Status and needs for ice tank testing in a changing climate

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Abstract. 150 years ago, the first modern icebreaker in the world was designed by the naval architect Carl Ferdinand Steinhaus and built for purpose of removing ice barriers on the river Elbe in Hamburg, Germany. No model tests were performed at that time. Later, in the first half of the 20th century, “model tests” for ships were carried out in natural ice on lakes. In the 1950th the first-generation ice model basins were put in operation and ice model testing became a standard method in the icebreaker design process. This paper discusses the influence of the economic and environmental development in arctic regions, driven by shipping and offshore activities in environmental changing Arctic Waters, on the ice model basin design, equipment and testing methods. The developments will be presented with examples from The Hamburg Ship Model Basin (HSVA). To complete the overview, an outlook to future trends is attempted.

1. Introduction

Climate change and the corresponding mitigation of arctic sea ice conditions have strongly affected the development of sea transport and exploitation of raw materials in arctic regions and continue to shape the Arctic maritime industry and research activities. For the economic development of Arctic regions like Alaska, the Canadian Arctic (Beaufort Sea), Norwegian Arctic (Barents Sea) and Siberia new hull designs of icebreakers, supply vessels, tankers and bulkers were requested by companies and authorities. Besides year around transport of coal and ores, oil and gas exploration, exploitation, processing, storage, and transport became more and more important. Full scale trials and expeditions were performed to study different sea ice features like level ice, floe ice, pressure ridges and icebergs and to determine their physical and mechanical parameters. Design offices and shipyards requested assistance from model basins and universities. The ice model basin dimensions were increased, and new model ice types were developed to meet the requirements of the customers. With the beginning of the 21st century the numerical calculation of forces and simulation of processes complemented the physical model testing.

In the following chapters, the adaptation of the ice model test technique to changing economic and environmental conditions is described and an outlook of the climate change impact on ice model test technology is attempted.

2. Change of Arctic Sea Ice

University institutes and government institutions have observed and documented environmental parameters like air and ocean temperatures as well as changes in sea ice and glaciers over the past 50 years. Satellites were used to determine sea ice extent, degree of coverage, ice floe size and thickness. The ice thickness was also measured with upward looking sonar devices from submarines and EM devices from ships, helicopters, or aircrafts. Pressure ridges were profiled by manual drilling or 3-D
sonar scanning of the keel and laser technique for the sail. Aerial photography was used to determine the ridge frequency. Over the past 50 years a decrease in sea ice volume, extent, and thickness was observed. In Figure 1 the arctic sea ice extent from 1980 to 2020 for the month with the lowest resp. highest sea ice extent of the year, September and March, are presented [1].

![Figure 1. Arctic Sea Ice Extent from 1980-2020 for March and September (data AWI)](image)

A concurrent decline of the multi-year ice is also observed in the Arctic. Figure 2 shows the near record-low amount of multiyear ice in the Arctic as of week 31 (July 30 to August 5) of the 2021 melt season, comparing this year to the same week in previous years of the satellite record that began in 1979. Historical data through 2019 are provided by Tschudi et al., 2019a [2] [3] and quick look data by the same authors for 2020-21 [4]. The loss of the multiyear ice since the early 1980s started in earnest after the 2007 record low minimum sea ice cover that summer, and while there have been slight recoveries since then, it has not recovered to values seen in the 1980s, 1990s, or early 2000s [5].

![Figure 2. Decline of multiyear Sea ice in the Arctic (data NSIDC, week 31 of melt season, 1979 to 2021)](image)

3. Economic development in Arctic Regions

3.1. Exploitation of natural resources in Arctic Regions

The economic development of the arctic regions started in the late 1960’s when large oil and gas deposits were discovered in the Prudhoe Bay area, Alaska, by ARCO, Humble Oil and BP. Prudhoe Bay Oil Field is a large oil field on Alaska's North Slope. It is the largest oil field in North America, covering 86,418 ha and originally containing approximately 25 billion barrels of oil. The field was operated by BP; partners were ExxonMobil and ConocoPhillips. In August 2019 BP sold all its Alaska assets to Hilcorp Alaska [6]. Intensive oil and gas exploration activity took place in the Beaufort Sea during the 1970s and 1980s. The economic development in Arctic regions gave momentum to increased research activities on Artic conditions and technology. Frederking and Timco stated in 2009 [7] “There was a
considerable amount of research performed and new, valuable knowledge was gained. However, the information is spread over a wide range of locations”. Their paper provides a brief overview of the activity and guidance on the type and location of data relevant to offshore operations in ice-covered waters.

