blade A, B and C plotted and standard deviations added to the mean values against blade root flap moments of blade A, $MxA1$, $MxB1$ and $MxC1$ versus $MxA1$.

3.2. The VG case

With VGs mounted on a completely clean blade the loads were measured, see Figure 3.

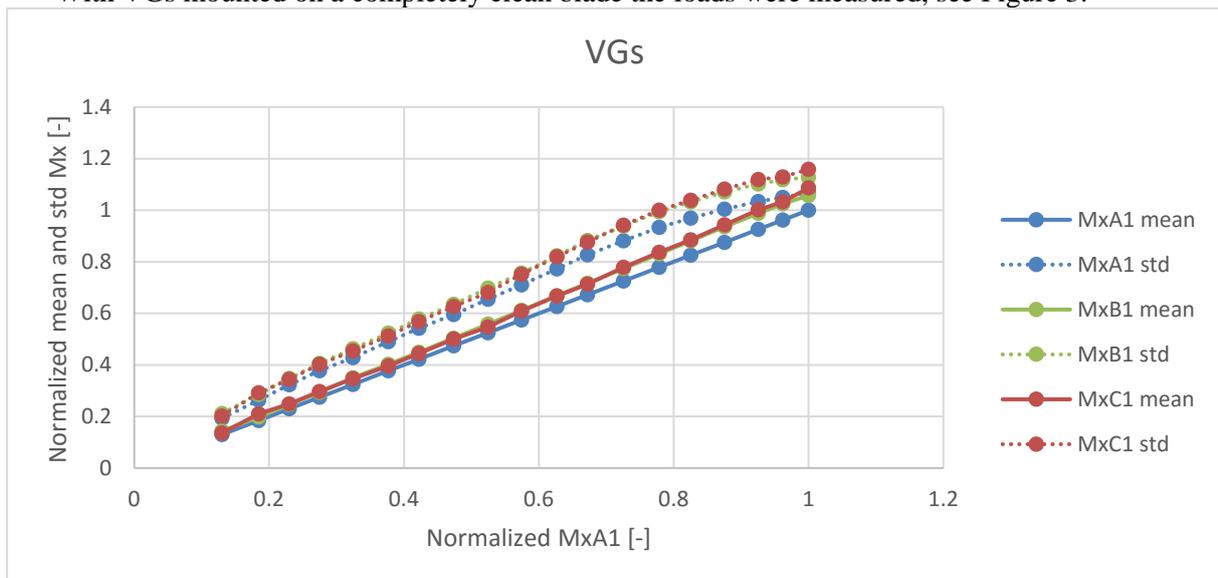


Figure 3 Mean blade root flap moments of blade A, B and C plotted and standard deviations added to the mean values against blade root flap moments of blade A, $MxA1$, $MxB1$ and $MxC1$ versus $MxA1$.

This case is carried out to investigate the worst case in terms of loading since the blades are new and clean and have not experienced a degradation in performance yet. The coefficients of determination, R^2 of the regression lines are between 0.9887 and 0.9988, which show high correlation between the blade root flap loading of blade B and C compared to blade A. It is seen that the blades experience a maximum load increase between 5.5% and 7.2% when comparing the binned mean values to the reference blade, and an increase between 5.5% and 7.2%, when comparing the standard deviations added to the binned maximum mean values. Note that the test VG layout is deliberately made more aggressive to validate the design tool predictions and thus not comparable to a common VG retrofit design for an existing turbine.

Thus, it seems that the loads including standard deviation scale the same way as the mean values. This increase corresponds well to the increase in slope of the curves, where the slope of the mean blade root flap moment increases between 4.9% and 6.9% for blade B and C respectively, compared to blade A. Analyzing the edgewise moment the coefficients of determination, R^2 of the regression lines are between 0.9725 and 0.9812 showing a less good correlation between the loading on the different blades compared to the baseline case. The reason for this can be the necessity to determine the pitch setting approximately within 0.1 degree.

