A study of wind-wave misalignment for the Irish coastline and its effect on the wind turbine response

Conference Paper · August 2022

2 authors:

Shubham Baisthakur
Trinity College Dublin

Breiffni Fitzgerald
Trinity College Dublin

A study of wind-wave misalignment for the Irish coastline and its effect on the wind turbine response

Shubham Baisthakur[1], Breiffni Fitzgerald[1]
[1] Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Ireland
email: baisthas@tcd.ie, Breiffni.Fitzgerald@tcd.ie

ABSTRACT: A wind turbine is one of the largest rotating structures on earth. More wind turbines are now being developed with taller towers and longer blades, making them more flexible. As a result, an offshore wind turbine can exhibit a significant dynamic response. The wind turbines are subjected to a time-varying, highly turbulent loading environment. The wind and wave loads may not always act in the same direction during the wind turbine operation. The misaligned wind-wave loading can excite the less damped side-to-side mode of vibration for a wind turbine, exhibiting an amplified response for a prolonged period. Therefore, the assumption of co-directionality of wind and wave forces may not always represent conservative wind turbine design. The wind-wave misalignment is a local phenomenon, and it depends on the properties of the coast and wind profile. This paper studies the characteristics of wind-wave misalignment for the East Coast of Ireland and its impact on the system loads and deformations. The environmental data from Irish Marine Weather Buoy Network (IWMBN) is used in this study. This study uses environmental data from the Irish Marine Weather Buoy Network (IWMBN). This network of five offshore buoys monitors weather and oceanographic conditions for the Irish coast in real-time. The method of bins is used to study the statistical properties of wind speed and wind-wave misalignment. The response of the IEA 15MW reference wind turbine model with a monopile foundation for co-directional and misaligned wind-wave loading is simulated using OpenFast. It has been observed that misaligned wind-wave loading amplifies the wind turbine response for some operating conditions.

KEY WORDS: Wind-wave misalignment, Irish coastline, IEA 15MW reference wind turbine

1 INTRODUCTION

The concerns around the climate crisis and greenhouse gas emissions are driving the demand for renewable energy worldwide. Offshore wind energy, in particular, is pursued as a domain of high potential as it offers access to a richer wind resource and the least disturbance to the built urban environment. Researchers are pushing boundaries to achieve higher hub heights and larger rotor diameters to exploit the richer wind resource available at higher altitudes. With increasing hub heights, wind turbines are becoming more and more flexible. The increasing turbine heights and rotor diameter lead to increased aerodynamic loads; the wind turbine foundation systems are getting larger to support this increased load. Due to the increased dimensions, the foundation system attracts higher wave loading. The combination of reduced natural frequency and increased hydrodynamic loads lead to a hydrodynamically sensitive structure. A detailed performance analysis under a range of possible operating conditions is necessary to ensure that there is no unanticipated resonance during the wind turbine operation. The misaligned loading can impact both the ultimate and the fatigue loads.

A wind turbine model is designed to produce a specific power output (power rating). The power rating governs the wind turbine features, i.e., the number of blades, rotor diameter and hub height. The structural design of a wind turbine structure is then performed for a set of Design Load Cases [1]. The standard wind turbine model, designed using this approach, is then installed at different locations for power generation. However, many parameters, for example, the load spectrum and natural frequency of the wind turbine, may vary from location to location [2, 3]. The local parameters influencing the wind turbine operation should be identified, and the wind turbine response should be simulated for local conditions to ensure reliable performance. During the operation of a wind turbine, the wind and wave load may not always act in the same direction [4]. Small misalignments between wind and wave loads are observed at all wind speeds, while large misalignments can be seen at higher speeds [5]. For large misalignments, the wave periods are closer to the first modal frequency of the support structure, resulting in higher dynamic amplification. The misaligned loading pattern can also excite the less damped side-to-side vibrations in wind turbine towers and cause vibrations over an extensive period, even for moderate excitations [6, 7]. Many researchers have studied the impact of wind-wave misalignment on various aspects of wind turbine operation [8-11].