However, the decline of the crude oil price in the middle of the 1980’s (see Figure 3) prompted the oil companies to reduce their activities in the Beaufort Sea. The emphasis was shifted from the North American Arctic to the Western Russian Arctic, Barents Sea, Kara Sea and Laptev Sea as well as the eastern Russian sub-arctic area around Sakhalin Island and the North-Caspian Sea. The various locations required new concepts for offshore structures; for larger water depth moored floating concepts were discussed and realized e.g. Sevan 1000, Goliat [8]. Latest arctic offshore Oil and Gas projects are located in areas where sea ice has a low probability of occurrence but still needs to be considered for limit state design [9].

New designs of icebreaking and ice-going vessel concepts were presented where the hull form was optimized for both, good icebreaking and open water capabilities, while earlier designs had concentrated on good performance in ice. The importance of combining good ice breaking and open water capabilities is shown in the Yamal LNG project. The Yamal LNG Project was launched in 2017 [10]. The gas field and related services in the Yamalo-Nenets Autonomous Okrug are expected to be operated for at least 20 years with an average amount of 27 bm³ of natural gas per annum. The natural gas is transported by a fleet of 20 ARC7 LNG carriers, each equipped with total power of 45MW used on three Pods which enables them to break 1.5m level ice ahead and more than 2.1m level ice astern. Even in pressured ice with hummocks and ridges the ships can proceed at profitable speed when running astern. Year around service to Europe and Asia via Northern-Sea-Route (NSR) is guaranteed.

3.2. Development of Arctic Shipping
As shown above, the extent of sea ice and especially multiyear ice in the Arctic has decreased over the past decades. Simultaneously, the areas covered with open drift ice have increased. This had an impact on Arctic shipping, as for instance the NSR has longer ice-free periods in the summer season, and general conditions along these routes are changing, allowing more diverse ship types and hull designs to transit. While in the past mainly icebreakers, supply vessels, fishing vessels, and tankers and bulk carriers with special dedication for arctic operations were found in Arctic regions, nowadays also polar cruise vessels, research vessels, exploration and transportation vessels for natural resources, and general cargo vessels are operating [11]. Figure 4 shows the increasing use of the NSR from 2011 to 2019 [12]. Note that the drastic increase of cargo volume is attributed to LNG transportation from Yamal project, accounting for 64% of total GRT volume of NSR traffic in 2019. However, data from Centre for High North Logistics (CHNL) also shows increasing use of the NSR by ships with lower ice class, and an increasing share of passenger vessels, breaking ships, and various kinds of offshore infrastructure installations. Due to the complex nature of the ice as a material, and its various types of failure against objects, designing such ships and structures is challenging. A common implement to aid the design is model testing.
No facilities were available when ice model testing was introduced. First tests with ship models were performed in wintertime on lakes in natural grown freshwater ice. In 1955 the Arctic and Antarctic Research Institute in St. Petersburg inaugurated an ice model basin of the 1st Generation with the dimensions of Length x Width x Depth = 13.4x1.85x1.1m. [13] Three years later in 1958 The Hamburg Ship Model Basin, HSVA, put another ice basin in operation with dimensions of 8x2x1m [14]. In the 1970’s and 1980’s, 2nd Generation ice model basins in Russia, Finland, Germany, USA, Canada, and Japan started their service for growing industry demand due to increasing Arctic activities. With dimensions of approx. 30x10x2m they were much larger than previous versions. One decade later 3rd generation ice model basins were put into service in Russia, Canada, Finland, Korea and Germany with average dimension of 70x10x2m while two have a squareish shape, 40x40x2m. Some have deeper sections for offshore structure testing. In 2015 Krylov State Research Centre in St. Petersburg started their service in a new ice model basin with dimensions of 102x10x2m [15]. In Table 1 an overview of existing ice model basins is presented.

