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New approach to determine equivalent ice thickness for ships in dynamic compressive ice

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ABSTRACT

Dynamic compressive ice is one of the most severe ice conditions which can lead ships to be stuck in the ice. In these cases, icebreaker assistances are needed to release the ships which complicate the traffic and lower traffic efficiency, adding additional economic and environmental costs. This paper investigates these situations by first reviewing current best practices and approaches to assess the compressive conditions for ships. Based on potential gaps, this paper aims to utilize a new model developed for ships in dynamic compressive ice to simulate performances of different types of ships by considering both no compressive ice situation and different compressive situations. In this way, various data are obtained and h-v curves for ships in normal level ice and dynamic compressive ice can be obtained. By comparing the relationships between the normal level ice and dynamic compressive ice h-v curves, an equivalent ice thickness can be determined, which is practically useful for system level winter navigation simulation and decision making. In addition, new features of h-v curves for ships in dynamic compressive ice are investigated and discussed.

KEY WORDS h-v curve; Dynamic compressive ice; Equivalent ice thickness, Ships.

INTRODUCTION

When navigating through ice-covered waters, ships may encounter different ice conditions including ice floes, level ice and deformed ridge or rafted ice, etc. Some severe conditions can cause difficulties for ships to pass through, which lower down ship speeds and in certain cases, ships need to ram into thick ice repeatedly to get through it. These difficulties for these conditions are often caused by general or local thicker ice. However, one condition can make the navigation condition even worse, which is usually referred as compressive ice or dynamic ice depending on different research. It means a converging ice cover with/without moving, or moving ice pushed against fast ice/shore. In this ice condition, ships will encounter additional resistance from ice pushing actions on the ship sides. The pushing actions are also directional depending on the direction of compression relative to the ship. The most critical case is that ice is pushed perpendicular to the ship sides, which induces largest additional resistance. This not only can lower down ship speed, but also make the ship unable to reverse when it reaches widely on the midship section and closes the channel after the ship. The ship will get stuck in ice totally in this situation and cutting loose operations from external icebreakers are needed for the stuck ship to get rid of it. Therefore, compressive ice is considered as one of the most dangerous situations, especially when the pressure against ship sides exceeds hull tolerance or beset vessel is drifting with moving ice on shallows. It complicates the traffic and lowers traffic efficiency and can cause damage to ship hull and potential accidents. Therefore, this paper focuses on study of ships in dynamic compressive ice, of which the directional component is perpendicular to the ship side.

To estimate the ship performance in ice, there are usually two scales as describe by Milaković et al. (2019): high-fidelity and low-fidelity approaches. In a high-fidelity approach, ship performance in ice is modelled by solving ship equation of motion of high temporal and spatial resolution. In a low-fidelity approach, complex ice profile is simplified using the concept of so-called equivalent ice thickness, which averages the resistance of the complex ice profile into a single ice thickness value. The equivalent ice thickness approach may lose some accuracy; however, the single-value-based approach can provide fast practical information to decision makers, which is very useful especially in large scope or system level decision making for ship navigations. Milaković et al. (2019) summarized existing definitions of equivalent ice thickness study which mainly focus on ice ridges. To the authors' knowledge, there is no equivalent ice thickness definitions formed for dynamic compressive ice yet. Therefore, the detailed research topic of this paper is forming a new approach for equivalent ice thickness of dynamic compressive ice.

Following sections are organized as such, Section 2 describes current research and practical status of compressive ice indications for ships. Section 3 illustrates the method to form h-v curves and the equivalent ice thickness. Section 4 shows results and Section 5 discusses and concludes.

