A hydroelastic solver applied to wave-ice interactions

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Background

Since the 1970s, the Arctic ice extent has been observed to decrease rapidly with the effect of global warming, evidenced by an obvious transition from ice-covered areas to open water, consequently more ocean waves. The changed polar geography has provided increased research interest in modelling the wave-ice interactions and predicting their influence on human activities.
Sea ice typically exists as level ice sheets that can be kilometres long, or broken into small ice floes. For the ice floe, according to its small dimension compared with the dominant wavelength, it usually undergoes rigid-body motions with ocean waves. However, for a large ice sheet, as its thickness is very small compared to the length, it may exhibit elastic deformations under a wave excitation, known as the hydroelasticity of sea ice. In such a situation, traditional CFD becomes incapable as it assumes structures to be rigid; a Fluid-Structure Interaction (FSI) approach is required to obtain the ice deformation and couple it with surrounding fluid.

Numerical Approach

Based on OpenFOAM, an FSI solver has been developed and incorporated with the Volume of Fluid method to enable the simulation of multiphase flows. It employed a partitioned scheme to achieve a two-way coupling between the fluid and structure. Specifically, velocity and pressure are calculated in the fluid sub-domain, and accordingly the fluid force on interface is applied as a boundary condition to the solid sub-domain; the solid deformation is then solved to update the shape, and the velocity of solid interface is given back as a boundary condition of fluid. Iterations are performed over these steps until the kinematic and dynamic conditions are satisfied at interface, as illustrated in Figure 1.
Based on the FSI solver, a two-dimensional computational domain was established for simulating the hydroelastic wave-ice interaction, as shown in Figure 2. The domain is filled with water to a depth, with air filling the remainder of the fluid sub-domain. The solid sub-domain represents an ice sheet floating on the water surface and subjected to periodic regular waves inducing its deformation; meanwhile, the presence of ice affects the wave field.

