Wave-induced drift of a thin floating plate: A numerical experiment

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1. Introduction

The wave-thin plate interaction problem has been widely used to model wave sea ice interactions theoretically, experimentally and numerically. This problem can provide meaningful results to investigate and also model wave propagation in ice-covered ocean and its effects (like bending and deformation of the ice). Most of previous experimental studies centering on this problem have neglected drift of the plate (see the experiments of [1] and [2]). Beside this, the overwash, i.e. the running water on the upper surface of the thin floating bodies with shallow freeboard that leads to dissipation of energy [1], is needed to be investigated. It is very hard and expensive to study the physics of the overwash phenomenon experimentally . The current available theoretical model of overwash, developed by [3], provides features of the ideal flow and neglects turbulence, breaking and collision of the bores (which may occur for the overwash [1]). To overcome this problem, viscous flow is needed to be considered for modeling of the flow. Authors of the current work are motivated by the fact that the viscous flow and the free floating (drift) assumptions together can provide a more accurate pattern for prediction of wave-thin floating plate interaction. To this end, drift and overwash phenomena of a thin floating plate are modeled using Computational Fluid Dynamics (CFD). Accuracy of the CFD simulations is investigated by comparing the results against experimental measurements of Nelli et al. [2]. Drift speed is computed and compared against experiments, and it has been seen that the drift speed is increased by the increase in wave steepness. It is shown that, drift leads to slightly larger water height at both edges of the plate, while it leads to decrease of the mean horizontal velocity of the flow.

2. Numerical Simulation

It is assumed that, monochromatic (regular) waves are incident on a thin floating plate with a length L and thickness h. The incident wave is given by

$$\eta_{in} = a_{in} \cos(\omega t + Kx + \epsilon_{in}), \tag{1}$$

where a_{in} is the amplitude of the incident wave, $K = 2\pi/\lambda$ is the wave number, $\omega = 2\pi/T$ is the wave frequency and ϵ_{in} is the phase lag (λ and T respectively refer to wave length and period). A proportion of the wave is reflected, a proportion is dissipated and the rest is transmitted by the thin plate. The plate is allowed to have vertical and longitudinal motions (heave, pitch, surge and drift). To model the problem, two coordinate systems, including an earth fixed frame and a body fixed frame are considered. The first one is located on the calm water line and is fixed. The other is attached to the center of gravity (CG) of plate and moves with it. The governing equations on the motion of the plate are set as the

$$m\ddot{z} = \sum F_z \qquad \text{and} \qquad I\ddot{\theta} = \sum M, \tag{2}$$

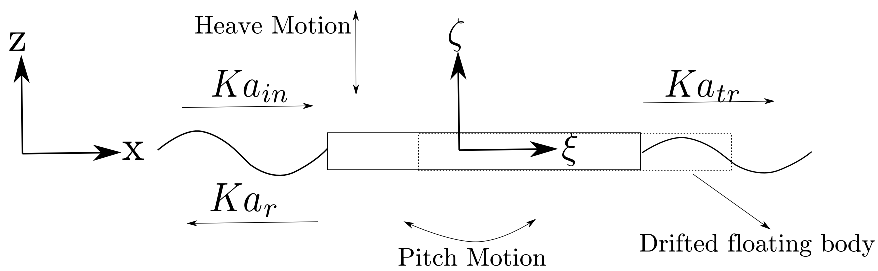

Figure 1: Schematic of the problem.