CURRENT RESEARCH AND PRACTICES

Research on compressive ice is diverse however lacking in general. On ship performance estimation, Riska et al. (1995) proposed a modelling framework for ships in dynamic compressive ice and proposed ice compression index to account the contact between dynamic ice and midship sections. Kaups (2011) and Külaots et al. (2013) modelled the ship resistance in dynamic compressive ice. Li et al. (2019) made a preliminary overview of ships in compressive ice. Lu et al. (2021) proposed a model for ship resistance estimation and dynamic transit for ships in dynamic compressive ice. On ice forecast and compression estimation, Leisti et al. (2009) researched in-situ IceCam method for observing compression in sea ice field and Lensu et al. (2013) investigated forecasting of compressive ice. However, the path to apply to ship scale performance prediction is not clear yet.

There are a few practices and units for ice compression. One is used in Russian Arctic, which divides the ice compression into 4 levels, as described in Table 1 (Heideman, 1996). The unit system is based on human visual observations of channel closing behind the ship, which makes it also somewhat relative to ship speed as observer moves away from observed ice dynamics. Same applies to SWE-FIN approach below. Generally, the system is difficult to convert into physical scale.

Table 1. Russian practical ice compression definitions (Heideman, 1996)

Unit	The channel behind the icebreaker in grey-white ice	The behavior of the ice along the side of the assisted vessel	The behavior of the ice at the channel edges	The response of the ship and the hull girder
0	n/a	n/a	n/a	n/a
1	The channel closes slowly	Individual floes of ice rise	The ice does not move aside or break when the icebreaker cuts the assisted vessel	The ship experiences occasional blows both in transverse and longitudinal directions
2	The channel is closed, a pressure ridge is formed in the channel	Ridging along the ship's side. The ice does not reach the deck	Ice floes becomes rafted when the icebreaker moves	Strong blows, the ice and the ship hull make noise, 1-2deg heel
3	The pressure ridge moves out of line causing ridging and rafting beside the channel	Heavy ridging. The ice builds up and falls eventually onto the deck	Multiple rafting when the icebreaker moves	Constant blows, the shell plating bends, ice damage possible, more than 4deg heel

In the Northern Baltic Sea, there is also a practical scale for Finnish and Swedish icebreakers, divided from 0-4 as shown in Table 2. Comparing with channel feature in Table 1, it is obvious that the ice compression definition for the Arctic is relatively more severe than the unit in the Northern Baltic Sea.

Table 2 Finnish and Swedish practical ice compression scale

Unit	Pressure level	Feature 1	Feature 2
0	n/a	n/a	n/a
1	Mild pressure	The vessel has proceeded over 0.5 nm before the channel closes	Towing assistance not required
2	Moderate pressure	The vessel has proceeded less than 0.5 nm before the channel closes	Weaker/smaller vessels must be towed
3	Strong pressure	The channel closes immediately	All vessels must be towed
4	Severe pressure	Even icebreakers have difficulties	Traffic interrupted/must be interrupted

It can be seen that the current practices are based on empirical indications. In order to further provide practical indications for ships in dynamic compressive ice, this paper focuses on investigating the ship performance in dynamic compressive ice and covert to h-v curves for different conditions, so that equivalent ice thicknesses can also be obtained easily from h-v curves. The method is described in following Section 3.

METHOD FOR H-V CURVE AND EQUIVALENT ICE THICKNESS

The h-v curve is a graphical representation of a ship's performance in ice-covered waters. It shows the relationship between the horizontal (h) ice thickness and vertical (v) ship speed as the ship moves through the ice. It allows ship operators to determine the maximum speed for the ship in different ice conditions. In order to obtain h-v curve for ships, the equilibrium between the propeller net thrust and ice resistance (T(v)=R(h, v)) needs to be achieved. Unlike the normal ice conditions where static equilibrium can be solved, dynamic compressive ice conditions usually induce a dynamic balancing process. Therefore, a time domain transit model is needed. Here the new model proposed by Lu et al. (2021) which has been validated with some realistic performance data in full scale is adopted. In addition, as the ship speed v may be varying all the time depending on different cases, ten-minute transit time is adopted for ships considering it can be a representative/steady ship speed. The ship speed at the end of the ten minutes will be correlated with the corresponding ice conditions.