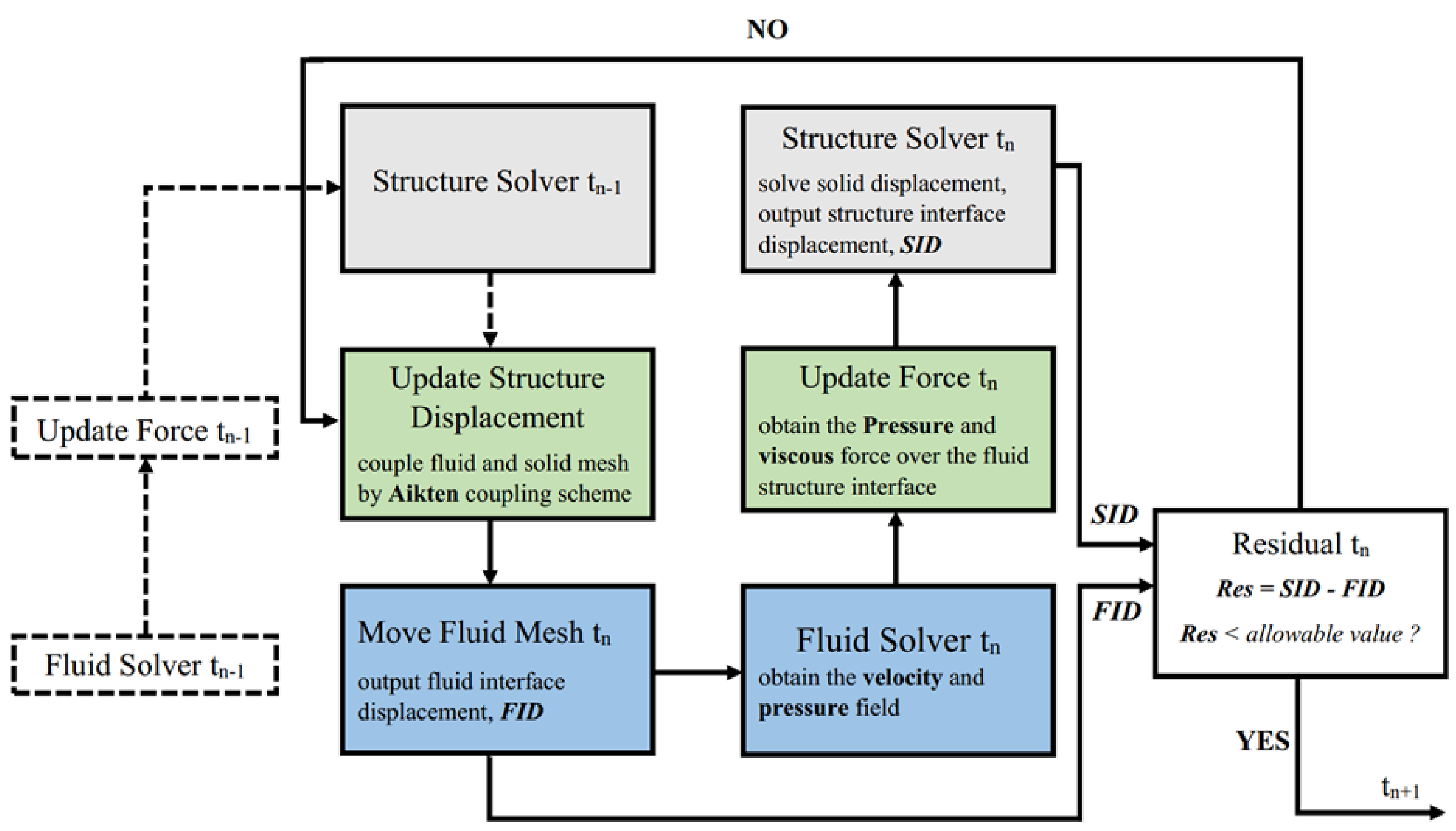

Fig 1 Flowchart of the FSI procedure.

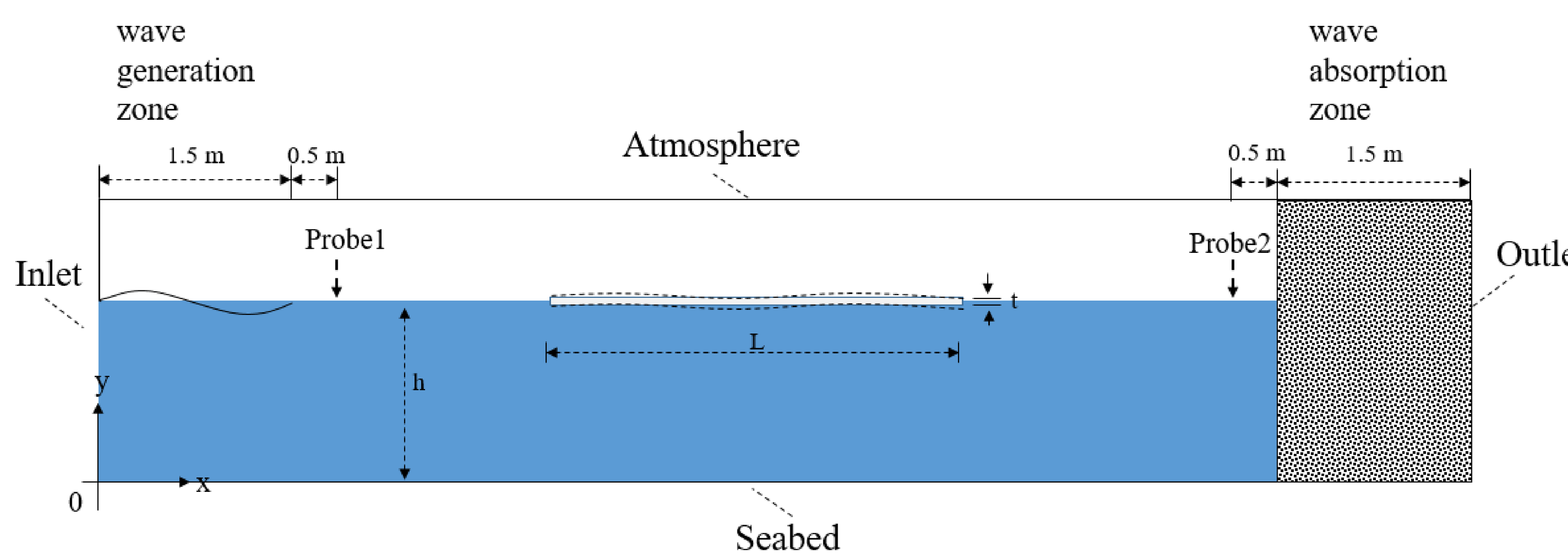

Fig 2 Schematic of the case: an ice sheet is floating on the water surface and subjected to incoming waves.

