Jiang, Zongyu; Suominen, Mikko; Tavakoli, Sasan; Kujala, Pentti; Hirdaris, Spyros

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Published in:
Proceedings of the 12th International Workshop on Ship and Marine Hydrodynamics

DOI:
10.1088/1757-899X/1288/1/012023

Published: 09/08/2023

Document Version
Publisher's PDF, also known as Version of record

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To cite this article: Z Jiang *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1288** 012023

IOP Conf. Series: Materials Science and Engineering 1288 (2023) 012023 doi:10.1088/1757-899X/1288/1/012023

A CFD investigation of the effects of passing ship on a small size ice floe

Z Jiang[1], M Suominen[1], S Tavakoli[1], P Kujala[1] and S Hirdaris[1,*]

[1] Marine and Arctic Technology, Department of Mechanical Engineering, Aalto University, Espoo 02150, Finland

[*] Corresponding author, e-mail address: spyros.hirdaris@aalto.fi

Abstract. A RANS (Reynolds Averaged Navier-Stokes) CFD STAR-CCM+ model is used to investigate the hydrodynamic interactions between a ship and a circular ice floe. The overset mesh technique is employed to simulate the advancing movement of the passing ship. The ship has a hull of similar configuration to the KCS MOERI container ship. The ice floe has a diameter of 30% of the ship's length and a thickness of 3 m. The paper primarily focuses on the motions of the ice floe and the hydrodynamic forces induced by the ship progressing in different speeds and calm water conditions. A parametric study on the influence of the ice floe surge and sway motions and associated hydrodynamic loads is presented. It is concluded that ship-generated waves can significantly affect the motions of the ice floe and the influence on sway is greater than that on surge. The ship speed is also found to have a distinct impact on ice floe motions.

1. Introduction

In recent years, the development of shipping corridors in the Arctic has been inevitably interlinked with the adverse effects of climate change leading to the reduction of sea ice cover. An example is the increase of traffic along the Northern Sea Route (NSR), which is recognized as a viable alternative to traditional shipping routes through the Suez and Panama Canals. Arctic shipping raises several unique challenges of relevance to ship safety and efficiency. For example, the collision with sea ice in Arctic waters challenges the structural integrity of ship hulls.

The hydrodynamic interaction between an advancing ship and ice floes may lead to unusual seakeeping responses of the ice floe and ship. For example, the motions of an ice floe induced by the forward ship might lead in a collision with the following ship. In such cases different speeds of the ship and ice floe result in disparate boundary conditions in way of the free surface. If the speeds of an ice floe and a floating structure are zero, it will be easier to describe the boundary condition in way of the free surface boundaries [1]. Some scholars consider the velocity of floaters but disregard the effects of surface waves [2]. Recently, Jiang et al. [3] proposed a potential flow analysis method to tackle the issue of free surface boundary conditions induced by different speeds. This method is based on the linear superposition of velocity potential and the encounter frequency method. Hence, it is constraint to low speeds. Recently, the RANS based CFD method has been extensively applied to study the hydrodynamic interactions between a passing and a moored ship [4].

This paper introduces a RANS based CFD model to simulate the hydrodynamic interactions between a passing ship and a small size ice floe. The overset technique is used to deal with the large amplitude motions of the passing ship. The study examines the surge and sway motions of the ice floe under the influence of three different advancing speeds of the passing ship. The fluid forces in surge and sway acting on the ice floe are presented to investigate dynamics.

2. Theory

2.1. Governing equations

The governing equations of the viscous fluid model are the Navier-Stokes (NS) equations, which consist of the mass conservation equation and the momentum conservation equation. These equations are defined as

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \rho \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

where t is the time, ρ is the effective fluid density, u_i and u_j are the Cartesian components of velocity vector with $i, j = 1,2,3$, p is the pressure, μ is the effective dynamic viscosity, $\rho\overline{u_i' u_j'}$ is the Reynolds stress.

The Volume of Fluid (VOF) method is adopted for the free surface capture with a volume fraction factor α, which represents the averaging the density ρ and viscosity v in partial elements

$$\rho = \alpha\rho_w + (1-\alpha)\rho_a, v = \alpha v_w + (1-\alpha)v_a \tag{3}$$

where w and a represent the water phase and air phase, respectively.

