Wake effects at FINO 1 – new observations since the construction of Trianel Borkum & Borkum Riffgrund I wind farms

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Abstract

Wind speed data from the FINO 1 platform in the North Sea have been investigated to characterise the wind conditions under consideration of the new wind farms constructed to the West of the platform. The main parameters considered were turbulence intensity (TI) obtained from cup anemometers mounted on the mast and wind profiles obtained from two vertical scanning Lidars on FINO 1 and the nearby converter station at Alpha Ventus. TI indicates significant broadening of the wakes from the northern most wind turbine cluster; an increase in TI is seen in what should nominally be a free sector to the NNW. Wind speed reductions as large as 7 m/s at the extreme are found in the wake of Alpha Ventus. Wind profiles up to a height of 200 m still show a reduced wind speed compared to an upwind measurement at the same height. This indicates that wind speeds are significantly influenced well above the blade tip height. Finally, turbulence spectra are investigated. Wakes from single wind turbines show explainable characteristic, however wakes from wind farms show far more variability, highlighting the complexity of wake behaviour.

Introduction

The construction of wind farms in the vicinity of the FINO 1 research platform in the North Sea began in 2008 with Alpha Ventus and its 12 turbines to the East of the platform. Operation of the wind farm began in 2009 and a measureable influence on wind measurements at FINO 1 was soon observed in the wind data. Since the spring of 2015 two new wind farms have been constructed to the West and South of FINO 1. Although these are further away – the nearest turbine is approximately 4 km distant – the wind farms are much larger, comprising 40 turbines each, as shown in Figure 1. This now leaves FINO 1 with only a narrow sector (the NW quadrant) in which no wind farms stand to windward of the measurement mast.

The measurement mast contains a range of wind sensors; cup anemometers on booms to the SE of the mast and on the mast top form the standard wind speed measurement tool, providing 10 minute mean wind speeds and statistics based on 1 Hz sampling (a recent update of the measurement system now allows the 1 Hz data to be recorded), wind vanes at four heights on booms to the NW of the mast provide wind direction and sonic anemometers interspersed between the wind vanes provide high temporal resolution (5, 10 and 20 Hz) wind speed data in three axes. A vertical scanning Lidar device provides wind speed and direction data for heights up to 200 m above the platform deck. Thus FINO 1 is now well positioned to provide measurement data for assessing park wake effects in the lee of wind farms over distances ranging from 400 m to 8 km.

Previously [1], turbulence intensity (TI) and mean wind speeds at FINO 1 were investigated over two roughly five year periods, before and after construction of Alpha Ventus. The influence of the individual turbines from Alpha Ventus located 400 m to 2.6 km from FINO 1 could clearly be identified in the TI data. Furthermore, a decrease of approximately 0.5 m/s in the 5 year mean wind speed (all directions included) was also found. More recently the spectral content of the turbulence has been investigated using a variety of techniques ranging from ultrasonic anemometers [2], through pressure sensors [3] to staring Lidar measurements [4]. Spectra calculated from measurements using both ultrasonic anemometers and Lidar have shown turbulent energy input at a scale of the order of the turbine rotor diameter.

The increase in turbulence in the wake leads to increased load amplitudes on downstream wind turbines, effecting the life span of both the structure and the mechanical load train. In addition, the presence of specific turbulent content within the wake can exacerbate the issue in the event that this matches harmonic frequencies of the turbine structure or drive train. Hence wake effects are significant not only for the reduction in wind speed and consequently the energy yield, but also for shortened life time of the downstream wind turbines. The results presented in this work investigate how wakes manifest themselves in the various data collected at FINO 1, over a range of distances downstream of a wind farm.

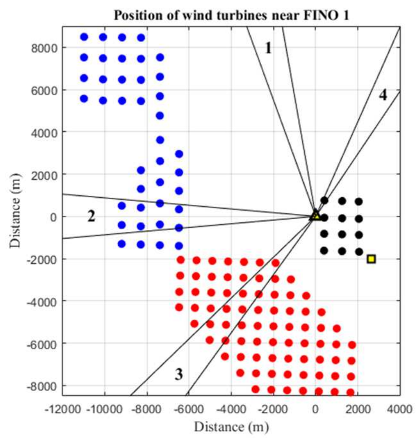

Figure 1: Position of FINO 1 relative to surrounding wind parks – black: Alpha Ventus, red: Borkum Riffgrund 1, blue: Trianel Windpark Borkum, yellow square: transformer station

Outline

Effects of the neighbouring wind farms on the wind conditions have been investigated in three ways: a before / after investigation of 10 min turbulence intensities, differential wind profiles measured using 2 Lidars at two locations, and a spectral analysis of wind speed data collected at 20 Hz using ultrasonic anemometers. To simplify the some aspects of the investigation, four sectors were defined to provide a representative conditions for 1. no turbines upstream, 2. turbines > 8 km upstream, 3. turbines > 2.5 km upstream and 4. turbines < 1 km upstream, as shown in Figure 1. The line of Alpha Ventus turbines due East of FINO 1 were not selected because the sonic anemometers are in the mast shadow under easterly winds and therefore cannot provide representative data.

