Study of Wind-Wave Interactions Based on a Wave-Modified Two Equation Model and Measurements at FINO1

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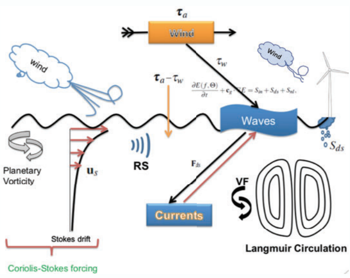
Introduction

In addition to the atmospheric forcing's, energetic ocean waves induce considerable dynamical (fatigue) loads to the offshore wind turbines and modulations to the wind fields, which influence the wake-flow statistics and the wake-wake interactions inside the wind farm. Therefore, complex turbine wake-flow phenomena resulting from the dynamical coupling between the wind and the waves may impose considerable challenges when designing offshore wind turbines/farms.

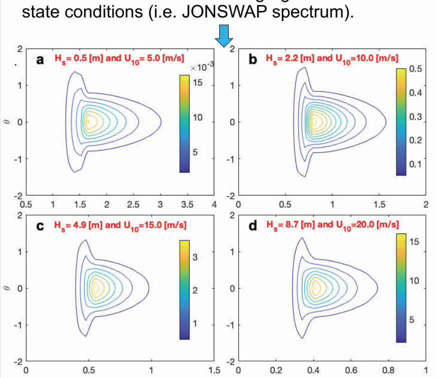
Primary objective is to better understand the wind-wave interactions through:

- Improving the predictive ability of *a two-equation model for the atmospheric boundary layer turbulence* by incorporating the effects of wind-wave interaction.
- Analysing offshore data measured from *two sonic anemometers mounted on* the German wind energy research platform FINO1 to study *wind-wave interactions.*

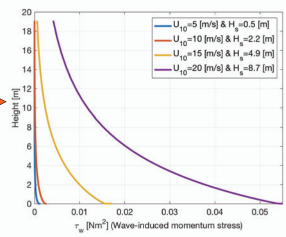


Wind-Wave Interactions: 1D Model

We investigate turbulence structures over idealised gravity wave fields under the effects of different sea state conditions. Following figure shows 2D wave energy spectra for different forcing and sea-state conditions (i.e. JONSWAP spectrum).



Wave-induced stress acting on atmospheric boundary layer calculated from the wave energy spectra as shown in the left-hand side figure



Wave wind decomposition:
Total=Turbulence+Mean+Wave

$$\mathbf{u} = \bar{\mathbf{u}} + \tilde{\mathbf{u}} + \mathbf{u}',$$

$$\tau_{tot} \simeq \tau_t + \tau_v + \tau_w,$$

Momentum

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[K_m \frac{\partial \bar{u}}{\partial z} + \tau_w\right],$$

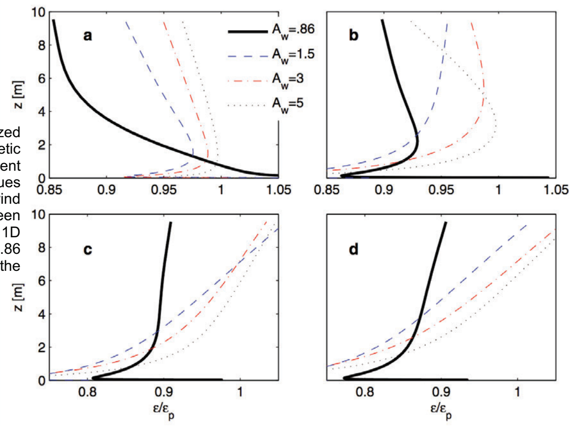
Energy

$$\frac{\partial e}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(K_e \frac{\partial e}{\partial z}\right) + P - \varepsilon,$$

$$\frac{\partial \varepsilon}{\partial t} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(K_\varepsilon \frac{\partial \varepsilon}{\partial z}\right) + \frac{\varepsilon}{e}(c_{1\varepsilon} P - c_{2\varepsilon}\varepsilon),$$

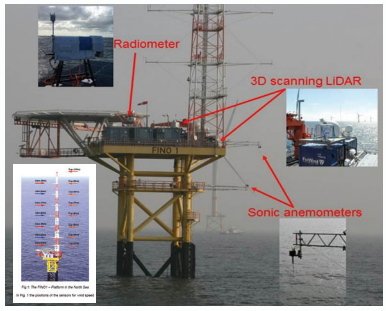
Here, τ_t τ_v and τ_w are turbulent, viscos, and wave-induced stresses, respectively. $\bar{\mathbf{u}}$, $\tilde{\mathbf{u}}$, and $\mathbf{u}'$ are mean, wave-induced, and turbulent wind fields, respectively. ρ Denotes air density, z and t denote height and time. K_m , K_e and K_ε are momentum and energy eddy viscosity, respectively. Epsilon and *e* are Turbulent Kinetic Energy (TKE) and its dissipation, respectively. *P* is shear energy production and c_x are tunable coefficients.