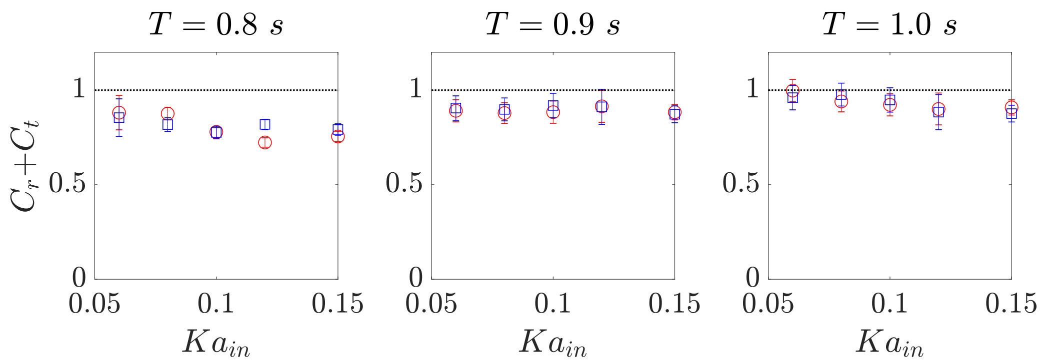

Figure 2: Summation of the transmission and reflection coefficients for the case with drift: broken line, circle with error bars and square with error bars denote theory, experimental results and CFD simulations.

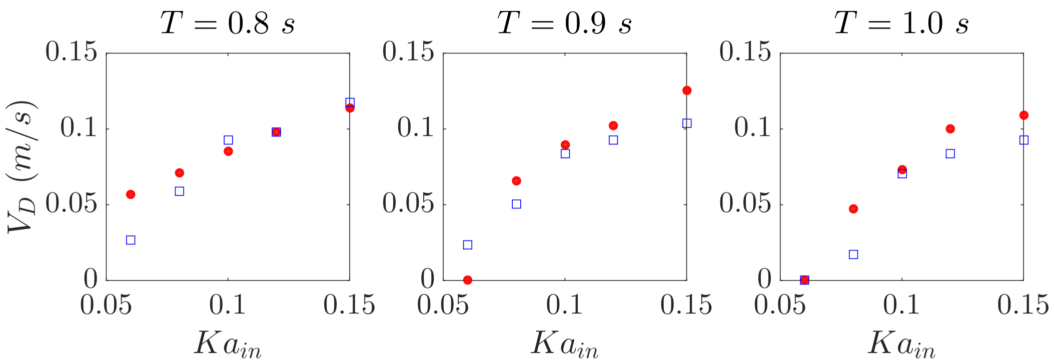

Figure 3: Measured (squares) and computed (circles) drift velocities for the thin floating plate.

where m and I are the mass and inertia of the plate respectively. F and M are the force and moments caused by the fluid (which are resulted by pressure and stresses). Pressure and stresses can be found by solving the fluid problem. By assuming a two-phase real flow, that is, by considering that the flow is viscous, the continuity equation and Navier-Stokes equation govern on the fluid as, respectively,

$$\nabla \cdot \mathbf{u} = 0 \qquad \text{and} \qquad \partial_t \rho_e \mathbf{u} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \mu_e \nabla^2 \mathbf{u} + \rho \mathbf{g}. \tag{3}$$

In the above equations $\mathbf{u}$, ρ_e, μ_e, p and $\mathbf{g}$ respectively denote the velocity vector, effective density, effective viscosity, pressure and gravity acceleration. The volume of fluid (VoF) method is used to model the two-phase flow (air and water). The water volume fraction is defined as

$$\alpha = V_w/V = 1 - V_a/V. \tag{4}$$

where V refers to the volume of a finite volume. Subscripts w and a refer to association of a parameter to water and air respectively. Effective density and viscosity are computed by

$$\mu_e = \alpha\mu_w + (1-\alpha)\mu_a \qquad \text{and} \qquad \rho_e = \alpha\rho_w + (1-\alpha)\rho_a, \tag{5}$$

The governing equation [4] on α is given by

$$\partial_t \alpha + \nabla \cdot \alpha \mathbf{u} = 0. \tag{6}$$

A structure mesh is used to discretize the domain. To avoid possible deformation of mesh, the floating thin plate is located in an overset domain. Governing equations are discritized using the Finite Volume Method (FVM). The open source code OpenFOAM is utilized to perform the simulations. The wave generation boundary is set on the inlet

