SIMULATION OF THE HYDROELASTIC RESPONSE OF A FLOATING ICE SHEET

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Introduction

In the polar region, ice sheets can be several kilometres long and subjected to the effects of ocean waves. As its thickness to length ratio is very small, an ice sheet may experience significant localised vibrations under continuous wave excitation. In such situations, the vibratory response of the large ice sheet is dominated by an elastic deformation rather than rigid body motions, which is also known as the hydroelastic response of sea ice. A review on this phenomenon has been given by Squire [1], indicating that understanding it fully will be a key challenge of polar engineering. The hydroelastic wave-ice interaction can induce wave reflection and transmission [2], which makes the wave field nearby very different from that in the open ocean and can lead to a considerable influence on any adjacent structures and/or passing vessels.

Previous studies on the hydroelasticity of sea ice have mainly been conducted analytically. Fox and Squire [2] considered the reflection and transmission of waves from open water to an ice sheet. They adopted the method of eigenfunction expansion for the velocity potentials of the water, and used the conjugate gradient method to impose continuity at the interface and edge condition. The reflection and transmission coefficients of the incident waves were obtained and found to be dependent on the wave period, ice thickness and water depth. A similar analytical study was also conducted by Chung and Fox [3] using the Wiener-Hopf method.

The analytical works have provided great insight into this problem. However, in order to formulate the case in mathematics, they were built upon specific ideal assumptions, where the fluid viscosity and non-linear behaviours were neglected. This limitation makes an analytic analysis insufficiently realistic and accurate, which motivates an improvement of developing a numerical model that has the ability to obtain a higher-order solution and capture the phenomena that have not been included in the analytical models.

Fluid-Structure Interaction (FSI) simulation through Computational Fluid Dynamics (CFD) is an advanced numerical method to model solid deformations induced by fluid, but has not to date been applied to ice hydroelasiticity. To develop a reliable CFD tool to fill this gap, Tukovic et al. [4] designed an FSI package using the opensource CFD platform OpenFOAM, and Huang [5] extended this package into multiphases so that it can model the hydroelastic problem where the floating structure is in contact with both air and water.

As shown in Figure 1, this work will use the the developed code [5] to simulate the hydroelastic response of a floating ice sheet, and assess its accuracy by comparing the computational results with the experimental data of Sree et al. [6]. The influence of environmental variables will also be investigated, including the incident wave period, ice thickness and water depth. Furthermore, the wave field affected by the ice sheet will be compared with its open water counterpart.

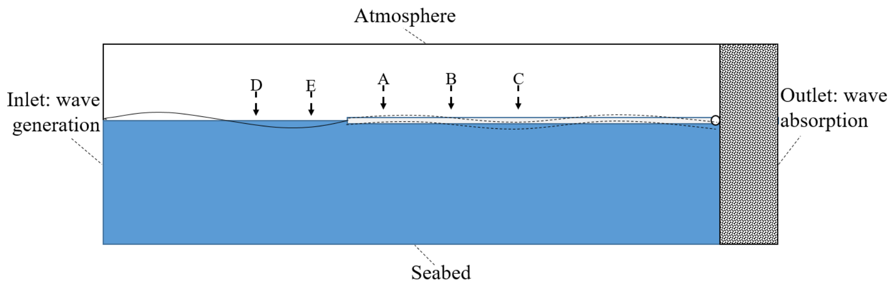

Figure 1: Schematic of the case: a thin ice sheet is floating on the water surface and subjected to incoming waves, with its elastic deformation induced. Three probes (A, B and C) are set at 0.1 m, 0.3 m, and 0.5 m inside the ice edge respectively to measure the local vertical vibration, and two other probes (D and E) are set at 0.1 m and 0.3 m outside the ice edge respectively to measure the free surface elevation.

Numerical Approach

A partitioned FSI scheme is applied to simulate the hydroelastic case, where the fluid and solid sides are solved separately and coupled via the fluid-solid interface. The fluid side is solved through the Reynolds-averaged Navier-Stokes (RANS) equations together with the Volume of Fluid (VOF) method. On the solid side, the ice deformation is solved according to the Saint-Venant Kirchoff constitutive model with the plane strain assumption. An extended introduction of this FSI scheme has been given by Tukovic et al. [7]. The solution procedure of this work is illustrated in Figure 2, with the details being explained in the steps outlined below:

- To start a new time step loop, the structural displacement is first updated according to the results of the previous time step. Then, to keep the fluid mesh in accordance with the solid mesh, the Aitken coupling scheme is employed, which introduces an Aitken Relaxation Factor (ARF), as defined in Equation (1).