Since wind-wave misalignment is a local phenomenon, it may exhibit different patterns at different locations. In this study, the nature of wind-wave misalignment is studied for the Irish coastline. The environmental data from Irish Marine Weather Buoy Network is used in this study.

2 METHODOLOGY

2.1 Modelling of wind-wave misalignment

Ocean waves are primarily generated as a result of momentum exchange between wind and the sea surface. Since wind and waves travel at different speeds, the waves generated by a specific wind profile reach a specific point later than the wind. Therefore, there is a high probability of misalignment in wind and waves. The formation of wind waves depends on various parameters such as the fetch length, wind speed, wind duration, width of fetch and water depth. The geometrical parameters such as fetch length and width are constant for a particular geographic location. Therefore, while studying the wind-wave misalignment for a specific location, the wind-wave misalignment angle can be modelled as a function of the wind speed alone. The wind speed can be modelled as an independent variable for all practical purposes. Under these assumptions, the joint distribution for wind speed and wind-wave misalignment can be given as

$$p(U,\beta) = p(U)p(\beta|U) \tag{1}$$

where, U is the wind speed, and β is the wind-wave misalignment angle. This statistical model is further used in this study.

The Irish Marine Weather Buoy Network (IMWBN) data is used to study the variation of wind speed and the misalignment angle for the Irish coast. The location of weather buoys in the Irish sea is shown in Figure 1. This study focuses on the East Coast of Ireland. The data from weather buoys M2, M3 and M5 is used for the analysis. More than 20 years of wind and wave data measurements are available for these buoy locations. The wind speed is averaged over a 10min period and is reported every hour.

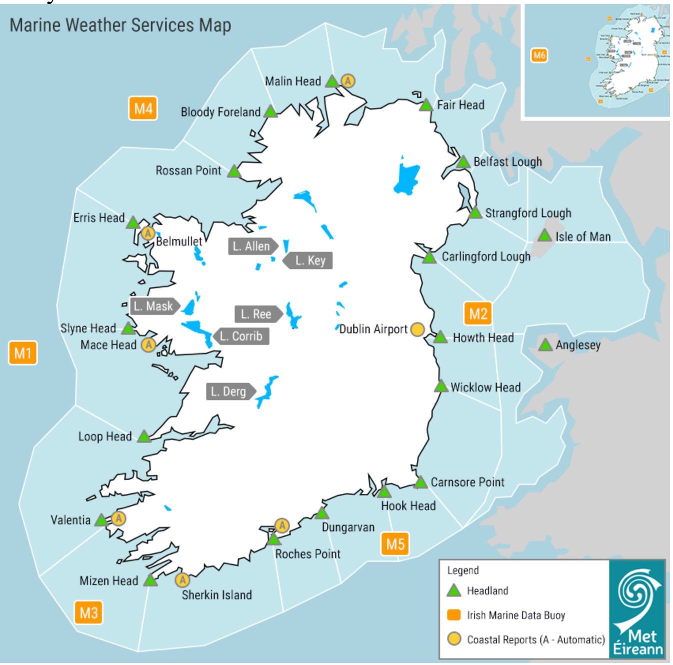

Figure 1. Location of weather buoys in the Irish Sea

2.2 *Metocean Data Analysis*

The wind speed data obtained from the buoys M2, M3 and M5 is analyzed using the method of bins. The method of bins is a statistical method for the analysis of random data. In this method, a number of bins (NB) are defined with a lower and upper limit. The number of observations falling within this range compared to the total number of observations (N) is called the frequency of bin, f. The difference between the lower and upper limits is bin-width(w), while the average is the mid-point(m). A bin width of 1m/s is used for wind speed analysis.