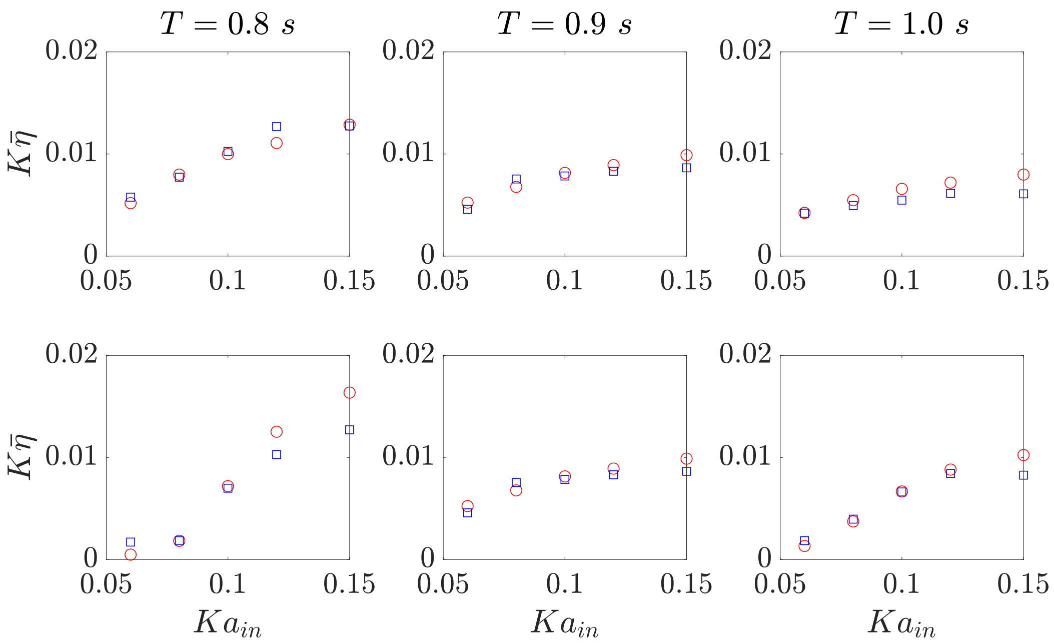

Figure 4: Time average of water depth of overwash at front edge (upper panel), rear edge (lower panel) of the plate. Circles and squares respectively refer to the case with and without drift.

patch. Wave absorption condition is implemented on the outlet boundary. Moreover, the plate is set to behave as a moving wall with no-slip boundary condition. A mesh study was perfromed, and it was found that, results converge for the mesh size 2.5 $mm \times 2.5\ mm$. The Crank-Nicolson method is used for discretization of unsteady terms of the governing equations. The maximum Courant Number is set to be 2.0. Numerical simulations were performed for the three wave periods $T = 0.8\ s$, 0.9 s and 1.0 s. Five wave-steepnesses ranging from $Ka_{in} = 0.06$ to $Ka_{in} = 0.15$ are considered. Two different motions were numerically modeled: (i) free drift, and (ii) no drift.

Numerical tests are chosen to replicate the laboratory experiments conducted by Nelli et al. [2] in the wave flume of the University of Melbourne (with length of 60 m and width of 2 m). They measured the waves in the front and rear fields. A polyvinyl chloride (PVC) foam with density of 596 Kg/m^3 was used. Waves were generated in a deep water condition, and a beach was used at the left-hand end of the flume to absorb the waves.