Validation and conclusions

The FSI model was verified through a mesh sensitivity test to select an appropriate mesh density to capture the elastic deformation of the ice sheet. The solid mesh density was globally scaled, resulting in four meshes of different cell numbers. With the four meshes, the wave-induced deformation was measured at different locations of the ice sheet, and the measured vibration amplitudes are presented in Figure 3, alongside corresponding experimental data. It shows the ice sheet is undergoing significant deformations near the edges while the vibration amplitude is small in the middle area, i.e. the ice sheet is bending due to the wave. Deviations between model and experimental results are small when the ice is discretised into no less than 100 cells per length and 4 cells per thickness.
A subsequent validation was conducted on wave reflection and transmission against the ice sheet (R & T), denoted by the proportions of energy reflected back and passing through respectively, for which, two probes were positioned at upstream and downstream locations to measure the wave energy. The comparison between computational and experimental results is shown in Figure 4, where good agreement can be seen for the examined wave conditions. With increasing wavelength, T increases and R decreases, which means a better transmission appears with longer incident waves.
In conclusion, a multiphase FSI solver has been developed within OpenFOAM framework, and a successful attempt has been presented to simulate the hydroelastic response of sea ice. Verification and validation shown the solver is capable of predicting ice deformations and the influence of ice on surrounding fluid field. Moreover, the proposed solver can also be applied to other wave conditions and deformable structures.

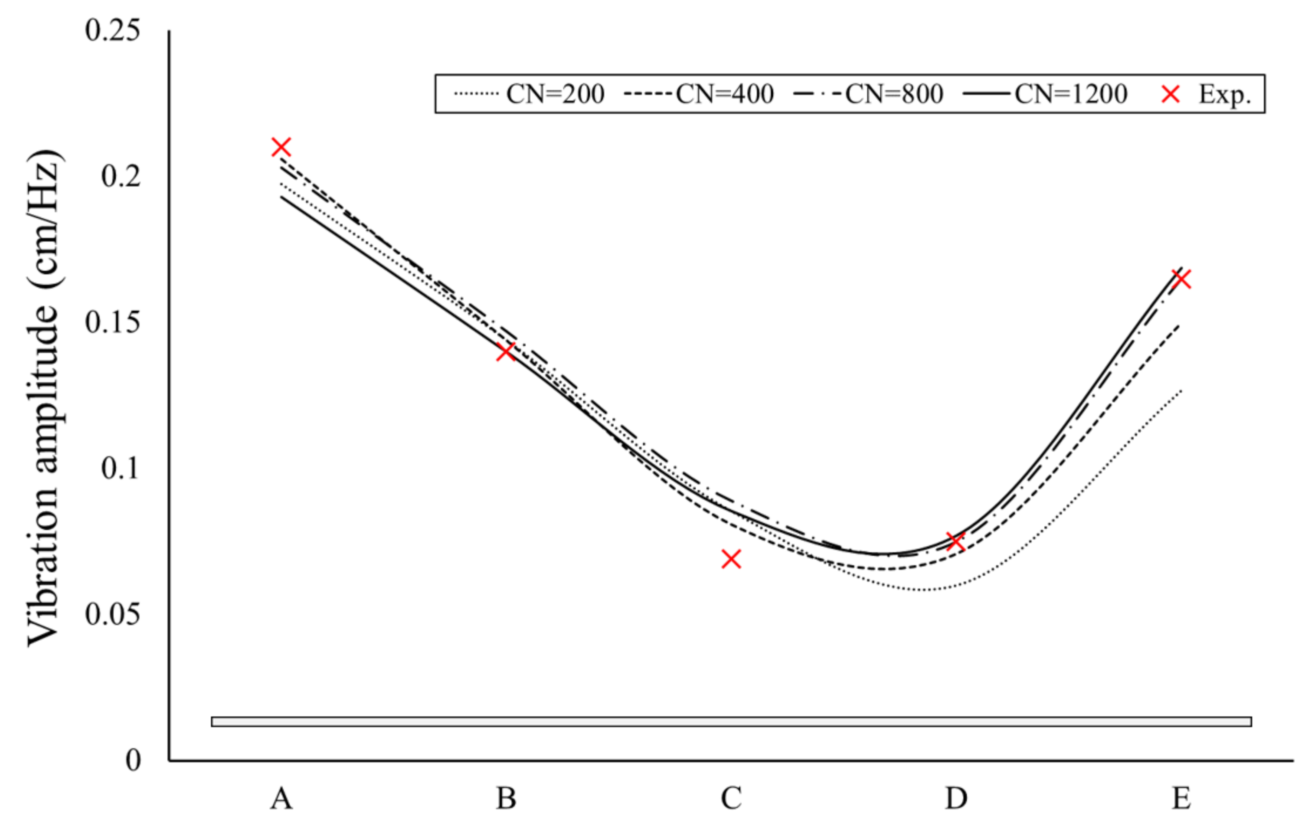

Fig 3 Vibration amplitude at different locations of the ice sheet, calculated with a range of solid cell number (CN).

