LIDAR Correlation to Extreme Flapwise Moment : Gust Impact Prediction Time and Feedforward Control

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DTU Wind Energy E-0156

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The gust detection on the Nørrekær Enge measurement campaign is discussed where the synnchronizaiton and set-up is analysed. A linear model which predicts the gust impact time, based on LIDAR measurement, is applied. The results are then discussed and the main findings of the campaign are summarized.

The second part of the report explores the possibility of the inclusion of LIDARs system in wind turbine controll in extreme load alleviation. A HAWC2 model, based on the Siemens Wind Turbine present on the side, is simulated using a constrainted turbulent box and the new LIDAR module. The results present promising results were load alleviation up to 18% is foundin the flapwise bending root moment peak.

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Figures and tables

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Chapter 1

1 Introduction

A Conventional wind turbine controller uses feedback parameters reacting to wind disturbances after they have already impacted the rotor. LIDARs are able to measure the wind speed before it reaches the wind turbine rotor. These anticipated values can be used in control systems designed to reduce turbine loads.

This report is focused on gust prediction events, based on nacelle mounted LIDAR measurements, which lead to large blade flapwise moments. The prediction could be used as a mitigation system decreasing the loading and extending the turbine lifetime. The data obtained from the UniTTe project (www.unitte.dk) is used in this task.

The measurements come from three different acquisition systems: a met mast, an Avent 5 beam LIDAR and a series of sensors installed on a SWT-2.3MW-93. The turbine is owned by Vattenfall and is placed in Nørrekær Enge. The impact of wind gusts on the blade root bending moment will be studied.

In this report, first the measurement data is synchronized and second a sub-set of cases are chosen based on the wind turbine status, mean wind direction and cause of the blade root bending moment peak. Then, the LIDAR measurements are compared to the met mast and wind turbine loads. Finally, a discussion of the prediction accuracy of the current LDIAR set-up and some aeroelastic simulations are performed.

1.1 Location

The Nørrekær Enge wind farm is located in Northern Jutland approximately 7 km NE from the city Løgstør and approximately 35 km W from Aalborg. The farm consists of 13 turbines and the distance between the turbines is 487 meters, around 5 rotor diameters. The instrumented turbine is number four from the West and named NKE04.

A meteorological mast is placed 2.5 rotor diameters (235 m) in the south-westerly direction (103° in reference to north) from the wind turbine. The mast is equipped for measuring wind direction, air temperature, barometric pressure, humidity and wind speed at different levels including hub height. Wind speed is measured by cup anemometers.

Figure 1: Turbine NKE04 Relative position to Met Mast and NKE05

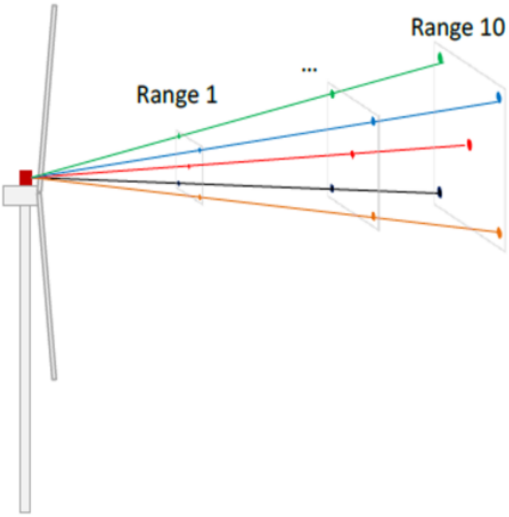
1.2 Acquisition System

The acquisition system needs specific treatment for synchronization since each measurement consist of its own clock. The LIDAR and the turbine timestamps are based on the Risø DAQwin system which timestamps the statistics at the beginning of the 10 minute period while the met mast datalogger timestamps at the end of the 10 minute period.

The LIDAR's clock is synchronized at least every 1024 seconds but not more frequently than every 64 seconds to a time server through the measurement computer handling the DAQwin. The loads measurements are synchronized every 15 minutes to the DAQwin system. The load acquisition system needs to do computations before starting to record the data which causes a few second delay. The complete measurement system and calibration can be found in the deliverable of UniTTe project (Andrea Vignaroli, 2016)

The LIDAR system used in this project is the 5-beam Demonstrator LIDAR , from Avent. The LIDAR has been programmed to measure at difference distances in front of the rotor, ranging from 0.5 to 3 rotor diameters. The Avent 5 beam integrates the readings over a long and thin volume, 24.7 meters from each side of the focus point (A. Borraccino, 2016).

The range number, range set and corresponding rotor diameter distance are summarized in Figure 2.



Range Number	Range to set	
	m	-
1	49	0.5 D
2	72	0.75 D
3	95	1.0 D
4	109	1.15 D
5	121	1.28 D
6	142	1.5 D
7	165	1.75 D
8	188	2 D
9	235	2.5 D
10	281	3.0 D

Figure 2: Avent 5 Beam Lidar Range Distance

At each second, the A.S. captures the value for only one LIDAR beam. Thus, the data from each beam is saved at a **5 Hz** sample frequency. The Radial Wind Speed (RWS) and LIDAR distance are used during the analysis. The real-time quality control flag is taken into account to discard the wrong measurements. The NKE04 wind turbine is extensively monitored but this analysis only focuses on the blade pitch angle, flap moment and anemometer output. The sensor calibration is done by DTU and can be found in the UniTTe project deliverable (Andrea Vignaroli, 2016)

The flap moment sensor is installed on both Blade A and C and placed 1.5 meters from the blade root flange. The hub radius is reported to be 1.31 meters, thus, the radius location of the sensor is 2.81 m. Blade pitch angle is saved as an output from the wind turbine controller in all blades. Finally, an anemometer is placed on the wind turbine nacelle. The sample frequency of the previously mentioned channels is 35Hz.

Table 1: Summary of Important Measurement Channels

Channel	Frequency	Acquisition System
RWS LIDAR	1 Hz x Beam	LIDAR
Met mast	10 Hz	Met mast
Nacelle Wind	35 Hz	Load
Blade Root	35 Hz	Load
Pitch Angle	35 Hz	Load

The met mast channel corresponds to the reconstructed wind speed at 76 meters. The RWS is the radial wind speed data measured by the LIDAR at the different ranges mentioned in Figure 2. The nacelle wind speed is measured by an anemometer placed on the wind turbine nacelle. The blade root bending moment is captured by the strain gages and the pitch angle is saved from the controller output.

Chapter 2

2 Case Selection

2.1 Filtering based on 10-min statics

The measurement campaign on the NKE04 turbine was carried out between June 2015 and April 2016, recording 33,282 ten-minute time series. First, the data is filtered according to data availability (all acquisition systems must have data). Then, it is decided to filter the data based on the mean wind direction coming from the met mast, 95.9 to 105.9 degrees. This condition is crucial for synchronization since the LIDAR (at range 235 meters) is measuring at the same point as the met mast.

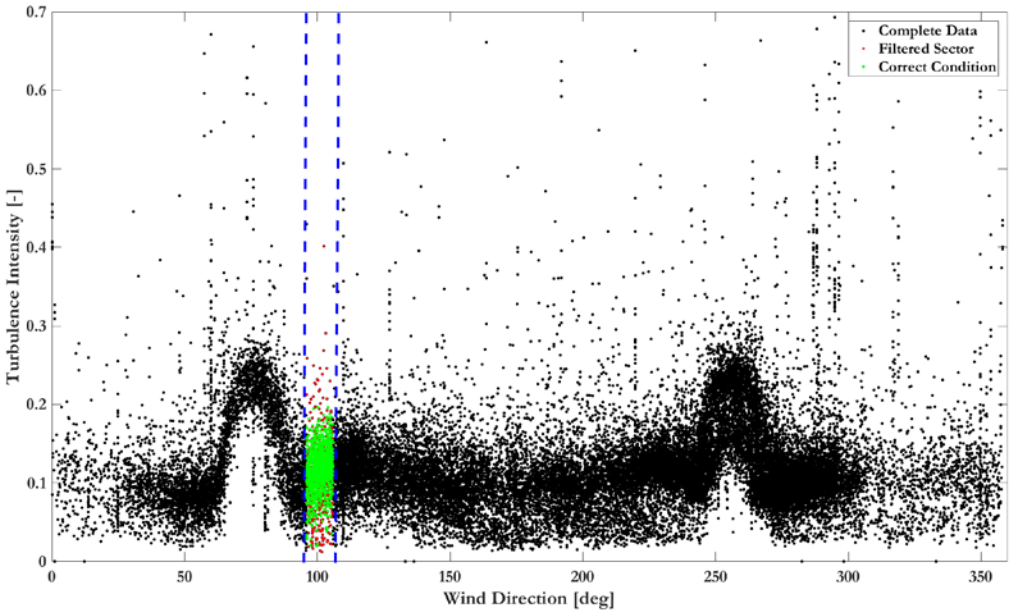


Figure 3: Overview of Complete Data Set, Turbulence Intensity vs Wind Direction

Figure 3 present the 10-minute mean turbulence intensity for the complete data available. It is possible to observe the two turbulence sector where the wind is influenced by the nearby wind turbine's wake. The highlighted red sector corresponds to the range where the wind direction is coming from the direction of the met mast, a total of **1474** cases. The green dots corresponds to the selected cases after the normal operation filtering.

