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RECENT ADVANCES IN MODELLING THE HYDRODYNAMIC EFFECTS ON ICE MOTION AND ICE-STRUCTURE INTERACTIONS OFFSHORE

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ABSTRACT
High-fidelity models of sea-ice dynamics and ice-structure interactions require proper accounting for the hydrodynamic forces. This paper gives its reader a systematic view on the recent achievements in the modelling of the hydrodynamic interactions of ice with winds, water flow, waves and floating structures. To emphasise relevant applications, the paper touches upon several topics such as the prediction of iceberg drift, modelling the dynamics of ice floes in the sea, physical ice management, station-keeping in Arctic waters, ice-structure interactions and the hydrodynamic aspects of ice loads on offshore structures. All the considered hydrodynamic problems are accompanied with references to well-established or newly-developed models that may be applied in particular cases.

INTRODUCTION
This paper is intended to give its readers a broad view of the scientific problems associated with marine operations in ice-covered waters and related to the estimation of fluid actions.. This is important in a number of research areas such as the prediction of iceberg drift, the modelling of ice floes dynamics in the sea, physical ice management (IM), station-keeping in Arctic waters, ice-structure interactions and the hydrodynamic aspects of ice loads on offshore structures. Nevertheless, instead of giving a complete overview of each subject in detail, an attempt is made to systemise the topics by examining their common features and considering the link between the hydrodynamic problems associated with them. Succeeding in this task would help in the development of comprehensive mathematical models needed by Arctic marine engineers and scientists involved in cold-environment research.
To keep practicality, all the problems that are mentioned in this paper are accompanied with references to well-established or newly-developed models that may be applied in particular cases. These references are chosen based on the author's subjective view such that the literature on a considered topic is covered sufficiently but not necessarily completely, and therefore the article should not be confused with an up-to-date literature review.

THE REVIEWED TOPICS
Based on literature review and input from SAMCoT industrial partners, the following research topics, presented in Figure 1, have been identified as the practical problems that both most frequently arise in Arctic offshore engineering and require thorough consideration of fluid mechanics in order to be solved. As can be seen from the figure, these problems are classified into two main groups. The first group refers to ice motion modelling, and the

second is associated with the prediction of ice loads on structures. However, as it will be shown below, many of these topics may have common features such as similar mathematical models used to describe the underlying physics, and therefore similar approaches may be used to deal with them.

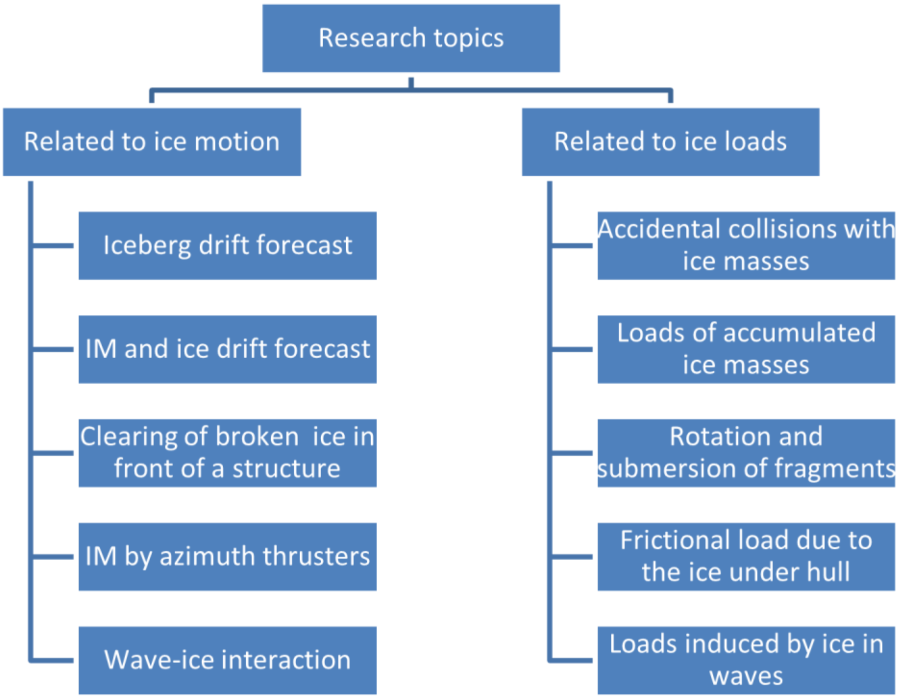

Figure 1. The ice-related research topics considered in the light of hydrodynamics.

