Simulation of Ship Advancement in Floating Ice Floes

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Background

Global warming has induced a paradigm change in the Arctic environment, pronounced by an obvious transition from level-ice coverages to broken ice-floe fields and open water. The changed condition makes the region more accessible to ships, with two major cargo-shipping routes becoming navigable, the Northwest Passage and the Northern Sea Route, which can be used as alternatives to the Panama and Suez canals to connect Europe, Asia and America; compared with their current counterparts, both new routes can reduce the travel distance by up to 40%, leading to significant fuel, cost, time and emission savings.

However, the potential navigation environment in the Arctic has been found more complex than anticipated. Rather than providing pure open water, the melting process results in that the ice coverage breaks up into numerous ice floes floating on the sea surface, as shown in Fig 1. Such ice-field fields have been reported to be the most ubiquitous condition for future Arctic shipping. However, the effect of the ice condition on ship performance has yet to be understood - this is the motivation of this work to build a computational model to simulate the process.

Fig 1: A ship in floating ice floes. Credit: Alessandro Toffoli.

Research Approach

The process of a ship advancing in floating ice floes can be summarised as the following ship-wave-ice interaction: ship advancement generates waves; waves interact with ice floes; ice floes contact each other and with the ship. To reasonably replicate the process, this work followed three steps: (a) Computational Fluid Dynamics (CFD), a standard model for ship advancement in open water, where fluid solutions are obtained, namely the wake of a ship. (b) Discrete Element Method (DEM), for modelling ice floes and their collisions with the ship and nearby floes; those floes obtain fluid force from CFD solutions so that the ship-wave-ice coupling is achieved. (c) floe-distribution algorithms, by which natural ice-floe fields are generated and implemented into the CFD+DEM model; this enables the ice floes to be of a range of sizes and that the location of each ice floe is randomly distributed. The completed computational model is shown in Fig 2.
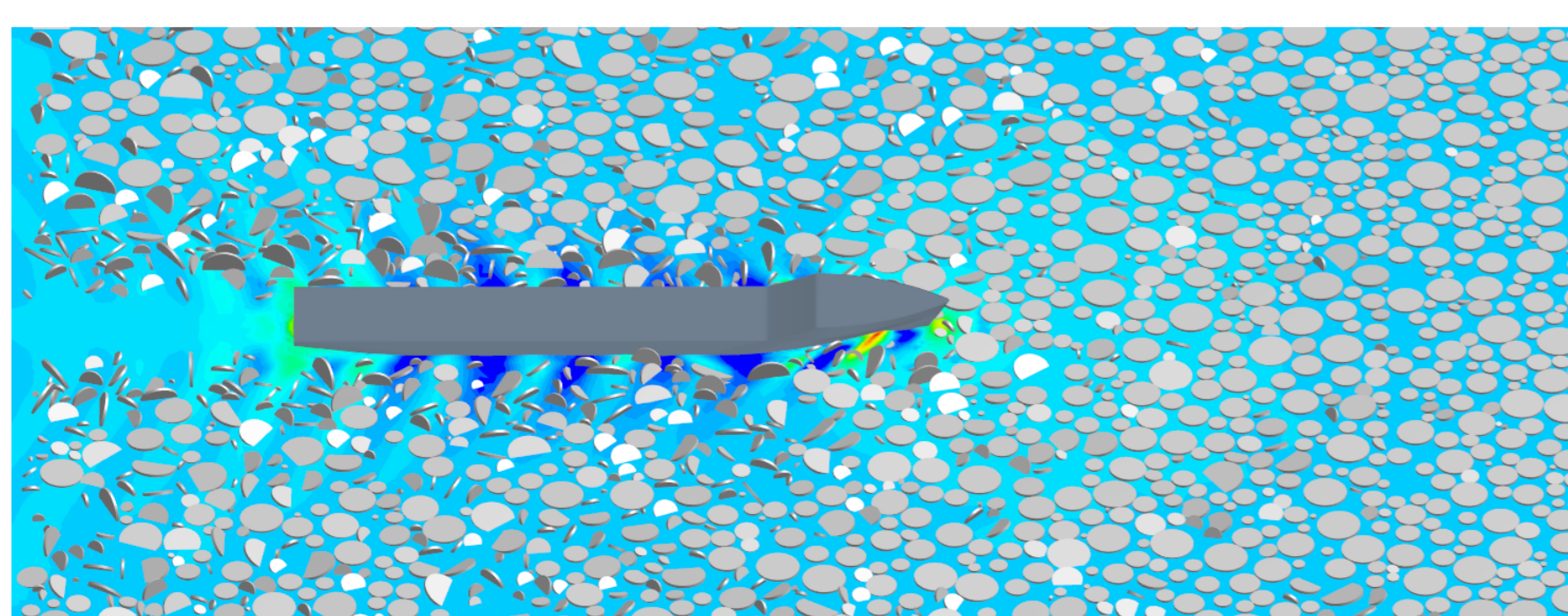

Fig 2: Simulation of a ship advancing in floating ice floes.