There can be several reasons for a large bending moment at the blade root. In this case study, the focus is set on the wind speed gust, thus, two conditions are defined to ensure that the gust is the origin of the peak: the wind turbine is operating normally and it has a low pitch angle before the event. In order to ensure normal operation the turbine must fulfil the conditions presented in Table 2.

Table 2: Normal Operation Conditions Used for Data Filtering

Normal Operation Wind Turbine		
Max. Pitch	<	25 deg
Min. & Max. Wind Turbine Flag	=	1
Min. & Max Grid Flag	=	1
Min. H.S.S.	>	546 rpm
Mean Power	>	550 kV

Based on the normal operation filtering, 1052 (green cases in Figure 3) of the 1474 cases are valid. Due to time constraints, the 250 largest bending moment cases are selected.

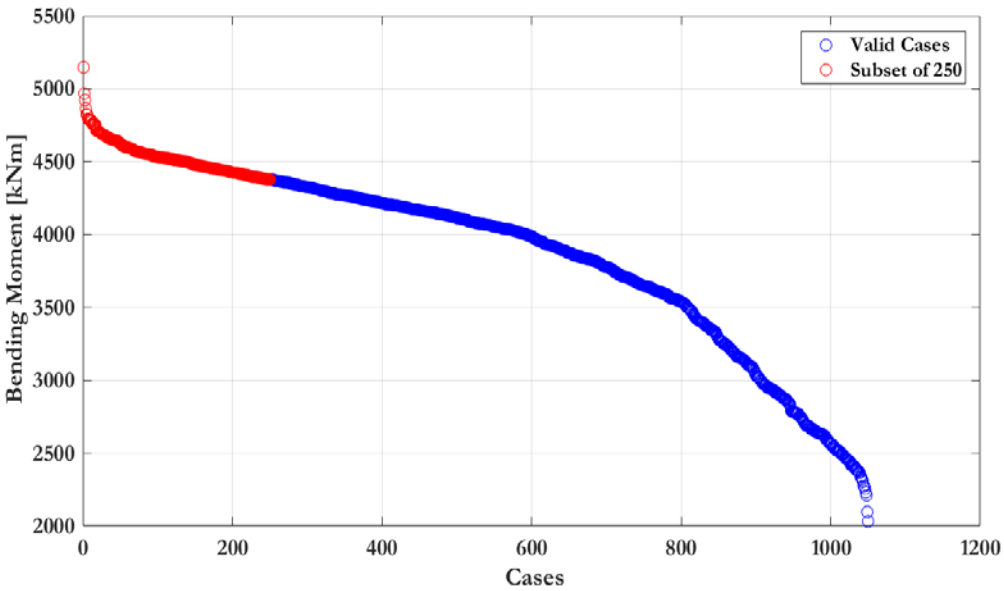


Figure 4: Selection of 250 Largest Bending Moment Based on Valid Cases After filtering

2.2 Filtering based on time-series – Data quality

The time-series of the 250 cases are analyzed to verify the correct functioning of the measurement equipment. First, the radian wind speed flag status on the LIDAR is check to detect malfunctioning cases. The remaining cases are considered considered invalid if the radial wind speed measured by any of the LIDAR ranges or beams is larger than 35 m/s or lower than 0. Based on the previously data filtration it is assumed that the turbine cannot be in operation if wind speeds lower than 0 m/s or higher than 35 m/s are present. On the other hand, negative and extreme positive values (over 40 m/s) indicates the wrong functioning of the equipment.

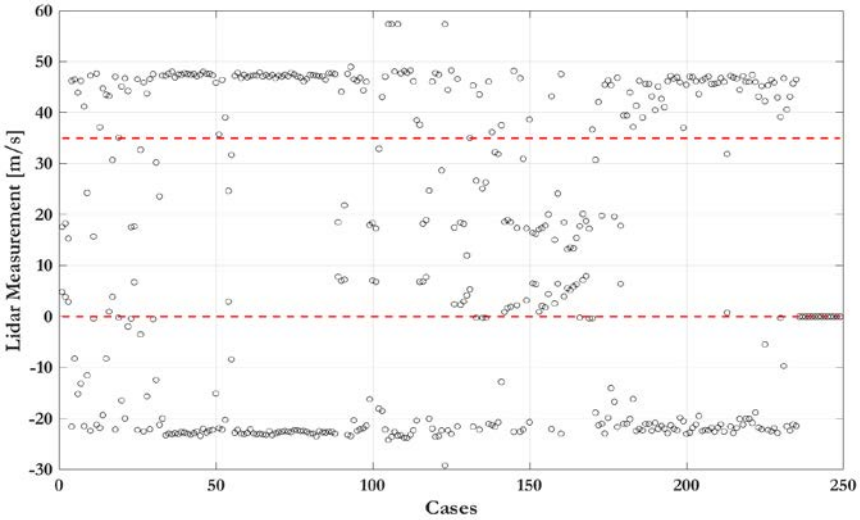


Figure 5 Result Case Selection based on maximum and minimum Lidar Value

The maximum and minimum wind speeds for all beams are plot in Figure 5. It is possible to observe the values which do not fulfil the criteria. Based on that condition, 76 series out of the 250 are valid. Finally, the pitch signal is evaluated to determine its value when maximum flapwise moment occurs. It is considered that the case is not valid if a pitch larger than 3 degrees is found.

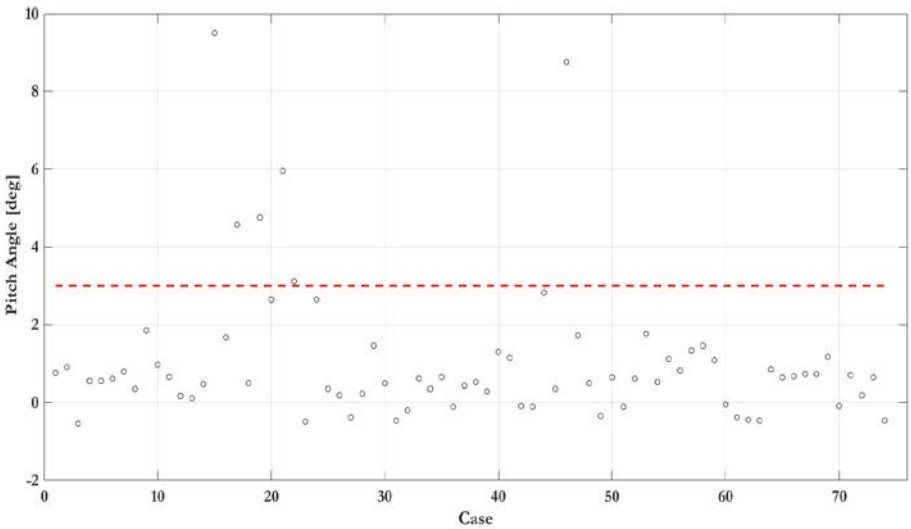


Figure 6 Pitch value when maximum flapwise moment occurs

Six cases present a pitch angle higher than 3 degrees and are discarded

2.3 Signal synchronization

The quality of the analysis is dependent upon data synchronization. The important synchronization is the Load and LIDAR acquisition systems. However, it is also important to synchronize the met mast data since it provides valuable information about the LIDAR performance. The first step is to synchronize the met mast and the LIDAR data, in order to verify the correct LIDAR measurements and data synchronization.

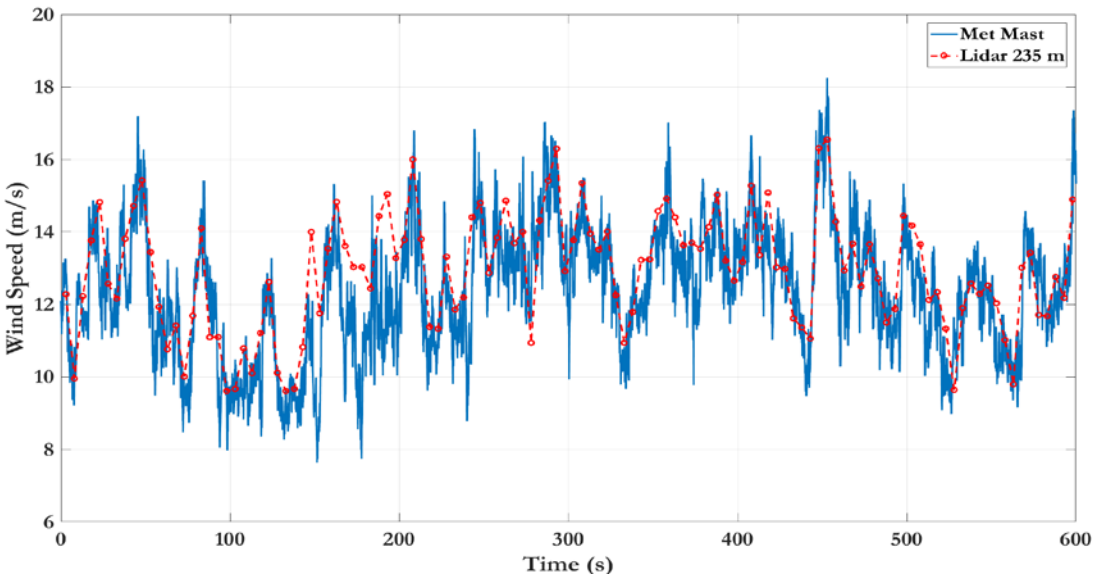


Figure 7: Met mast and LIDAR 235 m comparison

It is possible to observe in Figure 7 the *correlation* between the 5Hz LIDAR and the met mast (10Hz data from iSpin database). The mean wind direction for the 10 minute time series is 99.1 degrees which is close to the direction of the met mast from the wind turbine, 103 degrees. Once the LIDAR and met mast data are synchronized, the next step is to do the same with the load data and LIDAR. The nacelle wind speed measured by an anemometer (load system) is compared to the shortest LIDAR available range, 49 meters.

