Modelling of Wind Turbine Loads nearby a Wind Farm

B Roscher[1,2], A Werkmeister[1], G Jacobs[1], R Schelenz[1]

[1]Center for Wind Power Drives, RWTH Aachen, Campus Boulevard 61, 52074 Aachen, Germany

[2] Corresponding author: bjoern.roscher@cwd.rwth-aachen.de

Abstract. Each wind turbine experiences a variety of loads during its lifetime, especially inside a wind farm due to the wake effect between the turbines. This paper describes a possibility to observe a load spectrum while considering wake effects in a wind farm by through the turbulence intensity. The turbulence intensity is distributed along the wind rose of Alpha Ventus. For each turbulence intensity, a Weibull characteristic is calculated. The resulting wind fields are used to determine the loads through a multibody simulation of an imaginary wind turbine located at FINO-1, representing a closely placed wind turbine at the outer edge of a wind farm. These loads are analyzed and summed up. As expected, the change of the turbulence intensity due to the wake effect has an impact on the internal loading of a wind turbine inside a wind farm. Based on the assumed loading conditions, the maximum loads increased by a factor of almost 2.5.

1. Introduction

From 2010 till 2015, Germany installed more than 6900 wind turbines (WT) [1]. These WTs have to be placed somewhere. Unfortunately, almost 78% of the available onshore space cannot be used [2] either to logistical problems or social restrictions like the distance towards inhabited areas. One approach is to place the WT offshore, as there is more space available. But offshore space is regulated as well. Leading to the fact that space has to be used as beneficial as possible. This is mainly achieved by increasing the number of WT and therefore the annual energy production. The increased number of WTs means a closer spacing inside a defined area. Leading to an aerodynamic interaction between the WTs, also known as wake effects.

These wake effects result in higher turbulence intensities and greater dynamic inside the WT system. This could mean a faster damage accumulation and higher maintenance cycles, therefore an increase of downtime. This paper will inspect the influence of the wake effects on the damage accumulation on a single WT. As it is not possible to measure the direct influence on an existing turbine without an extensive measurement campaign, this paper will use the data of the research platform FINO-1 [3], where the wake effects can be observed by the wind farm Alpha Ventus. The damage accumulation will be determined through the use of a generic CWD reference turbine C3x126 [4], which is assumed to be located at the location of FINO-1. It needs to be stated that the FINO-1 is spaced rather close, which is occurs commonly at locations with a clear preferred wind direction. The turbine will be loaded in two different load situations and integrated over one year. To limit the displayed work, the considered WT components is the rotor hub as it observes all aerodynamical loads and is directly connected to the drive train.

2. Site Assessment of FINO-1 and Alpha Ventus

The measurement station FINO-1, as well as the wind park Alpha Ventus, are both located in the North Sea of Germany. The wind park consists out of 12 WTs orientated as indicated in figure 1. It can be noted the WT are spaced almost equally along the rectangular. The first 6 WT are REpower 5M and the last 6 are Areva Multibrid M5000, their configurations are given in table 1.
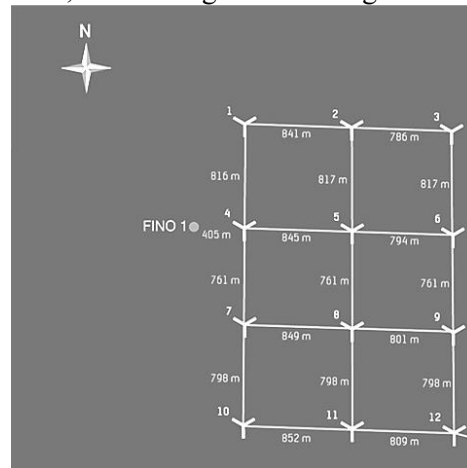

Figure 1. Spacing of WT inside Alpha Ventus, including location of FINO-1 [5]

Table 1. Wind turbine configurations inside Alpha Ventus, [5]

	Repower 5M	Areva Multibrid M5000
Wind turbine number	1-6	7-12
Rated power [MW]	5.0	5.0
Hub height over sea level [m]	92	90
Rotor diameter [m]	126	116
Rated wind speed [m/s]	14.0	12.5

The measurement station is included in figure 1 as well. It can be noted that FINO-1 is spaced close to WT 4, which leads to the biggest wake effect. However, FINO-1 will experience mostly a free stream inflow as the main wind direction is out of the southwest, observable in figure 2.