2.2. Numerical implementations

The Finite Volume Method (FVM) is used to solve NS equations in conjunction with the segregated flow solver that is used to solve the conservation of mass and momentum. The convective flux is computed by the second order upwind scheme. The $SST\ k-\omega$ turbulence model is used to calculate the transport of turbulent shear stress. The all $y+$ wall treatment is used to simulate the boundary layer around the no-slip wall boundaries, which uses a blended wall function to cover all three sublayers [5]. The time step is set in compliance with the Courant-Friedrichs-Lewy condition

$$C_r \geq \frac{U\Delta t}{\Delta x} \tag{4}$$

where C_r is the Courant number, U is the mesh flow speed, Δt is the computational time step, Δx is the cell dimension.

2.3. Dynamic fluid body interaction

The fluid force $\mathbf{F}$ and moment $\mathbf{M}_o$ acting on the structure can be obtained as

$$\mathbf{F} = -\int_S p \cdot \mathbf{n} ds + \int_S \mu \frac{\partial \mathbf{u}_\tau}{\partial \mathbf{n}} ds = \int_S \mathbf{f}^p ds + \int_S \mathbf{f}^s ds \tag{5}$$

$$\mathbf{M}_o = \int_S (\mathbf{x}_f - \mathbf{x}_0) \times (\mathbf{f}^p + \mathbf{f}^s) ds \tag{6}$$

where $\mathbf{u}_\tau$ is the tangent velocity component around the body surface, S is the body surface, $\mathbf{x}_f$ is the centroid of cell face f, $\mathbf{x}_0$ is the specified origin vector.

The motions of ice floe in 6 – Degrees of Freedom (DoF) are calculated by the Dynamic Fluid Body Interaction (DFBI) method. The translation and rotation of the ice floe can be calculated as

$$\mathbf{M}\frac{\partial \mathbf{u}}{\partial t} = \mathbf{F} \tag{7}$$

$$\mathbf{M}\frac{\partial \boldsymbol{\omega}}{\partial t} + \boldsymbol{\omega} \times \mathbf{M}\boldsymbol{\omega} = \mathbf{M}_o \tag{8}$$

where $\mathbf{M}$ is the inertia matrix, $\boldsymbol{\omega}$ is the angular velocity.

3. Numerical model setup

A Numerical Wave Tank (NWT) is established to conduct the simulation. The boundary conditions and dimensions of the NWT are depicted in Figures 1 and 2. The fluid domain of this NWT is a rectangle with a length of 8.4 times the length of the passing ship (L_p), a breadth of 3 times L_p, and a depth of 2.5 times L_p. The water depth is 1.5 times L_p.

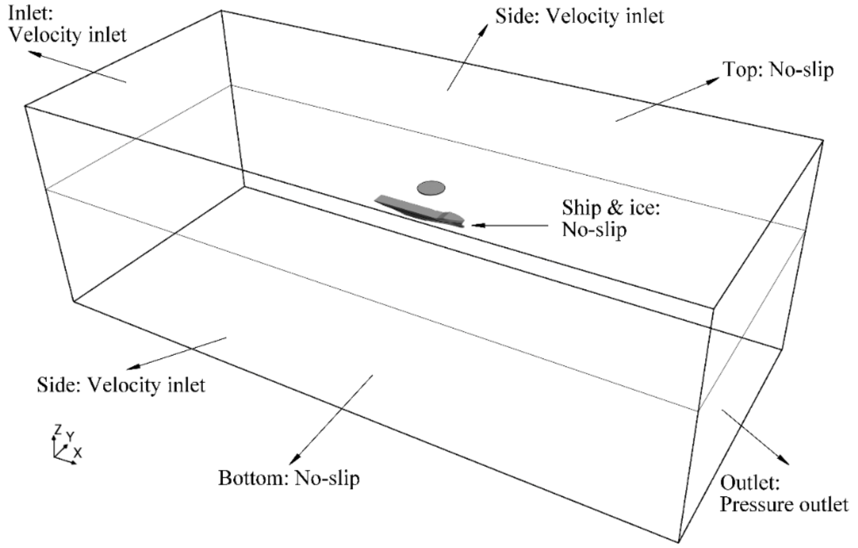

Figure 1. 3D view of Numerical Wave Tank and its boundary conditions.