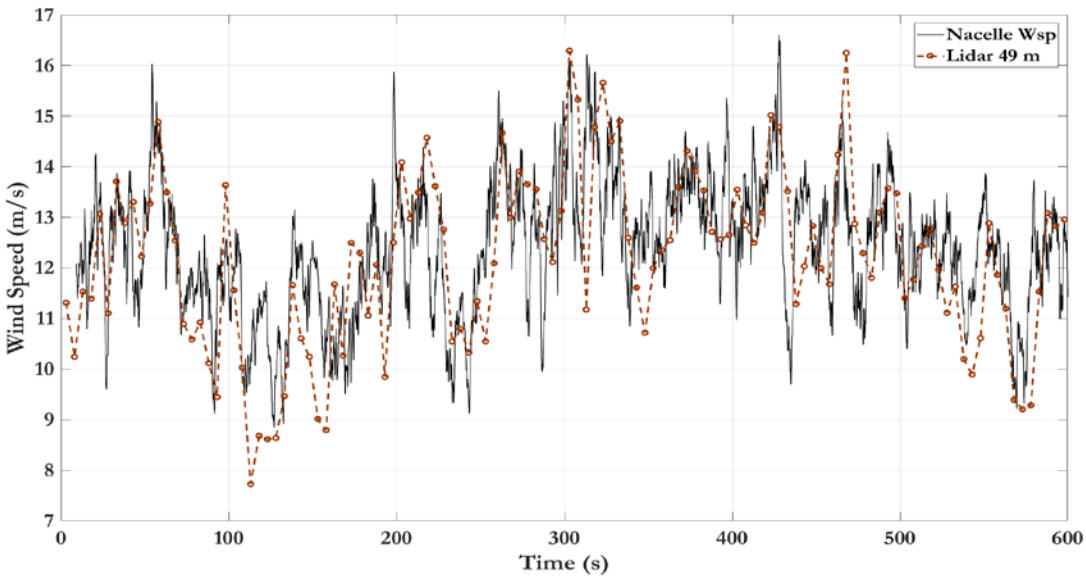


Figure 8: Nacelle Wind Speed and LIDAR 49 m comparison

Figure 8 shows the *synchronization* of both the shortest range LIDAR and the Nacelle anemometer data. The synchronization of these channels implies that the rest of the load outputs can be assumed to be on-time with the LIDAR data since they are based on the same clock.

Chapter 3

3 Model : Gust Impact Prediction

3.1 Purpose and Methodology

The objective is to predict a gust impact on the rotor. The preliminary analysis showed a large flapwise bending moment when a rapid change of wind speed is found and the wind turbine is operating normally at low pitch angle. An example is shown in Figure 9:

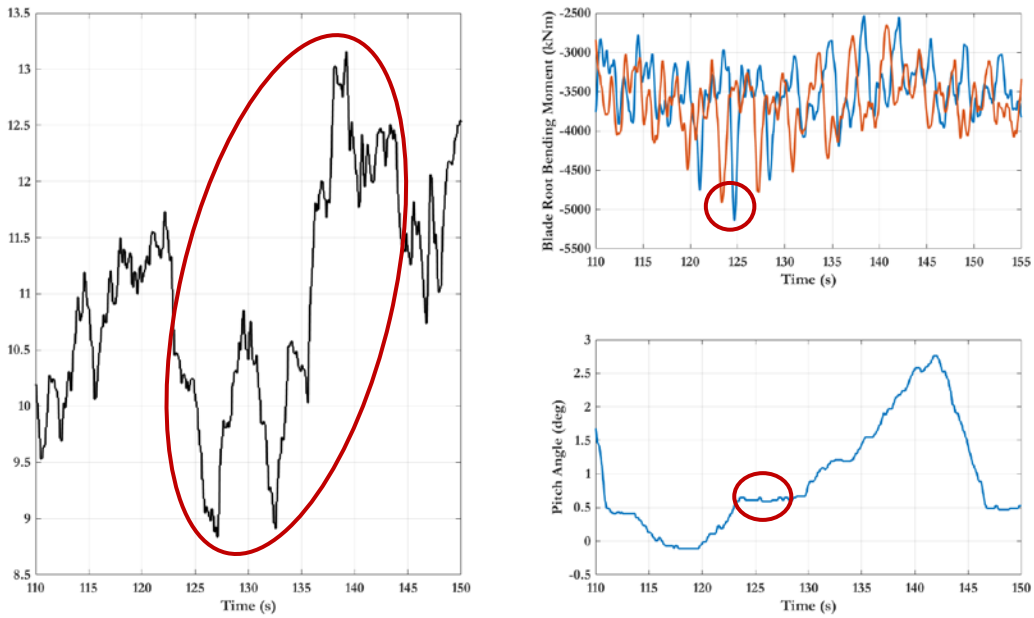


Figure 9: Wind Gust (left), Flapwise Moment for Monitored Blades (top right) and pitch angle (bottom right)

Figure 9 presents an example where the wind turbine is operating at a low pitch angle during a gust. It is clear that the maximum bending moment is caused by the fast-changing wind speed. The LIDAR data is used to calculate the expected time of the gust to impact the wind turbine. The time difference between the LIDAR peak and maximum flapwise moment as a function of LIDAR distance is obtained.

Three LIDAR combinations are proposed to predict the gust impact on the wind turbine:

- Furthest ranges: 281 m, 235 m and 188 m.
- Intermediate ranges: 281 m, 235 m, 165 m, 121 m, 49m.
- All ranges : 281 m, 235 m, 188 m, 165 m, 142 m, 121 m, 109 m, 95 m, 72 m, 49 m

The time difference of each of the LIDAR combinations are fit with the following form:

$$\text{time difference} = \text{a} \cdot (\text{LIDAR range}) + \text{b}$$

where the inverse of a estimates the wind speed and b estimates the delay in the structural response, or a synchronization issue. The gust impact prediction model is applied to the previously presented case.

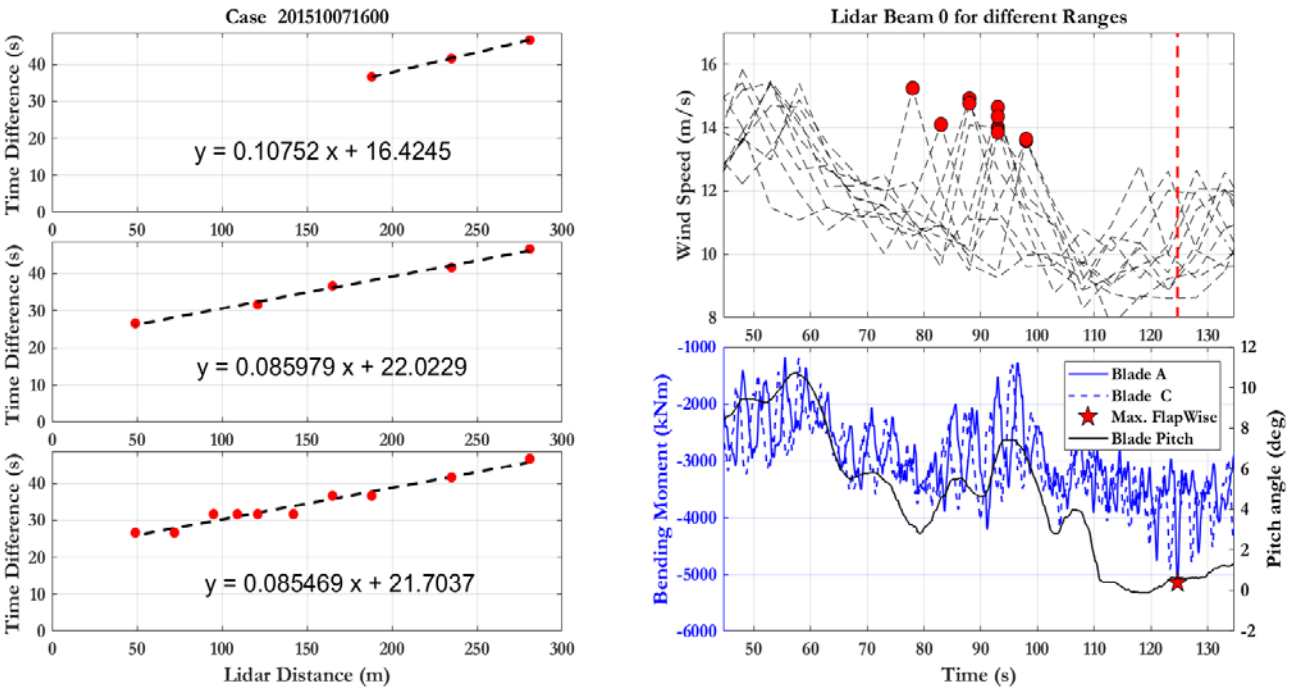


Figure 10: Gust Time Prediction Model, Model Fit for Different LIDAR Ranges (left), Used LIDAR Values to Fit (top right) and Blade Root Moment and Pitch Angle (Bottom right)

Figure 10 summarizes the three LIDAR combinations and linear regression used for gust prediction (left), the peak detected and used for each LIDAR range (top right) the pitch value and the flapwise moment before the peak (bottom right). The presented case shows a large time difference from the actual gust impact (the b constant is larger than 16 in the best fit case).

