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Computation of flow features and hydrodynamic coefficients around heave plates oscillating near a seabed

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A R T I C L E I N F O

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A B S T R A C T

For the past few years, heave plates have been used in the offshore industry due to their favorable hydrodynamic characteristics in oscillating flows, i.e., increased added mass and damping. The hydrodynamic coefficients of heave plates are strongly influenced by the proximity of solid boundaries. Assessing how this variation depends on the proximity to the seabed and on the amplitude of the oscillation is the main aim of this paper. In this process, a new model describing the work done by damping in terms of the flow enstrophy is described herein. This new approach is able to provide a direct correlation between the vortex shedding processes and the linear damping coefficient. Numerical simulations have been performed using the finite volume open source solver OpenFOAM. Simulations have been conducted on a solid circular disc oscillating axially in water at various elevations above an impermeable seabed boundary. Results for hydrodynamic coefficients are validated against previously published experimental data. At low KC numbers, a systematic increase in added mass and damping, corresponding to an increase in the seabed proximity, is observed. As seen in experiments, a critical KC where the monotonic trend of the hydrodynamic coefficients with KC is disrupted and that depends on the seabed distance exists. The physical behavior of the flow around the critical KC is explained through an analysis of the flow enstrophy.

1. Introduction

The topic of interest presented in this paper is the hydrodynamic force experienced by oscillating structures under water, more specifically, those with a shape characterized by sharp edges. Application areas of these structures are numerous, such as heave plates in offshore spar platforms (Tao et al., 1999; Nallayarasu and Bairathi, 2014), damping plates for offshore wind turbine structures, bilge keels on ships and seabed templates (Molin, 2011). In the case of floating spar platforms, resonant heave motions in sea states with long peak periods may be experienced. Hydrodynamic damping then becomes a critical factor in keeping the response amplitude of the structures under acceptable limits. Usually, these offshore structures are lightly damped, and therefore, although the magnitude of the exciting force may be small, the response of the system can be large. A commonly used device to enhance the damping mechanisms in the vertical (heave) direction is a heave plate, which

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is usually added to the base of the structure. This arrangement enhances the vortex shedding process due to isolated sharp edges, as well as increases the effective vertical mass of the structure, consequently changing the hydrodynamic properties of the body in question by introducing extra damping and increasing its natural period.

It is well-known that flow properties in general can be significantly altered in the presence of a close material boundary. Lamb (1945, Section 137) showed that a sphere constrained to move in a fluid along a line parallel to a wall experiences an "attraction" towards the wall. The re-alignment of the flow, due to boundary proximity, results in modified pressure and vorticity fields, in turn influencing the forces experienced by the body motion. In some offshore applications such as deployment of foundation templates and subsea structures, the penetration of a structure through the water surface and through the water column are important stages. An application mentioned in recommended practices, such as DNV-RP-H103 (April 2010), but not researched extensively, is the retrieval of installed equipment. Notwithstanding pull-out forces that are felt during contact with the seabed, it is possible that the structure may vibrate after severing from the foundation but within proximity of the seabed. In such cases, hydrodynamic properties are modified, thus emphasizing the importance of having an accurate knowledge of hydrodynamic loads in these conditions (Morrison and Cermelli, 2003).

Also within this context, the footings of jack-up wind turbine installation vessels may experience, when close to seabed during their touchdown, significant variations in damping and added mass, influencing in turn the dynamics of the whole vessel. Designers of such systems have to specify limiting environmental installation conditions, which requires modeling the motions of a jack-up platform with footings close to the seabed and predicting the resulting impact loads when the footings eventually hit the ground (Wind Jack MARIN JIP, Wind Jack, 2012–2014, looks at these matters).

The hydrodynamic forces represented by suitably non-dimensionalized (added mass and damping) coefficients are normally found to be functions of the Keulegan–Carpenter number KC and the frequency parameter β:

$$\mathrm{KC} = 2\pi \frac{A}{D_d}, \tag{1}$$

$$\beta = \frac{D_d^2 f}{\nu}, \tag{2}$$

where f is the frequency in Hz of the oscillation, A is its amplitude, D_d is the disc diameter and ν is the kinematic viscosity of the fluid. Discussion of these parameters can be found in Keulegan and Carpenter (1958) and Sarpkaya and Isaacson (1981).

Forced oscillation experiments on cylinders and discs (Thiagarajan and Troesch, 1998) show that the added mass and damping coefficients are linearly dependent on the KC number, and weakly dependent on the frequency parameter. Prislin et al. (1998) and Lake et al. (2000) focused their research on the added mass and damping of submerged horizontal plates. They were interested in the applicability of their research to spar type platforms, and hence assumed that the plates were deeply submerged. Tao et al. (1999) revealed that appendages such as discs could be added to the keel of a spar structure to effectively increase damping, also limiting the viscous excitation from waves due to the exponential decay with depth. Later, Tao and Dray (2008) performed experiments on solid and porous discs and confirmed Pistani and Thiagarajan (2006) research, who found the added mass to be dependent on the amplitude of oscillation. Vu et al. (2008) also observed similar trends for added mass and damping coefficients of a solid disc with a varying KC number.

More recently, An and Faltinsen (2013) studied forced harmonic heave motions of horizontally submerged perforated rectangular plates for both deep and shallow submergences. Their numerical results were partly obtained by combining the potential flow with linear free-surface conditions and a nonlinear viscous pressure loss condition at the mean oscillatory plate position. A domain decomposition technique was applied with a boundary element method in the inner domain and an analytical representation of the velocity potential in the outer domain. A drag term accounted for the vortex shedding at the outer plate edges. The numerically predicted KC dependent heave added mass and damping coefficients agreed reasonably with experimental values, in particular for deeper submergences. Li et al. (2013) conducted a series of experiments in order to examine the influence of the edge shape on the hydrodynamics of heave plates. They found that the plate with a rectangular edge yielded the largest added mass value. The results also showed that damping did not seem to be significantly affected by the shape of the edge. Lopez-Pavon and Souto-Iglesias (2015) showed that damping gets significantly reduced by the presence of a structural vertical flap at the plate edge.

Although the consideration of added mass and damping coefficients as a fundamental part of seakeeping dynamics models is well established since the early works of Sarpkaya and Isaacson (1981), up until the recent works cited above, their links to flow properties (vorticity, mechanical energy dissipation, pressure field, etc.) are not well formulated.

Wadhwa et al. (2010) conducted forced oscillation experiments on a solid disc oscillating at varying elevations from a sandy seabed. Their study suggests that, as a structure moves closer to the mean seabed, the added mass and damping coefficients increase monotonically and the slope of the added mass curve, versus the KC number, decreases as the mean position of the disk is closer to the seabed.

The aim of the present work is two-fold: first, theoretical formulations from first principles linking local flow physics with global force coefficients are presented. Second, a numerical solver based on the open-source libraries of OpenFOAM (OpenCFD Ltd., 2013) is used to compute the hydrodynamic coefficients in the case of an oscillating body in an unbounded domain. Since the predictions are found fairly accurate, the solver is used to study the flow around the body oscillating close to the seabed, where damping obtained from forces and also from flow field integrals are compared to each other.