The histogram plot for the wind speed distribution at the selected locations is shown in Figure 2. The height of a histogram is proportional to the frequency of the corresponding bin. A probability distribution curve is obtained by normalizing the histogram heights and joining the histograms' centres, as shown in Figure 2.

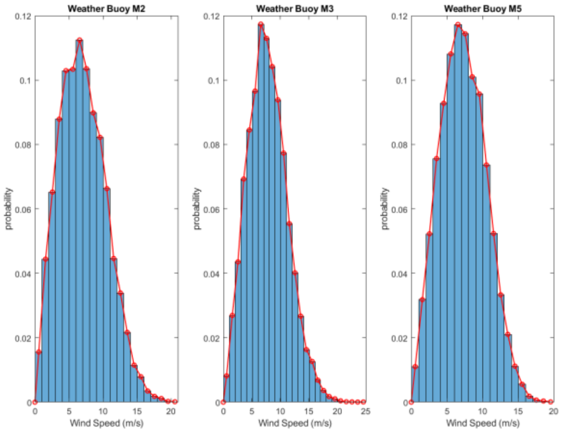

Figure 2. Probability Distribution of wind speed obtained using Method of Bins

This study aims to develop a generic model of wind-wave misalignment for the Irish coast. The data from a single weather buoy may not adequately represent the variations along the entire coast. The data from three weather buoys, M2, M3 and M5, are combined to capture the nature of wind-wave misalignment at different locations across the coast and take into account the information obtained from different locations. The histogram plot in Figure 2 shows that the wind speed at these locations shows similar characteristics. In this study, wind-wave misalignment is modelled as the function of wind speed alone. In this context, the data from these locations are combined to simplify the analysis. The Weibull distribution is found to best represent the wind speed data by performing a goodness of fit analysis. The Weibull distribution parameters for wind speed on the East Coast of Ireland are given in Table 1.

Table 1. Wind Speed Distribution Parameters.

Parameter	Distribution Type	Shape Factor	Scale Factor
Wind Speed	Weibull	2.17	7.90

After defining the wind speed model, wind-wave misalignment data is studied for its dependence on wind velocity. A wind-rose analysis is performed, which shows the recorded values of the wind-wave misalignment at different wind speeds [12]. Figure 3 shows that at lower wind speeds, an extensive range of wind-wave misalignment can be observed; however, as the wind speed increases, the wind-wave misalignment narrows down to a small range. The wind-wave correlation at high wind speeds is often combined with fully developed sea states and weather regimes. Also, the ocean waves generated at low wind speeds are weaker and travel at low speed. However, stronger waves generated at higher wind speeds can travel at higher speeds and exhibit a better correlation with wind speeds.

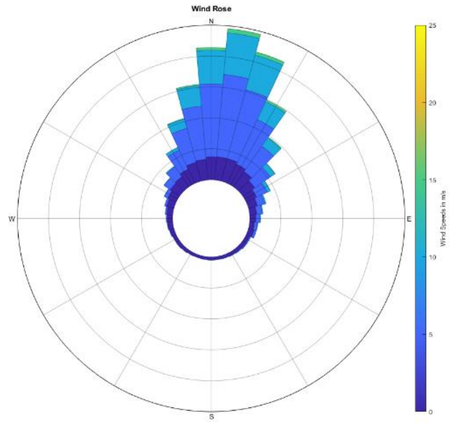

Figure 3. Wind Wave Misalignment on East Coast

The 2D method of bins is used to study the wind-wave misalignment data conditioned over wind speed. The wind speed data is categorized into different wind speed bins of width 1m/s, and the wind-wave misalignment angles observed for a given wind speed bin are recorded. The resulting joint histogram of wind-speed and wind-wave misalignment is shown in Figure 4. The high-intensity pixel shows the high probability of joint occurrence of (U, β) pair. Figure 4 shows that the probability of aligned wind-wave loading increases with an increase in wind speed up to a specific wind speed and decreases with a further increase in wind speed. However, there is not enough data available at high wind speeds, and a more detailed analysis is required to ascertain this phenomenon.

