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# DP in Ice Environment – Improving Safety and Efficiency of Arctic Operations

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## Abstract

This paper presents an overview of a five year research and development project aiming to develop dynamic positioning (DP) system technologies specifically for ice-rich environments. It has been initiated by the Centre for Marine Simulation (CMS) at the Fisheries and Marine Institute (MI) of Memorial University of Newfoundland, with its technical partner National Research Council's Ocean Coastal and River Engineering (OCRE-NRC) and commercial partner Kongsberg Maritime Simulation Ltd. (KMS). The primary objective of the project is to develop solutions for some of the critical challenges related to safe Arctic offshore operations by dynamic positioning. More specifically, the objective is to improve the safety and efficiency of oil and gas operations in ice infested environments through the enhancement of existing DP system technologies and training of DP operators in simulated realistic ice environments for ship operations. The project is envisioned to achieve its objective through developing a modularized simulation platform for prototype integration, validation, testing and operational studies/training. Prototypes of a DP control system, a vessel model, an ice force model, and other environmental force models will be developed.

The project commenced in 2013 and is set to complete in late 2018. In this first article of the project, a discussion on the contextual aspects and formation of the project, its planning and status to-date is presented. A synopsis of the scientific and engineering research performed to-date within the project scope, with a justification of their relevance to the safe DP operations in ice is given. The high level system design of the validation platform and the deployment strategies of its major components are presented. An introductory discussion on the novel ice force modeling approach is provided. Finally, an overview of the model test program of a fully DP controlled vessel in managed ice conditions, which was completed to provide a database for building and validating the ice force model, is also offered.

## 1.0 Introduction

Potential interest in future oil and gas exploration in deep water arctic regions in the presence of sea ice is expected to result in demand for customized dynamic positioning (DP) capabilities for drill-ships, offshore supply vessels, floating production, storage and off-loading (FPSOs), and icebreakers, allowing them to operate under challenging sea ice drift conditions. Dynamic positioning refers to the process whereby a vessel is kept on station by using its propulsion system(s) to counter any conditions (wind, waves, tide and current) that would alter the vessel's location (x, y) or orientation (yaw). The main advantage of using such systems compared to other stationkeeping solutions (e.g. mooring ) is the flexibility and the rapidity of the floating structure in response to constraints imposed by operational requirements or changes in environment conditions (Kerkeni et al., 2014). DP systems that exist in the market today are not designed and/or optimized to fully account for the effects of the ice and other parameters that exist in the Arctic environments. Consensus has been achieved within the relevant industry that understanding and modeling the dynamic interactions between these parameters and the stationkeeping vessel are the keys for effective and reliable DP design and operations. This unique challenge entails a statistically reliable ice force model to predict the loads encountered by the stationkeeping vessel due to the complex and dynamic ice-ice, ice-environment and ice-vessel interactions. Physical modeling is the key tool in understanding and validating the fundamental relationships between the ice environmental parameters and the dynamics of a DP vessel (Millan and Wang. 2011).

Limited experience in real world stationkeeping in managed and unmanaged ice has been gained over the last two decades. Early experiences include the Canmar/Dome drillship operations (Jolles et al., 1989), the Kulluk drilling campaigns (Wright, 1999) and the Sakhalin 2 phase 1 oil production operations that were using the floating storage and offloading tanker Okha (Keinonen et al., 2000, Keinonen et al., 2006a and Keinonen et al., 2006b). First time ever in the world, dynamic positioning operations in ice were performed in the offshore Sakhalin, May - June 1999 (Keinonen et al., 2000). The dynamic positioning operation in ice, in support of compression diving, was performed by CSO Constructor, a type B ice class vessel with support from two icebreakers acting as an ice management team. Ice management has been an integral part of exploration and production activities in the Arctic where stationkeeping is required. Rohlén (2009) discussed the relationship between ice management and stationkeeping in ice with specific references for some full scale efforts. Based on the experience in the Arctic Core Expedition (ACEX2004) and KANUMAS 2008 operations, the author stressed the importance and relevance of ice management in stationkeeping of floating structures during oil and gas related activities in the arctic region. Impacts from unmanaged ice floes and changes in the ice drift direction were found to be hazardous to the stationkeeping systems during the pioneering operations of the CSO Constructor (Keinonen et al., 2000) and the Vidar Viking (Keinonen et al., 2006a). Recently, a DP operations was performed by the icebreaking rescue and emergency vessel Baltika equipped with the Navis Nav DP4000 (DP System) and the Navis AP4000 Heading control system (autopilot) in the Kara Sea (Navis Engineering, 2015). A majority of the researchers above identified the need for developing technologies and training facilities for DP operations in heavy managed and unmanaged dynamic ice conditions.