(a)   (b)
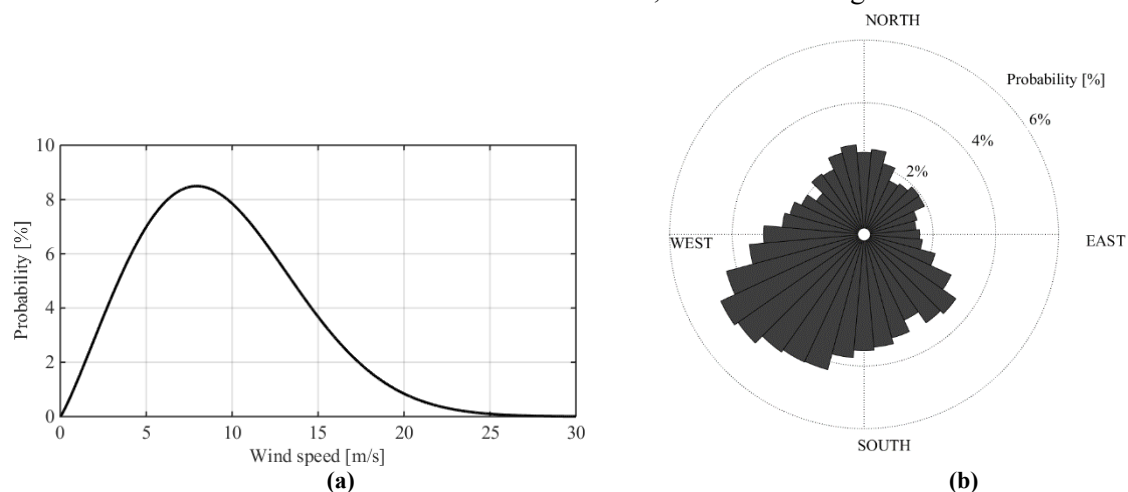
Figure 2. (a) Weibull distribution (A = 10.61 and k = 2.15) and (b) wind direction distribution at FINO-1 in 80 m height [3]

As mentioned the nearby placed WT will shed a certain wake, which needs to be modeled. The wake effect will be approached by an increased turbulence intensity (TI), as done by Fradsen [9] and according to the IEC-61400 [6]. The TI can be calculated out of the FINO-1 database using equation (1), where σ represents the standard deviation of the measurement and U the mean free velocity.

$$TI = \frac{\sigma}{U} \tag{1}$$

In figure 3 the TI distribution is projected against the inflow direction. The black line is equal to the TI distribution after Alpha Ventus was erected. As a reference, the TI distribution before the erection of Alpha Ventus was included as well, as a gray dashed-dotted line. It needs to be noted that the displayed lines represent the mean value of the TI at the certain direction.
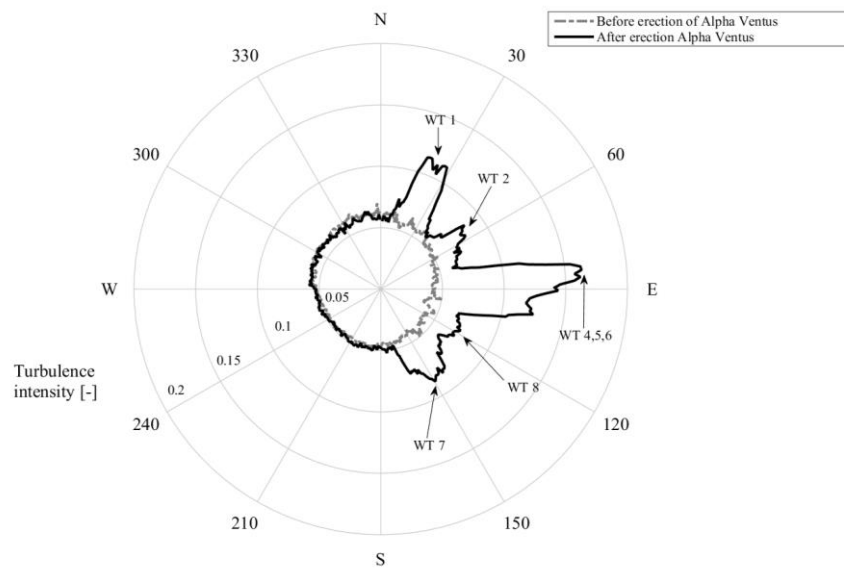