Iceberg drift forecast and the loads on structures during accidental collisions with ice masses

During the recent decades, a number of iceberg drift models have been developed for various Arctic regions, particularly those which are exposed to hydrocarbon explorations, such as the Barents and Kara Seas (Eik, 2009), the East Coast of Canada (Kubat et al., 2005) and Northwest Greenland (Turnbull et al., 2015). All such models are designed to forecast long-term iceberg drift over a large area and therefore include all environmental forces that may influence the drift according to the following equation:

$$m\left(1+C_{am}\right)\frac{d\mathbf{V}_i}{dt}=\mathbf{F}_c+\mathbf{F}_a+\mathbf{F}_w+\mathbf{F}_{wd}+\mathbf{F}_p \quad (1)$$

where m and $\mathbf{V}_i$ are the mass and velocity of the iceberg, respectively; C_{am} is the added mass coefficient; $\mathbf{F}_c$ is Coriolis force; $\mathbf{F}_{a,w}$ are the forces due to air and water drag, respectively; $\mathbf{F}_{wd}$ is the mean wave drift force; and $\mathbf{F}_p$ is the horizontal gradient force exerted by the water on the volume that the iceberg displaces. For some applications, Eq. (1) also includes a term due to interaction with sea ice, see (Eik, 2009).

In all the abovementioned iceberg drift models, the forces in the right-hand side of Eq. (1) may vary in time, whereas the added mass (C_{am}) is always assumed to be constant. In reality, we know that the latter assumption is not valid especially when the ice mass is in the vicinity of a large structure, as discussed below.

The focus of this section narrows down to modelling drift motions of ice masses (icebergs, bergy bits, etc.) locally near a large marine structure, such as a tanker or an oil platform, where the interaction forces between the structure and ice masses are of interest. Accidental collisions of ice masses with structures and the associated impact forces may be important considerations in offshore design under Arctic conditions (Kim, 2014). In order to determine the impact load on the structure during a collision, which depends on the velocity and acceleration of the ice mass, the drift history of the ice mass is needed. As shown by Isaacson and Cheung (1988) and later by Tsarau et al. (2014a), the velocity and acceleration of an ice mass prior to contact with a structure are influenced not only by the constantly acting environmental forces, such as Coriolis force, wind and water drag etc., but also by the fluid force that arises during the hydrodynamic interaction between the structure and the ice mass. To predict this force, Isaacson and Cheung (1988) developed a two-dimensional, two-body model based on potential flow theory which allowed simulating the added-mass effect (which is responsible for the hydrodynamic interaction) depending on the separation distance between the bodies and their configuration. This formulation has been developed further, and recently, a generalised, three-dimensional, multi-body model was presented by Tsarau et al. (2014a) for simulating drift motions of arbitrary ice features in the vicinity of a floating structure. Contrary to standard potential flow programs, such as WAMIT, the newly-developed model can handle arbitrary motions of rigid bodies by solving the equations of motion that are coupled with the fluid-flow model. As shown by Tsarau and Løset (2014) this model can also be used to simulate the drift of a scattered field of ice floes in front of a structure, accounting for the hydrodynamic interaction .

Ice management in variable ice-drift conditions, azimuth clearing

As known, the main objective of physical ice management is to avoid or reduce actions from any kind of ice features on the supported vessel(s). However, this section concerns only IM of drifting ice floes and is primarily focused on the challenges associated with variable drift conditions. For a successful IM operation where icebreakers are used to reduce floe size ahead of a stationary vessel, it is critical to insure that the assisted vessel remains within the managed ice channel as ice drift direction may continuously change.

Ice drift changes may be quite frequent phenomena in most Arctic offshore areas where hydrocarbon explorations have been taking place. For example, Rossiter and McKenna (2013) report that drift reversals in the Beaufort Sea can occur in only a few hours; likewise, surveys in the Greenland Sea (Yulmetov and Løset, 2014) and in the Barents Sea (Marchenko et al., 2010) suggest that the environmental conditions in those seas may be also very dynamic. For IM operations, the considerable variations in ice drift can be problematic when trying to maintain a station-keeping vessel in the managed ice channel for. To address this issue, mathematical models can be applied for local drift forecasting in a given site, such as a drilling platform or a ship. These models are based on physical principles of sea ice drift and work especially well when the free drift theory is applicable (see e.g., Leppäranta (2011)).

