Higher-order harmonics of non-breaking wave loads on offshore wind turbines

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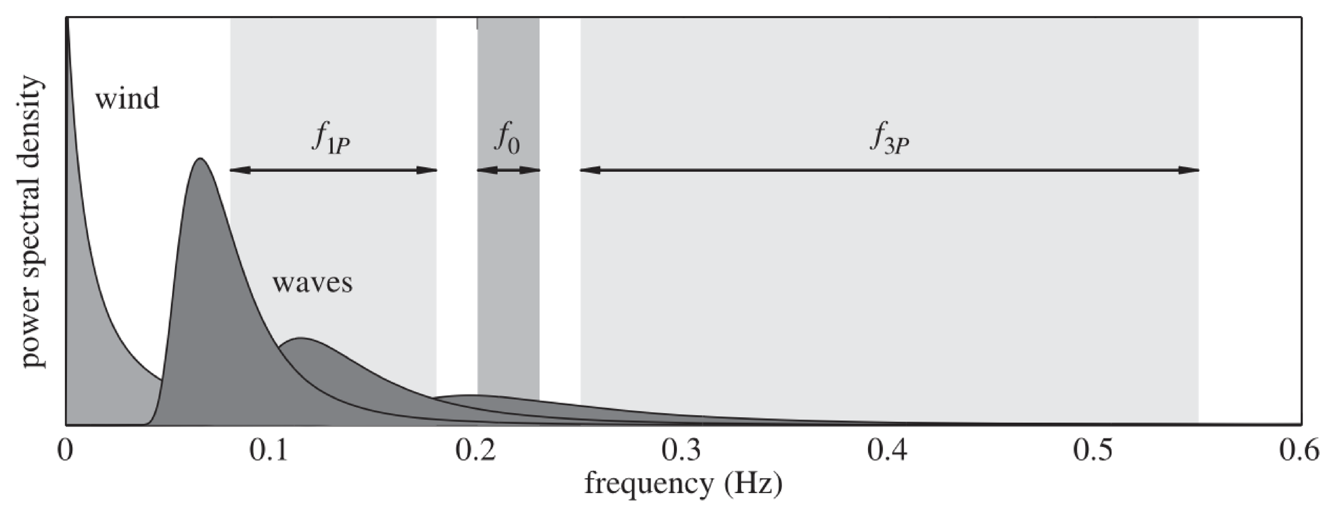
Background

Over 80% of offshore wind turbines currently installed are supported on monopiles. Wind turbines are dynamic structures, so engineers aim to design their natural frequency to be different from the loading frequencies. The figure to the right shows a typical design where the natural frequency of the structure is designed to sit away from the natural frequency of the ocean wave spectrum. The problem is that waves generate higher harmonics when they interact with structures the frequency of which will align with that natural frequency of the structure. This also increases the magnitude of the load significantly. Therefore, these may be important for design. However, engineers need models that are fast and straightforward.



From [1]. Typical frequencies of loading on an offshore wind turbine. The 1P and 3P frequencies are due to the rotation of the three blades. The wave spectrum shown is typical for storm waves. This will induce loads at the wave frequency but also at higher harmonics of the wave frequency which is the subject of this poster.