$$ARF- = ARF \times \frac{\sum(Res_{t=n-1} \cdot \Delta Res)}{\sum(\Delta Res \cdot \Delta Res)} \tag{1}$$

  Thus the ARF is updated according to the residual (Res), which is the difference between the structural interface displacement (SID) and the fluid interface displacement (FID), namely $Res = SID - FID$. Afterwards, the fluid mesh is adjusted with the updated ARF value, as in Equation (2).

$$FluidMesh+ = ARF \times Res \tag{2}$$

- The FID is extracted from the adjusted fluid mesh. Then its differential produces the velocity of the fluid interface and the mesh motion of the rest fluid region is obtained according to this interface velocity.
- Based on the moved mesh, the fluid solver calculates the velocity and pressure field. Meanwhile, the pressure and viscous force on the fluid interface can be obtained.
- The fluid load on the fluid interface is transferred to the solid interface, considered as the fluid load on the structure.
- According to the load on the interface, the structure solver calculates the displacement of the structure.
- The SID can be extracted from the structural displacement and then compared with the FID to obtain a new residual, Res. The solver switches to the next time step when either the residual criteria is satisfied or the pre-defined maximum FSI iteration time has been reached, otherwise it continues looping in the current time step.

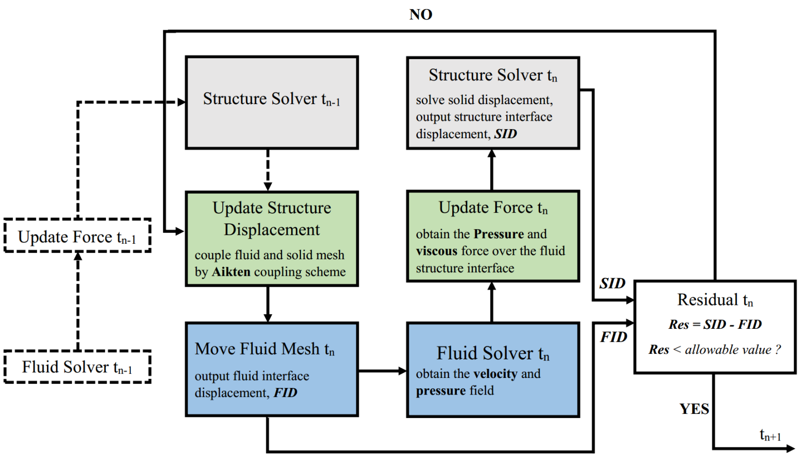

Figure 2: Flow chart of the FSI solution procedure.

Case setup

The general setup of the simulation case is shown in Figure 1. The case is set as a two-dimensional rectangular computational domain. It is filled with fresh water of density ρ_w = 1000 kg m $^{-3}$ to a depth of h = 0.3 m. On the top of the domain, a static pressure boundary condition is applied to model the atmosphere. The bottom boundary is defined as a no-slip wall to account for the presence of the seabed. Using the waves2Foam tool [8], regular waves of amplitude a = 0.0085 m and period T = 0.7 s are constantly generated at the inlet boundary without any current speed, and a wave absorption zone is set up in front of the outlet boundary to avoid waves being reflected here.

A thin ice sheet is initialised as one side free floating on the water surface and the other side fixed, with its length L of 1 m and thickness t of 0.01 m. The ice rheology is set as density ρ = 910 kg m $^{-3}$, Young's modulus E = 870 MPa and

Poisson ratio ν = 0.3. These properties may be varied to study their influence. Three probes (A, B and C) are set at 0.1 m, 0.3 m, and 0.5 m inside the ice edge respectively to measure the local vertical vibration, and two other probes (D and E) are set at 0.1 m and 0.3 m outside the ice edge respectively to measure the free surface elevation.

Results and discussion

To validate the proposed model, the vertical vibrations at the point A, B, C were computed and compared with the experimental data of Sree et al. [6]. In spectral analysis, both the computational results (CFD) and the experimental results (Exp.) are plotted in Figure 3, in which the proposed model reveals very good agreement with the experimental measurements at all the three points. The main oscillating frequency of the ice sheet (where the peaking amplitude occurs) equals to the frequency of the incident wave, which means the vertical oscillation of the ice has approached a steady state. Besides, the peaking amplitude gets smaller from the ice edge to the middle section of the ice (from point A to C).