3.3. The VG and LER case

With VGs mounted on a blade with leading edge roughness (simulated by zigzag tape) the loads were measured again. This case is carried out to investigate a realistic change in performance due to leading edge roughness and VGs. Plotting the 10 min mean values for $MxB1$ and $MxC1$ against $MxA1$ it is seen that the coefficients of determination, R^2 of the regression lines are between 0.9907 and 0.9973, which show high correlation between the blade root flap loading of blade B and C compared to blade A. They are shown in Figure 4. It is seen that the blades experience a load increase of between 0.0% and 0.7% when comparing the binned mean values, and an increase of between 1.5% and 1.6%, when comparing the standard deviations added to the binned mean values. Thus, also in this case it seems that the loads including standard deviation scale almost the same way as the mean values. The slope of the curves for the mean values are 0.999 and 0.983 for blade B and C respectively. Analyzing the edgewise moment the coefficients of determination, R^2 of the regression lines are between 0.9828 and 0.9855 showing a less good correlation between the loading on the different blades compared to the baseline case, but slightly better than the VG case.

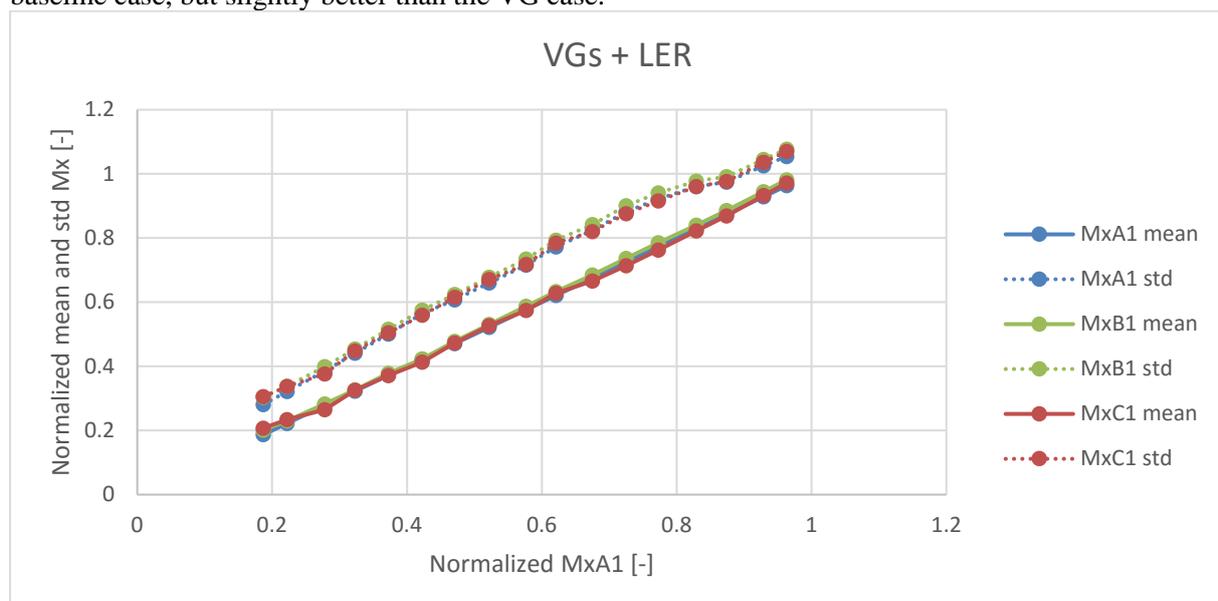


Figure 4 Mean blade root flap moments of blade A, B and C plotted and standard deviations added to the mean values against blade root flap moments of blade A, $MxA1$, $MxB1$ and $MxC1$ versus $MxA1$.

3.4. Predictions

Based on the prediction method described in section 2.1 and supported by wind tunnel measurements where airfoils were tested with and without VGs, the aerodynamic performance for the different configurations were computed. In Figure 5 the predicted blade root flap moments for blade B and C are plotted against the blade root flap moment for blade A.