The concept of the transit model is detecting ice contact to the midship section under the dynamic compressive ice at each time step and calculating additional resistance for solving new equation of motion in the next time step. A general scheme for a ship in dynamic compressive ice is depicted in Figure 1. V_i is the ice speed towards ship side, V_S is the ship speed, L_P stands for the length of parallel midship section, L_e stands for effective length of ice-ship contact when the dynamic compressive ice reaches the ship side and r is the radius of ice cusp broken near the shoulder. More details can be referred to Lu et al. (2021) to avoid unnecessary repetition. Here the focus is on the scenario that ice moves perpendicular to the ship side as shown in Figure 1 by V_i.

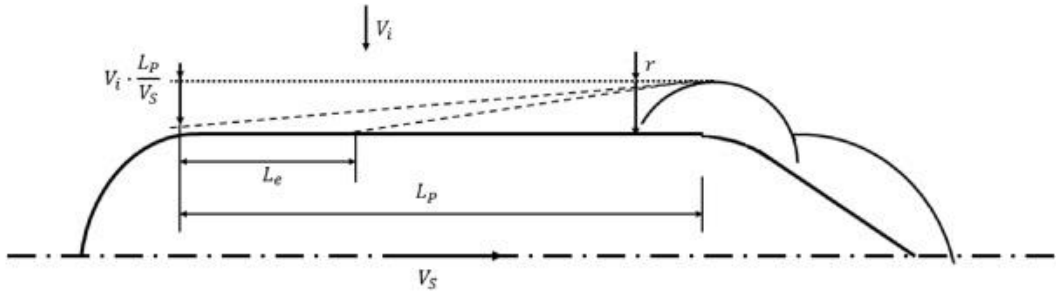

Figure 1. A ship in dynamic compressive ice. V_i is the ice speed, V_S is the ship speed, L_P stands for the length of parallel midship section, L_e stands for effective length of ice-ship contact, r is the radius of ice cusp.

When having the model, the focus come to the inputs. Except the ship-related parameters and initial navigation speed, the ice-related inputs include ice thickness h and dynamic ice speed v_i. The pressure is determined by ice pressure-area relationship when contact is detected. The targeted output is the ship speed v. To obtain h-v curves for ships in different dynamic ice conditions, a matrix with combination of h and v_i are defined for ice inputs, with h ranging from 0.025 to 1 m and v_i ranging from 0 to 0.3 m/s and both have 0.025 unit of interval. $v_i = 0$ means there is no compression, which is the benchmark for dynamic compressive h-v curves. With this definition, 520 scenarios are set up and will be simulated. Each scenario will give one output point, representing its performance in this ice condition. In total, 13 h-v curves will be formed for an individual ship’s performance, representing 13 types of dynamic compressive ice conditions. After having the h-v curves, by comparing the rest of 12 modes (v_i = 0.025-0.3m/s) with the first mode (v_i = 0 m/s, i.e., no compression), an equivalent ice thickness can be extracted from the graph.

H-V CURVE RESULTS FOR SHIPS IN DYNAMIC COMPRESSIVE ICE

Three different types of ships are investigated by applying the method mentioned above, they are Envik - a cement carrier with ice navigation capability, Aranda - a Finish research vessel with ice breaking capability and Nordica - a Finnish icebreaker designed for assisting merchant vessels in winter operations. Main parameters are listed in Table 3.

Table 3 Main parameters of the three investigated ships

	Envik	Aranda	Nordica
Ice class*	1A S	1A S	PC 3
Displacement (ton)	5583	1858	12800
Length (m)	96	59.2	116
Breadth (m)	16.5	13.8	26
Draught (m)	5.2	5	7
Open water speed (kn)	12	13.5	16
Power (kW)	2740	3000	15000

*Ice class classification: Aranda and Envik (Finnish-Swedish ice class); Nordica (IACS Polar class).