![Image](https://example.com/image.png)  
*Figure 4. Development of cargo volume passing NSR (left) and cargo types in 2019 (right)*

| Basin       | Basin dimensions | Cooling system | Model ice |
|-------------|------------------|----------------|-----------|
|             | L (m) | B (m) | T (m) | Cap. (kW) | Hice (mm) | Growth rate (mm/s) | Ice type | Dope | Air bubbling |
| Aalto Uni   | 40    | 32    | 2.5   | -        | 20-80     | 10.0          | f        | Ethanol | No |
| Aker Arctic | 75    | 8     | 2.1   | 500      | 15-150    | 10.0          | f        | NaCl   | No |
| HSVA        | 78    | 10    | 2.5   | 400      | 10-80     | 2.0-2.5       | c        | NaCl   | Micro |
|             | 60    | 5.0   |       |          |           |              |          |        |    |
|             | 30    | 6     | 1.2   | 60       | 0-250     | 1.6-2.0       | c        | NaCl   | No |
|             | 35    | 6     | 1.8   | 140      | 10-300    | 2.7           | c        | Propylene Glycol | Yes |
| NMRI        | 20    | 6     | 1.8   | 110      | 20-100    | 7.0           | f        | Urea   | No |
| JMU         | 102   | 10    | 2.0   | 1634     | 10-150    | 2.0           | f, c     | NaCl   | No |
| Krylov      | 80    | 2.6   | 668   |          |           |              |          |        |    |
| SRC         | 42    | 32    | 2.5   | 600      | 10-100    | 2.1           | c        | EGAD   | Micro |
| KRISO       | 32    |       | 3.0   | -        | 10-200    | 2.5           | c        | EGAD   | Micro |
| OCRC        | 90    | 12    | 3.0   | 220      | 10-160    | 2.0           | c        | Urea   | No |
| NRC         | 70    | 2     | 1.0   | 35       | 10-150    | 2.5-3.0       | c        | NaCl   | Micro |

In the beginning of ice model testing, 1955 to 1980, customers only required tests in uniform level ice of different thicknesses and bending strength and floe ice. End of the 1970’s and beginning of the 1980s, after scientists had examined first- and multi-year pressure ridges and identified them as a great danger for shipping and offshore structures, the demand for model tests with rubble fields and pressure...
ridges increased and became standard procedure. The regulations of winter navigation in Swedish and Finnish sub-arctic areas in the Baltic Sea boosted the ice model tests with self-propelled ship models in brash ice channels according to Finnish-Swedish Ice Class Rules (FSICR). With beginning of the 2nd decade of the 21st century ice management became an important factor to reduce ice forces on fixed and floating structures resulting in higher demands on the produced floe ice in the ice basins. Customers requested special floe size distributions and their documentation by bird view photos. Furthermore, the impact of local crushing, e.g., on steep bows, became more relevant over the years, as hull designs changed from pure dedication to performance in ice to also good open water and seakeeping ability.

5. Model ice

When model tests in ice were started in small basins, paraffin wax ice was used in Germany, Netherlands, and England [16] [17]. As the mechanical properties, especially the friction coefficient between model and ice and Young’s modulus, were very poor, the engineers switched to natural saline ice. Only Arctec Offshore Corporation in Colombia, Maryland USA and Arctec Canada Limited in Kanata used synthetic ice in their 2nd Generation ice model basins while all other companies and institutes used model ice grown from a sodium chloride solution [18]. To improve the quality of their model ice in the end of the 1970’s and beginning of the 1980’s model basins tried different initial solutions and textures. The result of this process is documented in Table 1 and shows that the majority of the basins are either using sodium chloride or EGAD(S) as initial solution. About 50% are growing fine grained (f) ice using spraying technique while the other half apply a seeding technique resulting in columnar grained (c) ice. Both types are based on the general approach that the material shall resemble sea ice as good as possible at a smaller geometric scale.