Results – Turbulence Intensity

The influence of the Alpha Ventus wind farm can clearly be seen in the TI data (Figure 2). The close proximity of the turbines to the platform means that the wakes from individual turbines (or lines of turbines in the case of AV 4-6) can be identified separately. By contrast however, the greater distance of the Borkum Riffgrund I and Trianel Borkum wind farms means that individual wakes are not as clearly identifiable, as seen in Figure 2. What is not obvious when looking solely at Figure 2 is that in the Western Sectors, where the TI is fairly constant against direction, the minimum level of TI is increased. This becomes apparent in a comparison with earlier data prior to the installation of the wind farms, as shown in Figure 3, for two years prior to the installation of the upstream wind farm Borkum Riffgrund 1 and one year since the wind farm began service.

Noteworthy in Figure 2 is also the nominally free northerly sector between 315° and 25°. Over the range 350 to 20° the TI is raised due to the presence of the bar of the lightning protection cage. The most likely explanation for the increased TI between 315 and 350 is broadening of the wake downstream. Also, some years have shown a slightly higher minimum TI for northerly winds, probably due to a higher frequency of unstable conditions resulting from the typically cooler air masses travelling southwards.

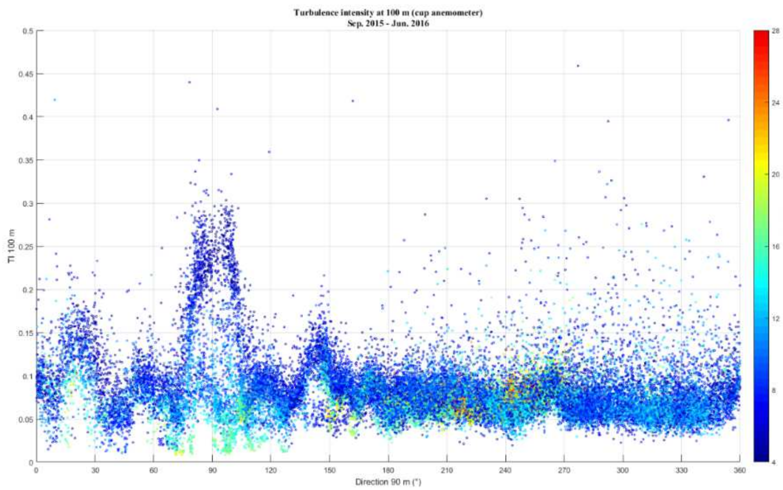

Figure 2 : Turbulence intensity data from 10 *months of measurements, plotted* against the wind direction at 100 *m and coloured for wind speed.*

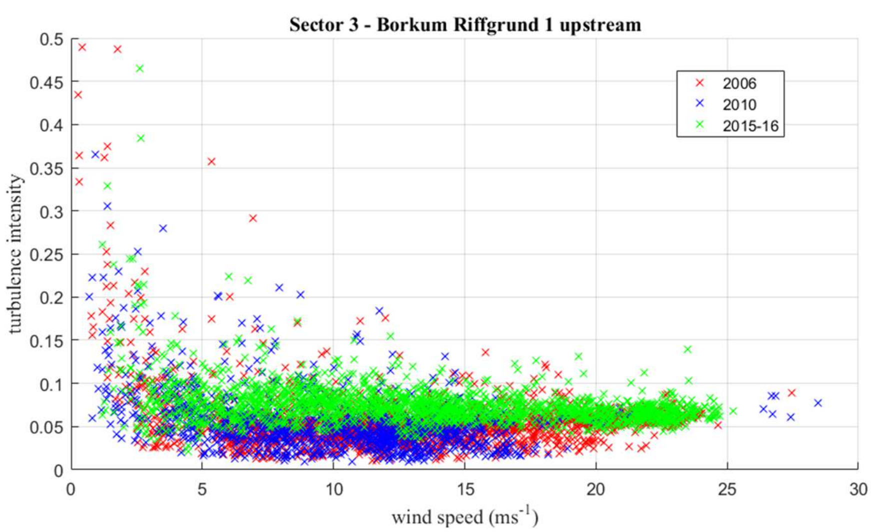

Figure 3 : Turbulence intensity for Sector 3, plotted against 10 minute mean wind speed for three one year periods.