Figure 3. Turbulence intensity distribution

Out of figure 3, it can be observed that if the wind appears from the northeast, east and southeast the TI is increased significantly. This can be traced back to the wake effects of WT 1, 4 and 7, as these turbines are the closest. Additionally, the wake effects of WT 2 and 8 can be observed as well. However, their effect will be neglect, as the greater TI is not significantly with respect to the other WT. The highest TI in the distribution can be found while the wind occurs from the east, this is due two facts. Firstly, WT 4 is spaced closer than any other turbine. Secondly, the wake effects of WT 4, 5, and 6 are summing up at this inflow angle. A clear distinction between the two influences is not possible without any additional information. Additionally, the TI could also be calculated using equation (2) [6] and equation (3) [9], where D represents the distance normalized by the rotor diameter.

$$TI_{IEC} = \sqrt{\frac{0.9U_{hub}^2}{\left(1.5 + 0.3D \cdot \sqrt{U_{hub}}\right)^2} + I_{ref}^2} \tag{2}$$

$$TI_{Fradsen} = \sqrt{\frac{1}{\left(1.5 + \frac{0.8D}{C_T}\right)^2} + I_{ref}^2} \tag{3}$$

Figure 4, displays the TI distribution with respect to equations (2-3) as well as the one out of the FINO-1 data. Additionally, the design TI of the Repower 5M is included in the graph, showing that after a certain distance the TI is below the design point. It can be noted that the function of Fradsen [9], aligns

with the measurements nicely. However, this alignment is based on an assumed thrust coefficient (0.644), which would introduce an additional uncertainty in this approach. Therefore, it was decided to use the TI distribution out of table 2 for the load calculations. This will neglect the effects of WT 2 and 8 but their effect is rather low with respect to the freestream inflow TI.
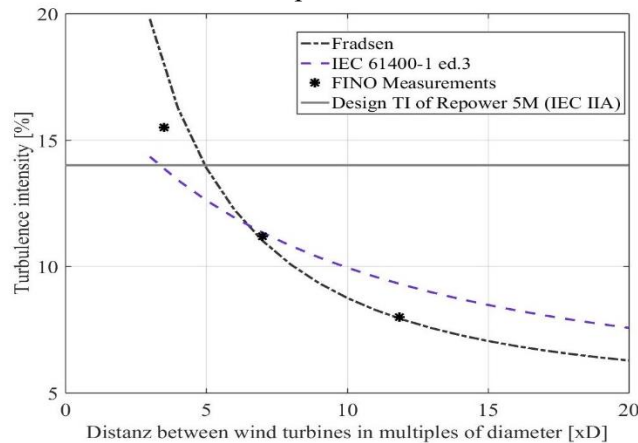

Figure 4: TI at various distances according to Fradsen [9] and IEC 61400-1 [6].

Table 2. Investigated inflow conditions, resulting out of the TI distribution

	TI = 5%	TI = 10%	TI = 15%
Represents:	Free stream	Wake effect of WT 1, 7	Wake effect of 4, 5, 6
Inflow angle span	Rest	[10°, 30°] [140°, 160°]	[75°, 115°]
Occurrence per year	79.9%	10.1%	10%