To improve the understanding and enhance the capabilities in the existing stationkeeping systems, a number of R & D projects have been initiated worldwide. HSVA in Germany led a 3-year (2010-2012) R & D project titled "Dynamic Positioning in Ice-covered Waters (DYPIC)" primarily aiming at developing and improving its numerical modeling and physical model testing capabilities of DP vessels (Jenssen et al., 2012 and Kerkeni et al., 2014). Norwegian University of Science and Technology (NTNU) led a five year (2010-2014) R & D project titled "Arctic DP – Safe and Green Dynamic Positioning Operations of Offshore Vessels in an Arctic Environment" primarily aiming at developing DP control system technologies for acceptable DP operations in the Arctic environment (Skjetne et al., 2014). Currently an eight year R & D project titled "Sustainable Arctic Marine and Coastal Technology, SAMCOT" is being carried out by a group of researchers led by NTNU with an aim to produce knowledge to ensure sustainable and safe exploration, exploitation and transport from and within the vulnerable Arctic region (SAMCoT).

One of the greatest threats to the stationkeeping systems of vessels and offshore installations is posed by drifting sea ice in the arctic regions consisting of a vast multitude of complex and interconnected parameters and characteristics (Metrikan, 2015). Such ice can encroach on an operational site in a wide variety of types and forms, ranging from isolated first-year floes to compacted multi-year ridges. Offshore floating structures equipped with a DP system for stationkeeping often need to operate in well managed ice field to ensure sustainable DP operation. Despite the DP operators need to be alert to the changing ice condition and ready to intervene should the vessel stray away from its set point and heading. This essentially warrants appropriate training for the DP operators in simulated extreme ice conditions such that the operators can experience various consequences of dynamic ice-structure interactions and understand the strategies for manual operations in case of an insufficient or failed DP system. Presently, such simulators only exist for open water applications.

The Centre for Marine Simulation at the Marine Institute (CMS-MI), with its technical partner National Research Council's Ocean Coastal and River Engineering (OCRE-NRC) and commercial partner Kongsberg Maritime Simulation Ltd. (KMS), initiated a five year research and development project to develop dynamic positioning system technologies specifically for ice-rich environments. This system is expected to enable vessels engaged in the exploration and production phases of the offshore petroleum industry to operate safely and efficiently in ice. The end result of this development project will be a functional DP in Ice Control System Prototype, which will be used by KMS as a proof-of-concept for real world full scale application. CMS-MI will use the prototype as a training simulator for procedural analysis and specialized course delivery. The use of a DP system with a module to simulate the dynamics of ice-structure interactions is considered an additional skill set required by DP in ice operators above their current training. Aimed at experienced personnel with the responsibility for DP operations in ice covered waters, a new training scope will be developed around the new simulator.

The primary objective of the R & D project is to develop solutions for some of the critical challenges related to safe Arctic offshore operations by dynamic positioning. More specifically, the objective is to improve the safety and efficiency of oil and gas operations in ice infested environments through the enhancement of existing DP system technologies and training of DP operators in simulated realistic ice environments for ship operations. The project is envisioned to achieve its objective through completion of the following key tasks:

- Develop a statistically reliable managed ice force model that enables predicting the ice-structure interaction loads on a DP controlled vessel in real time.
- Develop a modularized simulation validation platform for prototype testing (DP control system, vessel model, ice and other environment force models).
- Develop a vessel model and other environment force models that enable predicting the vessel load and motions due to interaction with environmental forces.
- Integrate, validate and test various components of DPIVP, including the ice force model with KMS's DP control system.
- Develop, implement and test a DP visualization system to augment the prototype, used for industry training analysis.

The project commenced in 2013 and is set to complete at the end of 2018. In this first article of the project, a discussion on the contextual aspects and formation of the project, its planning and status to-date is presented. A high level system design of the validation platform and the deployment strategies of its major components are presented in Section 2.0. An introductory discussion on the novel ice force modeling approach is provided in Section 3.0. A brief discussion on the modeling techniques for vessel and other environment forces is presented in Section 4.0. An overview of the model test program of a fully DP controlled vessel in managed ice conditions, which is completed to provide a database for building and validating the ice force model is presented in Section 5.0. Section 6.0 concludes the article.

## 2.0 DP in Ice Validation Platform

This section presents a high-level design of the pure software parts of the DP in Ice Validation Platform. The system consists of six main distributed components that communicate with each other using custom network message protocols on TCP/IP over Ethernet, see Figure 1. Being distributed has several advantages, including potential performance gains by dividing the computation load among several computers, enforces loose coupling between major components, creates a clear separation of concern for design purposes while at the same time clearly dividing labor among distinct teams, and allows easy replacement of components with alternative implementations. With the exception of the Visualization, all components will run on standard Windows 7 workstations (e.g. configuration Intel Core i5-4590 at 3.30 GHz, 8 GB of RAM). A further discussion of each of the major components of the DPIVP is presented in the following sub-sections.

- *Simulation Designer*: This is used to create a simulation scenario which is saved to a Simulation Project file for use by other system components.
- *DP in Ice Simulator (or just Simulator)*: This component runs and controls the simulation specified in the Simulation Project file. Internally, it utilizes the numerical models contained in the Simulation Engine.
- *Simulation UI*: A basic user-interface to load, play, stop, and monitor the simulation.
- *Vessel Control*: Supports manual (user) and automated control of the vessel, including on the fly switching between DP and manual control
- *Visualization*: Renders a graphical representation of the simulation.
- *Data Acquisition System (DAS)*: A data acquisition system that taps into the internal variables of the simulation and allows third party tools to acquire said data.

