Parametric Wave Excitation Model for Floating Wind Turbines

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Problem description

A state-space model is fitted to the wave-excitation force coefficient from panel-codes for two floating wind turbine (FOWT) models. As shown on the right the wave excitation transfer function (step 1) allows the derivation of a complete, "unified" linear description of the FOWT model (step 2) together with existing radiation force models. The transfer function to structural FOWT states has been set up and verified successfully.

The motivation for this work is:

- Derive a parametric wave-disturbance model for FOWT time-domain simulations
- Generate a "unified" linear FOWT model for controller design & optimization
- Set up a transfer function necessary for a wave-feedforward controller

Keywords: State-space modeling, wave excitation force, disturbance model, integrated floating wind turbine model, radiation force model.

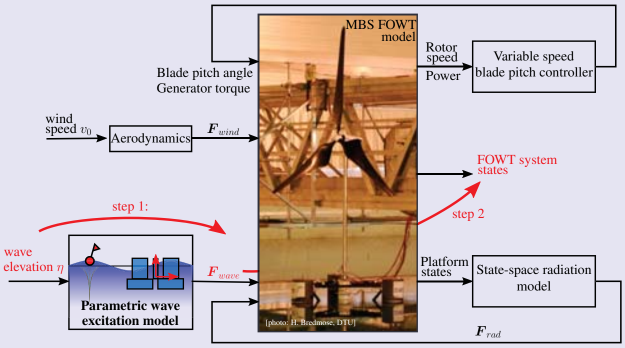
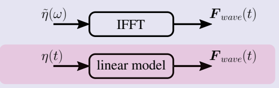


Figure 1: State-space FOWT model: Wave excitation transfer function is subject to this work.

Introduction

Panel codes provide the first-order wave excitation force coefficient $\boldsymbol{X}(\omega)$. For time-domain simulations an inverse Fourier transform prior to a simulation is usually necessary. Here, a linear model shall be fitted in order to obtain the wave forces $\boldsymbol{F}_{wave}(t)$ directly from a time-domain wave height input $\eta(t)$:



As proposed by [1] a state-space model is fitted to the impulse response of the wave-excitation force transfer function (e.g. the force response to a wave height impulse). Before this is done a causalization is necessary.

Causalization

The transfer function from wave height η to the forces and moments on the floating body $\boldsymbol{F}_{wave}$ is not always causal, depending on the position of the wave height measurement. Forces might arrive at the hull prior to the corresponding free-surface elevation. Figure 2 (grey line) shows that the wave force impulse response has a response at negative times, which proves the non-causality.

However, if the wave height is measured at a sufficient distance from the platform, against wave direction, the problem is causal. Therefore, prior to the model fit the impulse response is shifted in time by $\tau_c = 6\,\text{s}$, see the red line in Fig. 2.

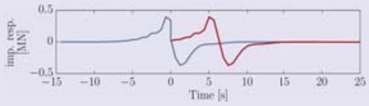


Figure 2: Non-causal (grey) and causalized (red) wave excitation impulse response of the OC3 spar in surge.

In frequency-domain the time-delay is represented by a frequency-dependent phase-lag $\varphi_c(\omega)$

$$\varphi_c(\omega) = \omega\ \tau_c \qquad (1)$$

Wave excitation model fit

A state-space model is now fitted to the causalized time-domain impulse response: Two hull shapes have been used for an assessment of the method: The cylindrical OC3-spar shape as well as the more complex OC4-semi submersible. Figure 3 shows the frequency-domain transfer function as well as the impulse response for the phase-shifted panel-code results with the model fit of $n_{states} = [4, 6, 8]$ in surge and pitch direction. Figure 4 shows the time-response of the 6-state model to a linear irregular wave input with peak period $T_p = [10, 15]s$.

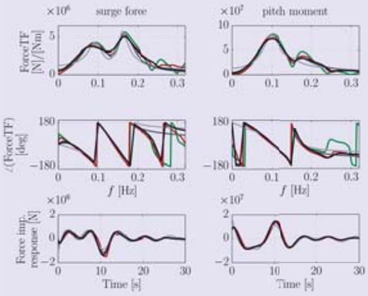


Figure 3: Panel code (green), causalized (red), model fit for OC4 semi-submersible with $n_{states} = [4, 6, 8]$ (grey, increasing darkness): 6-state model selected.

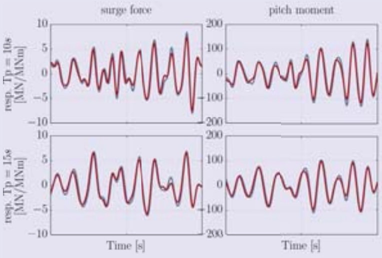


Figure 4: Wave force response by inverse Fourier transform (grey) and 6-state fitted model (red) for $T_p = [10, 15]$s, OC4 semi-submersible.

The model with 6 states shows a good agreement to the IFFT method in frequency and time-domain for the surge and pitch response of the OC4 semi-submersible. While the 6-state-OC4 model fits with 74.9 % the simpler OC3-model with 6 states shows a 87.9 % agreement.

Coupled transfer function

Now, the transfer function from wave height to tower-top displacement can be calculated and verified: A coupled nonlinear FOWT model of the OC4 semi-submersible is run with regular unit-amplitude wave force timeseries as input until it reaches a steady state.

Figure 5 shows for each frequency the amplitude and phase towards the wave input (red) and compares it to the linear wave transfer function of Fig. 3 in series with the linearized structural model (grey). The model is a 2D model with the degrees of freedom surge, pitch, tower-top displacement and rotor speed. It is run here without aerodynamic forces.

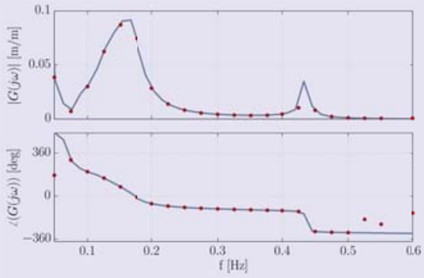


Figure 5: Transfer function from wave height η to tower-top displacement x_t for OC4 semi-submersible. Linear model (grey), nonlinear model (red).

Conclusions

A state-space model has been fitted to the linear wave excitation force coefficient from a panel-code. The results for two hull shapes of different complexity show that with few states it is possible to obtain a good agreement with the panel code for realistic ocean wave frequencies.
The overall transfer function from wave height to the wind turbine tower-top displacement has been calculated and verified through a comparison with the nonlinear FOWT model.
In future works the model will be used for the design of advanced FOWT controllers for improved power production and load reduction. A wave-feedforward control of a scaled model in a wind-wave basin is scheduled for March 2016.

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[1] Yu, Z., Falnes, J. (1995) State-space modelling of a vertical cylinder in heave. *Applied Ocean Research;* 17(5):265-275.