For local ice drift forecasting, the main challenge is to properly define the air (τ_a) and water (τ_w) stresses on the ice. By using the quadratic drag law, the necessary parameter of which is the drag coefficient, the atmospheric and oceanic drag stresses can then be written in general form as:

$$\tau_a = \rho_a C_a \left(\mathbf{U}_a - \mathbf{u}\right)^2 \quad (2)$$

$$\tau_w = \rho_w C_w \left(\mathbf{U}_w - \mathbf{u}\right)^2 \quad (3)$$

where ρ_a and ρ_w are air and water densities, C_a and C_w are air and water drag coefficients, $\mathbf{u}$ is the drift velocity, $\mathbf{U}_a$ and $\mathbf{U}_w$ are the velocities of air and water, respectively. If geostrophic flow is used for $\mathbf{U}_a$ and/or $\mathbf{U}_w$, then a second stress law parameter (the turning angle) is required to accounts for the Coriolis effect in the boundary layers, see e.g., Leppäranta (2011) . Although geostrophic flow is a natural reference velocity, other references are often used. In particular, surface wind measurements at10 m altitude provide more accurate surface stress estimates and are therefore preferable in modelling applications. For sea current measurements beneath ice, the reference depth of 1 m has been often used. Local measurements (Table 1) conducted in several regions and valid for undeformed ice surfaces suggest that a representative surface wind drag coefficient is about 1.5×10^{-3}, but over deformed ice the drag may be twice as much. For the water drag, the measurement results vary a lot, see Table 2. This is because oceanic drag coefficients depend significantly on the roughness characteristics of ice surface and the dynamic conditions in the boundary layer. Another reason for such variation is the fact that drag coefficients obtained from field experiments often include both skin friction and form drag due to ridges which are arguably of similar magnitudes. Finally, Leppäranta (2011) concludes that there is a natural variation of ±50% in the drag coefficients due to the stability of the stratification and roughness variations. Different parametrisation techniques of the ice-ocean drag coefficient, including form drag and skin friction, are considered by Lu et al. (2011).

The knowledge of the wind and water stresses (Eqs. (2) – (3)) is normally sufficient for modelling free drift of ice floes upstream of a vessel in variable environmental conditions. If the wind speed and current vary dramatically at the site of the vessel, the hydrodynamic interaction between the floater and ice (as that considered above between ice masses and a structure) is most likely of minor practical importance for predicting the floes' drift and can be neglected. However, for special applications, the viscous drag forces can be easily included in the model presented by Tsarau et al. (2014a).

Table 1. The drag coefficient for surface wind measured at the standard altitude of 10 m (reproduced from Leppäranta (2011)).

Region	Method	$C_a \times 10^3$	Reference
Gulf of St. Lawrence	Mast	1.4	Smith (1972)
Beaufort Sea	Sonic anemometer	1.6	Banke et al. (1980)
Weddell Sea	Mast	1.9	Andreas and Claffey (1995)
Baltic Sea	Mast	1.5	Joffre (1982)

Table 2. A summary of ice-ocean drag coefficients for the reference depth of 1 m (adapted from Lu et al. (2011)).

Region	Ice type	$C_w \times 10^3$	Reference
Barrow Bay	1 km smooth floe	5.4	Shirasawa and Ingram (1997)
Barrow Strait	smooth landfast ice	1.32	Langleben (1982)
Beaufort Sea		7.6	Hunkins (1972)
Beaufort Sea		4.1	Langleben (1980)
Beaufort Sea		20	McPhee (1979)
Bering Sea	rough floe	22.28	Bruno (1990)
Greenland Sea		7.1 – 8.3	McPhee (1989)
Hudson Bay	landfast ice	0.13 – 7.42	Shirasawa et al. (1989)
Lancaster Sound	landfast ice	7.3	Shirasawa (1986)
Robeson Channel	flat first-year ice	1.05	Shirasawa and Langleben (1976)

The situation is different when the dynamics of managed ice must be modelled downstream of a structure (in the wake). This may be needed when considering a tandem of two vessels where one of them is designed to operate in the open wake behind the other (e.g., offloading operation) while the oncoming ice fragments tend to clog the channel. If a current is present, the upstream vessel generates eddy patterns in the downstream flow, which may significantly influence the ice dynamics in the wake. Tsarau and Løset (submitted for publication) provide a method for modelling ice rubble drift in such conditions.