At the same time, the ice is supposed to be weakened compared to sea ice, which lowers the forces during model tests, and which is a consequence from the widely used Froude and Cauchy scaling laws [19]. Columnar model ice represents the mostly columnar structure of sea ice, but typically suffers from too low Young’s modulus and a smaller ratio of compressive and flexural strength compared to sea ice. Fine-grained ice does not allow the ice to be scaled correctly in either uni-axial compressive strength or confined compressive strength [19], which may lead to a premature ice failure and therefore underestimation of ice loads in specific interaction cases [20]. Both model ice types do not show the same brittleness as sea ice. The density of model ice is inherently larger than the density of sea ice. Therefore, 40% of the ice model basins (Table 1) have developed methods to incorporate air bubbles into a growing ice sheet, which does not only decrease the density, but also effects the brittleness and gives the ice a white appearance [21].

6. Testing methods

Testing methods have developed over the decades along with the changing customer requirements. Some have become standardized and are for example recommended by the International Towing Tank Conference (ITTC). Others are tailor-made for specific designs or load scenarios. The following subsections give an overview on state-of-the-art ice model testing with ships and structures.

6.1. Model testing with ships

In the beginning, the only objective of ice model tests was to determine the total ship resistance in level ice and to document the breaking pattern at the bow area. The required power was then calculated from the total resistance assuming certain propeller efficiency. In the 1980’s propulsion tests in ice became more and more important when engineers and researchers observed the significant influence of the propeller ice interaction on the icebreaking capability of ships. One decade later towed propulsion tests were introduced allowing determination of propulsion values, thrust, torque, revolution rate, and resistance at the same time.

Along with the development of model testing, prediction methods have been proposed and refined to assess the ice resistance in the early design phase. Runeberg proposed the first formula for predicting the ice resistance of a ship sailing in level ice already in 1888/89 [22] based on mean angles of the bow
shape. Later attempts base on the concept to subdivide the total resistance into different components, which are differently affected by hull form and ice parameters. One of the most established semi-empirical ice resistance prediction methods was published by Lindqvist in 1989 [23]. He describes the effects of different components by simple, but physically sound formulas. Nowadays, Lindqvist’s formula is widely used for assessment of the order of magnitude of the ice resistance of a ship. However, the formula cannot take into account the actual propulsion efficiency, and highly simplifies the hull shape. The prediction gets increasingly inaccurate with increasing stem angle and smaller waterline entrance angles, thus with ships more deviating from a traditional ice-breaking ship design. Hence, such prediction methods aid the design and supplement the tests, but physical ice model tests remain state-of-the-art tool to predict resistance and required power for ships in ice.

6.1.1. Resistance tests. In the ITTC Recommended Procedures and Guidelines 7.5-02-04-02.1 Rev 02 from 2017 [24] it is stated “The main reason for the towed resistance tests for ships in level ice is to determine the effectiveness of the hull-form in breaking ice and progressing through it. The specific results from these tests include ice resistance at certain speeds and ice thickness, the ship performance diagram (i.e., speed versus ice thickness), and limiting ice thickness for a continuous motion.” Two pulling methods are described, 1) load cell attached inside the model and 2) load cell attached on the bow of the model (see Figure 5L). In both cases the model should be free to roll, pitch and heave while being constrained in surge, sway, and yaw. The measured force in longitudinal direction, $F_x$, contains the ice resistance $R_I$ and the water resistance $R_{IW}$ and is called the total ice resistance $R_{IT}$. It can be derived from the following equation:

$$R_{IT} = \frac{1}{t_2-t_1}\int_{t_1}^{t_2} F_x(t)dt = R_I + R_{IW}$$

Typically, $R_{IT}$ is the value of interest in ice model tests with ships. The water resistance $R_{IW}$ is measured in open water tests. If further insight into the composition of $R_{IT}$ is required, the net ice resistance $R_I$ can further be interpreted as the sum of icebreaking resistance $R_{br}$, clearing resistance $R_c$, and buoyancy resistance $R_b$. $R_c$ and $R_b$ can be derived from pre-sawn ice tests, where the breaking resistance is omitted. Then, $R_{br}$ can be derived from above relations. As the ice thickness is affecting all components of $R_I$, the net ice resistance shall be corrected using the following formula:

$$R_I = R_{I,meas} \left( \frac{b_{target}}{b_{I,meas}} \right)^x$$

The exponent $x$ needs to be determined by each individual model test basin. Corrections due to deviations of the actual flexural strength $\sigma_f$ from the target value shall be applied. The ITTC Specialist Committee on Ice recommends a linear correction of the breaking resistance by the ratio of target and actual flexural strength.