By setting the initial ship speed of 5 kn, the defined h-v curves for Envik in different dynamic compressive ice are obtained as shown in Figure 2. For ice speed below 0.05 m/s, there is no effect from dynamic compressive ice on the ship, i.e., h-v curve stays the same as in normal level ice condition without compression. When ice speed towards midship section increases to 0.05 m/s, there is some minor effect at thin ice situations (below 0.075 m). The ship speed drops about 1 kn in these ice conditions. However, when ice thickness becomes thicker, the situation goes back to the no compression situation. After investigation into the ship resistance components, it is found the reason is that as the cusps broken by a ship has a proportional relationship with the ice thickness and inverse relationship with ship speed, while the cusps define the ice edges, the ice edge action on ship of dynamic compressive ice is then affected by the ice thickness. Therefore, for 0.05 m/s ice speed, when ice thickness increases from 0.075 m, ice channel is wider and ice edge cannot reach the ship side. The h-v curve goes back to the normal trend, i.e., no compression situation.

This phenomenon becomes most evident when ice speed equals to 0.075 m/s, ship speed drop dramatically before ice thickness reaches to 0.175 m. However, ship speed jumps to the normal no compression trend with ice thickness increases. This is an abnormal behavior which seems even wrong. However, this is indeed caused by ice cusps change with ice thickness. The jump to normal trend indicates that the ice edge defined by cusps reaches a point that ice just cannot touch midship section, which make it a normal level ice situation. This can be defined as a critical ice speed which indicates very distinctive h-v curves after this dynamic ice situation. And the ship may still have chance to escape from ice in this critical ice speed condition. When ice speed further increases, the ship drops almost linearly with increasing ice thickness and reaches to zero at 0.125 m ice thickness, except for 0.1 m/s ice speed, there is still a narrow jump at 0.3 m ice thickness.

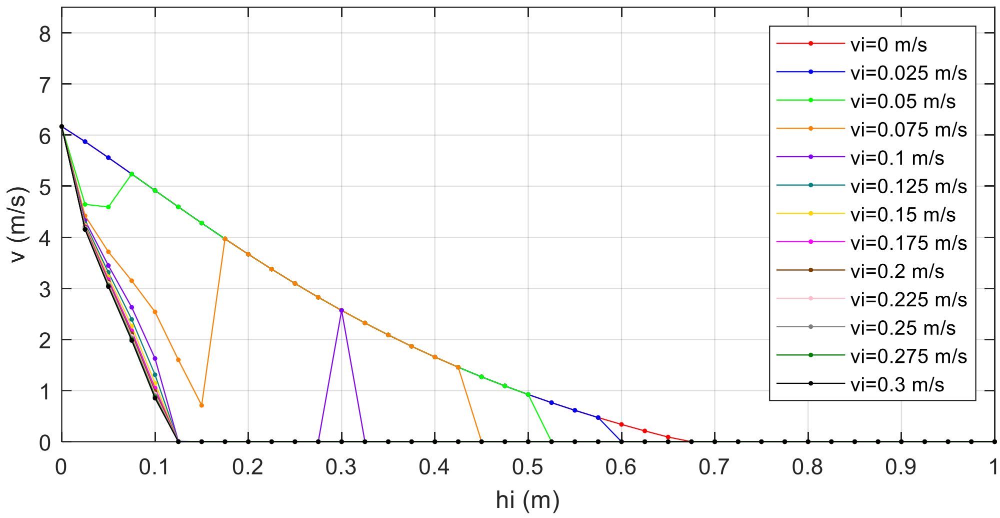

Figure 2. h-v curves for Envik in dynamic compressive ice, ship initial speed 5 kn

Overall, for Envik, there are two types of h-v curves. One is for the normal level ice condition and the other type is consisted of dynamic compressive ice conditions, most of which fit similar trend, i.e., almost linear from open water speed to zero speed at ice thickness 0.125 m. In-between, there is an identified critical ice speed at 0.075 m/s, where h-v curve jumps between normal trend and general dynamic compressive ice trend.

