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Effects of a Ship Moving in a Lead between Flexible Ice Sheets

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1 INTRODUCTION

The number of ships that operate in the Arctic continues to increase with the changing climate. Traditionally ships traveled to the Arctic to explore this remote part of the planet in the spirit of conquest and adventure, but now it is traversed by cruise ships and tankers. The increase in traffic also brings the need for search and rescue vessels. The prospect of fossil fuel resources is stoking interest amongst energy companies to operate in the Arctic. Furthermore, the current geopolitical environment has also placed pressure on many nations to have an expanded surface ship presence in the northern latitudes. With the increased human maritime traffic comes the need to more carefully understand the performance of ships in icy waters.

Operation in ice takes many forms due to the various conditions that can be encountered. Ice itself is incredibly complex as it varies in thickness, and material properties that depend on weather, the water salinity, how the ice was formed, and many other lesser factors. There is a great body of work on the icebreaking performance of specialized ships, but much less work has been done on the interaction of the wave field of a ship that is traveling near ice but not in direct contact with it. This lesser studied problem is related to how ships that transit the Arctic normally operate, and both the effects of ice on ship performance, and the influence of ships on the ice[1]. For example ship captains will use satellite imagery to identify open water leads (or large cracks in the ice) that they can follow without having to break the ice. Figure 1 shows an image from the bridge of a ship traveling through a lead.

In this abstract the idealized problem of a ship moving with constant speed through an openwater lead of constant width is studied. A combined computational fluid dynamics (CFD) and finite-element analysis (FEA) framework is used to simulate the interaction of the ship and the ice environment. The method tightly couples the hydrodynamic and structural solutions in the time domain. The numerical results include the deflection of the ice, the over wash of the ship wave field onto the ice, and the stress field in the ice. The idealized problem of the constant width lead is shown in the right of Figure 1.

2 METHODS

The idealized problem is studied using a coupled CFD and FEA framework. The CFD solver is based on the finite-volume discretization of the URANS equations using the open-source library OpenFOAM (v1812). The air-water interface is tracked with the Volume-of-Fluid method. The CFD domain includes a rectangular parallelepiped that translates along the ship track. The computational domain has a length of $7L$ with the ship centered at a

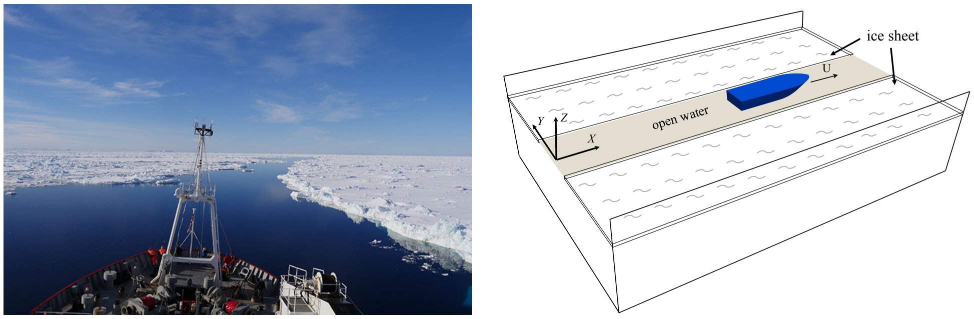

Figure 1: Ship in a lead.

distance of $3L$ from the upstream boundary. The half domain width, which is the combination of open water portion $w/2$, and the width of the ice sheet, has a large value of $10B$ to minimize the wave reflection from the lateral extent of CFD domain. The ship accelerates from rest up to a constant speed over a time window of $0 < t < 10U/g$, where U is the final constant speed, and g the acceleration due to gravity. The ship sinks and trims according to the heave and pitch equation of motion, and the grid deforms around the ship to account for this relative motion. A custom morphing function is used where the cells around the discretized ice sheets and ship hull are frozen and the deformation takes place in the other regions of the flow domain.