Figure 5. (Left) Resistance rests in level ice (method 2) and (Right) Time plot of normalized torque

6.1.2. Propulsion tests. As the typical desired result of model testing is to determine the required power during design stage, the prediction of the resistance is only one part of the solution. In the late 1970s
several model basins started to carry out propulsion tests in ice and investigated the impact of ice on propellers by experiments [25]. Typically, two different propulsion test methods - the towed propulsion test and the free running propulsion test - are applied. In addition, propulsion tests in ice free water are optionally carried out as reference for the propulsion efficiency in ice [26]. This leads to a formal definition of propulsion efficiency in ice as introduced among others by Puntigliano [27]:

$$\eta_{ice} = \frac{\eta_{d_{ice}}}{\eta_d} = \frac{(1-t_{ice})(1-w)T_{ice} Q_{ice}}{(1-w_{ice})(1-t)T Q} n_{ice} n$$

(3)

With $\eta_d$: propulsion efficiency; $t$: thrust deduction fraction; $w$: wake number; $T$: thrust; $Q$: propeller torque; $n$: propeller revolution.

The measuring methodologies for propulsion tests in ice were mainly adopted from calm water testing using dynamometers for the acquisition of thrust and torque on the propeller shaft which is typically driven by an electric motor. The number of peak values (Figure 5R) in a propeller torque signal directly measured in ice model tests also provides information on the frequency of propeller ice interaction which depends on hull shape, speed, ice type and ice thickness.

In the early 90s more and more ships sailing in ice were outfitted with rudder propellers and later also with podded drives. As for ships maneuvering in restricted waters, the use of thrust for steering improved the maneuverability of ships in ice significantly. Tests with models equipped with scaled pods became standard service of the ice basins.

Although the technology of propulsion model tests has developed over decades, some challenges still remain for accurate prediction of propulsion efficiency in ice. These include improved prediction and correction of propeller-ice-interaction, as similarity between model test and prototype is in this respect breached in favor of correctly scaled hull breaking forces. Also, the response characteristic of the prototype propulsion system is not fully reflected by the scaled model.

In order to address the first item HSVA, among others, has started to investigate the dependency of ice impact on propeller thrust and torque within research work. So far a clear correlation between the tendencies in thrust and torque and compressive strength of model ice could be found [28]. To achieve a more realistic response behavior of the model propulsion system in case of ice impact HSVA has integrated a feedback loop in the control system of the model propellers. Prior to the ice model test limitations for maximum allowable torque and available power can be set in the control unit. During the ice model test the actual measured propeller torque is then provided as input to the control unit which instead of keeping the propeller revolution constant will respond to fluctuations exceeding the limitations and temporarily reduce the propeller revolution.

6.1.3. Other tests

Depending on the project’s objectives, several other tests are performed with ships in model ice additionally to the investigation of resistance and required power. These include maneuvering tests, i.e. breaking out from the own broken channel, a star maneuver to inverse the course or initial turning circles, ridge ramming, and many more. In some applications, local ice pressure on the hull is investigated, or lateral ice pressure is applied to the level ice to simulate pressurized conditions.

6.2. Structures in ice

The relevance for ice model testing with structures has increased over the past decades due to increasing arctic offshore activities, requiring new testing methods and setups. Basically, structures can be subdivided into two main groups: Floating structures that have some sort of anchoring system, and structures fixed to the seabed. The following subsections briefly introduce typical testing methods for both types.

6.2.1. Floating structures. Floating structures are often found in arctic offshore activities, e.g., FPSO, FPU, SPAR and shallow draft buoys, floating offshore wind turbine support structures, and many more. A large group of floating structures are ship-shaped floaters; however, several other designs such as semi-submersible or buoy-type platforms exist. Typically, these floaters are moored in a way that a
limited offset due to wind, current and ice loads is permissible. In case of drilling or storage platforms, this limit corresponds to disconnection of risers and pipes. The main task for ice model tests is typically to verify that the offset in ice does not exceed the design limits of the mooring system. Due to basin limitations, a truncated mooring system is typically applied to maintain reasonable physical scale factors [29]. Also, the prototype mooring system is usually simplified, e.g. by reduction of the number of mooring lines involved and simplification of the load-deflection characteristics as stepwise linear.