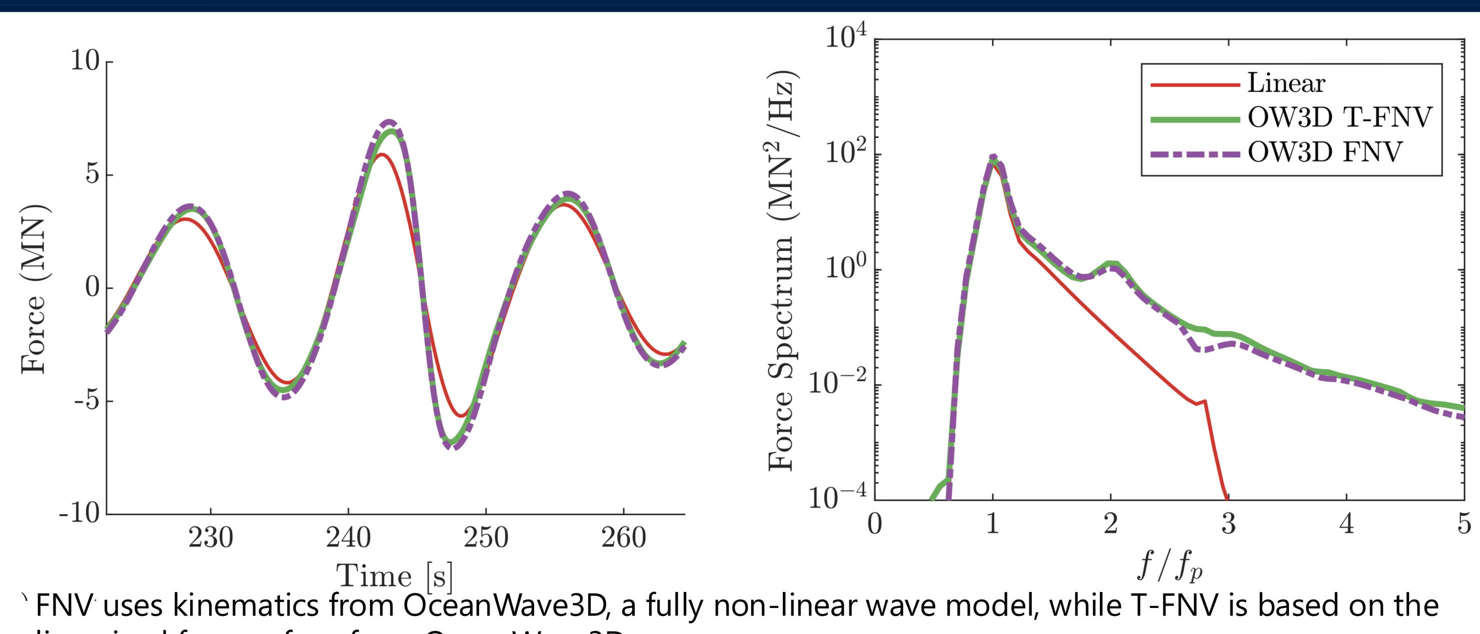
Experimental/CFD approach

It is possible to investigate use either CFD or experiments to investigate the higher harmonics of loads on structures. The problem is that it is not feasible to do this quickly or cheaply in the way needed for design. To tackle this, we assume that the loading can be modelled as harmonics of a linear force (a "Stokes-type" perturbation approach). Thus

$$F = \mathcal{F}_1 \cos\varphi + \mathcal{F}_1^2 F_2 \cos(2\varphi + \phi_2) + \mathcal{F}_1^3 F_3 \cos(3\varphi + \phi_3) + \cdots$$

The linear component is relatively straightforward to calculate. The task is then to infer the magnitude and phase of the harmonics which will be a function of depth and column radius. We do this primarily from laboratory data using data-sets from the Danish Hydraulics Institute and Kelvin Hydrodynamics Laboratory. We then infer the coefficients using a Gaussian Process [2] to create the "Stokes-GP" model.

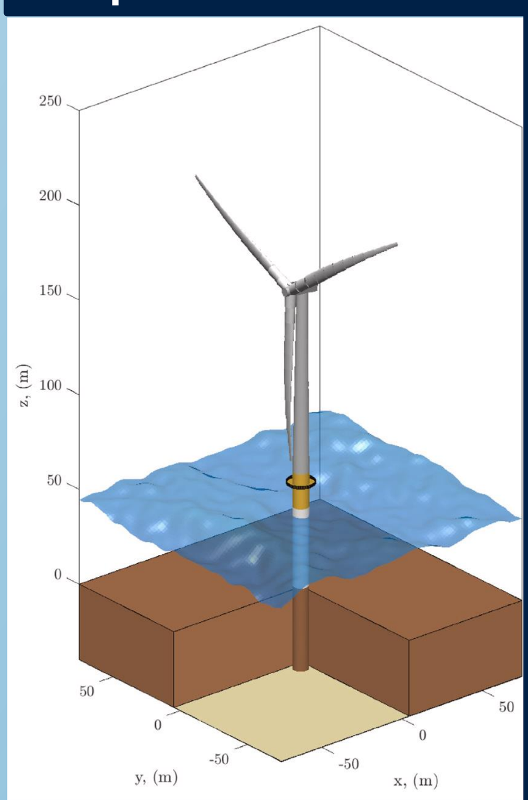
Analytical approach



FNV uses kinematics from OceanWave3D, a fully non-linear wave model, while T-FNV is based on the linearised free surface from OceanWave3D.

The two classic approaches to analytical calculations are the FNV model [3] and the very similar model due to Rainey. A key problem with these models is that they require non-linear wave kinematics which is computationally difficult and expensive. To make these models computationally efficient, we have made some further assumptions to create the "Transformed-FNV" method [4]. This accurately captures the non-linearity of the original model but only requires a linear free surface profile. It is thus practical to use it for fatigue calculations.

Impact on design?



We use an in-house hydro-aero-elastic code OxDyn [5] to investigate whether including the higher harmonics has a significant impact on design. The model is shown schematically on the left. We use typical metocean conditions for Dogger Bank and run through multiple load cases. For a 10 MW turbine results are summarised in the table on the right showing a significant difference in the peak forces. For larger 15 MW turbine the differences are less significant as wind loads play a larger part in the loading. However, given the increase in load and the simplicity of applying either of the non-linear models we recommend that one of them is used for calculations.

	Shear at base (MN)	**Bending moment at base (MNm)**
Linear	15	793
Analytical	19	953
Stokes-GP	25	981

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