The same analysis has been carried out for the previously filtered cases concluding:

- The estimated wind speed (a^{-1}) is lower than the ”measured mean in the time-series”
- The constant time delay (b) is larger than expected
- There is no correlation between the delay and mean wind speed

The quality of the model results are subjected to two main factors discussed in this section: LIDAR ability to capture a gust and signal synchronization.

3.1.1 Gust detection

The LIDAR's ability to capture a gust (or rapid wind speed change) is studied comparing the met mast data, which has a high sampling frequency (10 Hz), and the LIDAR measurement (0.2 Hz per beam).

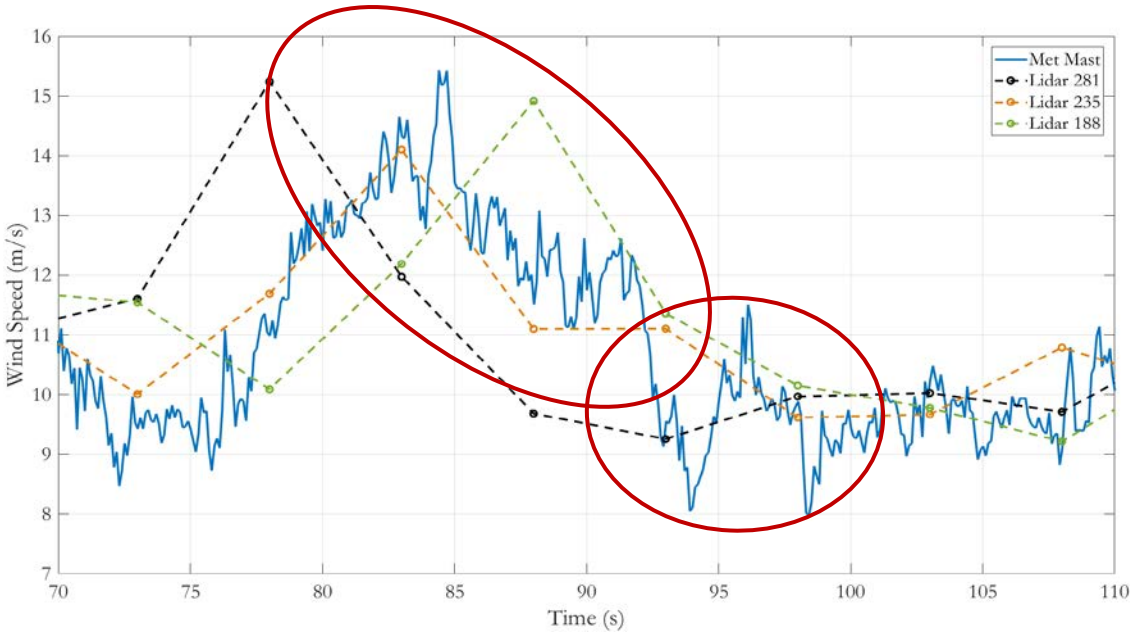


Figure 11: Low and High Frequency Wind Speed Variation, Met Mast vs LIDAR

Figure 11 presents the comparison between the met mast and LIDAR measurements. It is possible to observe that all three LIDAR ranges (281, 235 and 188) capture the slow wind speed variations (left highlighted area). On the other hand, the fast variation (right highlighted area) is not captured by any of the LIDAR's ranges. The large flapwise moment is most likely caused by wind speed variations which are faster than the controller response. The low sampling frequency of a single beam (0.2 Hz) and the beam length used to calculate the wind speed average (49.4m) limits the possibility of capturing fast wind speed variations. Thus, the current set up is not able to capture fast wind speed fluctuations.

3.1.2 Signal Synchronization

The synchronization detail in this project is focused on the 10 minutes statistics where delay within seconds is not considered crucial. However, for the purpose of this analysis, the synchronization must be as accurate as possible. Figure 8 presented the comparison between the LIDAR at 49 meters and the nacelle wind speed. It is expected that the shortest range LIDAR predicts the wind speed variations ahead the nacelle wind speed anemometer but it does not.

In order to characterize a possible issue, the load and met-mast data are studied where the nacelle wind speed and the met mast data channels are used. It is possible to compare both wind speed signals when the wind direction comes from the met-mast to the wind turbine.

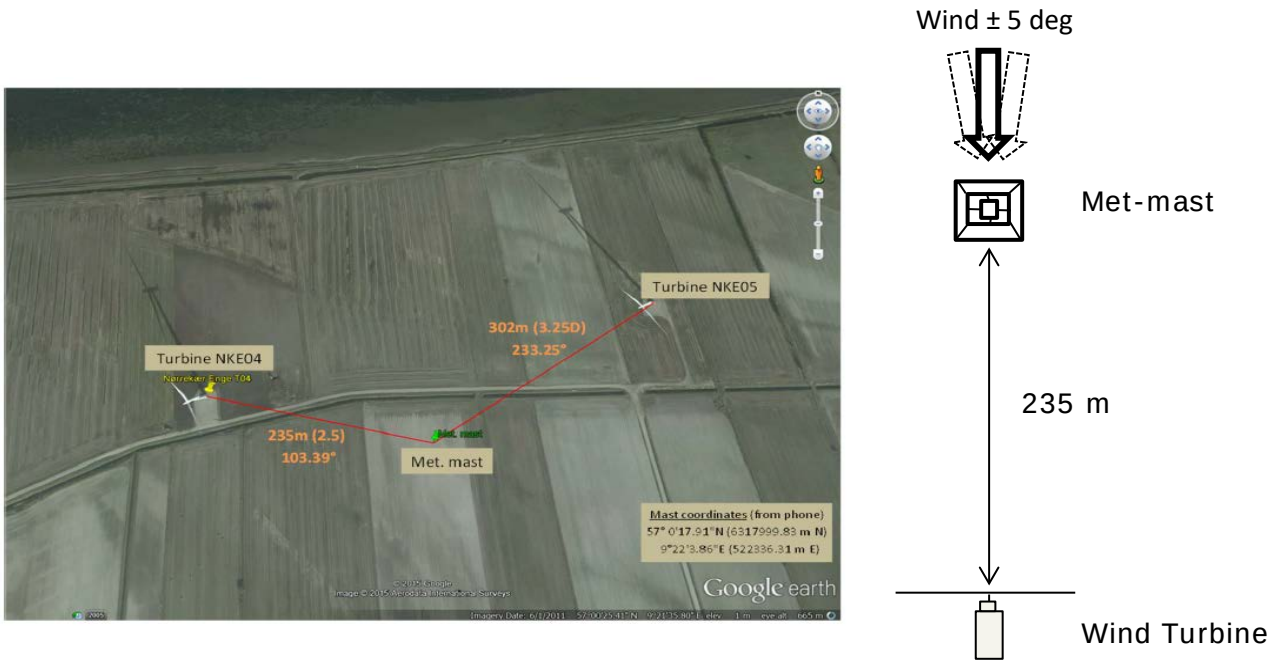


Figure 12: Met Mast vs Wind Turbine Disposition

The met mast data always presents the wind speed variations before the nacelle wind speed since it is 235 meters ahead of the wind turbine as it is possible to observe in Figure 13.

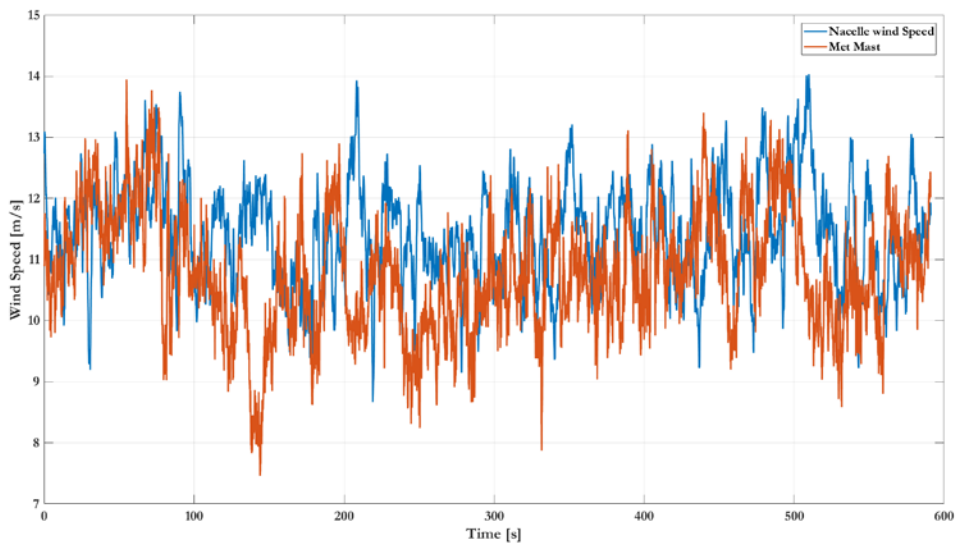


Figure 13: Met mast vs Nacelle Wind Speed Comparison

In order to study a possible synchronization issue, the wind travel time is studied. Among different methods, it is decided to find the optimal time shift to the met-mast data which minimize the error between signals as:

$$Err = \sum_1^N (Met\,mast - Nac.\ wsp)^2 / N$$

when different shifts to the signal are applied, it is possible to compare the quadratic error between signals and find an optimal value which minimizes the error between the studied signals.