Figure 2 displays a simplified scenario of a ship corresponding to the MOERI container ship KCS passing by a circular ice floe with a diameter of $0.3L_p$ and a thickness of 3 m at three constant speeds of the order of 6, 8,10 knots (see Figure 1 and Table 1). The transverse distance between the ice floe edge and the port side of the passing ship is $1/3\ L_p$. The simulation starts when the passing ship's bow is $0.5L_p$ from the centre of the ice floe and ends when its stern is $0.5L_p$ from the center of ice floe. The main settings of the numerical simulation are presented in Table 2. The fluid domain is discretized by a trimmed mesh (see Figure 3). An overset mesh technique is used to handle the translation of the passing ship over the long distance at constant speed. The ship is contained in the local region, while the ice stays in the background and idealised by the DFBI method. The mesh around the ship's course and the ice floe is refined to better describe the fluid flow.

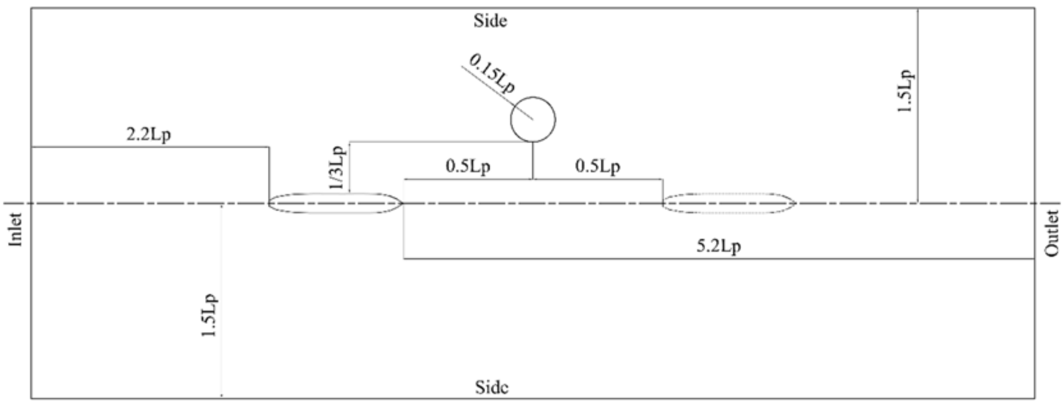

Figure 2. Top view of the Numerical Wave Tank and positions of the ship and ice floe.

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Table 1. Main dimensions of KCS.

Item	Symbol	Units	Value
Length between perpendiculars	L_p	m	230
Beam	B	m	32.2
Draft	T	m	10.8
Displacement	Δ	m^3	52030
Vertical center of Gravity	KG	m	7.28
Long. Center of Gravity	LCG	m	111.6
Roll radius of gyration	k_{xx}/B	-	0.4
Pitch & Yaw radius of gyration	k_{yy}/L_p & k_{zz}/L_p	-	0.25

Table 2. Main settings in RANS simulation

Item	Setting
Turbulence model	SST $k-\omega$
Time model	Implicit unsteady
Time step	0.01 s
Solver formulation	Segregated
Velocity-pressure algorithm	SIMPLE
Free surface capture	VOF
DOF of passing ship	Surge
DOF of ice floe	6 DOF

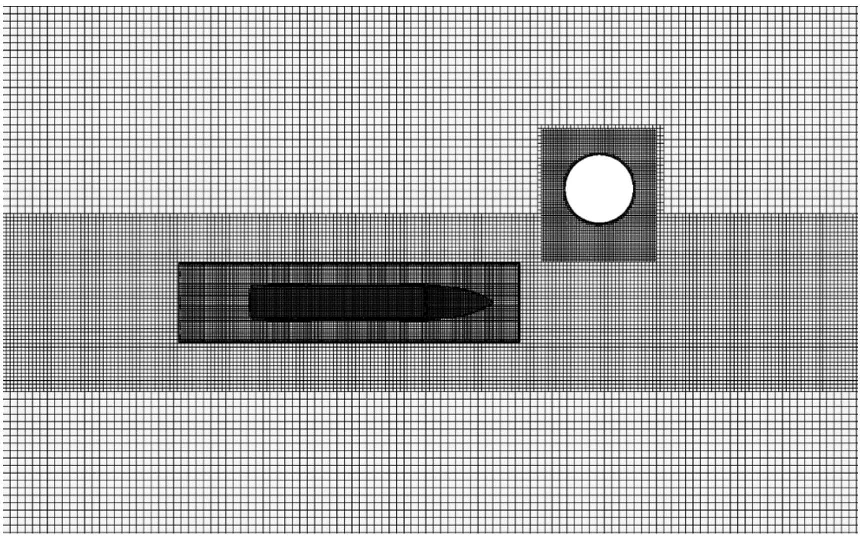

Figure 3. Trimmed mesh in the fluid domain.