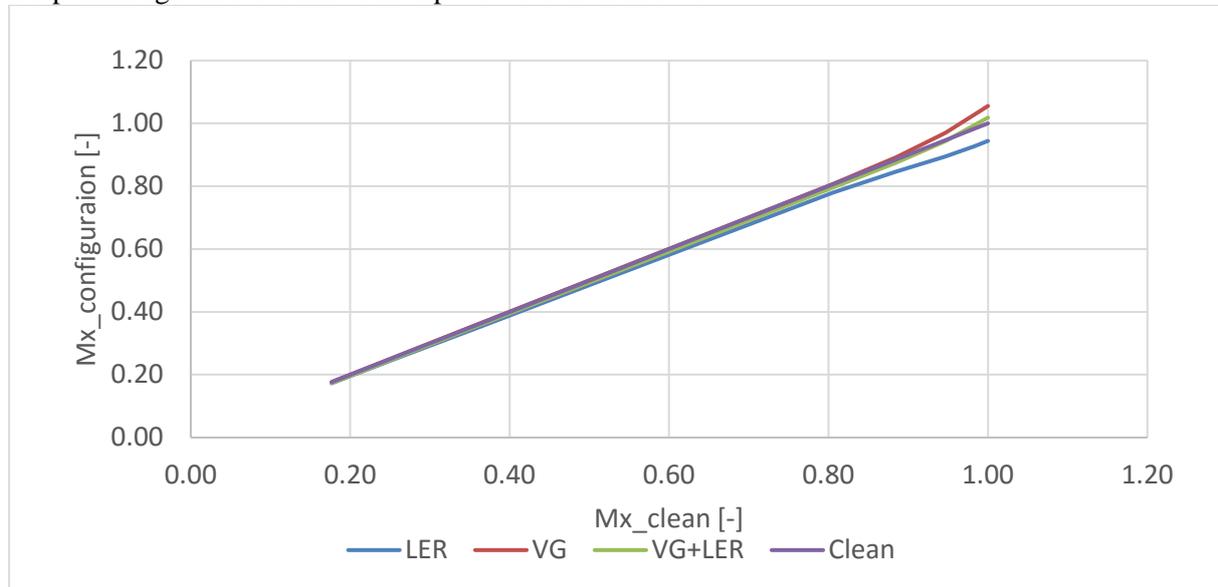


Figure 5 Predicted blade root flap moment for different configurations as a function of the blade root flap moment in the baseline case.

There is an increase in slope of 4.8% when VGs are mounted and an increase of 1.2% when both VGs and LER are mounted. It is also seen that the slope decreases with 6.2% if only the given amount of LER exists on the turbine. Figure 6 shows power as a function of blade root flap moment for blade A.

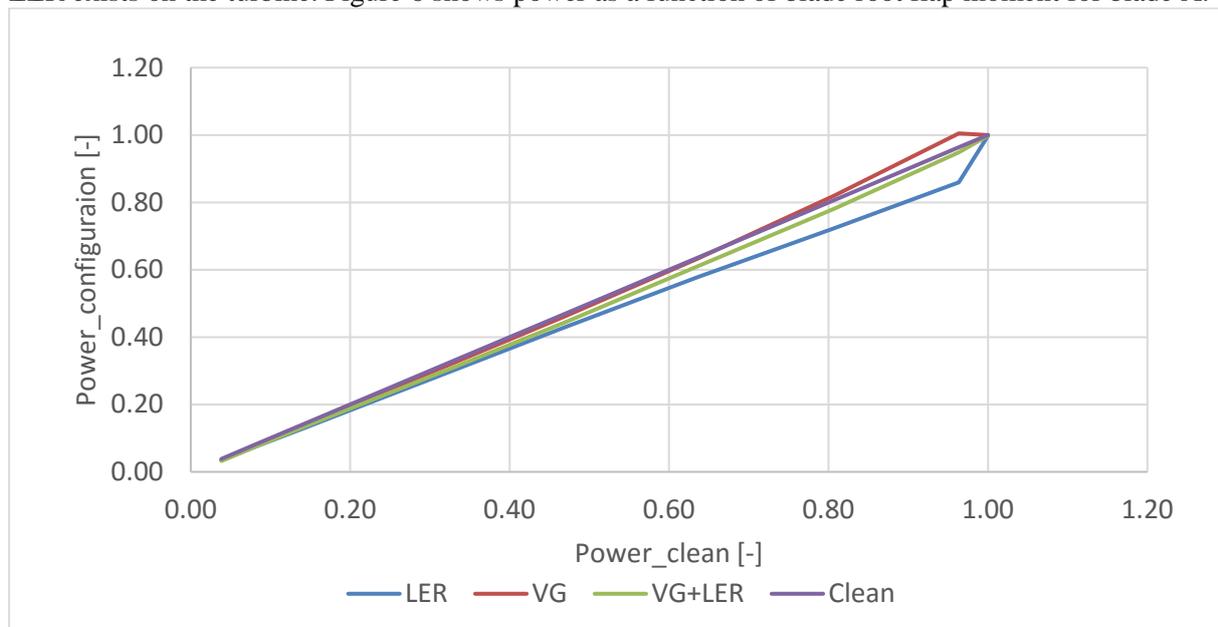


Figure 6 Power for different configurations as a function of the root flap moment of the baseline case.