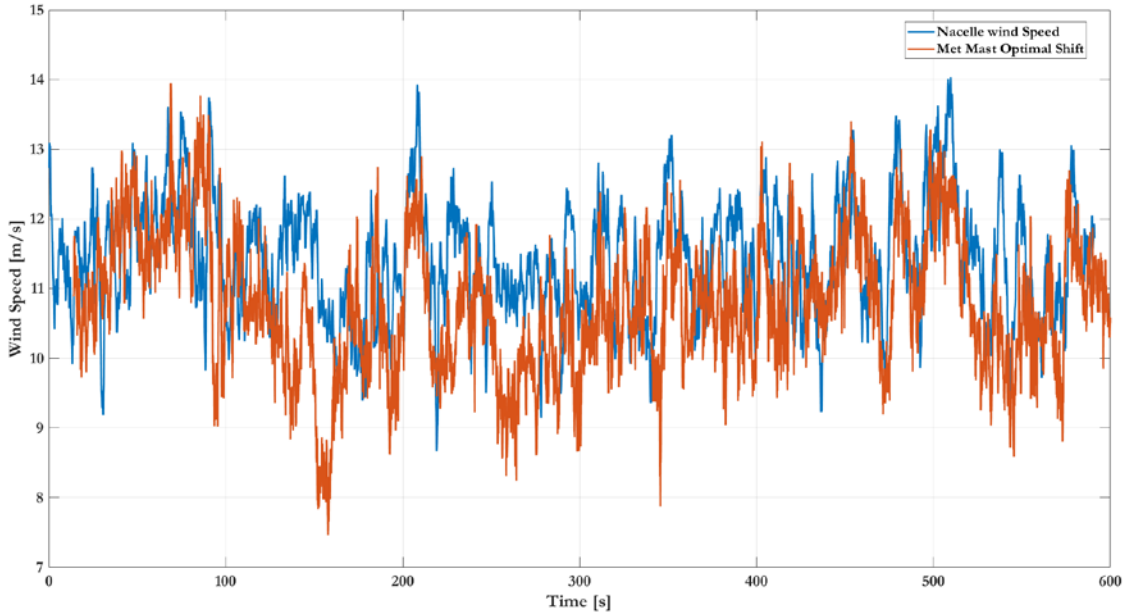


Figure 14: Met mast Time vs Nacelle Wind Speed Comparison

Figure 14 shows the comparison of both signals once the optimal time shift is applied to the met-mast signal. It is possible to compare the good agreement between signals and the implementation of the method. The analysis is carried out for 150 cases where the mean travel distance is calculated as the mean wind speed for the 10 minute time series times its optimal shift. Due to the induction effect, distances larger than 235 meters are expected.

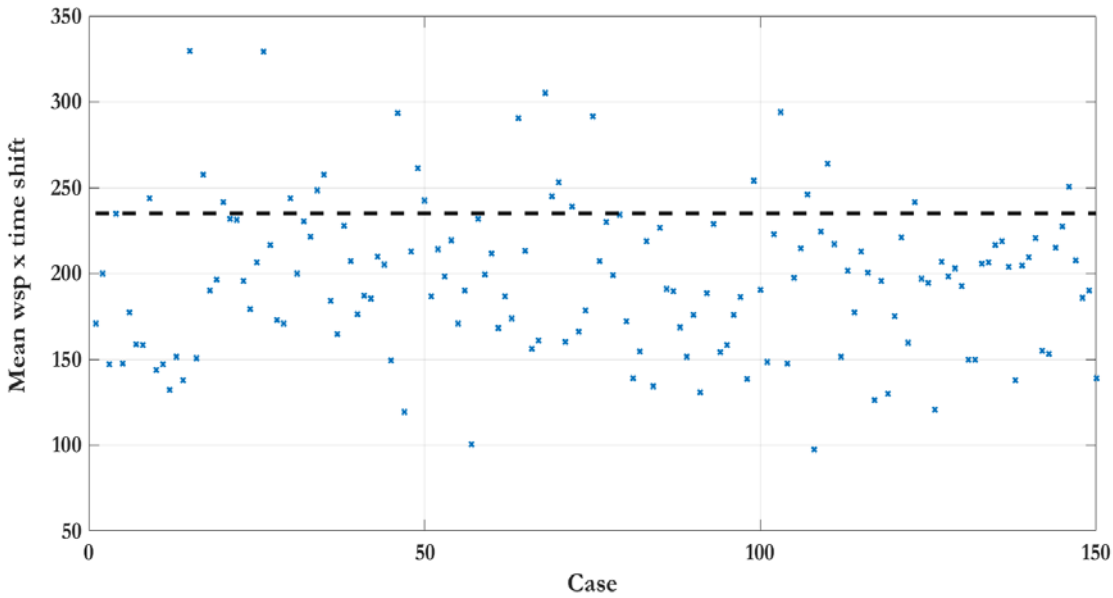


Figure 15: Travel Distance Obtained after Optimal Time Shift vs Reference 235 meters

The results present in Figure 15 show that only 15.3% of the studied cases predict a larger distance than 235 meters. Based on that analysis it is possible to conclude that there is a delay not taken into account in the current synchronization. The cases are sorted as a function of wind speed and in event occurrence in order to identify a possible time-delay or shift correlation.

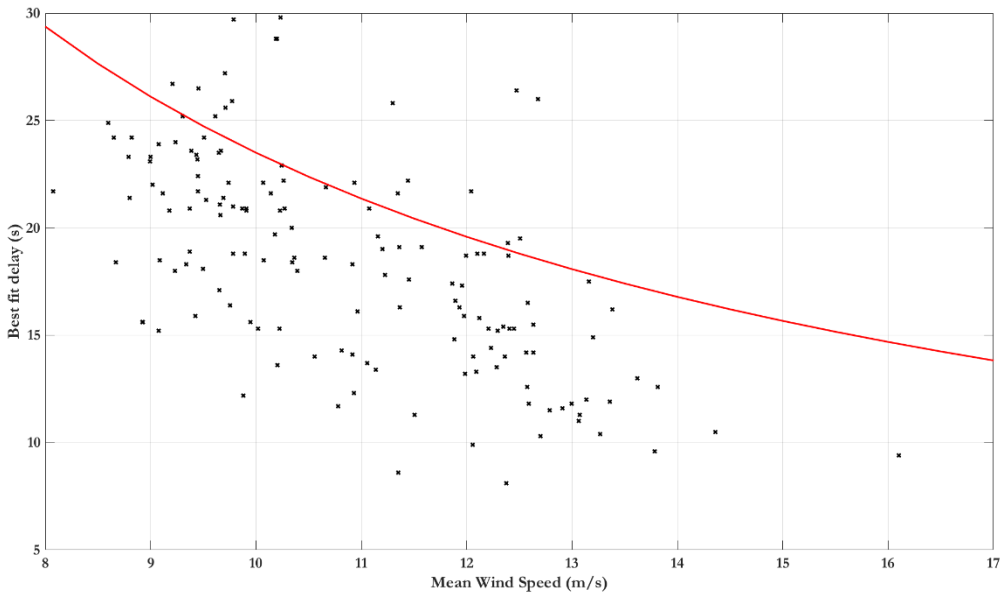


Figure 16: Optimal Time Delay vs Reference Time to Travel 235 m

Figure 16 illustrates the optimal fit delay as a function of wind speed for the studied cases. The red line corresponds to the time shift needed to match 235 meters as a function of wind speed. No correlation between the mean wind speed of the 10 minute time-series and the optimum fit delay is found. The data versus time is analysed to observe if drift exits. In this case, the difference of time to the reference distance (235 meters) is used.