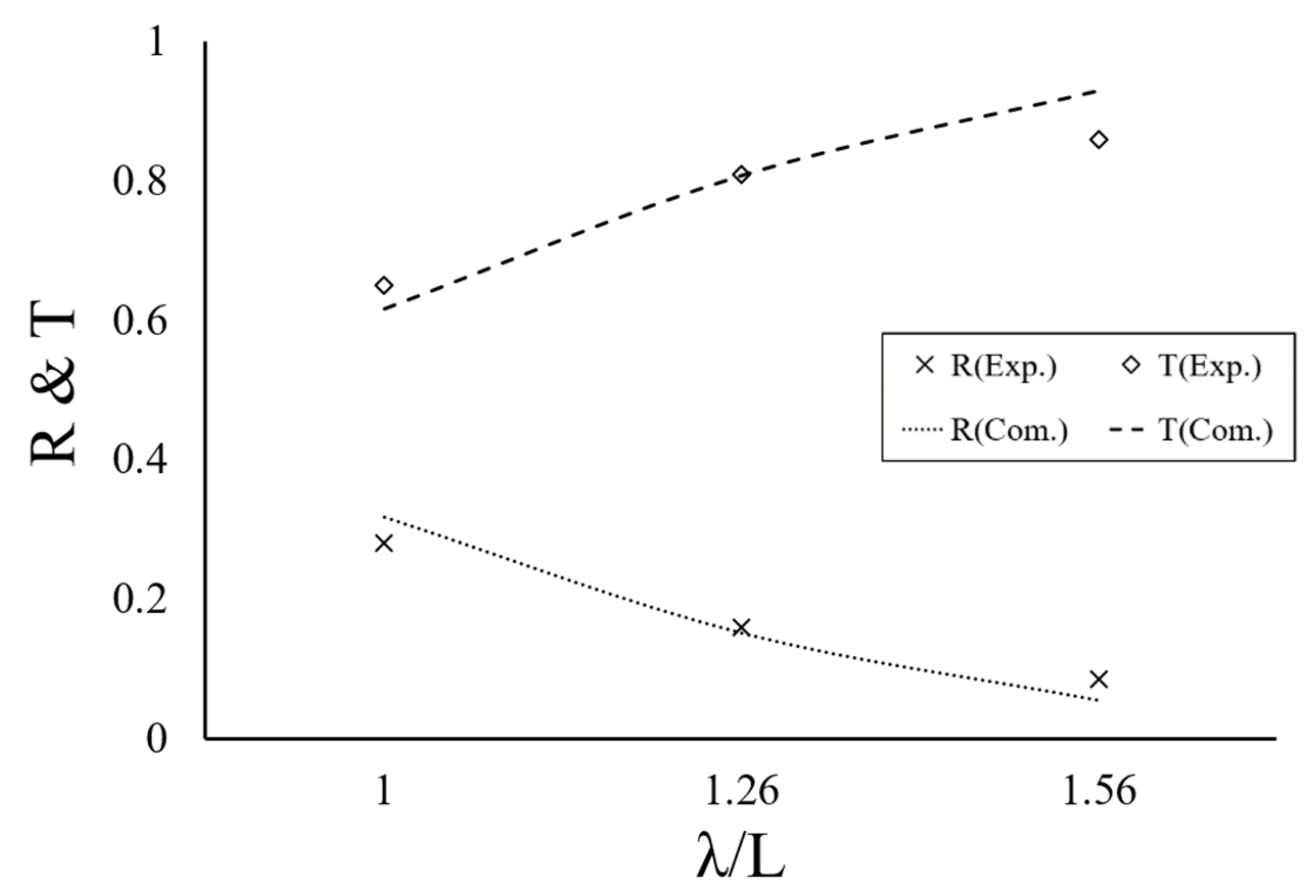

Fig 4 Computational and experimental R & T, as a function of wavelength divided by ice length.

*For full papers please check: [1] Huang et al. Fluid-structure interaction of a large ice sheet in waves. [2] Cardiff et al. An open-source finite volume toolbox for solid mechanics and fluid-solid interaction simulations. [3] Tukovic et al. OpenFOAM Finite Volume Solver for Fluid-Solid Interaction
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