Results – Lidar Wind-profiles

Vertical scanning Lidar devices have been installed on FINO 1 (an upgraded Leosphere Windcube V1) and on the transformer station at Alpha Ventus (a Leosphere Windcube V2). The two locations are only 3 km apart, wherefore it is assumed that in the absence of a wind farm, the wind conditions should be identical. Any differences between measurements at the two locations can therefore be attributed to the presence of the wind farms. During easterly winds, the Lidar at FINO 1 is in the wake of Alpha Ventus, whereas the Lidar on the transformer station is in the free stream. During winds from the southwest quadrant, both devices have a similar distance to the wind farm Borkum Riffgrund 1 and so should be exposed to similar wind conditions. In the northwest quadrant, the Lidar on the transformer station is in the wake of Alpha Ventus while FINO 1 is 8 to 10 km in lee of Trianel Winpark Borkum and so it would be expected that FINO 1 is subject to somewhat stronger winds.

Data were collected for a 10 month period from 01.09.2015 to the 30.06.2016. The difference in the 10 min mean wind speed between the two measurement locations was calculated for each height from 70 to 240 m and a wind speed difference profile established. Here it should be noted that at heights above 200 m the interval between measurement points on the transformer station Lidar was increased to 30 m. These difference profiles were grouped into bins according to the wind direction at 90 m from the Lidar on FINO 1 in 2° increments. The wind difference profiles up to a height of 200 m are shown in Figure 4 for two directions, 0-2° (both Lidars undisturbed) and 89-91° (Lidar at FINO1 in wake). The profiles are coloured approximately for wind speed. The average profile for the whole set is shown as a black line superimposed on the rest.

It can clearly be seen that on average, when both Lidars are in undisturbed flow, both will measure the same wind speed across the full height, with the exception of a few outliers. However, even in this situation the spread of values is relatively large, up to ± 1 m/s. By contrast, in easterly winds where the Lidar on FINO 1 is in the direct wake of the three Alpha Ventus turbines, a distinct reduction in wind speed is observed. On average this is approximately 2 m/s at hub height, with extremes of 4 – 7 m/s. From the data available the range of wind speed reductions could not be clearly linked to stability criteria based on a difference in temperature between the air and the sea surface. Also, the operation (or non-operation) of one or more turbines could not be determined to filter the data sets.

Another interesting observation is that the wind speed reduction extends well beyond the blade tip height, with an average decrease of the order of 0.7 m/s at 200 m, i.e. 50 m above the blade tip height. This implies a significant change in the boundary layer thickness even over a relatively small wind farm such as Alpha Ventus.

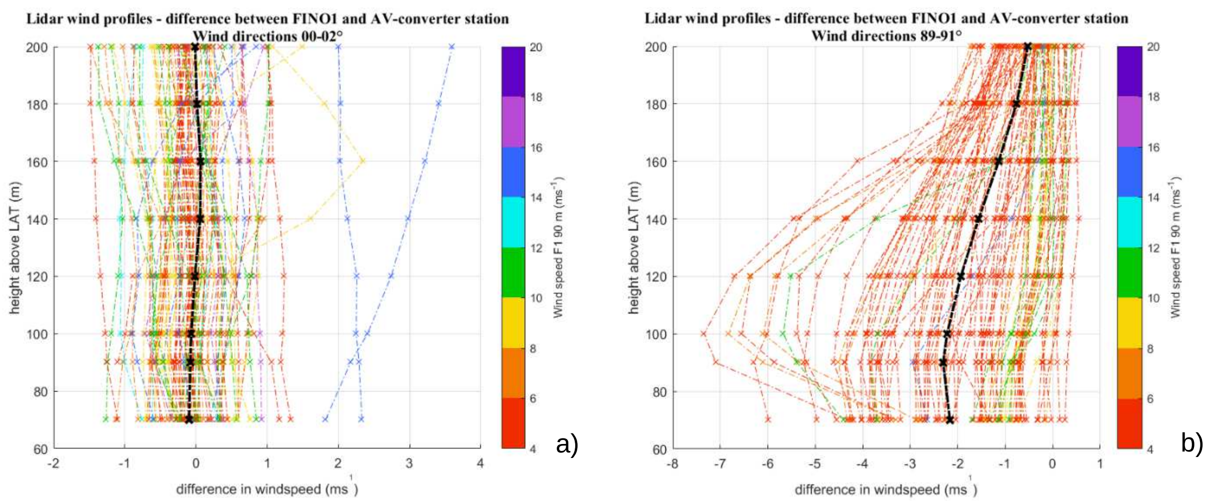

Figure 4 : Wind speed difference profiles obtained using the two Lidar devices on FINO 1 and the transformer platform of Alpha Ventus for a) a northerly wind and b) an easterly wind.