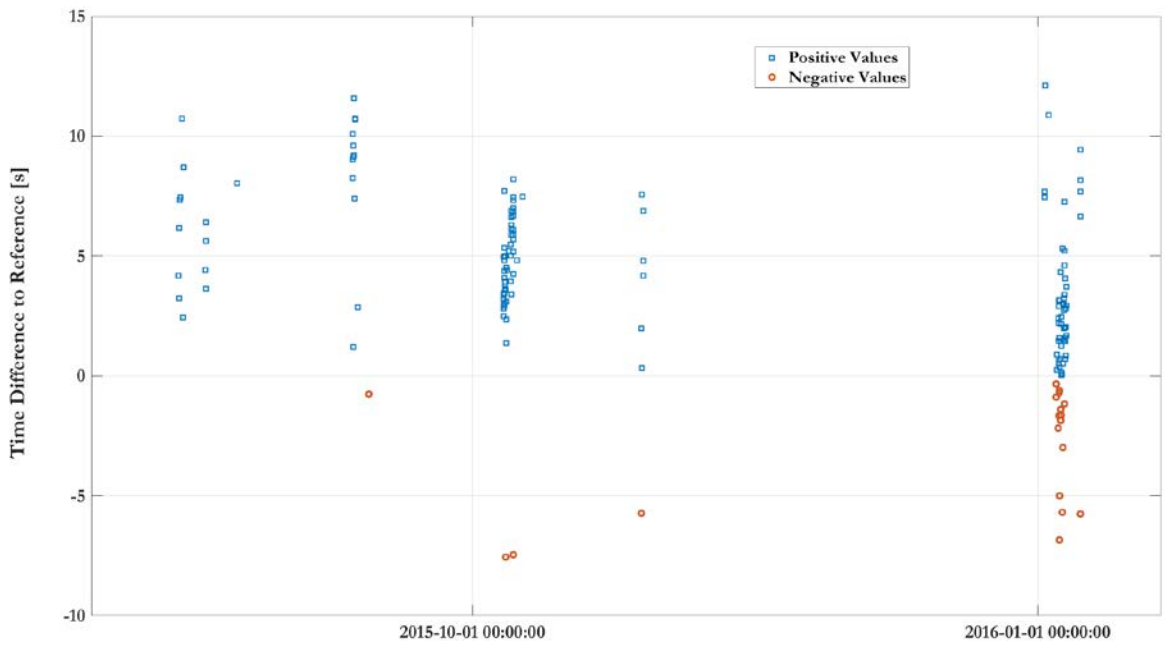


Figure 17: Time Difference to Reference vs Event Occurrence

Six days present the total number of studied cases as it is possible to see in Figure 17. The negative time difference values, red dots, correspond to the simulations which predict a mean distance larger than 235 meters. Conversely, the blue square predict a shorter distance. The results are shown on the exact date in Table 3.

Table 3: Date and Time Difference for Top 15 Positive and Negative Values

Date	Time difference [s]	Date	Time difference [s]
06-Oct-2015 09:40:00	-7,56	11-Sep-2015 16:40:00	12,10
07-Oct-2015 15:20:00	-7,46	02-Jan-2016 18:50:00	11,59
04-Jan-2016 13:40:00	-6,84	11-Sep-2015 23:00:00	10,88
07-Jan-2016 23:00:00	-5,76	14-Aug-2015 16:50:00	10,74
28-Oct-2015 12:40:00	-5,73	11-Sep-2015 23:10:00	10,73
04-Jan-2016 23:30:00	-5,69	11-Sep-2015 13:30:00	10,69
04-Jan-2016 15:00:00	-5,00	11-Sep-2015 15:00:00	10,10
05-Jan-2016 01:30:00	-2,99	07-Jan-2016 22:20:00	9,59
04-Jan-2016 07:50:00	-2,18	11-Sep-2015 16:30:00	9,43
04-Jan-2016 17:20:00	-1,86	11-Sep-2015 14:30:00	9,21
04-Jan-2016 11:10:00	-1,66	11-Sep-2015 12:20:00	9,12
04-Jan-2016 20:00:00	-1,64	15-Aug-2015 00:10:00	9,04
04-Jan-2016 18:00:00	-1,40	11-Sep-2015 13:20:00	8,71
05-Jan-2016 09:10:00	-1,18	07-Oct-2015 14:30:00	8,26
04-Jan-2016 00:40:00	-0,89	07-Jan-2016 23:50:00	8,20

The comparison of data versus time does not show a relation between the time difference and the date. It does not seem to relation between the delay and time or (and) day. The synchronization could be further investigated by adding more LIDAR beams into the analysis and increasing the number of studied cases. However, due to time restrictions it is not further investigated.

Chapter 4

4 LIDAR: feedforward control

A case demonstration is defined in HAWC2 in order to demonstrate the use of LIDARs for feedforward control to alleviate extreme load cases (Mikkelsen, et al.). The idea is to use the spinner LIDAR, output already built-in in HAWC2, as a detection system for rapid wind speed changes. Then, based on different criteria, a flag is sent to the controller which changes its desired operational point to alleviate the loads of the incoming gust.

4.1 Model setup: HAWC2 and LIDAR Control

The HAWC2 model used is based on the SWT-2.3MW-93 placed in Nørrekaer Enge. The wind turbine controller is given by Siemens as a dynamic library. A new module, which uses the built-in output from HAWC2 to estimate the LIDAR value based on the 3D field, is programmed and coupled with the controller to detect a gust.

First, the demonstration of the LIDAR sensor implemented in HAWC2 is done. The LIDAR at 200 meters versus the nacelle wind speed is compared. The HAWC2 sensor is included in the wind turbine model. The example shows the results based on a normal turbulence box. It is possible to observe how the spinner LIDAR output predicts the wind speed variations before it hits the rotor plane.

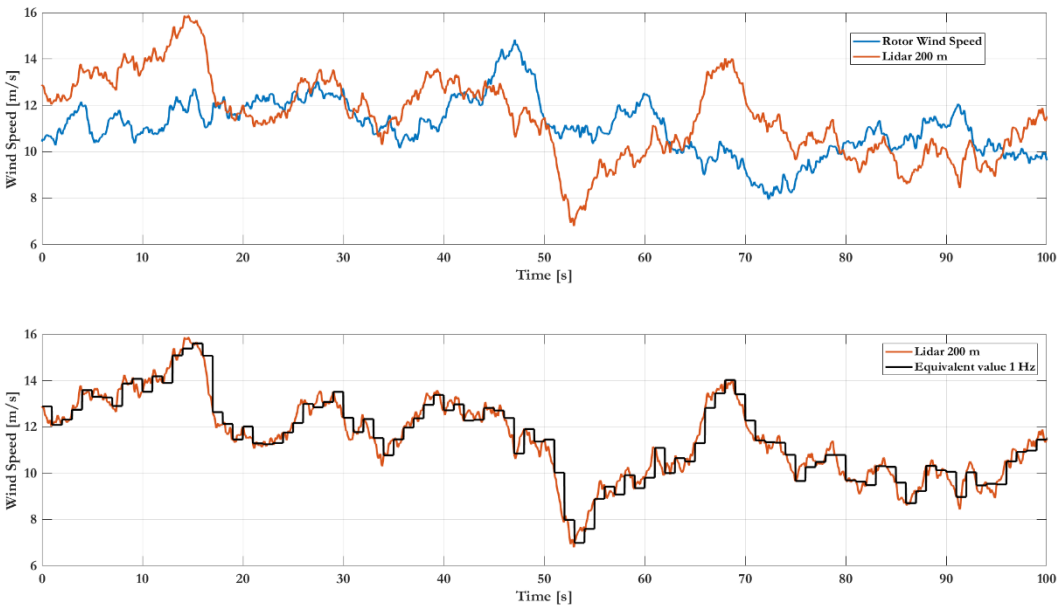


Figure 18 Demonstration Spinner LIDAR output

Figure 18 (top) presents the comparison of the measured wind speed by the LIDAR at 200 meters from the rotor and the free wind seen at rotor position. The bottom plot presents the equivalent 1 Hz value of the measured LIDAR. It is possible to adjust the frequency used to better match the set-up on the specific site.

Three criteria have been defined to identify a gust based on the spinner output. The first one considers a gust or fast change of wind speed if the difference of wind speed exceeds a certain threshold. Two consecutive values exceeding the threshold defines the second criteria. In order to consider it a gust, the last option must find two consecutives values of different sign higher than the threshold.

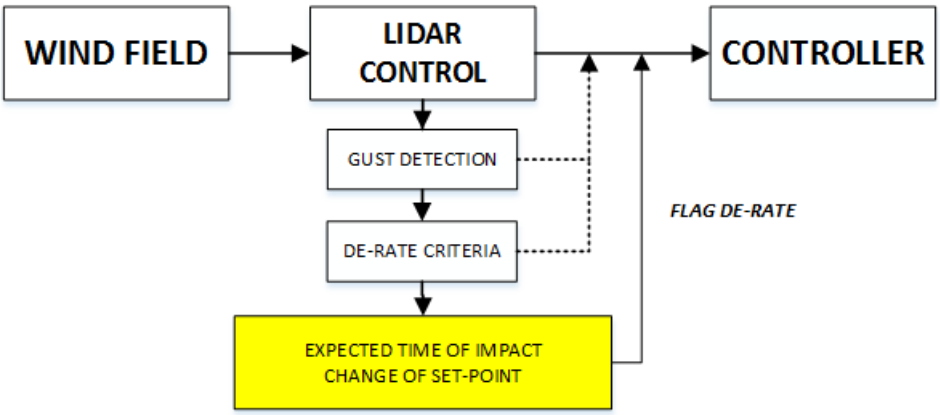


Figure 19: LIDAR Control Scheme Implementation

Once the gust is detected, there are two criteria to determine if the wind turbine should be de-rated. The first one considers the longest LIDAR range while the second option takes into account three LIDARs and their focus ranges to calculate the gust propagation. In this case, the de-rate flag is only deployed if the gust condition is fulfilled on all LIDARs.