In the light of IM needs, azimuth clearing (Keinonen and Martin, 2012), or propeller-flow washing of ice, is another interesting topic which requires thorough consideration of fluid dynamics. Tsarau et al. (2014b) give an idea how this effect can be efficiently modelled. Their approach also requires a proper parametrisation of viscous drag on ice, which is in this case due to the propeller-induced flow.

Clearing of broken ice in front of a structure and the loads due to accumulated masses

The focus of this section is modelling the clearing of either managed or naturally broken small ice floes in front a structure which is exposed to constant ice drift. Such a problem often arises when considering the ice loads on a drilling vessel in ice-covered waters (broken-ice conditions are typical because most of the known drilling operations in ice rely on IM support).

As shown by Tsarau and Løset (2014), free drift of a scattered field of small ice floes in front of a structure may be significantly affected by the hydrodynamic interaction between the structure and ice. In such a case, the approach presented by Tsarau et al. (2014a) can be used for to simulate both the motions of the ice and the single-floe impacts. However, in full-coverage ice fields, especially in pressured ice, the internal interaction between the floes influences the ice dynamics and associated loads on a structure much stronger than the mentioned hydrodynamic interaction, and therefore a different model should be applied in these cases.

According to Palmer and Croasdale (2012), managed ice loads are mostly due to the clearing of broken ice and are much more sensitive to pressured ice fields than loads calculated in the traditional way for unbroken ice features. When some pressure exists, a stationary wedge (false prow) of ice may often be seen in front of the platform. The ice load on this wedge, which is transmitted to the structure, is approximated as:

$$F_{Sw} = pDh\left(1+\frac{\mu}{\tan\alpha}\right) \quad (4)$$

where p is the pressure imposed by the surrounding pack ice, D is the platform width, h is the ice thickness, μ is the friction coefficient, and α is the wedge angle. The friction on the sides of the structure is

$$F_f = 2pLh\mu \quad (5)$$

where L is the length of the structure along the drift direction. Both components, F_{Sw} and F_f, contribute to the total load on the structure and, as it can be seen from Eqs. (4) – (5), are proportional to the ice pressure. However, the prediction of pack ice pressure is a complex task by itself. One approach, as suggested by Palmer and Croasdale (2012), is to employ an ice movement model for the entire region. As an example, if the pack ice pressure p is to be derived from wind stress, the following expression for the internal pressure in the ice due to the wind can be used:

$$p = \frac{\tau_a s}{h} \quad (6)$$

where s is the fetch length, and τ_a is the wind stress estimated from the models reviewed above (Eq. (2)). This example shows a scheme to evaluate managed ice loads on a structure in a pressured field and once again emphasises the importance of modelling fluid-induced stresses on ice.

To close this section, a short comment should be given to subsurface ice clearing. Under-hull ice increases the loads on the structure and may pose a risk to the turret. To deviate the ice, special deflector can be introduced in the hull design. Bonnemaire et al. (2010) confirmed the efficiency of a wedge under the bow to deviate fragments of level ice, and they also reported the application of bow propellers for clearing the ice. The latter is closely related to the propeller-wash effect that has been already mentioned above in connection with IM applications.

Rotation, submersion and sliding of fragments during icebreaking

When considering ice resistance of icebreaking ships, the following components are usually taken into account: the load associated with the bending failure of ice, the resistance contribution due to the rotation of broken pieces and the resistance due to the sliding of submerged floes (Valanto, 2001). According to the same author, all these components may be equally important for evaluating the total load on a ship. In this section, the two latter resistance components are considered from a hydrodynamic point of view.

The rotation phase can be represented as the following sequential process: the ice floe breaks off and accelerates to the speed required by the steady advance of the ship; then the floe rotates, possibly ventilating the water above itself; and finally, the rotation stops when the floe slams against the ship hull. After that, the floe being parallel to the hull will be pushed further downwards by other floes. Thus, the sudden change of the floe's rotational motion occurs twice, in the beginning and in the end of the rotation phase, causing also the change of the fluid momentum that is often considered as the added-mass effect, which influences both the ice dynamics and the load on the ship. As already mentioned, such hydrodynamic effects, if they are purely due to the fluid inertia, may be simulated by the model presented by (Tsarau et al. (2014a)). However, if the ventilation dominates, significantly changing the free-surface conditions, a different technique should be used (see e.g., Valanto (2001) and Lu et al. (2014)).