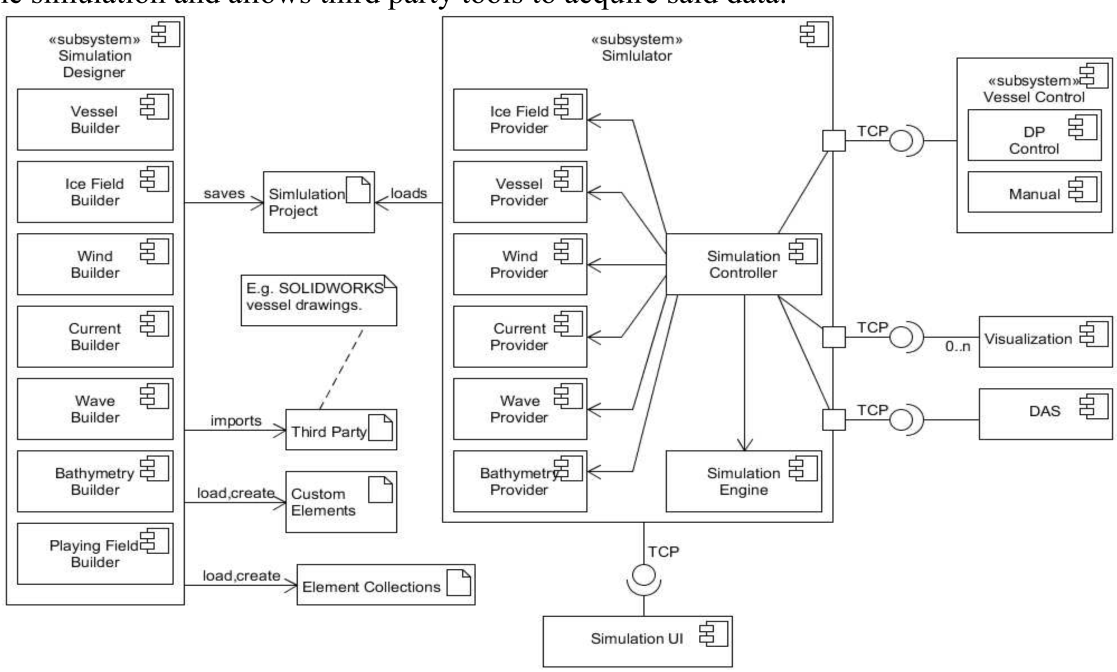


**Figure 1: High level static view of the main system components (UML).**

**2.1 Simulation Designer.**

The Simulation Designer component is a Windows 7 desktop software application used to prepare a simulation, see Figure 1. It's executed independently of the simulation, as a standalone piece of software. When designing a simulation, the user builds the simulation time line. This involves the initial (default) conditions, duration of the simulation, conditions along non-overlapping time ranges on the time line, and discrete events at certain times. The user can create playing field elements required to design a simulation. Element types include a vessel, ice field, playing field (the region of interest), waves, bathymetry, current, and wind. The modules are realized in a graphical user interface (GUI) as separate windows or tabs, but are designed to be user interface (UI) independent. The GUI uses text-control based components (drop downs, menus, buttons, tables, etc.) for input and display, with limited use of 2-D or 3-D graphics for visualization. The main output is a Simulation Project file. The project file is a single file that can be moved around, copied, deleted, etc. just like any other OS file. The project file has its own proprietary definition.

A major feature of the Simulation Designer is ice field creation. There are four methods of creation: random, rectangular, tessellation, and importing from images. The first three requires the user to enter ice parameters, such as desired floe size distribution, ice coverage, thickness, density, strength, and number of sides, from which the system generates an ice field that meets the specification captured by the parameter values. The differences between the three are in how the ice shapes are created. In the first case the ice shapes are randomly generated under the constraint that the number of sides on floes fits the user specified distribution. In the second case the shapes are forced to be rectangular with the possibility of corner rounding and length-width ratios that fit a user specified distribution. The third case uses a tessellation algorithm constrained mostly by flow size and ice coverage.

The forth approach for creating an ice field is different in that it involves segmentation of ice floes from top down imagery of scaled physical ice fields created during the DP in ice model experiments described later in Section 5.0. Such ice fields can be saved as reusable Ice Field Element files, see Custom Elements in Figure 1, and used as part of any future simulation scenario design. Designed simulations using such ice fields have the benefit of having a very realistic, validated ice field, and one that has been used in part to create some of the Simulation Engine models documented in sections 3.0 and 4.0. It is anticipated this segmentation approach will be expanded to include creation of simulated ice fields from aerial photography of real, in the field, full scale ice fields.

The Vessel Builder component of the Designer allows the user to specify the principle particulars and mass properties of a vessel to be used in the simulation. It also allows the user to define thruster parameters, which are important to the vessel control (DP and manual) and the vessel model in the Simulation Engine. The physical vessel models used the DP in ice model tests, see Section 5.0, will be predefined and can be imported for use in any simulation experiment, thus providing validated simulation scenarios.