Figure 6 shows an example of such a submerged model mooring system installed in HSVAs’s ice basin. The model mooring system is fixed to a framework running on underwater rails. This frame is pushed through the model ice basin by the main carriage to mimic ice drift. Loads are typically measured in the mooring lines and, if applicable, at the rotating turret, or at the mooring line attachment points. Offset of the floating structure is monitored by optical tracking systems [30]. Standard tests for ship shaped floaters include weather-vaning tests, meaning a change of ice drift direction by 180° which turns the floater around and puts it 90° to the ice drift direction during turning. This situation is critical because ice crushes against the long, typically straight side walls, and broken ice accumulates alongside the vessel. The floater then typically heels considerably.

Instead of a submerged mooring system, a dry mooring system setup as presented in Figure 6 (right) can be chosen. It is fixed to the y-axis of the main carriage; thus, ice drift direction can be modelled in x- and y-direction, allowing not only tests with full reversal of ice drift direction but also any other curvature. A downside of the dry mooring system is, however, that the point and angle of attack of the mooring line forces is not fully realistic. The main objectives of each individual test campaign define the type of model mooring system to be used.

Another standard application for model tests with floating structures is to evaluate the effectiveness of an ice management system. Model tests are conducted in level ice as well as in managed ice fields with different floe sizes and coverage. Furthermore, DP systems can be evaluated [31].

Figure 6. (Left) Submerged truncated mooring system and (right) dry mooring system

Figure 7. Examples of fixed structures tested in level ice

6.2.2. Fixed structures. Model tests of fixed structures are manifold and can be conducted for various types of structures, e.g. bottom-founded monopiles or multi-legged structures, gravity-based-structures
(GBS), man-made islands, and many more. The abundance of different fixed structures that can be tested incorporates numerous testing objectives. If structure and seabed are modelled, ice encroachment and grounding can be investigated [32]. A setup with rigid, fixed structures enables, for example, study of global and local ice loads as well as ice flow around the structures and blocking effects of adjacent located structures. It is also possible to model the foundation stiffness and stiffness of the structure to investigate coupled dynamic effects of ice crushing. Some examples are shown in Figure 7.

7. Numerical modelling

The history of early numerical model development is strongly linked to the progress of ice tank testing capabilities. The largest benefit of numerical modelling over physical model testing is that it is not limited by natural laws. While physical testing is limited by material properties and physical laws, numerical modelling theoretically enables scientists to develop almost any material or interaction model, if its properties can be described by mathematical formulas. The possibilities to perform systematic testing under controlled conditions, to instrument ship models and structures and to observe in detail the interaction of ice with these structures above and under water by video cameras allowed to develop and calibrate dedicated numerical models.

Milano [33] introduced the first attempt for an entirely physically-based numerical model. Valanto [34] developed a 3D numerical model of the ice breaking process at the waterline. He combined his numerical model with the formula of the submersion component according to Lindqvist [23] resulting in a newly semi-numerical ice resistance prediction method.

The tool linking physical and numerical modelling is called a “Numerical Ice Tank”. The first concept was proposed by Valanto and Puntigliano [35], aiming to simulate the icebreaking of a ship in level ice to determine the ice resistance. Later complete tools have been developed to meet the need of the offshore industry performing DP operations in ice-covered regions. Within the DYPIC [36] and Arctic Dynamic Positioning [37] research projects, a numerical ice tank was developed and calibrated allowing investigation of new scenarios to enlarge the scope of the testing matrix. Subsequently, some simulation codes were developed based on this concept and validated by ice basin testing and full scale trials, for example the “Simulator for Arctic Marine Structures” (SAMS) [38], the “Simulation of Interaction between Broken Ice and Structures” (SIBIS) [39] [40], and a numerical model simulating the steering processes during interaction between a moored structure and drifting intact level ice (SimShipIce, SSI) [41].