For ship Aranda, results are presented in Figure 3. The general trend is similar as Envik, i.e., two types of h-v curves and some in-between. However, the detailed behaviors are different. The critical ice speed for Aranda locates from around 0.125 m/s to 0.15 m/s, which is almost twice of that for Envik, indicating more capability for stronger dynamic compressive ice. Meanwhile, the cluster of curves for dynamic compressive ice have a more raised shape rather than the linear curve for Envik, and ends at around 0.175 m ice thickness, 0.05 m thicker than that of Envik. All of these indicate the different compressive ice capability of the two ships.

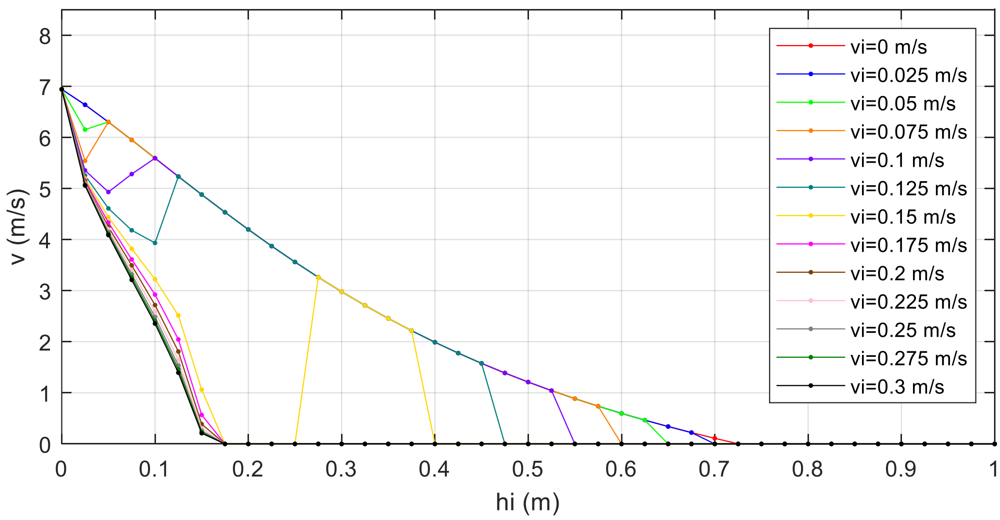

Figure 3. h-v curves for Aranda in dynamic compressive ice, ship initial speed 5 kn

Figure 4 shows h-v curves for ship Nordica. Overall, the general trend of the curves looks different comparing with Envik and Aranda. The difference is that the transition from normal no compression curve to compressive conditions is more clearly seen and the distinctions between different ice speed situations are more obvious. This relates to the wide range ice capability of the ship as an ice breaker, has bow wider than the midship and stern. The range of the curves are much wider than the other two ships, reflecting stronger ice navigation capability. This makes the transition and distinctions have more chances to appear. The critical ice speed for Nordica can be identified as 0.175 m/s. However, it should be noted it is not that so-called critical comparing to the previous cases as the difference e.g., between 0.175 m/s and 0.2 m/s is relatively smaller. The ending ice thickness for dynamic compressive ice conditions is at 0.8 m ice thickness, much larger than the other two ships designed with ice breaking capability.