**2.2 DP in Ice Simulator.**

The DP in Ice Simulator component (or just Simulator) is a standalone Windows 7 application whose main function is to execute the simulation of a DP vessel operating in ice with a set of contributing environmental factors, as specified in the Simulation Project file. The key components of the simulator are the providers, simulation controller and the simulation engine (Figure 1). The actual execution, control loop, loading of project input, I/O to external components, and all other operations except the algorithms and data structures that implement the smarts of the simulation are handled by the core Simulation Controller sub-module, a key component of the simulator. The Simulation Controller coordinates the activities of the other modules and the data flow between them. Properties of the playing field are encapsulated in modules called providers, another component of the simulator. The initial state and any chronological state updates are loaded from the Simulation Project file and managed by the providers. There are three types of providers: static (e.g. Bathymetry Provider), deterministic dynamic (e.g. Current Field Provider), and non-deterministic dynamic (e.g. Ice Provider).

One key feature of the Ice Provider worth mentioning is that it maintains a consistent ice field with as-designed characteristics (e.g. floe size distribution and coverage) for any simulation duration. This means that as ice floes move in response to the wind and current characteristics, ice must leave the simulated playing field (viewable ice field in the region of interest around the vessel) and new ice must enter. Creating one super large ice field that simply moves under a viewport (the playing field) will limit the possible run duration and may place heavy computational burdens on the ice management module (i.e. the Ice Provider).

The Simulation Engine component will be utilized by the Simulation Controller and will encapsulate the numerical models (analytical, empirical, semi-empirical, statistical, and logical) required realizing the smarts of the simulator. The vessel model, see Section 4.0, ice force model, see Section 3.0 and other environment force models, see Section 4.0 are considered the key components of the simulation engine. This will serve as a roadmap for the key elements to be designed and implemented by the research group, as well as describe the functional interfaces delegating implementation responsibilities of the software group and the research group. Low-level details of implementation have been included where necessary for conceptual explanation, though no such detail is considered a final design at this time.

### 2.3 Simulation UI.

The Simulation UI component is a separate application. It is the user interface for the DP in Ice Simulator component, see Figure 1. The user can select a Simulation Project file, configure the simulation rate (default is real time), start the simulation, pause the simulation, and stop the simulation. The UI also includes support for monitoring simulation and the status of external components on which the Simulator depends. The Simulation UI connects to the DP in Ice Simulator and communicates over TCP using a custom messaging system. The Simulation UI can run in the absence of a Simulator, but it can’t do anything useful until a Simulator is running and connected.

### 2.4 Vessel Control.

The Vessel Control console enables both manual and automated control of the vessel under test. The Vessel Control UI console is equipped with interface devices to provide manual control capability to the operator. In addition to the usual mouse, keyboard and touch-screen, these devices may eventually include game controllers such as joysticks, joy wheels, yolks, and throttles. The vessel control console has graphical elements that represent real-world control devices. This module provides a communication interface for dynamic positioning, and allows on-the-fly switching between DP and manual control.

It should be noted that the Vessel Control module is decoupled from the Simulator component using a network interface, see in Figure 1. In addition to the performance gains of spreading the computation burden to multiple computers, this eases the task of replacing the DP in Ice Validation custom Vessel Control console with a third party console, such as that provided by KMS during the integration phase. Either the third party console can implement the DP in Ice Validation platform Vessel Control network interface, or a third party specific adaptor can be quickly developed to adapt the third party console communication interface that the DP in Ice Validation Platform requires. Furthermore, the Manual Control module is distinct from the DP Control module, see Figure 2. This allows integration of a third party DP Control system that may not have a manual control component. In this case, the platform can keep using its Manual Control module.

The Dynamic Positioning (DP) system is encapsulated in the DP Control component. This component communicates with the Vessel Control component using a custom TCP/IP based messaging protocol. NRC's DP system consists of three application modules, four services, and a target vessel. The application modules include a DP configuration module, a DP controller module, and a DP visualization module; the services include a vessel tracking service, a dynamic positioning server, a remote control service, and vessel systems monitoring service. NRC's DP system was initially design for physical vessel models under DP and manual control. When used in the DP in Ice Validation Platform, the services that the DP controller module depends on will be communicated directly to the DP controller from the Simulation Controller, see Figure 1. Much of the information that the services provided are still available via the single simulator Data Acquisition Software (DAS). The DP visualization module taps into the DAS data channels as the source for vessel and thruster animations.