4. Results and discussion

When a ship passes by a small size ice floe, the ship generated waves instigate 6-DoF motions. Amongst those, sway and surge may be considered as the most relevant to ship-ice collision scenarios. In this paper, to better analyze the spatial effects, a parameter D_L is introduced to represent the longitudinal distance between the passing ship amidship region and the center of an ice floe. $D_L < 0$ indicates the ship is approaching the ice floe, while $D_L > 0$ indicates the ship is departing.

4.1. Sway motions of the ice floe

Figure 4 illustrates the sway motion of an ice floe with respect to the relative longitudinal position between the ship and ice floe over time at ship speeds 6,8,10 knots. At first instance, the sway of ice may be considered negligible until $D_L/L_p \approx -0.8$. At this point, the curves start to diverge. When the ship speed is 6 knots, sway motion amplitudes become negative. This indicates that the ice floe moves toward the passing ship. In 10 knots forward ship speed, the ice floe initially advances- and then reverses-toward the ship. In 8 knots forward ship speed, the sway motion remains close to zero until $D_L/L_p \approx -0.4$. This phenomenon can be revealed by the sway velocity of the ice floe, as shown in Figure 5. This figure shows that the sway velocity is small when $D_L/L_p < -0.8$. Subsequently, velocity fluctuations become proportional to the ship speed for $D_L/L_p < -0.4$. At this stage, the velocity is negative when the ship speed is 6 knots, and positive when the ship speed is 10 knots. For 8 knots ship speed the velocity curve is approximately evenly positioned above and below 0. Eventually, all three curves indicate a continuous negative pattern.

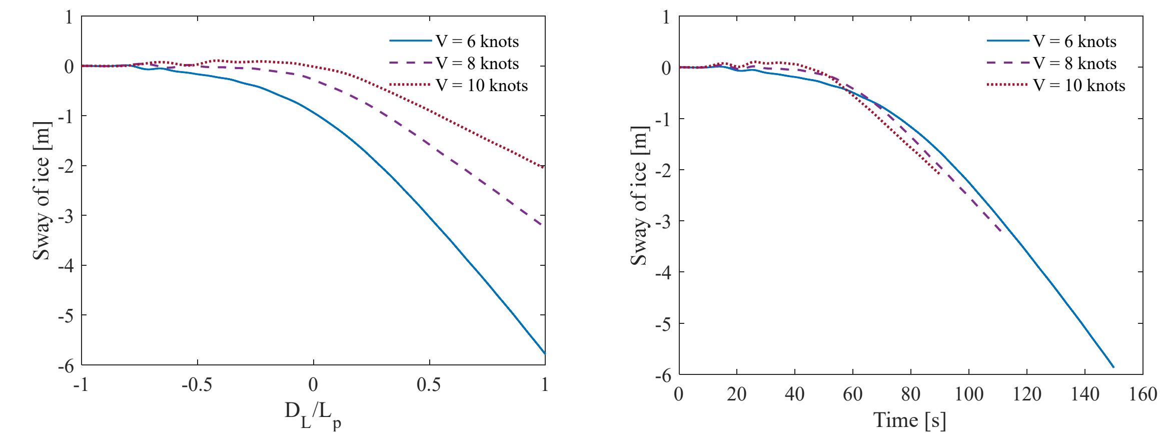

Figure 4. Sway of the ice floe under the waves generated by the passing ship.