In order to evaluate the effect of the various TI, a Weibull distribution for each of them is determined by filtering the wind speeds with respect to their inflow angle, as done in figure 5. The solid black curve equals the Weibull distribution of the low TI. The dashed gray line corresponds to the Weibull distribution of TI equals 10%. The dashed-dotted line serves as the Weibull distribution of the high TI. Additionally, the overall Weibull distribution was included with a dotted line. It can be noted that through the increase of the TI, the mean wind speed is reduced, following from the fact that the previously WT that exploited the wake already extracted energy out of the flow.
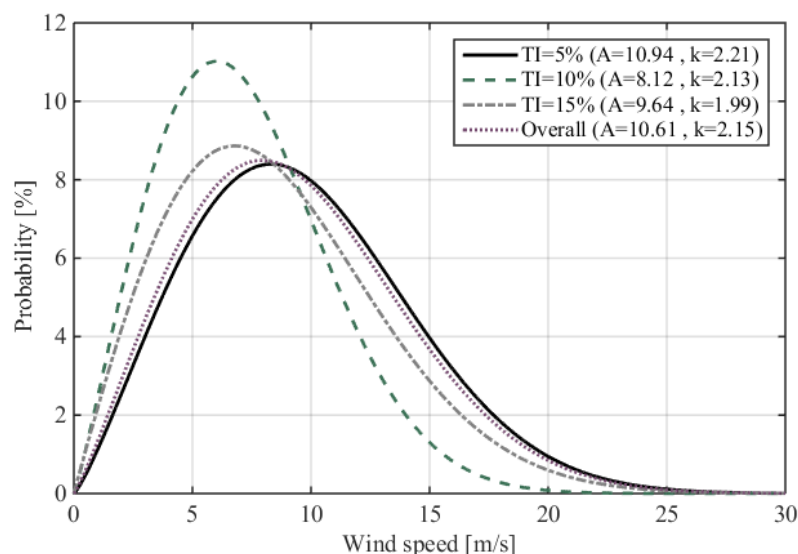

Figure 5. Weibull distribution for different inflow conditions

3. Load determination

In order to evaluate the wake effects without computational costly CFD calculations, it will be assumed that at the position of FINO-1 a wind turbine is located, that experiences the wind profiles according to the existing measurements. In this paper, the loads on this fictional WT will be determined by a Multibody Co-Simulation using SIMPACK with AERODYN [10] and MATLAB. The generic WT C3x126 is the reference WT of the Center for Wind Power Drives [4]. The turbine consists out of multiple flexible bodies such that deflection and displacement can be observed. The configuration of the WT can be found in table 3. The WT will be loaded with variations of turbulent wind velocities along the power curve, similar to the IEC 61400-1 DLC 1.1 [6] with a normal turbulence model. The WT produces power in a wind speed range between 3m/s and 25m/s. The loads will be cumulated over one year using the weighting of the probabilities, shown in figure 5, and then compared to each other.

Table 3. Wind turbine characteristic of C3x126 [4]

	Value	Unit
Rated power	3.0	MW
Tower height	112.0	m
Rotor diameter	126.0	m
Cut-in wind speed v_{in}	3.0	m/s
Cut-out wind speed v_{out}	25.0	m/s
Rated wind speed v_{rated}	11.0	m/s
Gearbox ratio	1 : 92.28	
Main suspension	4-Point	
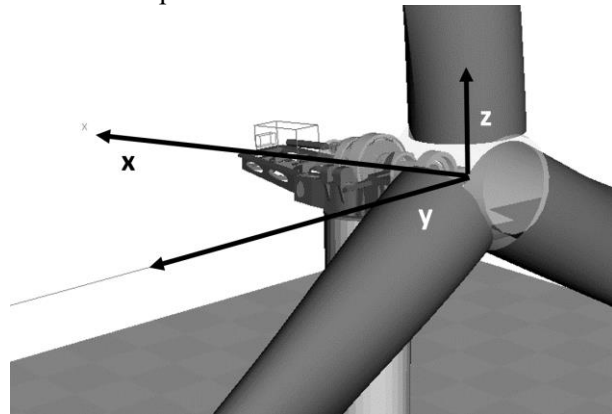
Figure 6. Graphical interpretation of the C3x126 and the coordinate system