To investigate the influence of environmental variables on the hydroelastic response of the ice sheet, the ratio of the local vertical oscillation amplitude (A) to the incident wave amplitude (a) was calculated and plotted out, as a function of different incident wave period, ice thickness and water depth, in Figure 4, 5 and 6 respectively. Generally, the deformation of the ice sheet is found to increase as the wave period is increased, and decrease with increasing ice thickness. However, the variation is undistinguished when the water depth is changed, with a slight increase in the shallow water situation and nearly constant in deep water.

Figure 4 shows the ice deformation reducing dramatically when the incident wave period is less than 0.5 s, which is because the waves become very short then, corresponding to a wavelength of less than 0.4 m. As the wave period increases, the vibration amplitude of the ice can approach the incident wave amplitude. Figure 5 shows the ice deformation becomes very weak when the ice thickness increases to a level of the incident wave height, and when the thickness keeps decreasing, the oscillating amplitude can be larger than the ice thickness.

The ice sheet is found to have a significant influence on the wave field, where there is a superposition of the ice-reflected waves and the incident waves. The free surface elevation at points D and E is plotted in Figure 7, alongside a comparison with the open water situation of no ice. It shows that the existence of the ice sheet weakened the waves at point D but induces stronger waves at point E, which suggests the ice sheet can influence the wave field to a large degree and the influence is dependent on the location.

Conclusions

This work provided an available CFD code to simulate the wave-induced FSI problems. After validation against experiments, the code reveals very good accuracy on predicting the hydroelastic response of a floating ice sheet. It can also be applied to other deformable floating bodies, not just the sea ice case.

Acknowledgments

The code was developed during the OSCFD project organised by Håkan Nilsson, and it is publicly downloadable at `http://dx.doi.org/10.17196/OS_CFD#YEAR_2017`, with a report [5] including its detailed development process. In this manner, we hope to promote the development of opensource CFD tools.

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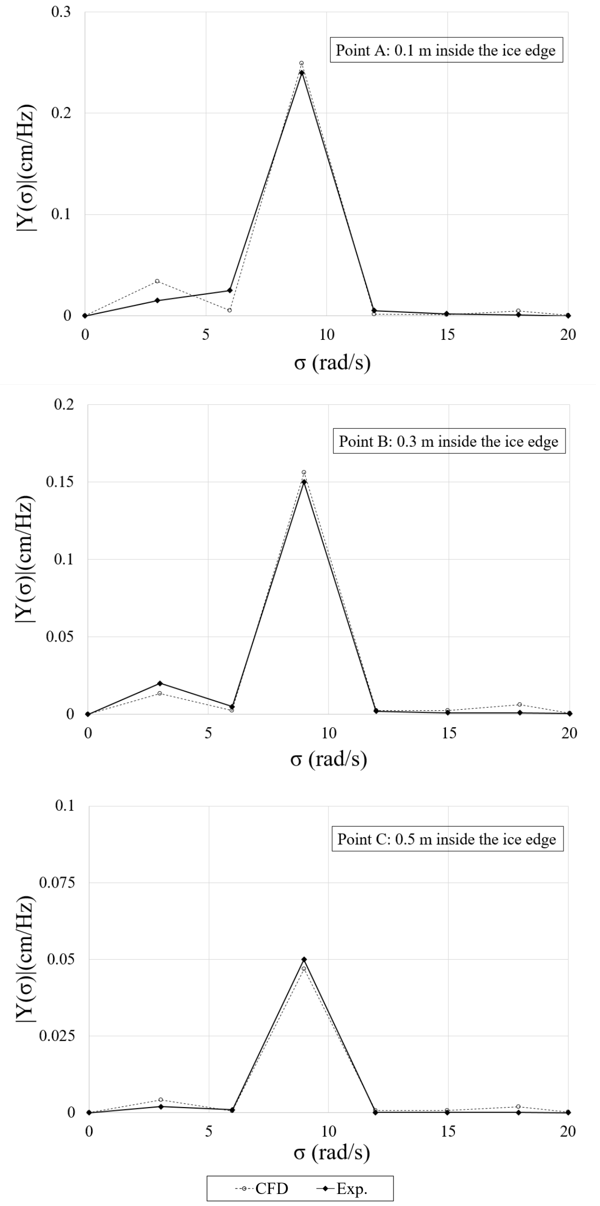

Figure 3: Spectral analysis (discrete Fourier transform, $\mid Y(\sigma) \mid$) of the vertical vibration at different locations along the ice sheet: a comparison between computational and experimental results.