It is clear that the mounting of VGs increases the power output compared to the baseline at least when approaching rated power whereas blades with only LER experience a decrease in power. Thus, adding VGs to an otherwise clean blade will increase AEP with 0.3%. A rotor with aforementioned LER will experience a reduction in AEP of 7.5%, but if VGs are added this reduction will only be 3.6%. This means that AEP will be increased with 3.9% compared to starting point with LER.

3.5. Comparisons

The predicted values are compared to the measured values in Table 2. It seen that both the predicted mean maximum loads and the slope of the curves in general are in very good agreement with the measurements. Uncertainties in the aerodynamic input and assumed control of the wind turbine rotor (rotational speed and pitch scheme) may be the cause of the differences that are observed. However, the differences are small and it is shown that the predictions follow the measured trends. Even though measurements for the ‘LER’ case were not available the predictions are shown in the table.

Table 2 Comparisons of 1) the slopes of the curves for the blade root flap moments as a function of the blade root flap moments for the baseline and 2) the maximum mean values for the different configurations.

| Configuration | Slope | | | Max mean value | | |
|---------------|------------------|------------------|-----------|------------------|------------------|-----------|
| | Measured Blade B | Measured Blade C | Predicted | Measured Blade B | Measured Blade C | Predicted |
| Baseline | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| VG | 1.049 | 1.069 | 1.048 | 1.055 | 1.072 | 1.056 |
| VG+LER | 0.999 | 0.983 | 1.012 | 1.007 | 1.000 | 1.018 |
| LER | - | - | 0.938 | - | - | 0.944 |

3.6. Sensitivity study

When retrofitting VGs on existing wind turbines the control is not necessarily known. The maximum rotational speed is often known, but the pitch is often not known. In Table 3 the results from a sensitivity study is shown, where P_0 is the pitch setting corresponding to the test and $P_{0\pm 2^\circ}$ are pitch settings that are 2° off the reference setting. It is seen that the loads and AEP are changing only slightly depending on pitch. Especially in the case of ‘VGs and LER’, which is the main configuration to consider when retrofitting VGs the changes are small.

Since mean edgewise moments are much smaller than the mean flapwise moments and since there is an uncertainty in the pitch setting, the uncertainty in the numbers from the measurements are higher for this sensor. However, an analysis of the edgewise moment indicates that the relative changes in the edgewise moments are in the same range as the flapwise moments, which is in agreement with the predictions.

Table 3 Predicted sensitivity of the pitch setting on blade root moment, flap and edge, and AEP. P_0 is the reference pitch setting and the performance with pitch settings $\pm 2^\circ$ from this is shown.

| Sensor | Baseline | | | VGs | | | VGs and LER | | | LER | | |
|-------------------|-----------|-------|-----------|-----------|-------|-----------|-------------|-------|-----------|-----------|-------|-----------|
| | P_{0+2} | P_0 | P_{0-2} | P_{0+2} | P_0 | P_{0-2} | P_{0+2} | P_0 | P_{0-2} | P_{0+2} | P_0 | P_{0-2} |
| Root moment, flap | 1.000 | 1.000 | 1.000 | 1.021 | 1.048 | 1.086 | 0.995 | 1.012 | 1.036 | 0.946 | 0.938 | 0.931 |
| Root moment, edge | 1.000 | 1.000 | 1.000 | 1.030 | 1.057 | 1.095 | 0.984 | 0.999 | 0.982 | 0.903 | 0.893 | 0.875 |
| AEP | 1.000 | 1.000 | 1.000 | 0.992 | 0.997 | 1.006 | 0.958 | 0.964 | 0.970 | 0.930 | 0.925 | 0.914 |

4. Discussion

In this section the questions posed in the introduction will be discussed. We would like to answer what the relation is between power increase and load increase when VGs are mounted both in the case of clean blades and blades with leading edge roughness (LER). Analyzing the power has shown to be challenging with the needed precision. One of the reasons to this is that the coefficients of determination, R^2 of the regression lines are somewhat lower for the edgewise moments when VGs are

added to the blades. The reason for this is e.g. uncertainty of the pitch setting that needs to be determined with a precision below 0.1 degree to avoid too much influence from the flapmoment.