The wind fields with the three different TI, 5%, 10% and 15% (see figure 5) are scaled toward the hub height using the logarithmic scaling law, used in the IEC 61400[6]. Sequentially, the corresponding 3D-wind fields are calculated with TurbSim [7] and step size of 0.5 m/s, such that a representative resolution was reached. This means for each TI distribution 45 wind fields and simulations covering ten minutes production time are calculated. All three TI distributions are generated with the same random seed values, such that the wind fields can be compared without the influences of random numbers. The results are analyzed at the hub coordinate system (see figure 6) in order to compare the loads at the drive train. This coordinate system is not rotating, meaning that the y-component equals an in-plane (rotor plane) component. The z-component represents gravitational effects and vertical upwards streams. For convenience, the moment around the y-axis will be called pitch moment and the moments around the z-axis yaw moment, inspired by the aeronautics terms.

4. Results

In order to evaluate the effect of the different inflow conditions, this paper will analyze the cumulated loads of two different conditions. At first, the influence of the TI has to be analyzed. For this two TIs are compared the 5% and the 15% with the Weibull distribution of FINO-1 (see figure 5, "overall") in order to show the impact of the TI.

After each multibody-simulation, a rain flow counting is applied and multiplied with the Weibull frequency of the corresponding wind speed. Subsequently, the load cycle for each amplitude is calculated, given in subsection 4.1.

The second part (subsection 4.2) compares the design loads for a wind turbine which is sited at FINO before and after Alpha Ventus was build up. Before Alpha Ventus was build up a wind turbine sited at FINO would have seen a TI of 5% with the Weibull distribution (see figure 4, "5% TI"). The label "FINO after Alpha Ventus" is a combination of the three TIs (5%; 10% and 15%), their individual Weibull characteristics (see figure 5). The different TIs are cumulated and weighted with the occurrence

per year (see table 2). For the analysis, the hub coordinate system is used in order to quantify the effect on the wind turbine loads.

4.1. Impact of the turbulence intensity between 5% and 15%

It is expected that the impact of the turbulence intensity will result in a higher load at the yawing and pitching torque of the rotor, because of a higher imbalance of the inflow wind speed. The results are displayed in figure 7-12 and are as predicted. It can be noted that the presented results are partially discontinues and zigzagged, this is based on the bin-size used in rain flow counting. It could occur that at certain loadings no values are available. However, the main relevance in these plots is a trend with respect to the load cycles. The thrust at the rotor does not change significantly (see figure 7). The amplitudes of the side force for lower load cycles increases because of the higher turbulence effects in the rotor plane (see figure 8). According to this, also the torque in z-direction raises (see figure 12). The load in z-direction does not change much, which is logical as the biggest contributions origin from the rotor weight.

The main shaft torque has a different gradient for load cycles between 10^4- 10^6. The main shaft torque relates mainly to the control strategy. One would expect higher amplitudes for a higher turbulence intensity, but it seems to be that the control of the model is fast enough to compensate the higher TI. It might be that the results change if more random seeds for one wind speed are considered.