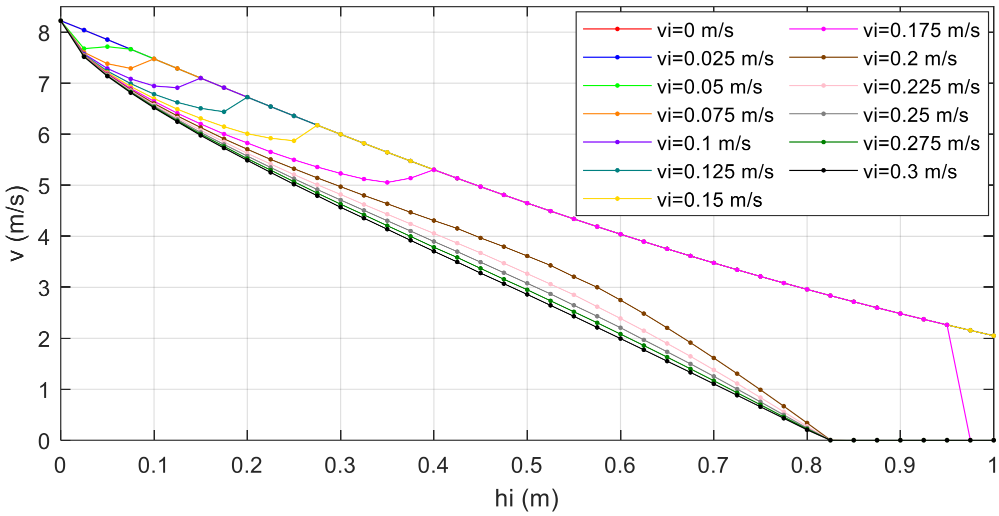

Figure 4. h-v curves for Nordica in dynamic compressive ice, ship initial speed 5 kn

As mentioned in the method, the h-v curves reply on the dynamic model solving equation of motion rather than analytically solving the equation to obtain the ship speed. The ship initial speed may have impact on the h-v curves. Therefore, to investigate this, initial ship speeds of 7.5 kn and 10 kn are simulated for all three ships in addition to 5 kn and the obtained h-v curves are summarized in Figure 5.

The results indicate that ship initial speed does not affect the general trend and shape of the h-v curves. However, it has obvious effect on the h-v curve at the critical ice speed. For example, the critical ice speed for Envik with 5 kn initial speed is around 0.075 m/s, while the 0.075 m/s ice speed curve changed to better performance with 7.5 kn initial speed and the critical ice speed even tends to shift to 0.1 m/s. However, when initial ship speed further increases to 10 kn, the performance drops back to similar level of 5 kn initial speed. For Aranda, the influence of changing initial ship speed from 5 kn to 10 kn is reflected by the increasingly improved performance at the critical ice speed 0.15 m/s. The others remain the same. For icebreaker Nordica, increasing initial ship speed continuously improve the ship performance at critical ice speed 0.175 m/s and drives 0.2 m/s ice speed to the critical level, i.e., having chance to jump to normal no compression status. Overall, varying initial ship speed is important for changing ship performance at critical ice speed situations.

