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Experimental and numerical investigation of wave resonance in moonpools at low forward speed

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ABSTRACT

In order to study the behavior of resonant piston-mode resonance in a moonpool at low forward/incoming current speed, we performed a series of experiments and compared them to a nonlinear hybrid method which couples potential and viscous flow. The setting is a 2D box section with a moonpool gap in the middle, forced to oscillate in heave with a given amplitude and frequency, while simultaneously travelling at a given constant forward speed. The numerical method couples a Navier–Stokes (CFD) solver using the Finite Volume Method (FVM), with a potential flow method using the Harmonic Polynomial Cell method (HPC). It is found that the moonpool behavior is slightly reduced with a low forward velocity, and the reduction is dependent on the heave forcing amplitude.

1. Introduction

Marine operations from ships often involve moonpools to lower or lift devices such as subsea modules and ROVs. Resonant piston-mode resonance can be excited by the relative vertical ship motions in the neighborhood of the moonpool and cause strong amplification of the dynamic wave elevation in the moonpool. The fact that the resonant piston-mode frequency is typically in the vicinity of the heave natural frequency of the ship limits possible sea states for a marine operation. The stronger the shed vorticity due to flow separation at the moonpool entrance and inside the moonpool is, the larger the damping is, and the smaller the maximum resonant piston-mode wave amplitude is for a given ship and main moonpool geometrical parameters in a given sea condition. It is of practical interest to know the free-surface elevation in the moonpool and the ambient flow velocities and accelerations in the vicinity of the moonpool in order to assess the loads on lifted or lowered devices through the moonpool.

Several authors have studied the importance of including viscosity and flow separation in the resonant moonpool problem, due to the fact that a potential flow solution will greatly overpredict the piston-mode amplitude at resonance for sharp-edged lower entrances of the moonpool. Faltinsen et al. [5] investigated forced heave of a two-dimensional moonpool section using a domain-decomposition (DD) scheme within the framework of linear potential flow theory. Their DD scheme led to a system of integral equations on the transmission interfaces that solved for the piston-mode natural frequency and the steady-state piston-mode amplitude. To improve the potential flow models some authors have tried to fit an artificial, empirically based damping to the free-surface condition inside the moonpool. This is known as a numerical damping lid. Lu et al. [15] investigated the possibility of finding this damping coefficient based on experimental and CFD results. The damping coefficient was in their work observed not to be sensitive to the variation of moonpool gap width, body draft, breadth-to-draft ratio and body number. Their focus was on wave forces, where Lu et al. [16] used the same setup with focus on the wave elevation in the moonpool. It is not known when using a numerical damping lid how well the flow in the vicinity of the moonpool is predicted. Lu and Chen [14] investigated what contributed to the dissipation of the piston-mode amplitude generated from incoming waves. Both the dissipation from the boundary layers inside the moonpool gap, and in which fluid areas around the moonpool gap the vorticity dissipation was largest.

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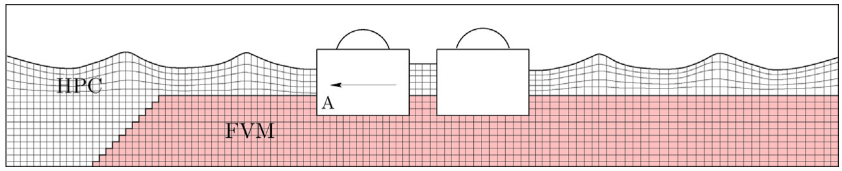

Fig. 1. Domain overview with the HPC domain close to the free surface (Ω_{pot}) and the FVM domain around the ship edges and down to the bottom of the tank (Ω_{CFD}). Notice how the grid in the HPC domain follows the free surface.

Kristiansen and Faltinsen [10,11] showed how a hybrid method based on a linear potential solver coupled to a viscous Navier–Stokes (CFD) solver could be used to predict the piston-mode in a 2D moonpool under forced heave oscillations. The viscous domain covered the inlet of the moonpool where the vorticity would be shed, and later advected before dissipating. The rest of the domain, including the free surface was discretized using linear potential flow theory, where it was solved for the linear acceleration potential ψ. A direct coupling between ψ in the potential domain and the pressure p in the viscous domain was used. This guaranteed continuity in pressure and normal velocity across the intersection between the two domains. Both domains where solved using a Finite Volume Method (FVM) with second order accuracy in space. Their thought is that potential flow is best at propagating waves, and that the viscous domain can incorporate vorticity separated from the edges. The method is extremely fast relative to solving the complete viscous flow problem with nonlinear free-surface conditions by means of a CFD solver with, for instance, the Volume of Fluid (VOF) method for capturing the free surface. Later, Kristiansen et al. [12] demonstrated that the method gave good results also for the 3D moonpool problem, with modest computational times.