The biggest influence of the TI can be seen in figure 11 and figure 12 at the rotor pitching and yawing torque. The amplitude for load cycles lower than 10^5 is more than two times higher than before.
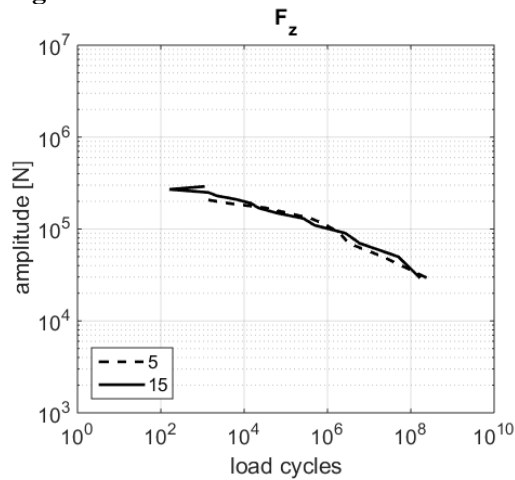
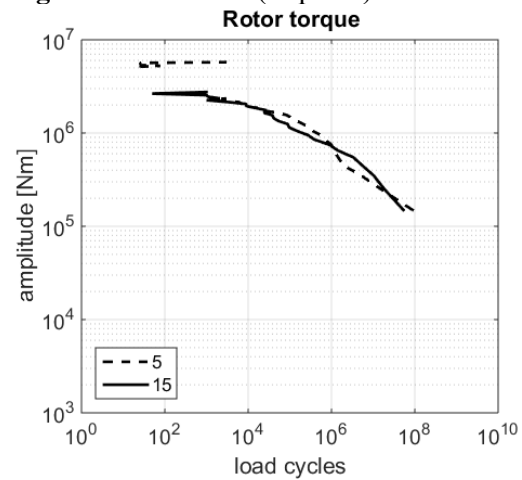**Comparison of a turbulence intensity of 5% and 15%**
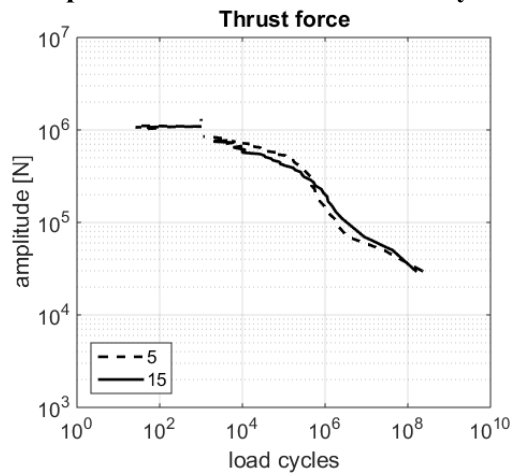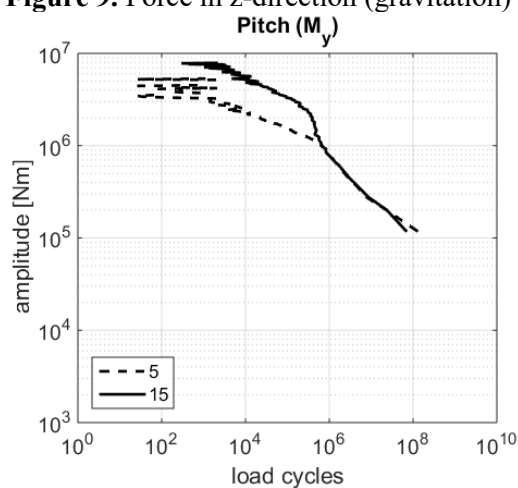

Figure 7. Thrust force of the rotor
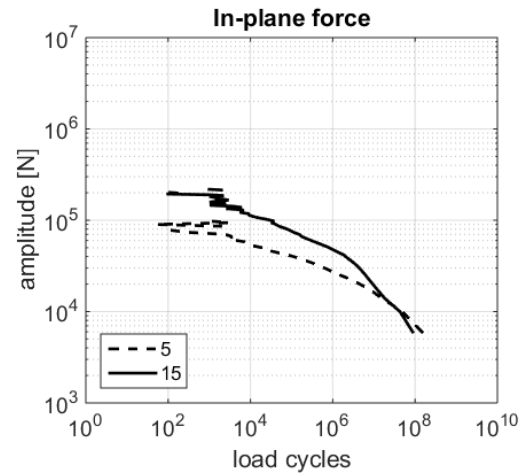
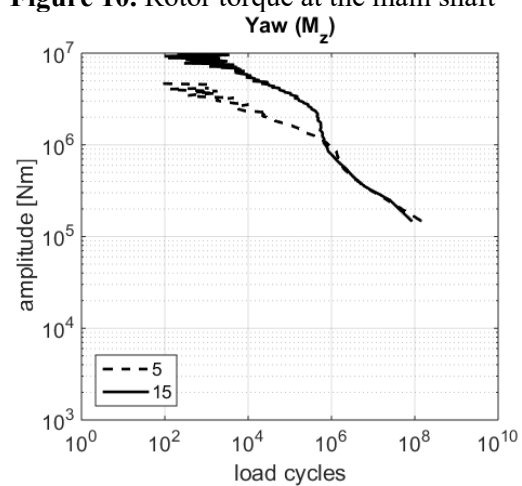**Figure 8.** Side force (in-plane)