An example of gust detection is shown to further explain the implementation. In this case, the first option is chosen for gust detection. Once this happens, the controller then estimates the gust impact time based on the LIDAR distance and measured wind speed

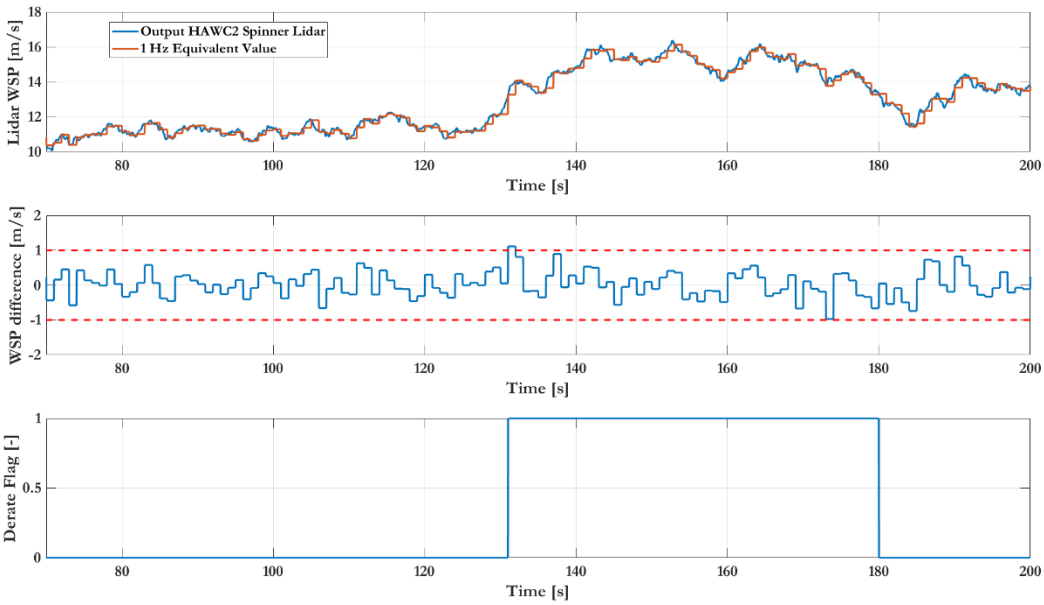


Figure 20: LIDAR value (top), Difference Previous Value (middle) and De-rate Flag (Bottom)

The controller then changes the operational set-point, decreasing the rotational speed before the gust impacts the wind turbine. The de-rate strategy is gradually applied avoiding transients at the beginning and ending of its applications. This is done by ramping the coefficients used to feed the controller up and down.

4.2 Wind Field : Coherent gust

The synchronization issues and uncertainties presented before compromised the quality of the analysis. The definition of a valid case to demonstrate the use of LIDAR as part of the control strategy must be defined. The synchronization issues are not present in the numerical model but the uncertainty of the wind field exists. The wind field must present a coherent gust which can be detected by all LIDARs.

In order to define a wind field which presents the needed characteristic, the constrained turbulence box tool is used. The algorithm uses an unconstrained field which is modified to satisfy the imposed constraints (Anand, 2016). A random turbulence box is generated and constrained to present a gust at the user-defined time. The constraints are defined for all the nodes in the wind field. An initial drop on the wind velocity and a sudden change is defined at 150 seconds of the turbulence field.

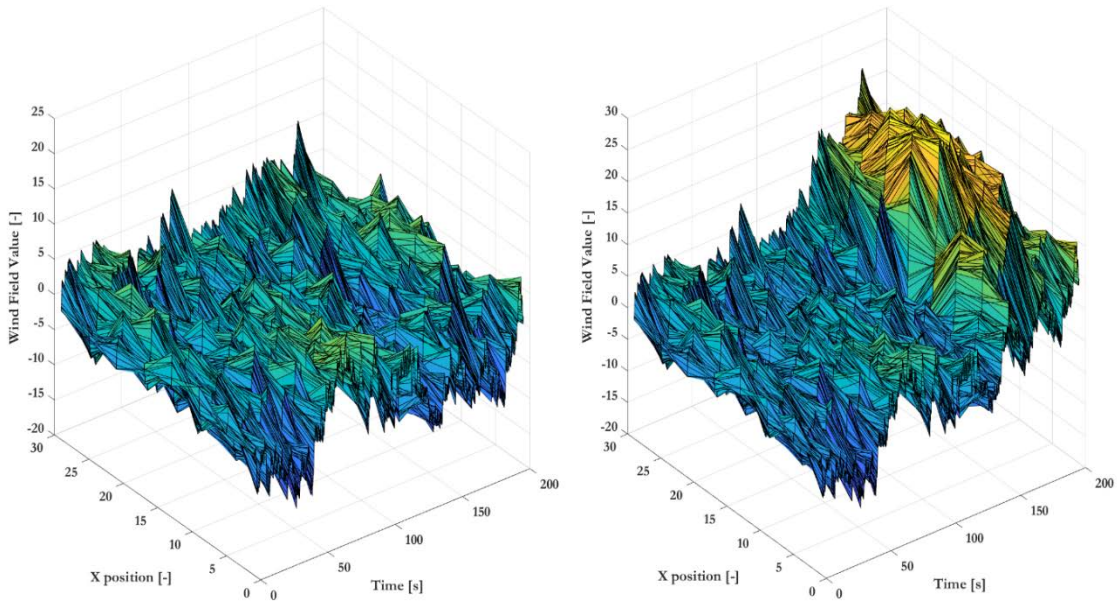


Figure 21: Unconstrained Wind Field (left) and Constrained Wind Field at Hub Height Position (right)

Figure 21 presents the comparison of the unconstrained and constrained wind field. It is possible to observe the presence of a fast wind speed change around 150 seconds. The rest of the field is re-calculated to meet the spectrum and conditions of the unconstrained one. The generated turbulence box fulfills the requirements and is used for the demonstration case.

4.3 Refernece Case vs LIDAR Control : Load Simulation

The case is run using the constrained turbulence box previously generated. A gust impact on the turbine rotor is expected around 150 seconds. Consequently, a peak of the blade root moment should appear afterwards.

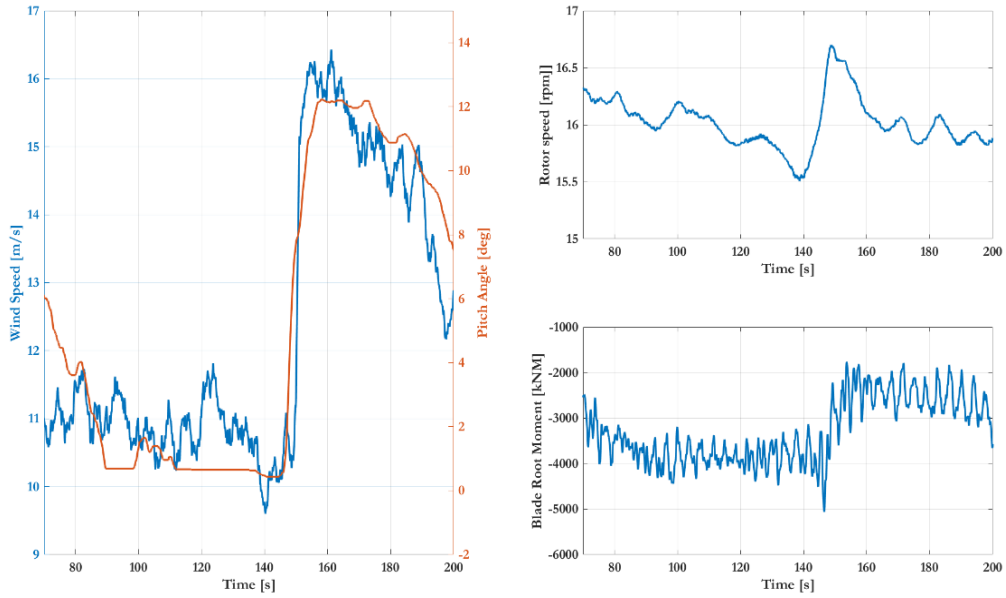


Figure 22: Wind Speed and Pitch Angle (left), Rotor Speed (top right) and Blade 1 Root Moment (bottom right)

Figure 22 presents the hub wind speed, pitch, rotor speed and blade root moment of Blade 1. The rotor speed value over speed when the gust impacts causing a peak in the blade root moment of 5,060 kNm. The pitch of the wind turbine follows the same tendency. The HAWC2 model resemblance the performance of the selected cases. The same case is run including the LIDAR prediction module. Different LIDAR ranges has been used in order to study the required prior time to de-rate the wind turbine.

The presented case uses a LIDAR at 200 meters and 1Hz frequency. The gust detection is set to first option (a single value exceeding the threshold). The implemented controller detects a gust at 131 seconds and expects the impact at 148 seconds. The relevant channels are shown in Figure 23.