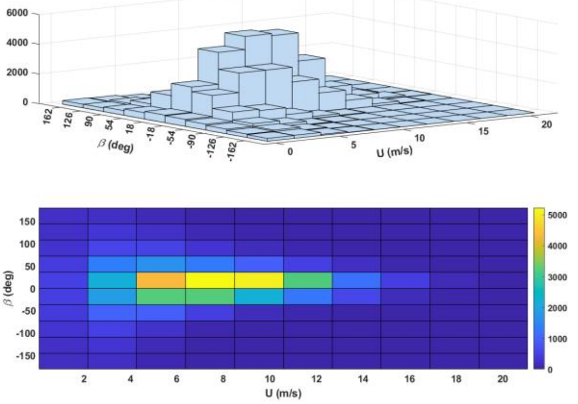

Figure 4. Joint histogram plot of wind speed and wind-wave misalignment

Marginal pdf of wind-wave misalignment angle $(p(\beta|U))$ is presented in Figure 5 to examine the gradual change in the nature of misalignment angle with the increase in wind speed. The wind-wave misalignment for each wind speed bin is shown in Figure 5, where the x-axis represents the wind-wave misalignment angle in degrees.

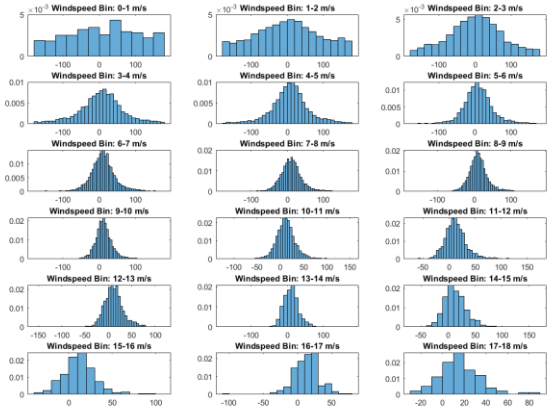

Figure 5. Variation of wind-wave misalignment angle at different wind speeds

From Figure 5, it can be inferred that at low wind speeds, the wind-wave misalignment angle is very weakly dependent on wind speed, whereas, at higher wind speeds, a better correlation is observed. In this context, using a single distribution to model the marginal pdf of wind-wave misalignment $(p(\beta|U))$ may not represent the actual nature of its variation. A critical wind-speed range can be defined below which the wind-wave misalignment angle can be modelled as an independent random variable following a uniform distribution. Further study needs to be carried out to check if the critical wind speed can be defined as a characteristic of a particular coastal location. For the Irish coast, the weak correlation between wind-wave misalignment angle and wind speed is observed below 3m/s, the cut-in wind speed of the IEA-15MW reference wind turbine, so this phenomenon is not discussed in depth. From the statistical analysis, the mean and standard deviation of wind-wave misalignment angle at different wind speeds is mentioned in Table 2. The mean (μ_β) and standard deviation (σ_β) parameters are calculated by following formulas:

$$\mu_\beta = \frac{1}{N}\sum_{i=1}^{N} U_i \tag{2}$$

$$\sigma_\beta = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(U_i - \mu)^2} \tag{3}$$

Further study is required to find the best fit distribution to represent the marginal pdf of wind-wave misalignment angle at different wind speeds.

Table 2. Mean and Standard Deviation of wind-wave misalignment angle at different wind speeds.