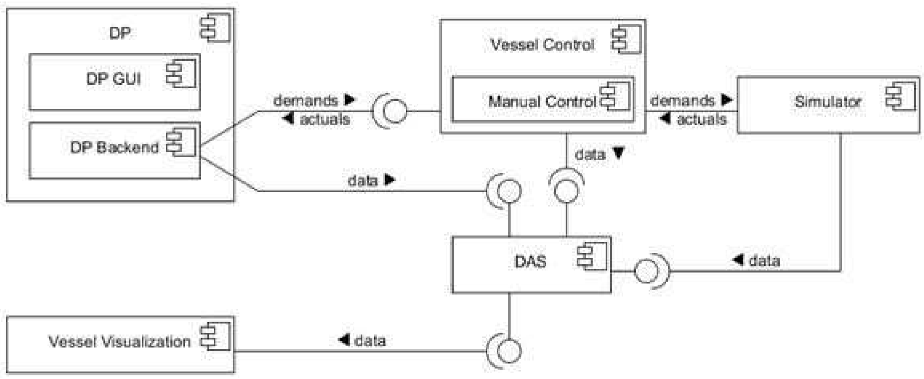


**Figure 2: Static design of NRC's DP system when embedded in the DP in Ice Validation Platform.**

### 2.5 Visualization.

The Visualization component is a separate application and is being developed by the CMS-MI. It renders the current state of the simulation playing field in real time. This includes rendering the vessel and the ice field. Communication between the Visualization and the Simulator component follows the client-server model over TCP/IP. At the start of simulation (at runtime), the initial playing field ice field is sent to the Visualization component. With respect to the ice field, this includes location, orientation, size, and shape for each piece of ice. The Visualization, with some artistic license, renders the ice field. During simulation, a continuous stream of changes and events resulting from ice-vessel-environment interactions are sent to the Visualization. As above, the stream includes size, position, orientation, and basic dimensions of ice, but also includes combinations of events such as crushing, bending, breaking, rafting, submerging, stacking, and rotating. It is the Visualization component's responsibility to render the state and events in a realistic manner.

### 2.6 Data Monitoring & Analysis.

The DP in Ice Simulator component supports logging and live monitoring of all signals deemed important using OCRE-NRC's proprietary Data Acquisition Software (DAS), see Figure 1. This is accomplished by means of a custom plugin implementing the protocol defined in the Data Acquisition Interface. The protocol follows the client-server, command-response model. Signals collected during simulation can be saved for off-line viewing, analysis and storage.

## 3.0 Ice Force Model for Managed Ice

### 3.1 Challenges.

One of the challenging tasks within the project deliverables is to develop, implement and validate a numerical model to determine ice-structure interaction loads on floating structures equipped with a specialized DP system for operations in ice environments. This numerical ice force model is to be used to compute the force contribution of managed pack ice at every time step *t* of the simulation. It will utilize ice environment state information provided from the Ice Provider via the Simulation Controller, and also vessel information provided by the Vessel Model. It will produce the resultant force and moment on the vessel to be passed to the core Simulator to calculate the vessel response. The primary requirements of the ice force model are:

- Realistic modeling of ice-ice and ice-ship interaction and prediction of average and time varying ice forces/moments and the resulting motion responses
- Real time or faster than real time simulation with simulation plausibility
- Computation stability
- Realistic ice events, both in terms of computed physics and the "look" and "feel" for visualization

Note that the realistic modeling of ice-ice and ice-ship interactions in real time is the key focus that leads to realistic visualization and load. This model entails the largest research and development effort within the project. Efforts have been given to investigate various existing and novel models for possible candidates for the current application. Further details on the state of the art of ice force modeling approaches are outside the scope of this article. Suffice it to say that most of the high fidelity methods, such as Finite Element (FEM), Partial In Cell (PIC), classic 3D Discrete Element (3D DEM), Smoothed-particle hydrodynamics (SPH), are not appropriate for the current application, primarily because of the requirement of real time calculation. The more suitable modeling approaches are, as also claimed in the literature, the physically based models (PBM), 2-D DEM, empirical and some of the hybrid approaches. OCRE-NRC is currently developing a novel approach and corresponding methodology to meet the ice force model specifications; see Section 3.2. This development is likely to entail a multi-modeling approach, involving a combination of existing and novel modeling techniques.

**3.2 Ice Force Modeling Approach.**
OCRE-NRC is currently exploring a hybrid ice force modelling technique, consisting of three distinct modeling approaches with different levels of sophistication and fidelity. Sufficient effort will be devoted at the early stage to assess and blend the approaches to develop an ice force model that meets the project's specification. The three candidate approaches to develop the hybrid model are:

- Physics-based discrete element - analytical modeling approach
- Model test data based non-linear system identification approach
- Model test based empirical-probabilistic approach

Each approach will have some novel features that will pose some challenges, especially during the algorithm implementation. During ice-ice and ice-ship interactions in managed ice of up to 7/10 ice concentration, one can expect a much higher concentration, up to 10/10, locally at the vicinity of the ship due to its obstruction; hence, a wide range of ice concentration is anticipated. One of the three approaches may be more suitable than the other two for a particular range of ice concentration. For example, the physics-based discrete element modeling approach and empirical-analytical approach may be more applicable for low to medium-high concentration up to 8/10 condition, where modeling of individual ice interaction events are important. The non-linear system identification technique is expected to be more effective for high concentration with less computational requirement, where modeling of the individual ice interaction events have no apparent advantage. The advantages and disadvantages of each ice modeling approach in context to the project requirements and their application range are provided in **Table 1**. The hybrid ice force model is envisioned to consist of multiple layers of ice force models each more suitable than others for certain ice conditions. During the simulations, the ice force calculation will be done by dynamically switching between the models appropriate for the encountered ice field conditions. Further details of each of the modeling approaches are provided in the following sections.

