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Nonlinear vertical accelerations of a floating torus in regular waves

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ABSTRACT

The longitudinal motions and vertical accelerations of a floating torus as well as wave motion inside the torus are studied by model tests in regular deep-water waves. Comparisons are made with linear and partly with second-order potential-flow theory for the smallest examined experimental wave height-to-wave length ratio 1/120. Reasonable agreement is obtained, in particular for the linear problem. The importance of 3D flow, hydroelasticity and strong hydrodynamic frequency dependency is documented. Experimental precision errors and bias errors, for instance, due to tank-wall interference are discussed. Numerical errors due to viscous effects are found to be secondary. Experiments show that the third and fourth harmonic accelerations of the torus matter and cannot be explained by a perturbation method with the wave steepness as a small parameter.

1. Introduction

Wave-induced loads on a fish farm with a circular plastic collar motivate our studies. The interaction with other parts of the fish farm, such as the netting structure, bottom rings, chains, ropes and a realistic mooring system, are important but are not investigated. Both wave and current loads matter but current is neglected. Dynamic behavior of a fish farm in real conditions is a complex scenario (see Fig. 1), which for the floater can involve large relative vertical motion compared to the cross-sectional dimensions, large local accelerations, hydroelastic effects and violent wave structure interaction with local wave overtopping and out of water phenomena.

Dedicated model tests and numerical simulations by Kristiansen and Faltinsen (2015) investigated the mooring loads through a detailed and broad numerical study and assessed the physical effects which are relevant for the prediction of the mooring loads. Amongst them, a rigid floater significantly alters the mooring loads if compared with a realistic elastic floater. He et al. (2015) demonstrated by model tests with live fish occupying a representative volume 2.5% of the net cage that fish could have a non-negligible influence on the mooring loads in waves and current.

The considered floater is a torus even though it is more common in practice to operate with two adjacent tori. Wavelengths of practical interest are of the order of the torus diameter but long relative to the cross-sectional diameter. Engineering tools for net cages often estimate the wave-induced floater loads using strip theory with linear potential flow and drag-force corrections from Morison equation, which disregard important 3D flow, frequency dependency and nonlinear effects.

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Fig. 1. Illustrations of overtopping and out of water on the floater of a fish farm without net in a storm. (Photo: Marius Dahle Olsen).

Newman (1977) analyzed a rigid floating torus by linear potential flow. Li and Faltinsen (2012) derived a long wavelength slender-body theory for the vertical added mass, damping and wave excitation loads on an elastic semi-submerged torus by matching a near-field and far-field solution. Here long wavelength means that the wavelength is long relative to the cross-sectional torus diameter. A Haskind-type expression for the wave excitation loads was presented. 3D frequency-dependent hydrodynamic interaction on the scale of the torus diameter was significant and resulted, for instance, in frequencies with zero wave-radiation damping. A beam model described the elasticity effect of the torus and a representative bending stiffness for the floater of a fish farm was applied. Hydroelasticity played a major role in the studied cases. The results were verified by complete 3D linear frequency-domain potential-flow calculations.

Li et al. (2014) reported numerical simulations and experiments of an elastic circular collar of a floating fish farm. The floater model without netting structure and moored with nearly horizontal moorings were tested in regular deep-water waves of different steepness and periods without current. Local overtopping of waves were observed in steep waves. The focus was on the vertical accelerations along the floater in different conditions. The experiments showed that higher-order harmonics of the accelerations are significant. A 3D weak-scatter model with partly nonlinear effects due to Froude-Kriloff and unsteady hydrostatic pressure loads as well as a 3D linear frequency-domain method based on potential flow were used. From their comparison against the measurements, strong 3D and frequency dependency effects as well as flexible floater motions matter. The weak-scatter model can only partly explain the nonlinearities present in the measured accelerations.

The present experimental investigation is a continuation of the experimental work by Li et al. (2014) by considering a nearly rigid circular floater. In that way, state-of-the-art second-order potential flow solvers for rigid bodies is used to explain some of the nonlinear experimental results. In the next section the model tests are outlined, then the adopted numerical solvers and the applied elastic curved-beam theory are briefly described and the physical investigation is discussed. Emphasis is given on the discussion of experimental and theoretical error sources. Main conclusions and further steps are drawn in the last section.

2. Experimental set-up

The Marine Cybernetics Laboratory at the Marine Technology Centre in Trondheim was used for the experiments. The wave tank is 40 m long, 6.45 m wide and 1.5 m deep. It is equipped with a towing carriage, a hinged flap-type wave maker and a damping beach covered by a porous mat to increase its energy dissipation ability. The wave maker is digitally controlled by using linear wave maker theory to estimate the necessary stroke of the paddle for generating waves with a given height and period. A scale factor 1:25 with Froude scaling was in mind for the floater model. In order to get a cross-sectional diameter similar to the one used for the elastic model in Li et al. (2014), i.e. 36 mm, a 32 mm nearly rigid standard water pipe for houses was covered by a transparent elastic tube of thickness 1.5 mm and a waterproof adhesive electrical tape. The water pipe is made of a high-density polyethylene (HDPE) type plastic with Young's modulus of elasticity $E = 0.8 \times 10^9\ \text{N/m}^2$. The second moment of area of the pipe in bending is $I = \pi\left(D_2^4 - D_1^4\right)/64$, where the inner and outer diameter are $D_1 = 26\ \text{mm}$ and $D_2 = 32\ \text{mm}$, respectively. This means a bending stiffness $EI = 23.23\ \text{Nm}^2$. The combined bending stiffness of the HDPE plastic tube, transparent elastic tube and the adhesive electrical tape was found by static tests in the linear elastic regime. An arc of the torus was clamped to one end and kept free on the other and an increasing load, whose range was comparable with the one recorded during the tests in waves, has been applied on the free end and the corresponding displacement has been measured. The static tests confirmed the linear behavior of the material and enabled the calculation of the bending stiffness $EI = 23.74\ \text{Nm}^2$, that is, about 200 times the bending stiffness used in the