Results and discussion

When a ship is advancing in ice floes, ship-ice collisions occur at the bow area, causing the floes to be pushed aside and rotate within the wake, and some floes can slide along the ship for a certain distance. This work extracts the ship resistance, namely the force born by the ship in its advancement direction, which determines the power required for such shipping. The total resistance of the ship consists of an ice resistance R_{ice} induced by the floes, and a water resistance R_{water} similar to an open-ocean case ($R_{total} = R_{ice} + R_{water}$). R_{ice} occurs due to ship-ice collisions at the bow area as well as the force due to floe sliding.

The relationship of R_{ice} with essential variables have been investigated. Figure 3 presents the ice resistance for varying ship speeds (Fr) and ice concentrations (C). The upper panel shows the variation trend of R_{ice}; regression analyses indicate the increasing powers of ship speed and ice concentration are respectively around 1.2 and 1.5 in the examined range. The lower panel presents the ratio of R_{ice} to the corresponding R_{water}, which indicates ice floes can induce significant resistance increments to a ship. It also shows R_{ice} is more influential when the ship is relatively slow and such an effect is more pronounced for high ice concentrations. This is because a faster ship generates larger waves, which tends to push the floes away thus reducing the ship-ice contact. Apart from Fr and C, The influences of ice thickness and floe diameter on R_{ice} have also been analysed - both were found to be have a linear effect. More variables including hull parameters shall be studied in future work.
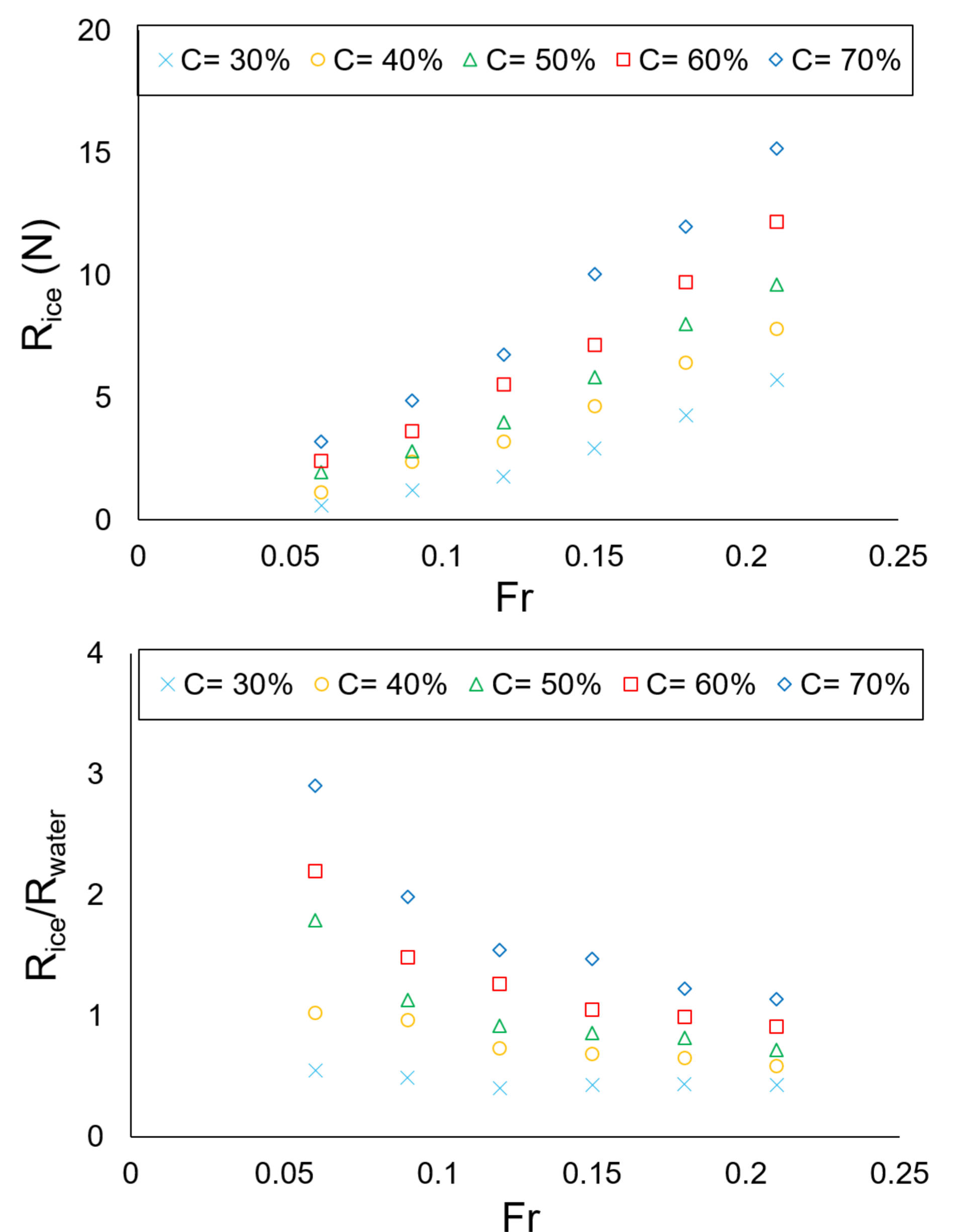

Fig 3: Ice-floe resistance in varying ice concentrations and ship speeds, for the KRISO Container Ship at model scale.