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Drag, added mass and radiation damping of oscillating vertical cylindrical bodies in heave and surge in still water

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ABSTRACT

Forced heave and surge motion of axisymmetric vertical cylindrical bodies with flat and rounded bases are simulated using the advanced CFD software STAR-CCM+ where the overset method is used so that the mesh local to the body moves within a stationary outer mesh. Viscous effects generating drag, and also influencing added mass and radiation damping, are determined. The Reynolds-Averaged Navier–Stokes (RANS) equations are adopted with different turbulence closure models and the water surface is captured by the volume of fluid (VOF) method. These results are of basic interest but the main motive is to assess appropriate drag coefficients for use with linear diffraction models of wave energy converters (WEC) and we have particular interest in the multi-body WEC M4. A basic dynamical model is set up so that drag, added mass and radiation damping coefficients may be obtained from the CFD results. Added mass and radiation damping coefficients were also obtained from the potential flow solver WAMIT for comparison. Mesh convergence studies were undertaken and while mesh independence was achieved for total force it was not possible for the very small shear force. In the laboratory a free heave decay test was undertaken without mechanical contact for bodies with rounded bases and the inferred drag and added mass coefficients were very close to those from CFD. Some general observations are possible for motion in heave. For the hemispherical base the drag coefficient C_d is very low for small amplitudes but this increases as amplitude is increased. For the rounded base with a flat central area the C_d is larger and for the wholly flat base it is larger again but with values less than 0.35. For a larger geometric scale (times 32) for the hemisphere and round base cases the C_d are generally somewhat reduced. For surge motion the C_d show less variation and are always greater than heave values by at least a factor of 2 which is indicative of effects due to separation and wake generation.

1. Introduction

Floating cylindrical bodies are widely used in offshore engineering, e.g. spar, tension leg and other semi-submersible platforms for oil production and point absorbers for wave energy conversion (Drew et al., 0000; Falcão, 2010; Babarit, 2015). We have particular interest in the multi-body WEC M4 composed of several connected cylindrical bodies (Stansby et al., 2015b, a; EatockTaylor et al., 2016; Stansby et al., 2016; Sun et al., 2016, 2017; Stansby et al., 2017). Linear diffraction analysis

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in the frequency and time domains is quite standard practice for operational conditions and extreme conditions require model testing (Drew et al., 0000; Falcão, 2010; Santo et al., 2017) or full CFD simulation for nonlinear conditions. Linear (and second-order) diffraction analysis can be undertaken with standard modern computing while CFD requires massive parallel processing with numerical convergence, and hence accuracy, uncertain. It is thus attractive to add viscous effects to the linear diffraction analysis based on potential flow theory (Stansby et al., 2015b; EatockTaylor et al., 2016; Stansby et al., 2016; Sun et al., 2016, 2017; Stansby et al., 2017). This may be achieved through drag coefficients with body motion relative to the fluid defining an additional drag force. Viscous effects also have a small influence on added mass and possibly radiation damping and this is a secondary consideration.

In spite of the widespread use of cylindrical bodies offshore there is little information on drag coefficients, at least in the open literature. While CFD is computationally demanding or even possibly unattainable for general configurations undergoing multi-mode motion in waves, which are generally irregular and multi-directional, high resolution CFD is possible with simple geometries in single modes of motion. The aim is to determine drag coefficients to enable drag forces to be added to linear diffraction analyses. This strictly requires knowledge of the body motion relative to the fluid motion, due to incident waves with additional diffraction and radiation effects in these cases. This is difficult (or impossible) to represent as a single velocity and we consider only still water cases. This might appear consistent with the linear diffraction analysis for moving bodies where the forces due to fixed and moving body are superimposed. There is no evidence to suggest that viscous effects may be simply superimposed in this way although for oscillating bodies in line with steady flow (defined by a single velocity) this can give accurate results, with different drag coefficients for steady and oscillatory components (Verley and Moe, 1979). This is unlikely to be possible in waves with a spatially varying velocity field without an obvious representative single velocity. The aim of this study is thus to determine drag coefficients for cylindrical bodies with flat and rounded bases for heave and surge motion in still water. This is of fundamental interest and informs suitable values to be included in linear diffraction analysis; these values are basically tuning parameters accounting for complex boundary layer and wake effects. We determine the prominent component for viscous interaction, that due to body motion.

In Section 2 the dynamical equation is described which enables viscous effects to be determined from the CFD results. This also enables some experimental free decay tests to be analysed. In Section 3 the CFD methodology including mesh configuration is described. Results for forced heave and surge motion follow in Section 4 including comparison with coefficients from the free decay tests. Results for near full-scale conditions are included. There is a discussion in Section 5 and conclusions are drawn in Section 6.

2. Dynamical equation

The forces on an oscillating body may be categorised as added mass in phase with acceleration, radiation damping and drag both in phase with velocity and buoyancy in phase with vertical displacement if the body motion is small, i.e. the problem is assumed linear. Nonlinear effects associated with free surface movement may become significant as amplitudes increase. If viscous effects are negligible, which is often assumed for large bodies, potential flow may be assumed and linear radiation/diffraction panel methods may be applied for small motions. Here we use WAMIT version 6.3 (WAMIT, 2004) to evaluate the associated added mass and radiation damping forces. In general for sinusoidal body motion forces may be defined by constant added mass, radiation damping and drag coefficients to a close approximation. For vertical sinusoidal oscillation of a body with immersed volume V in still water level, with frequency ω and amplitude z_0, displacement z (positive upwards) is defined by:

$$z = z_0 \sin(\omega t) \tag{1}$$

giving body velocity and acceleration as:

$$\dot{z} = z_0 \cos(\omega t) \tag{2}$$

$$\ddot{z} = -z_0\omega^2 \sin(\omega t) \tag{3}$$

If F is the total body force with static buoyancy $\rho g V$ subtracted, equal to the mass of the body where ρ is water density and g is gravitational acceleration, according to Newton's law $F = m\ddot{z}$, where $m = \rho V$. This fluid force on the body may be represented using added mass, radiation damping and drag coefficients, C_a, C_{rd}, and C_d, with a buoyancy or hydrostatic stiffness term. With a linearized drag term, e.g. Sarpkaya and Isaacson (1981),

$$F = -\rho V C_a \ddot{z} - \rho g A z - C_{rd}\dot{z} - \frac{1}{2}\rho A C_d \frac{3\pi}{8}\dot{z}_{rms}\dot{z} \tag{4}$$

where A is cross sectional area at the water plane (also frontal area normal to relative velocity in drag term), and $\dot{z}_{rms} = z_0\omega\sqrt{2}/2$. To determine C_a the hydrostatic stiffness term is subtracted from F, giving F', and the component in phase with acceleration (and displacement) is determined from

$$\int_0^{2\pi} (F' + \rho g A z_0 \sin(\omega t)) \sin(\omega t)\, d\omega t = C_a \int_0^{2\pi} -\rho V z_0 \omega^2 \sin(\omega t) \sin(\omega t)\, d\omega t \tag{5}$$