Figure 9. Force in z-direction (gravitation)

Figure 10. Rotor torque at the main shaft

Figure 11. Torque around y-axis (pitch)

Figure 12. Torque around z-axis (yaw)

4.2. Before and After Alpha Ventus

As a next step, the influence of the different TIs for a wind turbine placed at the site of FINO-1 is quantified. The situation before Alpha Ventus is calculated with a 5% TI and the one at the position of FINO-1 after Alpha Ventus was built is called "FINO after Alpha Ventus" in the following figures. The simulations are done with all three TIs analyzed with a rain flow classification and their specific Weibull characteristic. After this, the load cycles are weighted by the occurrence per year of each TI. The results are shown in figure 13-15 and are as suspected. The influence of the TIs is visible for the yawing and pitching torque and the side force. In all three diagrams, the wind turbine experiences a higher load at higher TIs.

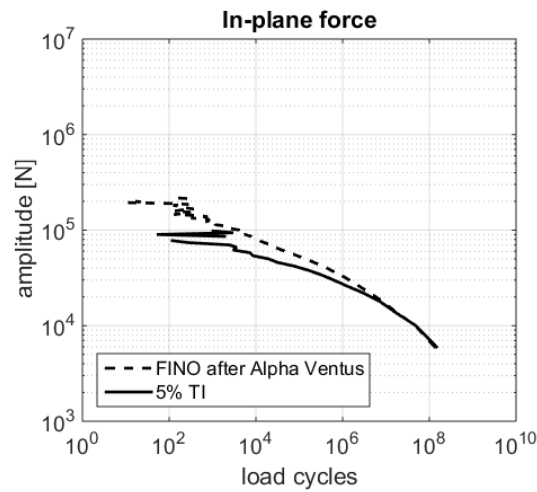**Comparison of a turbine in the free stream between one placed at FINO-1**
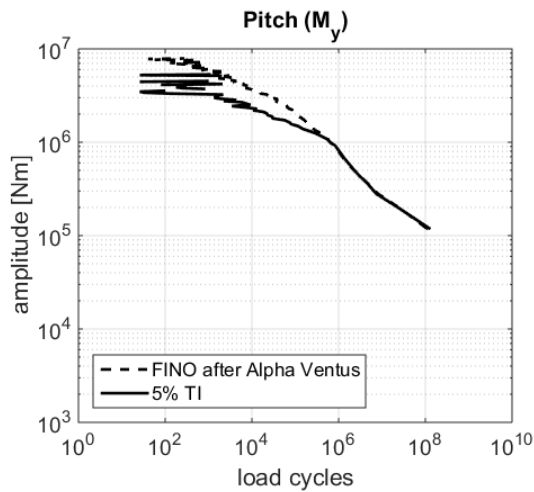

Figure 13. Side force (in-plane)

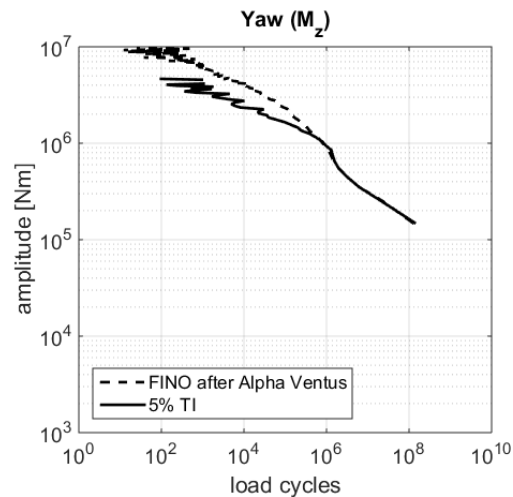**Figure 14**. Torque around y-axis (pitch)

Figure 15. Torque around z-axis (yaw)

The differences are observable but only at low load cycles. Additionally, the presented results are reduced to a one level load cycle collective with equation (4) according to DIN 50100 [8].

$$DEL = \sum S_i^k \cdot \left(\frac{N_i}{N_{eq}}\right)^{\frac{1}{k}}, with\ k = 3 \tag{4}$$

Equation (4) is used to calculate a torque or force for an equivalent load cycle, therefore often is used 10^7 load cycles. This is determined by every combination of load cycles and amplitudes. Afterwards, all load cycles can be summed up to one amplitude with an equivalent load cycle. Comparing with respect to an equivalent load cycle was done, in order to observe the load variance due to the variation of the TI. The results are shown in table 4.