In the previously described works, there was no current or forward velocity. Fredriksen et al. [7] developed the method introduced by Kristiansen and Faltinsen [11] in order to account for this. A linear perturbation of the free surface is adequate to capture the moonpool flow at zero forward velocity and no incoming current. However, a linear perturbation method is insufficient to capture the wave-current interaction. Here in our hybrid coupling method a higher order perturbation method is unsuitable since a single unknown (pressure p in the viscous domain) can not be coupled to several unknown velocity potentials in the potential flow domain. Fredriksen et al. [7] used nonlinear free-surface conditions in a non-rotating body-fixed coordinate system to overcome this problem. The body-boundary conditions are then exactly satisfied, but a new complication with the free surface is introduced. The matrix system now needs to be updated each time-step to satisfy the nonlinear free-surface conditions on its exact position. The current work is a further development of this nonlinear hybrid method, where we use the recently developed Harmonic Polynomial Cell (HPC) method in the potential domain instead of the FVM.

The HPC method was first presented for solutions of the 2D Laplace equation in [19], where both computational speed and accuracy were compared against boundary element methods and other field solver methods. It was later verified in 2D with wave propagation over a submerged trapezoidal bar, see [20]. The first extension to 3D was done by Shao and Faltinsen [21], where again, its high efficiency and accuracy was compared with other solvers. Forces on a bottom-mounted free surface piercing vertical circular cylinder in nonlinear regular waves were studied. Nonlinear forces describing up to the fourth harmonic was computed and compared against other numerical results and experimental values with satisfactory results.

There exist several other strategies for coupling viscous flow and potential flow models. It can simply be done by using a potential flow model to generate initial conditions to a viscous flow model. An example of this is by using a potential flow model to simulate a wave breaking up to when the free surface intersects itself, then use the potential flow results to generate initial conditions to a viscous flow simulation, see [9]. A stronger coupling strategy which is similar to ours is summarized in Ref. [8]. Basically they solve a potential flow problem on a large domain using the boundary element method (BEM). On a smaller viscous CFD domain, the NS-equation is split in an inviscid and a viscous part, $\mathbf{u}=\mathbf{u}^I+\mathbf{u}^V$ and $p=p^I+p^V$. Since the inviscid part is known from the potential flow BEM calculation, the NS-equation can be solved for $\mathbf{u}^V$ and p^V. They use this strategy to solve a sediment transport model, where the viscous CFD domain is located close to the sea bottom.

We start by presenting the numerical method in Section 2, then give an overview of the experimental setup in Section 3. The results are given and discussed in Section 4. At the end a conclusion about the present work will is given in Section 5.

2. Numerical approach

We present a coupling strategy between a potential flow outer domain with a viscous flow inner domain. Only the water domain is considered (see Fig. 1). The chosen method for the potential flow domain is based on the HPC method and the flow in the inner viscous domain is solved based on a laminar flow assumption using FVM. The governing equations will be solved in a body-fixed non-rotating coordinate system, with exact boundary conditions. The numerical method is then capable of simulating free-surface flows with flow separation from free-surface piercing structures. Only flow separation from sharp corners will be considered which implies that the details of the boundary-layer flow are not needed. We will here consider the case with forced heave oscillations of a 2D moonpool with low forward velocity. The Earth-fixed coordinate system is here defined fixed in the initial position of the body, with $z=0$ on the mean free surface and the z-axis positive upwards. Correspondingly the body-fixed coordinate system is following the motion of the body in heave and sway.

We will solve the Laplace equation for the absolute velocity potential φ in the potential flow domain, which is valid for irrotational flow of an incompressible and inviscid fluid, i.e.

$$\nabla^2\varphi = 0 \quad \text{in} \quad \Omega_{\text{pot}}. \tag{1}$$

The absolute velocity is defined as $\mathbf{u}=\nabla\varphi$. We will solve for the absolute velocity potential φ in a body-fixed and non-rotating coordinate system. In the CFD domain we will solve for the relative velocity $\mathbf{u}_r=(v_r, w_r)$ in the same body-fixed non-rotating coordinate system. The governing equations for mass and momentum conservation in an incompressible, laminar viscous fluid flow in an accelerated non-rotating coordinate system are given according to Ref. [4] as

$$\nabla\cdot\mathbf{u}_r = 0 \quad \text{in} \quad \Omega_{\text{CFD}} \tag{2}$$

$$\frac{d^b\mathbf{u}_r}{dt} + \mathbf{u}_r\cdot\nabla\mathbf{u}_r = -\frac{1}{\rho}\nabla p - g\mathbf{k} + \nu\nabla^2\mathbf{u}_r - \mathbf{a}_0 \quad \text{in} \quad \Omega_{\text{CFD}}, \tag{3}$$

where $d^b\mathbf{u}_r/dt$ means the time-differentiation for a fixed point in the body-fixed coordinate system, $(dv_r/dt)\mathbf{j}+(dw_r/dt)\mathbf{k}$, i.e. we do