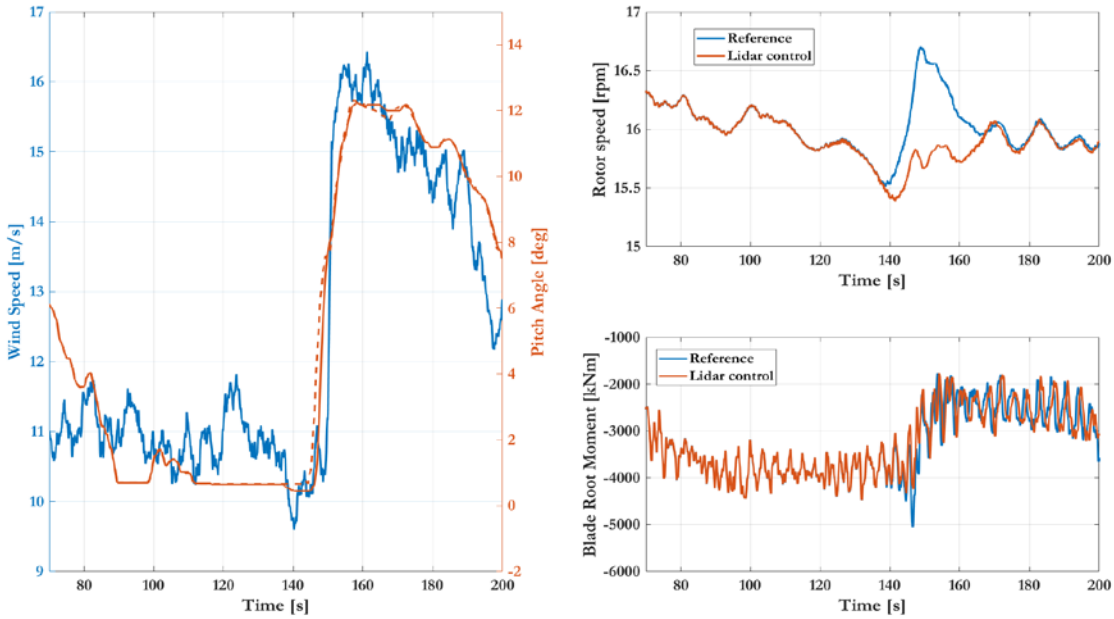


Figure 23: Comparison Reference Case vs Lidar Control (200 meter focus at 1Hz): Wind Speed and Pitch Angle (left), Rotor Speed (top right) and Blade 1 Root Moment (bottom right)

By changing the controller set-point, the rotor speed of the wind turbine is decreased before the gust as shown in Figure 23. The flapwise moment does not present a peak on the signal reducing the blade root vale by 16.2 % compared to the reference value (4,238 kNm). The same analysis is done with four additional LIDAR ranges in order to identify the needed action time of the wind turbine. Thus, shorter and longer LIDARs are used.

Table 4: Summary Load Reduction for Different LIDAR Range

LIDAR Range [m]	Detection Time [s]	Response Time [s] *	Load Reduction [%]
250	127	19.5	18.0
200	131	15.5	16.2
150	136	10.5	12.8
75	143	3.5	10.1
50	146	0.5	0.8

The response time is based on the time difference of the detection time (the de-rate strategy is starting to be applied) and the maximum peak found (146.5 seconds). Table 4 presents the load reduction and response time of the turbine for different LIDAR ranges. The load is reduced more than 10% when the turbine uses LIDAR ranges longer than 75. On the other hand, ranges closer to the turbine does not give enough response time and the load reduction is lower, 0.8 % in this case.

4.4 Gust Prediction Model Based on HAWC2 Results

The model previously defined for time estimation of impact gust time is used with HAWC2 model. The focus length are the same as for the Avent 5. First, the analysis was carried out using the same sample as in the measurement (5Hz). The results were not valid since some of the LIDARs did not capture the wind speed variation. The test is then repeated at 2 Hz frequency. The peaked values for the analysis (red dots in top right Figure 24) are based on the maximum difference found in the LIDAR values.

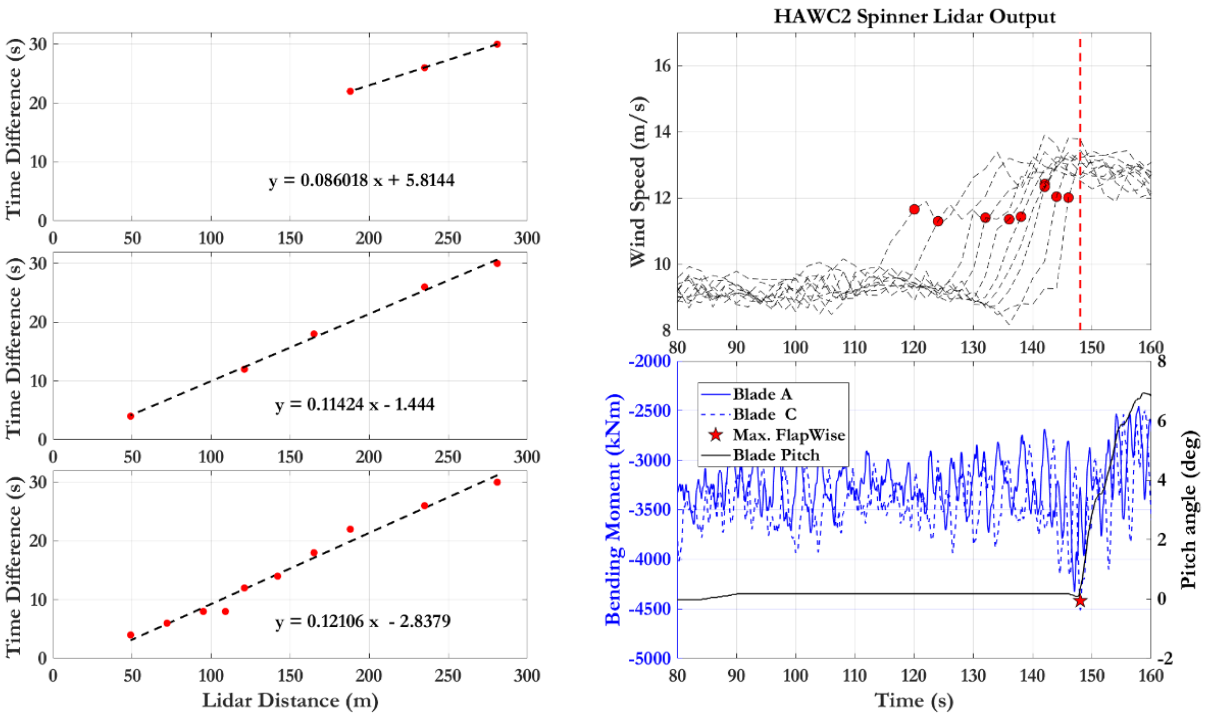


Figure 24: Gust Time Prediction Model, Model Fit for Different LIDAR Ranges (left), Used LIDAR Values to Fit (top right) and Blade Root Moment and Pitch Angle (Bottom right)

The results of the gust time prediction model anticipates more accurately this time. It is possible to observe that for the furthest LIDAR range (top left plot) the model predicts an impact time before the actual impact. This can be explained due to the induction effect that does not influence the furthest LIDAR (281 m, 235 m and 188 m). The other two fits, using intermediate and all the ranges, predicts the wind turbine gust with an error below 3 seconds.

Chapter 5

5 Conclusions

The first part of the report focused on the data analysis of the Avent 5 beam nacelle LIDAR system to predict the impact time of a gust. The data is filtered and synchronized before used in the developed model. The results indicate some time-lag and set-up limitations which are further investigated. The frequency of each LIDAR beam, 5 Hz, along with the integrated volume valuerestricts the capacity of the current set-up to capture fast wind speed variations as it is shown in Figure 11.

The synchronization is studied by comparing the met mast and LIDAR wind speed. A method to find the optimal time shift which minimize the quadratic error between signals is used. The mean wind speed and time shift are used to calculate the mean distance between the two sensors. The predicted distance is lower, in 84.7 % of the studied cases, than the physical which leads to think there is a synchronization issue. The time-delay versus event occurrence is also studied in order to identify a possible time-drift relation but no conclusion was reach.

The gust time prediction model is validated in Section 4.4 by means of HAWC2 results and a controlled case where a constrained turbulent box is used. The time impact error ranges from 5 seconds overestimation when using the furthest LIDAR ranges to an underestimation of 2.8 seconds when using all the LIDAR ranges. It has been demonstrated, in a basic and controlled test, that such models can predict the time impact of a gust with enough precision to change the wind turbine set-point to avoid load peaks.

A HAWC2 model of the SWT-2.3MW-93 is used to study the inclusion of a control module based on LIDAR values. The given controller is then coupled with a new feature which de-rates the wind turbine based on the wind speed difference of the LIDAR (spinner lidar output value) value in HAWC2. The cases are run with a constrained turbulent box which presents a coherent gust around 150 seconds replicating the conditions of the selected cases (measurements). A de-rate strategy is applied using different LIDAR's ranges presenting load reduction up to 18% when the wind turbine has a response time around 20 seconds. Notable reduction is found when using the LIDAR at 75 meters, 3.5 seconds of response, decreasing the peak by 10.1%. The shortest range, 50 meters and 0.5 seconds of response time, do not present a significant load reduction, 0.8 %. This results indicate that there is a direct correlation between the prediction time and percentage of load reduction. However, the time and load reduction percentage can only be used as a reference for the simulated case.

Special attention must be given in the gust prediction. In the presented example, a coherent gust in the 3D turbulent field was used. This condition is unlikely to happen and more sophisticated detection methods are needed where multiple LIDARs range and directions could be used. The used model is a simplification to demonstrate the capabilities to use LIDARs as feedforward control. It is fundamental that the LIDAR set-up (range, frequency, integrated volume) is adequate to capture fast wind speed variations with sufficient time for the controller to change its operational point. The de-rate strategy must be further investigated.

Concluding, a time prediction model has been developed which estimates the gust impact within an error of few seconds. Additionally, HAWC2 is used to demonstrate the possibility of using LIDARs as part of the wind turbine controller. The presented case shown a significant load reduction on the peak event.

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