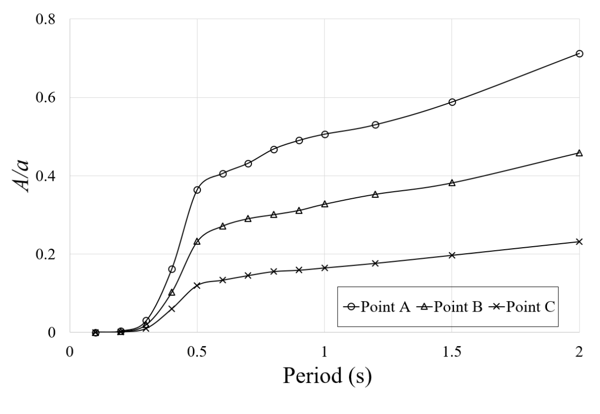

Figure 4: Local vibrations of the ice sheet, as a function of the incident wave period (T).

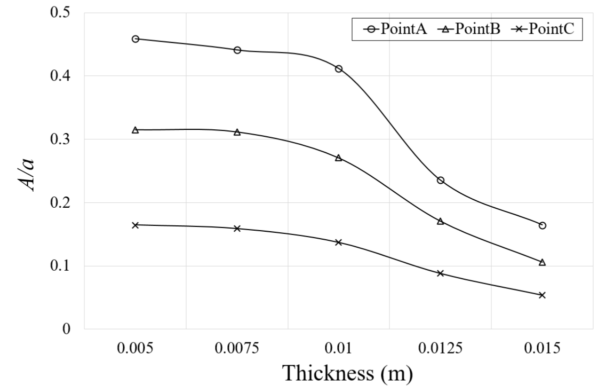

Figure 5: Local vibrations of the ice sheet, as a function of the ice sheet thickness (t).

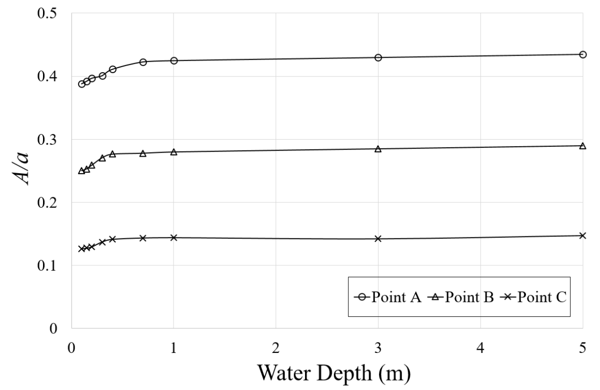

Figure 6: Local vibrations of the ice sheet, as a function of the water depth (h).

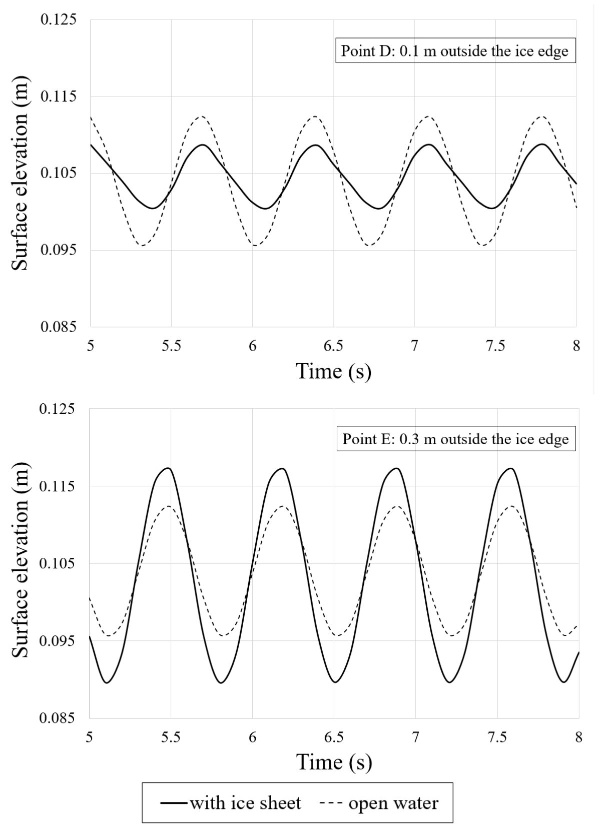

Figure 7: Free surface elevation at different locations outside the ice sheet: a comparison between the computational results and corresponding open water counterpart.