Using the present setup, where one blade is used as a reference and the two other blades are instrumented, it has shown to be possible to measure the differences in flapwise loads between the different configurations with high precision. Thus, it is possible to detect a few percent change in load using this method. In worst case with VGs mounted on a clean blade the blade root flap moment will increase with between 5.5% and 7.2%. Keep in mind that the VG layout in this test was deliberately made aggressive to validate the design tool and thus the herein results (in terms of percentage change) are not transferable to a VG retrofit designs made for an existing turbine.

Adding leading edge roughness in terms of 0.4mm thick zigzag tape reduced the load increase to between 0.0% and 0.7%. Comparing the predictions to the measurements it seems that the loads are predicted well in the worst case configuration (clean blades with VGs) with 5.6% load increase which is in the measured range between 5.5% and 7.2% increase. In the case of VGs on a blade with leading edge roughness the load predictions are slightly overestimated with an increase of 1.8% instead of the measured range between 0.0% and 0.7% increase. Thus, it seems that within around 1% percent certainty it is possible to predict the loads.

Finally, the possibility of predicting power and loads with rather high precision is important because the actions when retrofitting wind turbines with VGs depends on the size of the changes. According to the Secretariat for Approval of Wind Turbines under the Danish Energy Agency [10] where certification is based on the Danish Norm and IEC61400-22 it is interpreted that if the modifications result in 'a significant increase in the load spectrum' or if 'the rated power increases more than 5%' then a new type certificate is needed. Otherwise a certification for modifications is needed in Denmark. The latter certificate is less demanding because the changes are judged to be within the design load envelope and the uncertainty for load prediction for the existing wind turbine. However, such a certification is not needed in many other countries. Thus, for the given test turbine with leading edge roughness and VGs it is clear that since the load increase is around 1% compared to a new wind turbine, this turbine does not show a significant increase in load spectrum even though the layout of the VG configuration is made aggressive. Since the load increase with VGs in the clean blade case is up to 7.2% higher than for the baseline case, the intended significant test load increase was obtained so that it was detectable. However, this load increase is too high for a retrofit of turbines and therefore a less aggressive VG layout will always be chosen in such a case. The current VG layout showed however, that the tool was able with rather good precision to predict the increase in loading.

5. Conclusion

Full scale measurements on a Vestas V52 was carried out with different configurations of blades with and without vortex generators and leading edge roughness. Using these measurements the questions posed in the introduction could be answered.

1) The relation between power increase and load increase was challenging to obtain because there e.g. is a need for a very precise determination of the pitch setting. However, the analysis indicated that the edgewise blade root moment followed the trend of the flapwise blade root moment, which is in agreement with the predictions.

2) A few percent changes in load due to the different blade configurations are often very challenging to detect if all blades are configured in the same way. However, using one blade as a reference as done in this test a few percent changes showed to be detectable in a full scale wind turbine test. Differences in the power is however more challenging to detect.

3) The loads predicted with the tool developed were in good agreement with the measurements. Comparing the test measurements to predictions it is seen that the loads are predicted well within a 1% accuracy. Even in a sensitivity study where the pitch in the computations was varied the loads were in rather good agreement. The changes in power is more challenging to measure, but the analysis showed that the edgewise blade moments followed the trend of the flapwise blade root moments, which is in

agreement to the predictions. Since the power is a consequence of the edgewise blade root moments, this indicates that the predicted power are in agreement with the measurements.

4) Even with the aggressive VG layout used in this experiment, the load increase was up to 7.2% in worst case with a clean blade with vortex generators, but only 0.7% on a blade with leading edge roughness and vortex generators. Therefore, with a slightly less aggressive VG layout it seems that retrofitting a turbine with vortex generators in Denmark does not require a new type certificate, but only the much less demanding certification for modification. In most countries such a certificate is however not needed.

6. Acknowledgements

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