3. Results

Water surface elevation (predicted by numerical simulations) is computed using

$$\eta_n = \int_0^\infty \alpha dz. \tag{7}$$

at both rear edge (which provides the reflected wave) and front edge (which provides the transmitted wave). Transmission and reflection coefficients are

$$C_r = |\frac{m_{0,front} - m_{0,incident}}{m_{0,incident}}| \quad \text{and} \quad C_t = |\frac{m_{0,rear}}{m_{0,incident}}|, \tag{8}$$

where m_0 is computed by

$$m_0 = \int_0^\infty E(\omega)d\omega. \tag{9}$$

Figure 2 shows computed and measured values of $C_r + C_t$, the total amount of energy of the wave (the more divergence from 1.0 shows more dissipation of the energy). Also predictions of linear theory, which provides $C_r + C_t =$

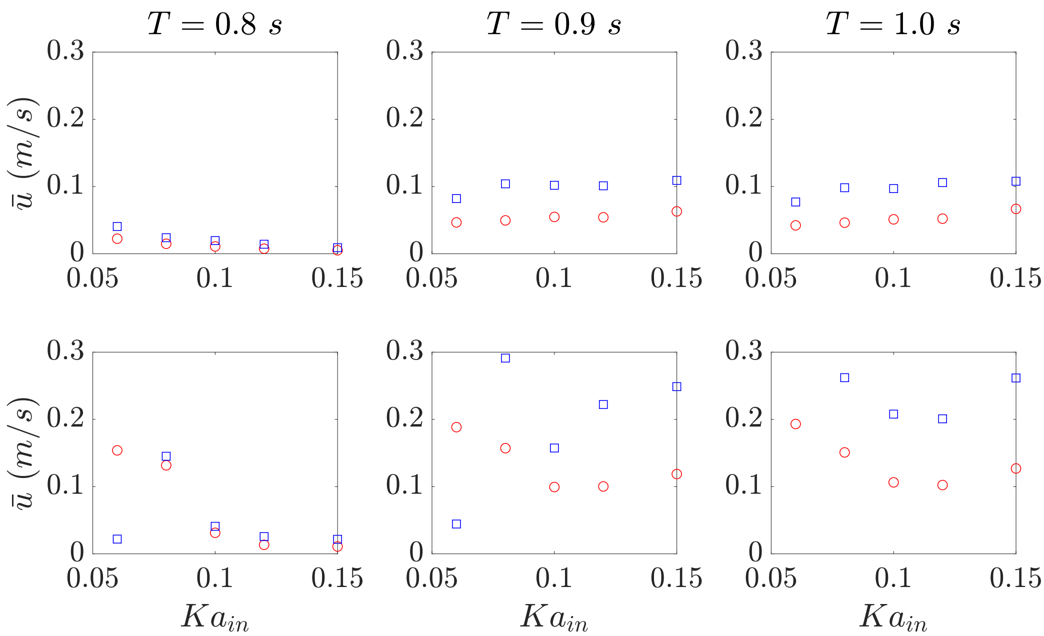

Figure 5: Time average of Energy flux (normalized by energy flux of inlet) for Ka_{in} = 0.06 (lower panel) and Ka_{in} = 0.15 (upper panel): Circles and diamonds respectively show the cases without and with drift.

1.0 (because theory doesn't consider any dissipation for energy) are shown. The results of this figure show that, CFD results agree with experiments and it has a reasonable good accuracy. Computed and measured values of drift speed of the thin, floating plate are shown in Figure 3. This figure shows that drift speed converges by the increase in wave steepness, i. e., as the wave steepness is increased, the slope of the increase of the drift speed gets smaller.

Water depth of the overwash at two edges of the plate are shown in Figure 4. It can be seen that, drift speed results in larger water depth at all both points at storm-like wave steepnesses. The horizontal velocity of the overwash is computed by

$$u_{x,ow} = \int_0^\infty u_x \alpha dz. \tag{10}$$

Results are shown in Figure 5. According to the results, presence of drift leads to decrease of the mean horizontal velocity at the front edge. In addition, at the rear edge, the time average of the mean horizontal velocity gets smaller when plate drifts (except the case with smallest wave steepness which has negligible drift velocity).

References

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