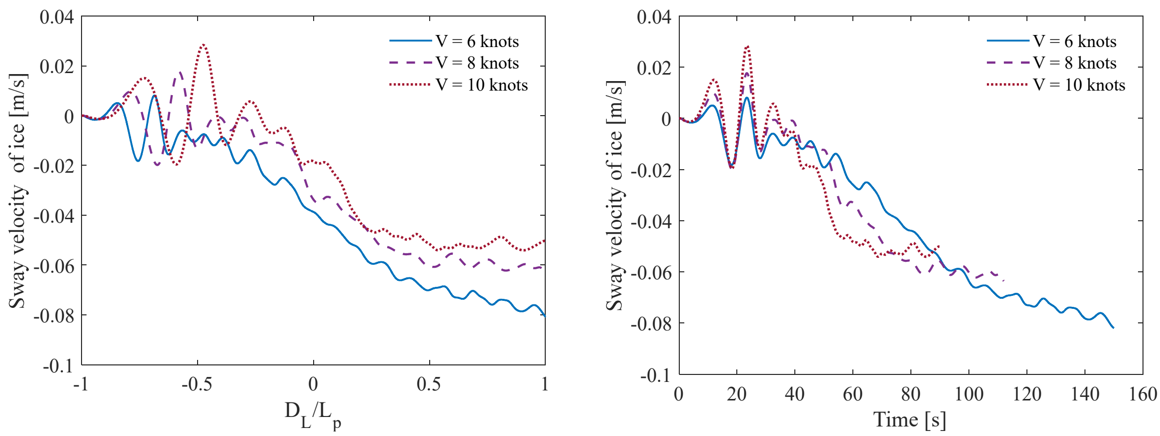

Figure 5. Sway velocity of the ice floe under the waves generated by the passing ship.

Figures 4 and 5 reveal that the ice foe is attracted by the passing ship for all three ship speeds. However, in 10-knots, the ice floe is initially pushed away by the ship waves, and then dragged back when their distance is short enough. Figure 6 shows the field of fluid velocity at the transverse section crossing the centre of the ice floe for 6 and 10 knots forward ship speed. Figure 6 demonstrates that the fluid velocity is higher in way of the part of the ice floe that is close to the passing ship. It complies with the expectation because the fluid velocity is induced by the passing ship. According to the Bernoulli's equation for incompressible fluids, the fluid pressure is inversely proportional to the velocity. Thus, the pressure gradient pushes the ice floe to the passing ship. Figure 7 shows the time history curve of integral fluid force on the ice floe in sway. It is demonstrated that that negative over positive sway forces dominate over time. The change of momentum depends on the product of force with time. Thus, the record of sway force agrees with the record of sway motion of ice. Similar results have been reported in the experiments by Tsarau et al. [2]. The large amplitude of fluctuation of sway forces at the initial stage could be attributed to the divergent bow wave.

Figure 6. Fluid velocity field at the transverse section crossing the center of ice floe.

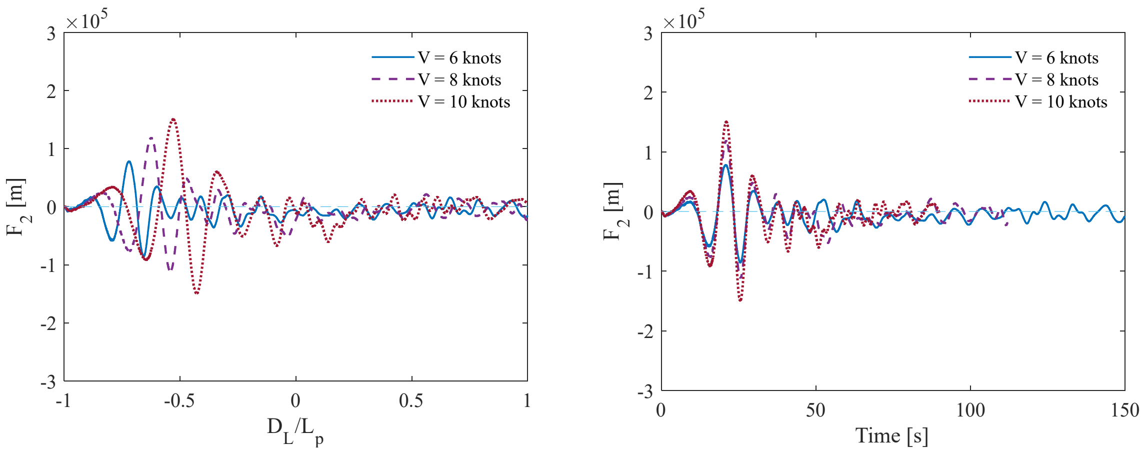

Figure 7. Transient fluid force in sway on the ice floe.