8. Conclusion and outlook

The changing climate has an impact on the ice conditions in Arctic areas. Along with the concurrent development of economic activities, this demands for increasingly complex maritime designs and a high safety standard. Future trends in ice model testing will need to focus on complex maritime activities like maintenance of fairways and ports for large gas exploitation projects, design of multi mission service and research vessels and development of safe marine facilities for ice. The main task will be to model the new environmental conditions resulting from global warming and climate change like simultaneous occurrence of ice and waves, increasing ice dynamics resulting in ice pressure and pressure ridges. As the feasible number of tests for each project is limited with respect to the related time and cost effort, a combination of physical model testing and numerical simulations will be the solution for the increasing complexity of projects. Along with the developing testing methods, the model ice and testing infrastructure need to be permanently assessed and case-specifically modified to meet future test objectives. Some examples are given below.

8.1. Ice and waves

The increase of sea ice dynamics related to the decline of permanent ice cover in the Arctic results in larger areas with drifting broken pack ice and ice-free surfaces. Therefore, the interaction between waves and ice becomes more important. Also, changing sea states are affecting the ice conditions along the Northern Sea Route. Both climate relevance and impact on maritime activities raised a demand for detailed investigation of wave-ice interaction effects. First experimental approaches for wave-ice
interaction studies were limited to tests at very small scale or tests in wave basins using solid elements (e.g. wooden plates) to simulate the motion of ice floes on the deformed water surface [42]. At HSVA a wave generator for the large ice model basin was commissioned in 2014 (Figure 8). First tests on model ice break up and correlation between wave parameters and resulting floe size distribution were conducted in 2016 [43]. The results of the tests showed typical zones of loose small ice floes at the ice edge facing the waves followed by zones with large, rafted floes (strong floe interaction in waves) and large ice fragments with few cracks on the opposite side (Figure 9).

![Figure 8. Wave generator in HSVA’s Large Ice Model Basin](image1)

**Figure 8.** Wave generator in HSVA’s Large Ice Model Basin

![Figure 9. Floe size distribution along ice basin after wave impact](image2)

**Figure 9.** Floe size distribution along ice basin after wave impact

Another major step for the future is to investigate the simultaneous impact from waves and ice on ships and structures. Model testing methodologies include the measurement of impact pressures from ice fragments pushed by waves against floating or fixed structures. For floating structures wave-ice testing will allow investigation of interaction of ice fragments with mooring system and determine mooring loads as response to simultaneous wave and ice impact. The vaning behaviour of floating structures in ice covered waves needs to be studied as ice floe accumulation and resulting forces during vaning motion will differ from drifting uniform or floe ice. Parametric studies on motions and resistance in ice and waves will help to select arctic shipping routes with respect to their safety and profitability.

8.2. Case based scaling of ice

Knowing that the standard model ice and scaling procedure has been derived for tests with ice-breaking ships in level ice, this standard can be questioned if the scenario to be tested significantly deviates from the initially focussed interaction type. Recent developments in model ice modification attempt to improve model ice in a way that it is more suited for crushing interaction, but in turn less applicable to bending scenarios [44]. A similar approach has been made to tune the model ice parameters to allow more realistic representation of wave-ice interaction (von Bock und Polach et al., 2020) [45].

8.3. Numerical simulation

The use of numerical simulations is expected to further increase its popularity over the next years as a design tool for the industry. Similar to what has been observed several decades ago with CFD methods, one can reasonably assume that the numerical ice simulations will be more and more used to optimise the shape of ice-going vessels and structures. Although the accuracy of uncalibrated tools is currently rather low, they allow comparative studies of several designs, thus assisting engineers in selecting one or two best candidates for ice basin test. Another use for numerical methods is to expand a matrix of investigations to perform further design optimization, improve operational safety or simply to reduce development cost after the simulation tool has been calibrated by a relatively small amount of ice basin model test results. This in turn includes an increased focus on the more complex interaction mechanisms.
in physical model tests. Basin investigations will require more solid validation and calibration cases related to topics like ice accumulation and dynamic feedback-mechanisms between ice and structure.

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