Wind Speed	μ_β	σ_β
3.5	4.98	61.92
4.5	7.71	53.98
5.5	8.27	44.00
6.5	9.95	38.00
7.5	10.23	32.50
8.5	11.00	28.50
9.5	11.83	25.42
10.5	11.66	21.90
11.5	12.93	22.65
12.5	11.12	21.55
13.5	10.67	24.00
14.5	13.00	21.00
15.5	12.40	20.00
16.5	12.83	19.40
17.5	15.40	19.25

3 EFFECT OF WIND-WAVE MISALIGNMENT ON THE RESPONSE OF IEA-15MW REFERENCE WIND TURBINE

To study the severity of the impact of wind-wave misalignment on wind turbine response, the wind-turbine response is simulated for co-directional and misaligned wind-wave loading, and the deformation and reactions under these conditions are compared. The wind speed and wave direction parameters mentioned in Table 2 are used for the simulation. This reference wind turbine is chosen for this study as it represents the largest standalone wind turbine model and is a leap ahead of current generation wind turbines. [13]. The IEA-15MW reference wind turbine is an IEC Class 1B direct-drive machine with a rotor diameter of 240 meters (m) and a hub height of 150 m. The wind turbine response is simulated using OpenFast, a computer-aided aero-servo-hydro-elastic tool widely used to model the horizontal axis wind turbines [14]. This tool uses the AeroDyn module to compute the aerodynamic forces and HydroDyn to compute the hydrodynamic loads. This simulation assumes that the rotor always faces the inflow wind, and the mean wave direction is equal to the wind-wave misalignment angle. A pictorial representation of the loading configuration is shown in Figure 7. The wave coming from the positive Y-axis is considered positively misaligned and vice versa.

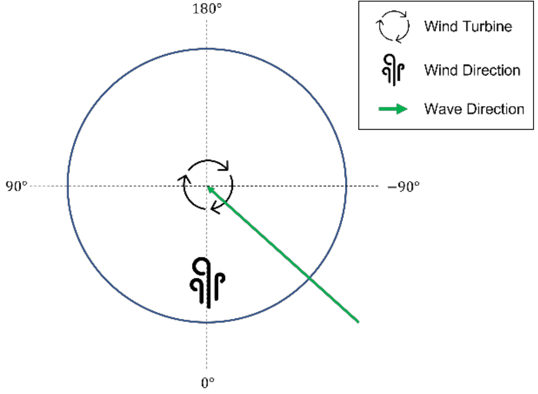

Figure 6. Wind-Wave loading configuration

The effect of misalignment on the tower side-to-side deformation and the forces generated at the tower base in the Y direction (perpendicular to inflow wind) are shown in Figure 7 and Figure 8, respectively.