Results – Spectral Analysis

For the spectral analysis, ultrasonic anemometer data recorded at 20 Hz was used. The data were broken into 10 minute periods, and only periods with no data gaps greater than 5 neighbouring missing values were considered. Missing data points were linearly interpolated between their nearest neighbours. The 10 minute periods were then assessed using the “pwelch” function from MatLab®. This gives a spectral power density estimate in which noise due to finite and imperfect signals is reduced at the cost of slightly reduced frequency resolution. In this case, the 10 minute periods were reduced to 8 segments of 2048 data points length (i.e. 200 seconds) with 50 % overlap of the segments. The analysis was centred on the 10 minute period, hence only the central 7.5 minutes of each 10 minute period were included in the analysis and allowing a range of frequencies from 0.01 to 10 Hz to be investigated.

Four sectors were defined in accordance with Figure 1: sector 1 representing a nominal free stream (no turbines directly upstream), sector 2 representing the medium distance to an upwind turbine of approximately 6 km, sector 3 representing a short distance of approximately 3 km and sector 4 being in the immediate vicinity, less than 1 km.

Sector 4, containing only a single wind turbine and having the closest distance to the source of turbulence, was chosen as a bench mark on which to verify the method. This is shown in Figure 5 for three wind speed categories (4-8 m/s, 8-12 m/s and > 12 m/s). The data were filtered for stable conditions according to the criteria that the air temperature at 33 m (lowest measurement height on FINO 1) is more than 1 °C greater than the sea surface temperature measured by a buoy adjacent to the platform. Each line is the average of all spectra that matched the filter criteria.

The peaks in the spectra correlate well with turbulent eddies at the scale of the rotor diameter. This can be assessed by normalising the frequency by the ratio of the wind speed and the rotor diameter. Similar to the Lidar profiles, each plot is the average of all spectra available for that sector and wind speed category. Due to differences in the number of data sets that make up the mean spectral plots, but the general trend that the peak shifts towards the right for higher wind speeds, and the approximate location of the peaks indicate that these are likely to be related to eddies induced by the wind turbine. Also, the larger peak at 8-12 m/s fits well with the maximum energy extraction from the wind at wind speeds around 10 m/s. At higher wind speeds the blades are feathered so that the power output from the turbine is levelled to its rated power.

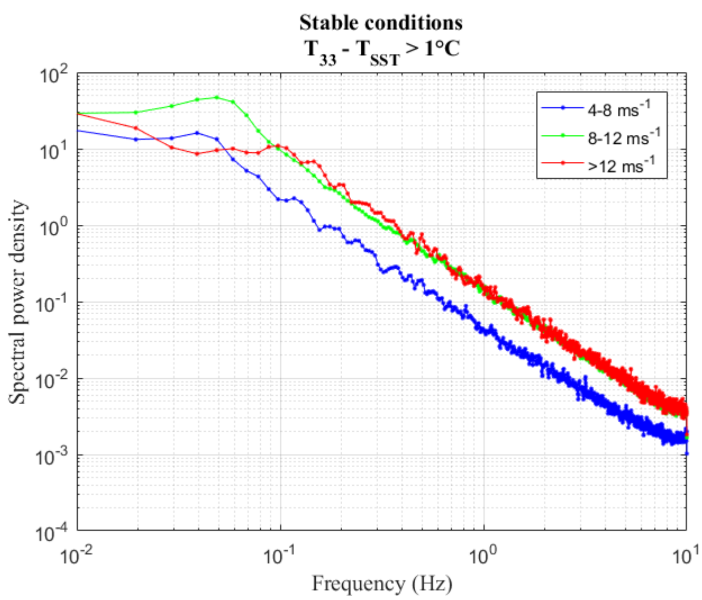

Figure 5 : Spectral power density spectrum as a function of frequency under stable conditions for three wind speed categories in the wake of Alpha Ventus (Sector 4 – wind turbine AV01)

Spectra from sectors 1-3 were also investigated. However, here it was not possible to identify any of the effects visible in the spectra from sector 4. This can have many reasons, not all of which could be considered in this study. In the following a few differences that were identified as generally applicable are presented.