**Table 1: Relative Advantage and Disadvantages of the Ice Force Modeling Approaches**

| Modeling Requirements | Physics-based discrete element - analytical approach | Model test data based non-linear system identification techniques | Model test data based empirical-probabilistic approach |
|---|---|---|---|
| Realistic modeling of ice-ice and ice-ship interaction | Yes | Yes | No |
| Prediction of average and time varying ice forces/moments and the resulting motion responses | Yes | Yes with the proposed novel approach | Yes with the proposed novel approach |
| Real time or fast time simulation with simulation plausibility | Questionable for large number of ice floe (>1000) | Yes | Yes |
| Computation stability | Yes with proper care | Yes | Yes |
| Visualization and feel for realistic ice events | Yes | Yes with the proposed novel approach | No |
| Development time and computation Intensiveness | Very High | Medium | Low |
| Application range (ice concentration) | <8/10 | >8/10 | All |
| Validation requirement | Proven approach with new enhancement | Novel approach, need careful validation | Proven approach with new enhancement |

### *3.2.1 Physics-based discrete element -analytical modeling approach.*

A physics engine based 3D discrete element method (DEM) based model will form the basis of the hybrid ice force model. To adopt the computation intensive DEM technique in real-time simulation effectively, the simulation space may be sub-divided into 3 areas – near, medium and far field, see Figure 3. The managed ice field of various geometry and size distributions may be modeled in 2-D for medium and far fields as a collection of floating rigid elements that interact with each other and boundary walls. The elements are subjected to buoyancy, drag force and added mass of current with current and wind forces acting as driving forces. Investigations are currently underway to evaluate various neighbor search, contact detection, contact force and resulting motion calculation algorithms that are built in various open source physics engine codes. In these engines, the contacts/collisions between ice floes are modelled as non-instantaneous where multiple contacts can occur simultaneously for fast calculation.

The events of ice breaking, crushing, floe rafting, ridging, floe field buckling, and submergence, may be modeled using an analytical 3-D model for the near field. A 3-D model is considered only for the small number of ice floes which directly or indirectly interact with the DP vessel because the 3-D modeling is computationally intensiveness and may not be favorable for real time simulation, see near field in Figure 3. Furthermore, all computation of discrete body dynamics, for example, DEM models used in medium and far fields, may be delegated to one computer and ice-hull interaction computation for near field may be delegated to another computer to potentially speed up the computation making use of the efficiency provided by a distributed framework.

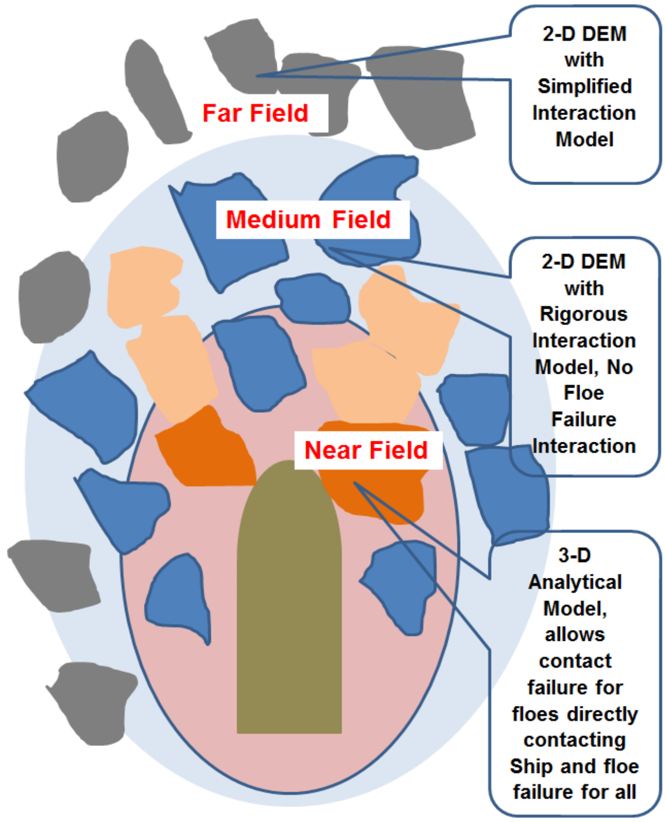


**Figure 3: Schematic Showing the 3 ice Fields and the Corresponding Ice Models**

### *3.2.2 Model Test Data Based System Identification Technique.*

This model is primarily applicable to ice-ship interaction modeling for the near ice field treatment, see in Figure 3, especially when many interactions occur simultaneous rendering detailed correlation of global interaction forces and corresponding individual ice impact events difficult and unnecessary in the context of real-time simulation e.g. in high floe concentration. In this modeling approach, a physics engine based 3D discrete element method (DEM) may be used to track ice pieces in the near field and the same treatment and modeling approach as in the Physics-based discrete element technique may be used for the far and the medium fields.

For the near ice field treatment, highly non-linear system identification techniques based on analysis of model test data/video and stochastic numerical simulation may be used. In the context of nonlinear system identification, this approach is completely flexible as no prior model is required. It is basically a "black box approach" where a correlation may be established between the ice-ship interaction phenomena and resultant forces and moments on the ship at a time instant using system identification techniques and probabilistic descriptors developed from experimental data and observations.