4.2. Surge motions of the ice floe

Figure 8 illustrates the surge motion of the ice floe in waves generated by the passing ship at different speeds. At first instance the amplitude of surge remains low for $D_L/L_p < -0.9$. Then, the ice floe progresses towards the direction of ship speed. When the distance between the ship and the ice floe is marginal, i.e., $-0.5 < D_L/L_p < 0.5$, the ice floe is dragged in the opposite to the ship speed and for $D_L/L_p > 0.5$ it reverses (see Figure 9). The large fluctuation of velocity observed at first may be

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attributed to the corresponding fluctuation of surge forces (see Figure 10), which could be induced by the divergent bow wave.

The surge and sway displacements of the ice floe are respectively proportional and inversely proportional to ship speed. This could be attributed to the longer acting time of fluid force acting on the ice floe when the ship speed is lower. As an example, Figure 11 illustrates the impulse of sway force during the whole course of simulation. As shown in Figure 11, the impulse of sway force is negative for all three ship speeds, and the absolute values continuously decline with the increase of speed. Correspondingly, the final sway velocity of ice floe is proportional to the ship speed. This can be applied to any time span of sway motion. As a result, the sway motion is largest when the ship passes at 6 knots.

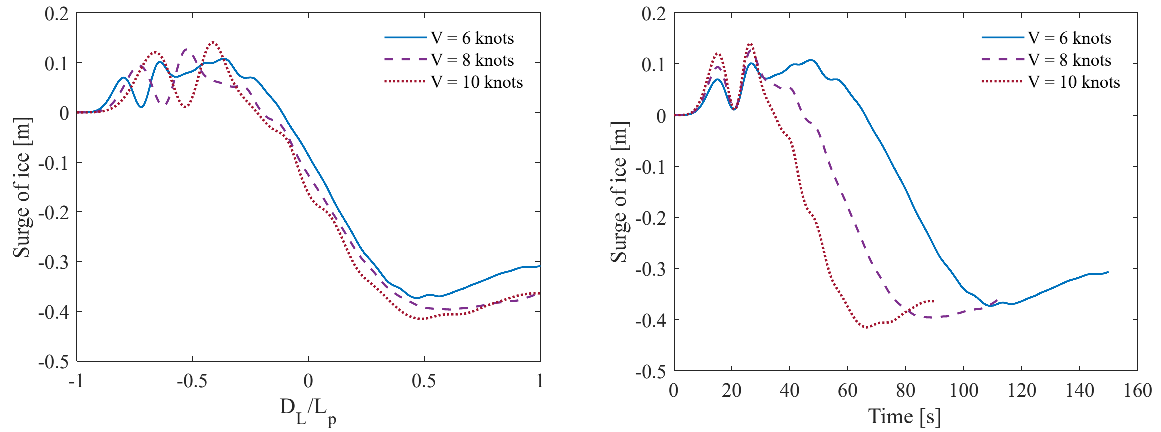

Figure 8. Surge of the ice floe under the waves generated by the passing ship.

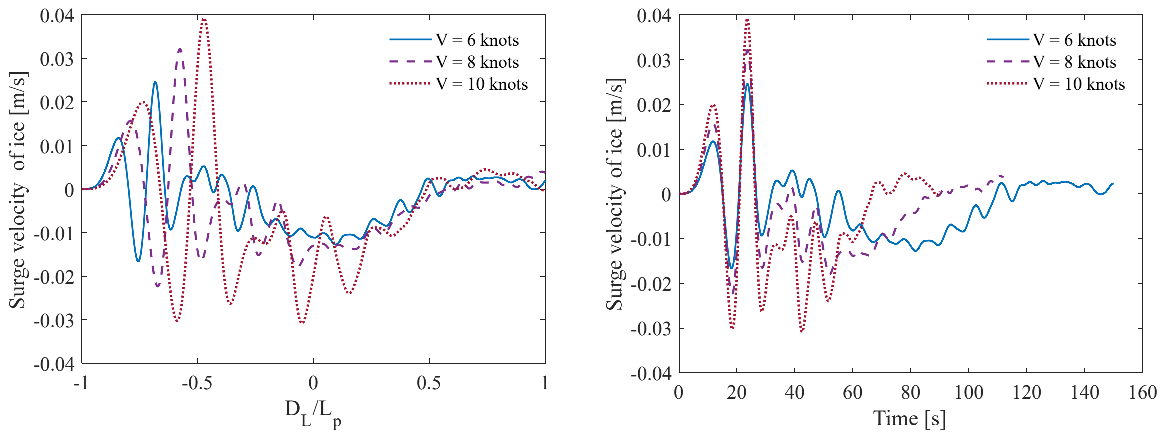

Figure 9. Surge velocity of the ice floe under the waves generated by the passing ship.