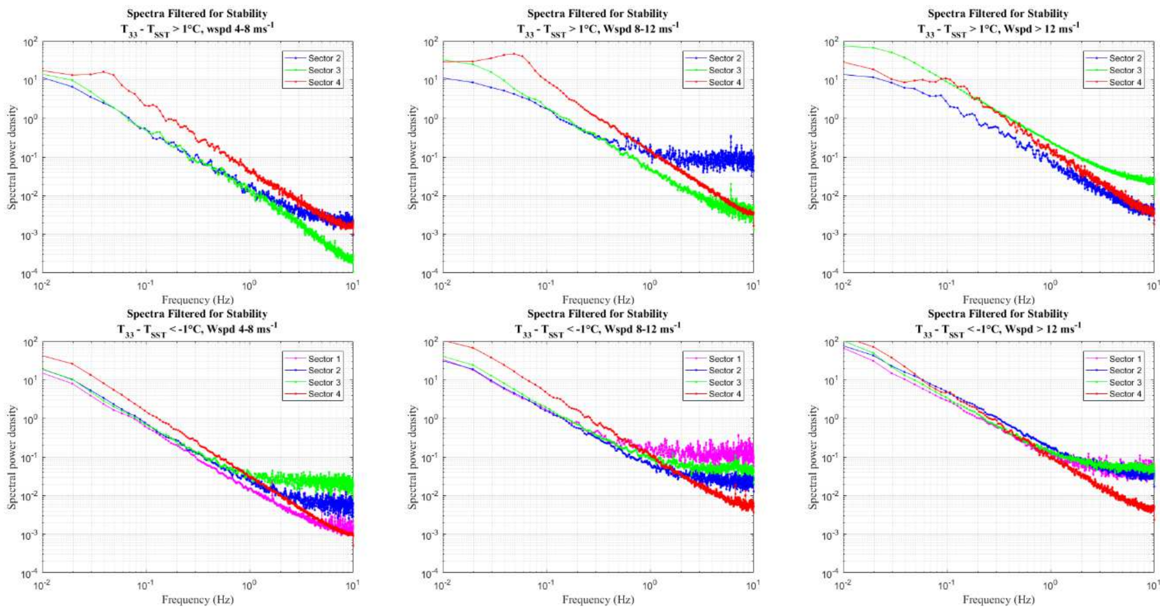

Figure 6 : Sector-averaged spectral power density plots as a function of frequency – top row: stable conditions, bottom row: unstable conditions – from left to right, wind speed categories, 4-8 m/s, 8-12 m/s and > 12 m/s.

No data were available to assess sector 1 under stable conditions. With the exception of sector 4, all spectra show a flattening of the spectrum at a frequency of approximately 1 Hz. This distinguishes the spectra from those obtained under stable conditions. The spectra become more noisy at frequencies above 1 Hz. This can be ascribed to greater variations in the individual 10 min spectra within that sector, but no common factors explaining this phenomena were identified. There is a general increase in the magnitude with increasing wind speed for all spectra under unstable conditions. This is to be expected as there is more energy available in the wind at greater wind speeds.

Data obtained during neutral conditions are not presented as no meaningful conclusions could be drawn from the resulting spectra.

Conclusion

TI remains a very good indicator of the presence of wake effects. As shown, at long distances (of the order of 10 km), wakes can show significant broadening and/or drift. Moreover, the wind farms also have a strong vertical impact on the wind speeds, well beyond the blade tip height.

The propagation and characteristics of wind farm wakes are however very sensitive to the local conditions. While for isolated cases it is possible to identify clear cause-effect relationships, such as specific frequency (turbulence scale) content within spectral plots, these features are not necessarily repeatable in similar data sets prohibiting generally applicable conclusions to be drawn. Atmospheric stability has proven to be an important factor, but other factors that could not be determined in this work might also play a significant role. These may include environmental factors such as wave height and direction, but also man made influences such as interactions between wind turbines, transformer stations, and wind farms.

With the construction of large wind farms all across the North Sea, single measurement points no longer suffice to provide representative measurements. Instead, measurements at any given location can only represent the local condition in their immediate vicinity, limited to perhaps only a few 100 m depending on the complexity and proximity of wind farms. With the ongoing construction of large wind farms in the North Sea, the wind field is becoming increasingly heterogeneous and new approaches to quantifying this wind field that incorporate multiple measurement locations to form a coherent measurement network are required.

Acknowledgements

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