In the proposed effort, an in-house developed real-time machine vision processing algorithm will be further developed (Gash and Millan, 2012). This system uses a combination of segmentation, edge intensity and morphological techniques to produce more accurate estimates of ice segmentation and their subsequent state parameters; see Figure 4. Some parameters that can be generated by this system are ice concentration, ice piece velocity/acceleration, ice piece rotation, ice piece size and shape and other statistical quantities regarding the ice pieces within defined areas surrounding the vessel. This information is essential to the analysis of the model test results and to defining, reproducing and correlating ice field parameters to measured vessel force/moments and motions and also to correlate results with numerical models (Millan and Wang, 2011).

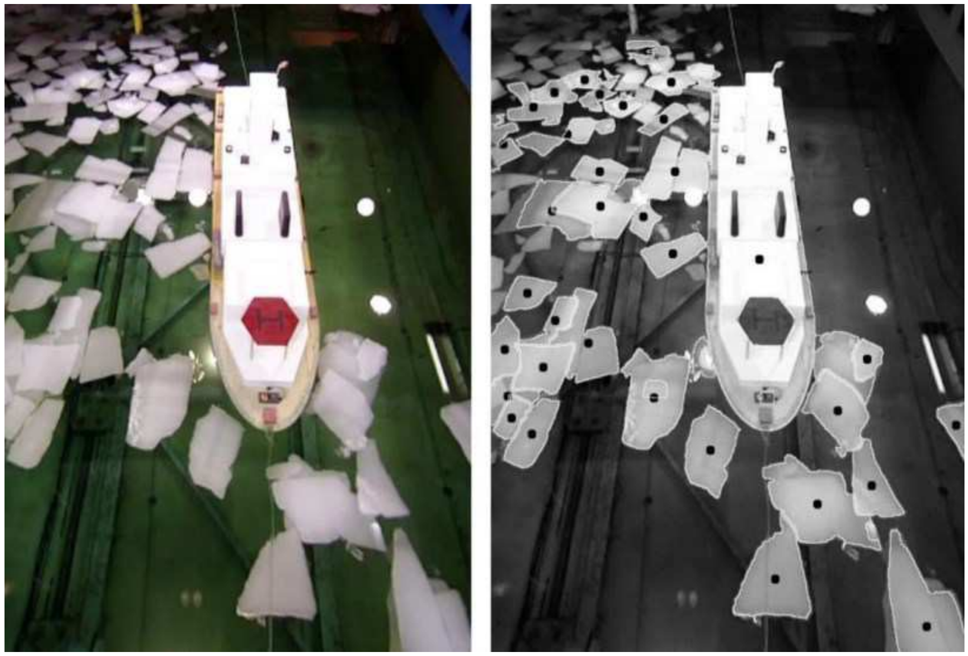

**Figure 4: Accurate Image Segmentation with Touching Pieces and Inconsistent Lighting (Gash and Millan, 2012)**

This approach will involve developing a large table of coefficients based on the video image and corresponding force/moment data analyses. A GUI-based software is developed to synchronize and analyze the video data in a semi-automatic fashion. This approach is novel and hence poses high risk as it is dependent upon two unknowns at this time: quality of the visual data processing and success of the system ID approach. However, it will fit naturally into the physics based DEM development. The applicability of this approach can be further extended by incorporating more video/data for other ships and ice scenarios from experiments and/or numerical simulations. At the writing of this document, this approach was considered the most appropriate for the initial development of an accurate, statistically valid, real-time model that satisfies the immediate requirements of the project.

***3.2.3 Model Test Data Based Empirical-Probabilistic Approach.***

In this approach, the ice load on ship will be computed using a novel empirical-probabilistic approach. Estimation of the nominal ice field characteristics as well as instantaneous floe size, concentration and velocity in the near field of the ship will be required. This is expected to be provided by the physics based DEM model. Details of the interaction as described in physics based discrete element approach will not be modelled; hence, computation time will be minimized. This approach relies on empirical data and extends its application to conditions beyond the range covered by the empirical data through analytical means. In a probabilistic approach, this model will also account for the stochastic nature and inherent randomness of the ship-ice interaction loads. The major shortcoming of the approach is its lack of details of the floe dynamics that would decrease the fidelity in visualization in the simulation. In order to improve the fidelity of this approach, the techniques as outlined in **Figure 5** will be implemented.