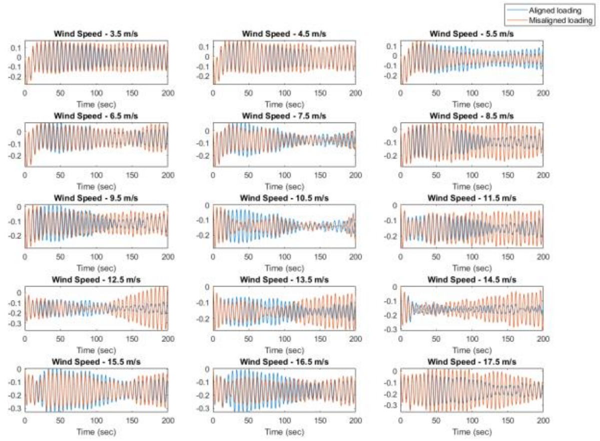

Figure 7. Effect of wind-wave misalignment on tower side-to-side deformation

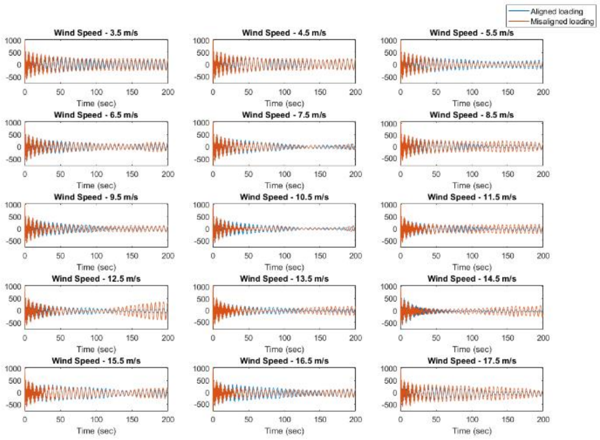

Figure 8. Effect of wind-wave misalignment on tower base reaction in Y-direction

4 CONCLUSION

Figures 7 and 8 show that the misaligned loading pattern creates high amplitude oscillations in tower side-to-side forces and deformation at certain wind speeds. These high amplitude fluctuations in tower forces will increase the range of stress reversal and can adversely impact the fatigue life of the wind turbine. A detailed analysis is required to quantify the effect of wind-wave misalignment on the fatigue life of the structure. These simulations show that the co-directionality of wind and waves may not always lead to a conservative design. The misalignment in the wind and waves should be accounted for to achieve a reliable fatigue life of the structure.

ACKNOWLEDGMENTS

This work has been supported by the SEAI RD&D Projects SEAI/19/RDD/511 and SEAI-21/RDD/601 . The authors are grateful for the support.

REFERENCES

1. CHANGE, T.S.T. and M. BE, *Wind energy generation systems–Part 3-1: Design requirements for fixed offshore wind turbines.*
2. Bhattacharya, S., *Design of foundations for offshore wind turbines*. 2019: John Wiley & Sons.
3. AlHamaydeh, M. and S. Hussain, *Optimized frequency-based foundation design for wind turbine towers utilizing soil–structure interaction.* Journal of the Franklin Institute, 2011. **348**(7): p. 1470-1487.
4. Li, X., et al., *Effects of the yaw error and the wind-wave misalignment on the dynamic characteristics of the floating offshore wind turbine.* Ocean Engineering, 2020. **199**: p. 106960.
5. Bachynski, E.E., et al., *Wind-wave misalignment effects on floating wind turbines: motions and tower load effects.* Journal of Offshore Mechanics and Arctic Engineering, 2014. **136**(4).
6. Fitzgerald, B., D. Igoe, and S. Sarkar. *A Comparison of Soil Structure Interaction Models for Dynamic Analysis of Offshore Wind Turbines*. in *Journal of Physics: Conference Series*. 2020. IOP Publishing.
7. Fischer, T., et al., *Study on control concepts suitable for mitigation of loads from misaligned wind and waves on offshore wind turbines supported on monopiles.* Wind Engineering, 2011. **35**(5): p. 561-573.
8. Verma, A.S., et al., *Effects of Wind-Wave Misalignment on a Wind Turbine Blade Mating Process: Impact Velocities, Blade Root Damages and Structural SafetyAssessment.* Journal of Marine Science and Application, 2020. **19**(2): p. 218-233.
9. Stewart, G.M. and M.A. Lackner, *The impact of passive tuned mass dampers and wind–wave misalignment on offshore wind turbine loads.* Engineering structures, 2014. **73**: p. 54-61.
10. Koukoura, C., et al., *Cross-wind fatigue analysis of a full scale offshore wind turbine in the case of wind–wave misalignment.* Engineering structures, 2016. **120**: p. 147-157.
11. Hildebrandt, A., B. Schmidt, and S. Marx, *Wind-wave misalignment and a combination method for direction-dependent extreme incidents.* Ocean Engineering, 2019. **180**: p. 10-22.
12. Pereira, D., *Wind Rose*. 2022: Matlab Central File Exchange.
13. Gaertner, E., et al., *IEA wind TCP task 37: definition of the IEA 15-megawatt offshore reference wind turbine*. 2020, National Renewable Energy Lab.(NREL), Golden, CO (United States).
14. Marshall Buhl, G.H., Jason Jonkman, Bonnie Jonkman, Rafael Mudafort, Andy Platt, Mike Sprague, *The New Modularization Framework for the FAST Wind Turbine CAE Tool*. 2022.