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Scaling of slow-drift motion with platform size and its importance for floating wind turbines

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ABSTRACT

Slow drift is a large, low-frequency motion of a floating platform caused by nonlinear hydrodynamic forces. Although slow drift is a well-known phenomenon for ships and other floating structures, new platforms for floating wind turbines are significantly smaller in scale, and it is yet to be established how important slow drift is for them. In this paper we derive an approximate expression for the scaling of the slow drift motion with platform size, mooring characteristics and wave conditions. This suggests that slow drift may be less important for floating wind turbines than other, larger, floating structures. The accuracy of the approximations is discussed; in the one case where detailed data is available, the approximate result is found to be conservative by a factor of up to 40.

1. Introduction

Floating wind turbines are increasingly of interest for their ability to access wind resources over deep water. Their development draws on both existing fixed-base wind turbines and other types of floating platforms, but introduces additional modelling challenges which require the development of new modelling tools. In this paper we consider the importance of the 'slow drift motion' for floating wind turbines; a wider discussion of modelling floating wind turbines is given in Ref. [1].

Slow drift is a large, low-frequency motion of a floating platform caused by nonlinear hydrodynamic forces which excite a resonant motion of the moored platform [2, chapter 5]. These second-order forces are much smaller than the main hydrodynamic loading, but occur at low frequencies where there is otherwise little excitation. Since there is typically little damping in the low-frequency modes of the moored platform, the response can be large despite the small magnitude of the forces. Slow drift is therefore one of the three main components of the loadings and motion in a mooring system, alongside static and wave-frequency forces [3]. Although we focus here on the low-frequency forces, there are similar high-frequency nonlinear forces which can excite structural vibration models of the structure [2].

As well as its practical importance for design, this motion presents challenges in modelling. In the time domain, the low frequency of the motion means that very long simulations are needed to properly capture the behaviour. In the frequency domain, although the spectrum of the nonlinear forces can be calculated fairly easily, the statistics are non-Gaussian, which adds a little to the difficulty of predicting the response. It is therefore useful to know how significant the slow drift motion can be for floating wind turbines. Note that it is not necessary to neglect it completely to achieve simplifications: in the frequency domain, simplifications can be made if the slow drift motion is small compared to the wave frequency motion, and its statistics can be approximated as Gaussian.

Although slow drift is well-known in traditional floating offshore structures, it has been studied in only a few cases for floating wind turbines. Lucas [4] calculated the first- and second-order response of the OC3-Hywind spar-buoy [5] and a semisub platform, using the commercial panel code WAMIT [6] together with an in-house code, for three regular-wave and three irregular-wave conditions. More recently, motivated by observations of possible second-order effects in scale model tests [7], Roald et al. [8] calculated first- and second-order forces and responses for two specific floating wind turbine designs, the same OC3-Hywind spar

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buoy, and a tension-leg platform (TLP). They also used WAMIT, together with linearised system matrices calculated by the wind turbine code FAST [9]. Although FAST does not yet account for second-order hydrodynamics, this is being addressed [10]. Bayati et al. [11] apply the same approach to a semisub platform.

The conclusions of these results for the different platforms and wave conditions vary: in some cases the slow drift response is smaller than the first-order motion, and in some cases it is larger. This contrasts with the expectation for traditional floating structures that the slow drift motion is large compared to the first-order motion, albeit for only the few results which are available. We suggest this difference in behaviour may be due to the significant difference in scale between floating wind turbines and other floating structures: some can be an order of magnitude larger than floating wind turbine platforms, while ships can be even larger.

To our knowledge there is no particular discussion in the literature of how slow drift motion scales with the size of the floating platform. In this paper, we derive an expression which approximates the scaling of the slow drift motion with platform size, mooring characteristics and wave conditions. While the studies mentioned above give results for particular platform designs and wave conditions, we aim to give a more general result. To do this several approximations and assumptions have been made, so the result is only an approximation. We conclude by discussing the expected accuracy of these approximations.

Frequency-domain models of floating wind turbines, whether or not they include second-order hydrodynamics, have previously limited themselves to the rigid-body dynamics of the floating platform [1]. Although this is often reasonable, it has sometimes been presented as a limitation of the frequency-domain approach itself. We therefore note that the approach described here is capable of including the flexibility of the structure, and give an example of the 'OC3-Hywind' floating wind turbine mentioned above.

Before beginning we should put these second-order low-frequency forces into perspective on a wind turbine. As Roald et al. [8] show, when the turbine is operating the low-frequency aerodynamic forces on the rotor are much larger than the low-frequency hydrodynamic forces, making the second-order hydrodynamic forces unimportant. However, they are still of interest whenever the turbine is not operating. This may be due to high wind speeds (in extreme environmental conditions), or due to faults (under any environmental conditions).