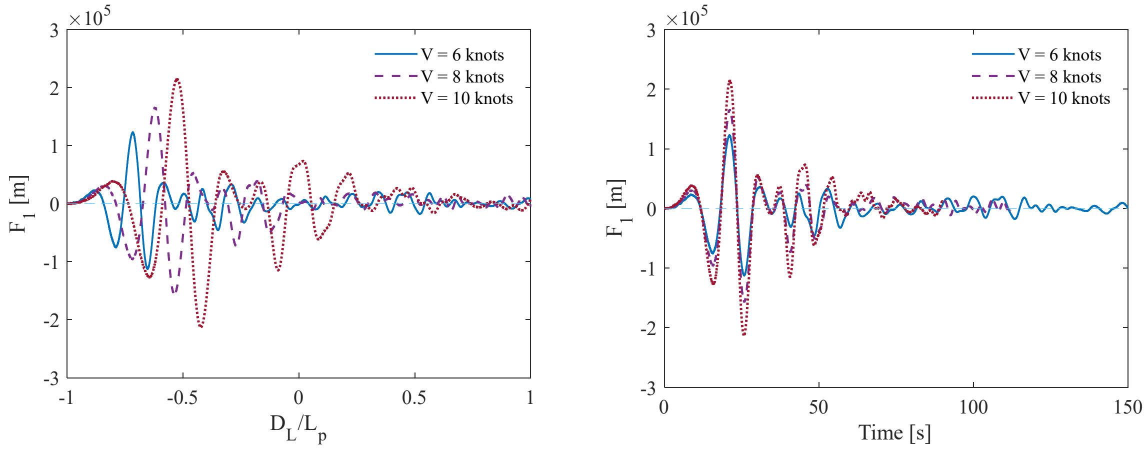

Figure 10. Transient fluid force in surge on the ice floe.

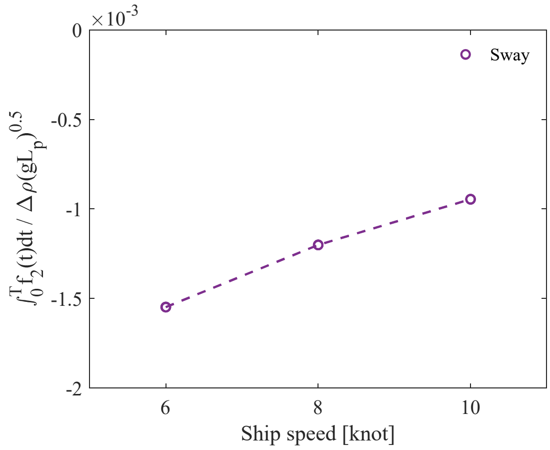

Figure 11. Impulse of sway force.

5. Conclusions

The study presents a RANS based CFD model that examine the hydrodynamic interaction between a passing ship and a small size ice floe. The overset technique is used to deal with the large amplitude motions of the passing ship. The study examines the surge and sway motions of the ice floe under the influence of three different advancing ship speeds. Based on the CFD simulation, the following conclusions can be drawn:

1. The motions of the ice floe can be significantly influenced by the passing ship. Yet, the influence on sway motions is much greater than the influence on surge motions.
2. The ship speed has a distinct effect on the motions of ice floe. The surge displacement of the ice floe is proportional to the ship speed, while the sway is inversely proportional to the ship speed. This is mainly attributed to the longer acting time of the fluid force on the ice floe at lower ship speed.
3. In sway, the ice floe is primarily attracted to the passing ship for all ship speeds. An exception is the scenario of 10 knots where the ice floe is initially marginally pushed away by the ship generated waves.

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4. The surge motion of the ice floe manifests in three subsequent stages depicting forth and back alignment to the direction of the ship's speed.

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