Vertical structure of normalized dissipation rate of turbulent kinetic energy (i.e. *x*-axis) for different inverse wave ages, A_w, and values of significant wave height and wind speed. These profiles have been calculated though solving above 1D differential equations. A_w=0.86 (inverse wave age) indicates the swell-dominated condition [2].



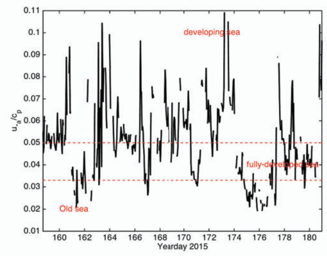
FINO1 Measurement Site

Picture of FINO1 offshore platform in the North Sea. The superstructure of FINO1 fitted with different sensors such as sonic anemometers and lidars. Meteorological measurement. To study the wind-wave interactions, we use measurments from two sonic anemometers mounted at 15 m and 20 m heights above the mean sea level. The deployment was part of the Offshore Boundary Layer Experiment at the FINO1 (OBLEX-F1).

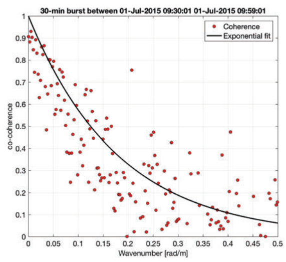


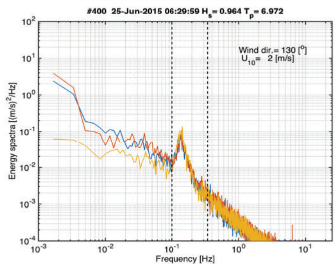
Results

*Air-side **friction velocity**, u_{*a}, calculated from cup-anemometer at 33-m height. Here, we show time series of wave age, c_p/u_{*a} and different sea-state conditions for days in 2015.*



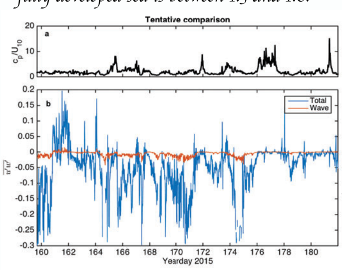
***Coherence structure** between 15 m and 20 m sonic anemometers.*





Effect of Wind-wave interactions for sonic anemometer at 15 m height as a clear peak at the wave frequency band. Wave peak frequency, f_p, has been extracted from a bouy deployed in the close vicinity of FINO1 and vertical lines are [$0.7f_p$, $1.5f_p$], [1,2].

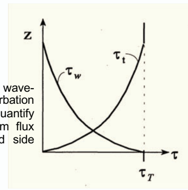
In following figure, c_p/U_{10} shows another representation for wave age which its values for fully developed sea is between 1.3 and 1.6.



Due to the lack of sufficient knowledge about the structure of the wave-induced pressure field, we can use either parameterization or measured velocity spectra to estimate wave-induced stress.

$$\rho_a \overline{\tilde{u}\tilde{w}}|_\eta = p_\eta \frac{\partial \eta}{\partial x}$$

It is possible to use the wave-induced air pressure perturbation and wave slope in order to quantify the wave-induced momentum flux (i.e. red curve in left-hand side figure).



Summary

In this work, we study the interactions between waves and wind from modelling and observational perspectives. In the modelling part, we use a simplified *wave-coupled 1D model* to study the effect of swell-induced motions on turbulence statistics (i.e. *dissipation rates of TKE*) under different wind and sea-state conditions. The observational component of the work contains analysis of data measured from two *sonic anemometers* mounted on FINO1 offshore platform at 15 m and 20 m heights above the mean sea level. We showed the characteristics of *coherence structures* between two heights and also detected clear signals of wind-wave interaction in our datasets. We have discarded several model-observation results in this poster for the sake of brevity.

References

[1] Mostafa Bakhoday Paskyabi, Martin Flügge, James B. Edson, and Joachim Reuder, Wave-induced characteristics of atmospheric turbulence flux measurements, Energ. Proced., 35, 102–112, 2013.

[2] M. Bakhoday Paskyabi, S. Zieger, A.D. Jenkins, A. V. Babanin, D. Chalikov, Sea Surface Wave-Wind Interaction in the Marine Atmospheric Boundary Layer, Energ. Proced., 53(2014) 184-192.

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