2. Frequency-domain model of flexible structure

The basic form of the frequency domain model is

$$\left\{ -\omega^2 \boldsymbol{M} + i\omega \boldsymbol{B} + \boldsymbol{K} \right\} \overline{\boldsymbol{q}}(\omega) = \overline{\boldsymbol{F}}(\omega) \tag{1}$$

or equivalently

$$\overline{\boldsymbol{q}}(\omega) = \boldsymbol{H}(\omega) \overline{\boldsymbol{F}}(\omega) \tag{2}$$

where $\boldsymbol{H}$ is the system transfer function matrix, and $\overline{\boldsymbol{q}}$ and $\overline{\boldsymbol{F}}$ are the complex amplitude of the response and applied force for sinusoidal motion at frequency ω:

$$\boldsymbol{F} = \overline{\boldsymbol{F}}(\omega) e^{i\omega t} \tag{3a}$$

$$\boldsymbol{q} = \overline{\boldsymbol{q}}(\omega) e^{i\omega t} \tag{3b}$$

with the convention that the real part is assumed. If the cross-spectral density of the force is $\boldsymbol{S_{FF}}(\omega)$, the cross-spectral density of the system response can be found as [12, chapter 6]:

$$\boldsymbol{S_{qq}}(\omega) = \boldsymbol{H}(\omega) \boldsymbol{S_{FF}}(\omega) \boldsymbol{H}^{*T}(\omega) \tag{4}$$

where ^{*T} indicates the complex conjugate transpose. The response variances can then be found from the covariance matrix,

$$\mathrm{E}\left[\boldsymbol{q}\boldsymbol{q}^T\right] = \mathrm{Re} \int_0^\infty \boldsymbol{S_{qq}}(\omega) \mathrm{d}\omega \tag{5}$$

These equations are very general. Next, the parts of the equation of motion (1) will be defined in more detail in relation to a general floating structure. Then the frequency-domain model is applied to an example floating wind turbine.

2.1. Equations of motion of a floating structure

For a flexible structure with hydrodynamic loading, the mass, damping and stiffness matrices which appear in Equation (1) can be written as

$$\boldsymbol{M} = \boldsymbol{M}_{\mathrm{struct}} + \boldsymbol{A}_{\mathrm{h}}(\omega) \tag{6a}$$

$$\boldsymbol{B} = \boldsymbol{B}_{\mathrm{struct}} + \boldsymbol{B}_{\mathrm{h}}(\omega) + \boldsymbol{B}_{\mathrm{v}} \tag{6b}$$

$$\boldsymbol{K} = \boldsymbol{K}_{\mathrm{struct}} + \boldsymbol{K}_{\mathrm{h}} + \boldsymbol{K}_{\mathrm{m}} \tag{6c}$$

Here $\boldsymbol{A}_{\mathrm{h}}$ and $\boldsymbol{B}_{\mathrm{h}}$ are the hydrodynamic added mass and radiation damping matrices; $\boldsymbol{B}_{\mathrm{v}}$ is a linearised viscous damping matrix; $\boldsymbol{K}_{\mathrm{h}}$ is the hydrostatic stiffness matrix; $\boldsymbol{K}_{\mathrm{m}}$ is the linearised mooring line stiffness; and $\boldsymbol{M}_{\mathrm{struct}}$, $\boldsymbol{B}_{\mathrm{struct}}$ and $\boldsymbol{K}_{\mathrm{struct}}$ are the structural mass, stiffness and damping matrices. Most commonly the submerged part of the structure will be assumed rigid and the hydrodynamic, hydrostatic and mooring matrices will contain only the terms relating to the six rigid-body degrees of freedom, while the structural system matrices will in general relate to all the degrees of freedom of the structure.

The applied forces consist of aerodynamic loads on the wind turbine rotor, wave excitation forces, and viscous drag forces. Here we ignore aerodynamic and viscous forces, although they could be included given a suitable linearisation. Mooring line forces are assumed to be accounted for by the linearised stiffness matrix $\boldsymbol{K}_{\mathrm{m}}$ and are not counted as applied forces here. Correct to second order, the wave excitation forces can be written as the first two terms in a Volterra series,

$$\boldsymbol{F}(t) = \int_{-\infty}^{\infty} \boldsymbol{H}_1(\omega) \zeta(\omega) e^{i\omega t} \mathrm{d}\omega + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \boldsymbol{H}_2(\omega_1, \omega_2) \zeta(\omega_1) \zeta(\omega_2) e^{i(\omega_1 + \omega_2)t} \mathrm{d}\omega_1 \mathrm{d}\omega_2 \tag{7}$$

where $\zeta(\omega)$ is the Fourier transform of the sea surface elevation, and $\boldsymbol{H}_1(\omega)$ and $\boldsymbol{H}_2(\omega_1,\omega_2)$ are the Fourier transforms of the first- and second-order Volterra kernels [13]. This shows that the wave loading consists of forces at ω which are linear in the wave amplitudes, and forces at $\omega_1 + \omega_2$ which are second order in the wave amplitudes. Because the range of the integrals above is from $-\infty$ to ∞, the second-order forces occur at both the sum and difference frequencies of the waves. The difference-frequency forces are of particular interest because they can excite large platform motions. Although in future it may be of interest to include sum-frequency forces, they are not considered further at present.