The structural domain, which is a single rectangular ice sheet of constant thickness h, is fixed in a lateral position and has a much larger extension than the fluid domain. The ice has specific gravity of 0.9 and is floating with 10% of its thickness above the calm water plane. The structure and fluid domains overlap at the ice surfaces within the perimeter of the fluid domain. The mutual interfaces include the upper and lower surfaces of the ice sheet, which are initially horizontal and parallel to each other, as well as the vertical ice edge. The upper surface of the ice sheet is included mainly for resolving the over wash effects. The ice sheet is subject to external forces from the fluid domain. The vertical deflection of the ice is determined from the equations of a thin-elastic-plate model that are solved with a modal decomposition method [2, 3]. The external forces include the hydrodynamic and hydrostatic forces acting on the lower surface of the ice, and the force on the upper surface of the ice due to over wash. The force due to over wash consists mainly of the fluid weight of the green water. The hydrostatic pressure $\rho g z$ acts on the entire lower surface of the ice sheet that extends beyond the fluid domain, and is determined by the elevation z of the deflected lower surface (which varies across the ice surface). The hydrodynamic pressure p_{rgh} is only evaluated within the fluid domain. With such an assumption, a sufficiently large fluid domain is needed to ensure the hydrodynamic pressure outside the fluid domain is small enough to be neglected.

The arrangement of the fluid and structural domains can be seen in Figure 2.

3 RESULTS

Numerical experiments are performed for the Office of Naval Research Tumblehome (ONRT) hull form that travels at speeds in the range of length-based Froude number between 0.2 and 0.4. The ice varies in thickness from 0.5 to 2 m. The width of the lead is

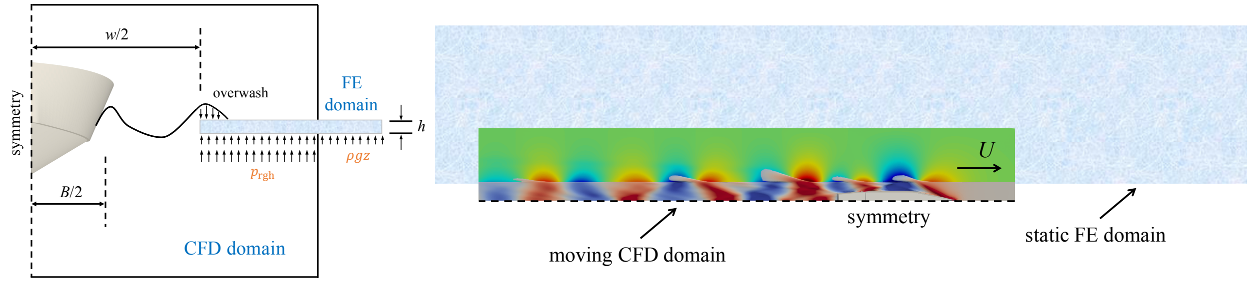

Figure 2: Description of the computational problem and domain.

twice the ship beam.

The wave field and deflection of the ice for two speeds are shown viewed from above in Figure 3. The ice thickness is 0.5 m. There is a clear correspondence between the ship waves and the deflection in the ice, and for the greater ship speed of $F_r = 0.4$ the deflection is larger. The deflection in the ice is observed only near the edge of the ice, and the deflection quickly decays away from the edge of the ice.

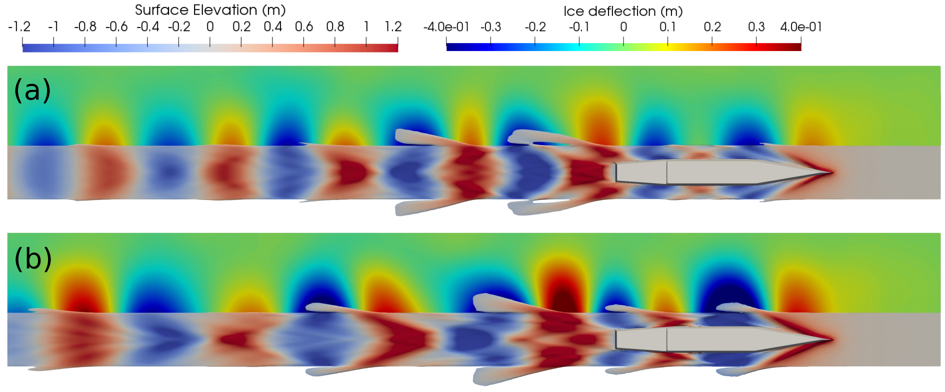

Figure 3: Wave field and ice deflection. Ice thickness 0.5 m. (a) $F_r = 0.33$, (b) $F_r = 0.4$.