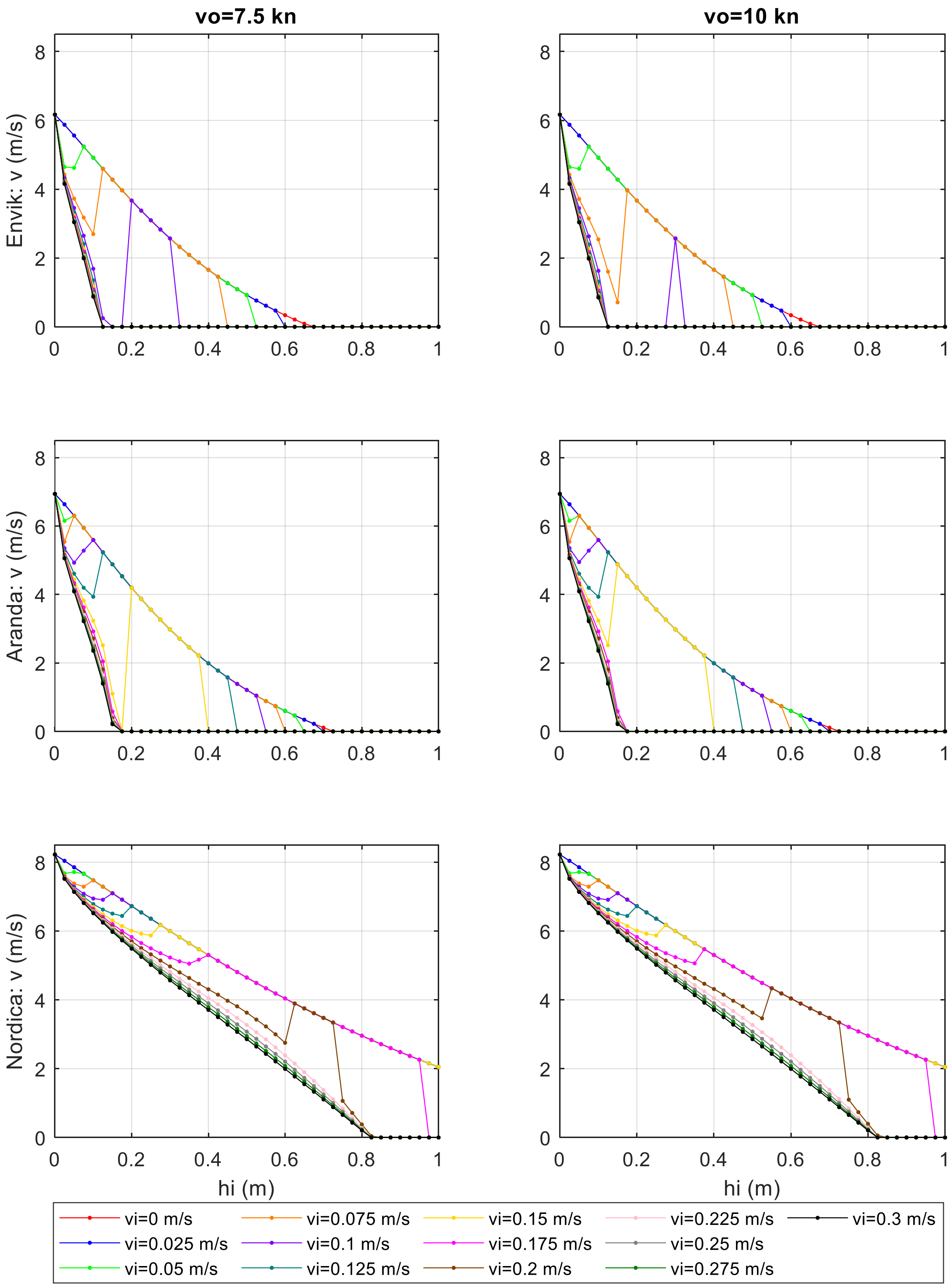

Figure 5. h-v curves for Envik, Aranda and Nordica in dynamic compressive ice, ship initial speed 7.5 kn and 10 kn respectively

CONCLUSIONS AND DISCUSSIONS

This paper reviews current research and practices for ships in dynamic compressive ice and applies a new model for simulating ship performance in different dynamic ice conditions to obtain new h-v curves in corresponding situations. Such h-v curves can provide simplified and useful guidance in practical operations and decision making, especially in the system level of winter navigations.

Three different ships are investigated, and the results show that 1) there are usually two types of clusters for h-v curves, one refers as no compression and the other as with compression. For weak ice capability vessels, the gap between these two types is large and the differences among different dynamic ice are small. For strong ice capability vessel, the transition is more visible. 2) In-between the two clusters, there are critical ice speed for ships, which jump between two clusters, indicating chances for a ship to escape the dynamic ice. The critical ice speeds for different ships vary with the ice navigation capability. It should be noted that the jumps and uneven curves are a bit abnormal considering the traditional family of h-v curves. This relates to the uncertainties of ice cusps and defined ice edge in simulation. In reality, ice edges may be more complicated and random, therefore such obvious abnormal speed jumps may be a bit different or disappear. However, it is also likely that this abnormal may be a feature for ships in dynamic compressive ice. Further investigations are worthwhile. 3) Ship initial speed has limited influence on the h-v curve for a ship at the critical ice speed. Generally, the results initially reflect experience from real life based on feedback from experienced expert, but it should also be further questioned/validated from other experienced navigators.

When h-v curves for a ship in dynamic compressive ice is obtained, equivalent ice thickness can be determined from the h-v curve relationships in the graph. Further investigations on more types of ships may help identify more general and broadly simplified relationships.

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