Submergence and sliding motion of broken ice floes along the hull causes a high load on the ship. This is due to both the work required to increase the potential energy of the submerged floes and ice-hull friction (Lindqvist, 1989). The latter may be affected by the water flow in the gaps between the submerged ice and the hull in such a way that due to the dynamic pressure the normal force on the ice-hull interface increases and so does the frictional force. Kämäräinen (2007) studied the effect of fluid flow on ice-ship friction using lubrication theory. He concluded that the force resulting from the pressure decrease in the gap between the hull surface and ice floes may be several times the force resulting from the static lift of the floes; however, the existence of this low-pressure phenomenon requires a continuous shear-driven flow of water in the gap and is very sensitive to the position of the ice floes.

Wave-ice interaction and the loads due to ice in waves

It is well known that ocean waves can penetrate into ice fields, whether they are composed primarily of continuous sea ice or are a concentration of discrete ice floes that are free to move. As waves pass, they may cause the sea ice to flex and to break up, and they are also scattered by any heterogeneity, including the edges of the ice floes themselves, with the result that their overall energy is systematically reduced in a way that discourages the passage of short waves (Squire, 2007). The dramatic attenuation of short waves in the marginal ice zone (MIZ) was confirmed by several field experiments, as e.g., Frankenstein et al. (2001). This is the reason why ocean waves typically have not been taken into account when considering ice loads on offshore structures.

The modelling of wave-ice interaction has been mainly focused on the manner in which the waves adjust during their passage through an ice field, and the typical objective is to find the amplitudes of the reflected and transmitted waves. Several such modelling techniques for both continuous and discontinuous ice fields are reviewed by Squire (2007). The author also recognises that destructive storms with associated high-amplitude waves will become more commonplace as global climate warming intensifies and that waves will be able to penetrate further into the pack ice because more open water is present.

Because of the growing seasonal activity in the Arctic offshore and the interest to trans-Arctic shipping, the problem of wave-ice interaction in MIZ may acquire an additional importance. In view of the ice depletion in recent years, the typically considered environment – large consolidated ice sheets drifting in calm water, may not be any longer representative for future Arctic offshore structures. Firstly, the presence of more open water and increased fetch can strengthen the wave climate in the Arctic, and secondly, the wave field may produce ice covers that are more fragmented than in the past (Sun and Shen, 2012). New guidelines for structures will need to be developed in order to account for ice-structure impact under this new type of ice conditions. As far as numerical modelling is concerned, very few researchers have been dealing with the development of models for simulating the compound effect of waves and ice on structures. (Sun and Shen (2012)), e.g., present a model that is used to determine the loads of a particular type of ice driven by waves and a current on circular cylinders. Their model is based on the discrete element method that has been commonly used for simulating pancake-ice dynamics. However, the wave field is defined explicitly, and thus the actual interaction between the fluid and ice is not captured. Currently, the problem of wave-ice-structure interaction is viewed as a research gap which may need to be bridged soon.

CONCLUSIONS

In summary, this paper presents different techniques that have been developed earlier to model various problems related to both ice-structure interactions and the interaction of floating ice with the fluid. It is clearly shown that the dynamics of the fluid, either water, air or both, may significantly affect the interaction processes between an offshore structure and sea ice. It is recognised that wind and water flow are important factors of ice drift motions and are therefore decisive for ice management and station-keeping in ice-covered waters. Not the least is the role of hydrodynamics in understanding ice loads on structures both in calm seas and in waves.

The main objective of this literature review, systematically conducted and presented, is to show that most of the considered hydrodynamic problems are interconnected with each other, have similar physical background and therefore may be addressed by applying similar models. In principle, there is no difference in modelling the added-mass effect of an iceberg approaching an oil platform and that of a number of ice floes (or any other ice features) drifting in the vicinity of a structure. Similarly, the knowledge about boundary layers is applicable for many types of fluid-structure interaction problems, including wind- and/or current-driven ice drift, viscous resistance of structures or ice in a fluid and water jet interactions with ice. In particular, this fact emphasises the importance of the presented research on wind and water stresses in ice not only for understanding the Arctic Ocean environment but also for modelling such specific problems as, e.g., ice clearing and accumulation in the vicinity of a structure.

Finally, the presented study also reveals the lack of knowledge on a certain type of ice-structure interactions, particularly when considering the impact of wave-driven sea ice on a floating structure. In the near future, this problem may receive special attention in the light of global climate warming and the growing interest to the Arctic.

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