Table 4. Investigated inflow conditions, resulting out of the turbulence intensity distribution

	5% TI	FINO after Alpha Ventus	N_{eq}
Load cycle Pitching torque N_{My}	13 MNm	32 MNm	$1 \cdot 10^7$
Load cycle Yawing torque N_{Mz}	12 MNm	33 MNm	$1 \cdot 10^7$

The results show that the higher turbulence intensity results in approximately 2.5 times higher dynamic load at the bearings of the wind turbine and the supporting structure.

The results do not cover a complete system design and do not cover the statistical safety. For a design load analyses, one has to calculate at least six wind fields with six different random seeds to be sure that the results are statistically safe. But the results show that it is important to calculate the influence of the TI within a wind farm and that it is not enough to measure the free stream velocities before a wind farm is built. In the case of Alpha Ventus, the wind turbines are designed with a turbulence class of A or B according to the IEC 61400-1 and meaning that the mean TI is always above 10% (see Figure 4).

Before Alpha Ventus was built the TI was particularly low and it is possible that a turbine does not change the TI above 15% while the distance between two wind turbines is higher than 5 diameters. In order to validate the effect, more data of downtime statistics or data of a condition monitoring system of wind farms is needed.

5. Conclusion

Overall, this paper presented a method to determine wake effects out the FINO-1 measurements and integrating those into a load spectrum. Such a load spectrum was used to determine load cycles acting on a fictional wind turbine based on MBS simulation environment implemented in SIMPACK. The results show that a higher turbulence intensity has an impact on loads of a wind turbine and therefore on the cumulated load cycles, especially with respect to the in-plane side force as well as the moments around the y and z-axis. In further studies, it will be necessary to include actual measurements of an entire wind farm in order to validate the shown approach.

References

[1]   German Wind Energy Association, Installed wind power capacity in Germany, *website*, (https://www.wind-energie.de/en/infocenter/statistiken/deutschland/installed-wind-power-capacity-germany) (accessed 02-13-2017)

[2]   Pfaffel S et al 2011, IWES Annual Report, *Windenergie Report Deutschland 2011* 54

[3]   Federal Maritime and Hydrographic Agency, FINO-1 Research Platform database, (http://www.fino1.de/en/) (accessed 02-01-2017)

[4]   Werkmeister A, Schelenz R, Jacobs G, Calculation of the design loads with SIMPACK, Simpack User Meeting, *Conference, 09-2015*, Augsburg

[5]   Alpha Ventus, Federal Ministry for Economic Affairs and Energy (https://www.alpha-ventus.de/english/) (accessed 02-01-2017)

[6]   Internation Electrotechnical Commission standard DIN EN 61400-1, design requirements, Release 2015

[7]   National Renewable Energy Laboratory (NREL), TurbSim A stochastic, full-field, turbulence simulator primarily for use with InflowWind/AeroDyn-based simulation tools, *website* (https://nwtc.nrel.gov/TurbSim) (accessed 02-17-2017)

[8]   Internation Electrotechnical Commission standard DIN 50100:2015, Load controlled fatigue testing - Execution and evaluation of cyclic tests at constant load amplitudes on metallic specimens and components, Release 2015

[9]   Fradsen S, Turbulence and Turbulence-generated structural loading in wind turbine cluster, Riso-R-1188, Roskilde, Release 2007

[10] János Zierath et al., Field test validation of Flex5, MSC.Adams, alaska/Wind and SIMPACK for load calculations on wind turbines, Wind Energy 2016, 19:1201-1222, DOI: 10.1002/we.1892