Next the wave field and the deflection at the ice edge are shown for two ice thicknesses for the speed $F_r = 0.4$ in Figure 4. In this figure the location of the bottom and top edges of the ice are shown in blue, and the wave elevation is shown in black. The shaded red region corresponds to the region where the wave elevation is greater than the deflected top ice edge. This is the region where over wash occurs. Also note the thinner ice has less freeboard than the thicker ice and the thicker ice has much less deflection due to its greater rigidity.

The over wash mass flux over the ice edge is defined as

$$\dot{m} = \int_{z_{\text{top}}(x,w/2)}^{\xi(x,w/2)} \int_{x_B}^{x_A} \rho v \; dxdz, \quad \text{for } \xi(x,w/2) > z_{\text{top}}(x,w/2), \tag{1}$$

Where v is the lateral component of fluid velocity. The normalized mass flux is defined as $\dot{m}' = 2\dot{m}L/mU$, where $m = 8507$ ton is the displacement of the full-scale ONRT.

The normalized mass flux for three ice thicknesses is shown in Figure 5 as a function of speed. As the speed increases, so does the mass flux. This quantity represents the fraction of the ship mass in water that flows onto the ice in each interval of time corresponding to traveling one ship length. It is interesting to note that the thicker ice, with proportionally greater freeboard, has larger mass flux. The reason for this is evident in Figure 4. The thinner ice is more conformant to the ship wave field, and the relative elevation, that is the elevation relative to the deflected top edge, is greater for the thicker ice, allowing for more water to flow onto the ice. This is also confirmed by performing simulations with the thin ice in a rigid configuration, as seen in Figure 5. The rigid ice clearly has more over wash.

If this abstract is accepted results for a new model for the over wash based on thin-ship theory will be presented, as well as additional results of the ice deflection and the propensity for fracture.

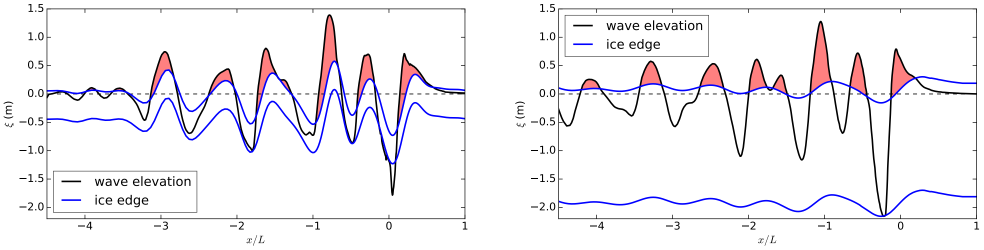

Figure 4: Wave field and ice-edge deflection (*left*) flexible ice $h = 0.5$ m, (*right*) $h = 2$ m.

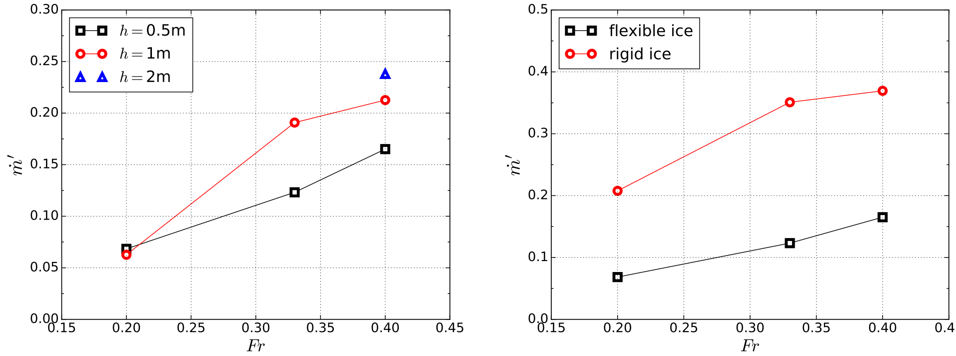

Figure 5: Over wash (*left*) flexible ice, (*right*) comparison of flexible and rigid ice $h = 0.5$ m.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

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