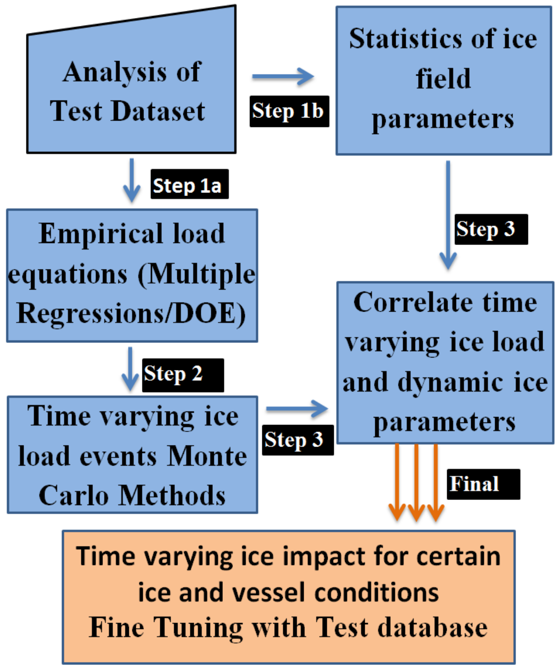


**Figure 5: Flow chart of empirical-probabilistic approach**

In this approach, a functional relationship between the time averaged ice load (response variable) and the nominal values of ice/vessel parameters (independent variables) in non-dimensional form is assumed. Equation 1 below shows such an expression for the vessel surge load coefficient. Multivariate Regression methods (Colbourne 2000, Woolgara and Colbourne 2010, Wang et al., 2010) and design of experiment (DOE) techniques (Islam and Lye, 2008) are used to determine the coefficients and develop the models. **Figure 6** shows a comparison of predicted time averaged surge load using a regression model and a DOE model with corresponding measurements for certain ice conditions as provided in the title of the figure. It is noted that the multivariate regression model accurately predict both magnitude and trend of drift speed effect on model surge load. Note the spread in surge load values due to repeat measurements.

$$\frac{F_X}{\rho_i B h_i V_i^2} = C_X = A\frac{\rho_i}{\rho_w}^B {f_c}^{C^2}\sqrt{\frac{\rho_i B V_i^2 h_i}{\sigma_f h_i^2}}^D C^E \frac{L_f}{B_S}^F \theta^G \alpha^H \beta^I \sqrt{\frac{V_i^2}{g h_i}}^J \qquad 1$$

Once the empirical expressions for time average ice loads are developed, the time varying ice load models are developed using statistical distribution, Monte Carlo methods, and empirical corrections, see Equation 2.

$$[\ F_X(t),\ F_Y(t),\ M_Z(t)\ ] = F\ (Ice(t),\ Vessel(t)) \qquad 2$$

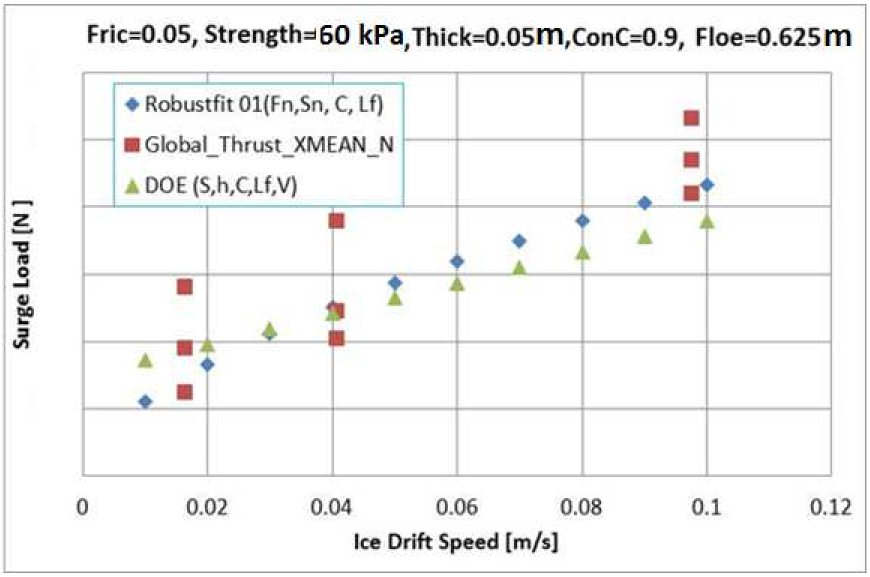


**Figure 6: Prediction of time averaged surge load using regression and DOE models**

### 3.3 Important Notes.

In the proposed hybrid ice force model, the physics based DEM model will be the basis for the three modeling approaches. Realistic modeling of ice dynamics and correlating local ice impacting events and the corresponding local loads will require some sort of DEM modeling but it can be computation intensive if the number of ice pieces becomes large. The Empirical and System ID based model are expected to improve the computation effectiveness, especially in high ice concentrations where DEM methods would become too intensive and modeling of hundreds of individual ice impact events or their individual loads would be neither required nor feasible.

Regardless of the approach taken, availability (and quality) of measured data will be paramount to the success of the ice force model development. For the range of managed ice scenarios of interest (dictating the floe size and shape distributions, concentration, drift speed), for each global region and seasons of interest (dictating ice property ranges such as thickness, densities, strengths, etc.), and for each vessel of interest (e.g. drillship, supply vessel, ice breaker, etc.), it will be required that the numerical models developed herein be validated – and possibly calibrated – against realistic data. Moreover, the development of any statistical, empirical, semi-empirical, or hybrid-event model will require that this data be available in order to begin development. An extensive model test program has been carried out within the scope of the project in an effort to generate such a dataset as discussed in Section 5.0.

## 4.0 Vessel and Other Environment Models

### 4.1 Low Speed Vessel Manoeuvring Model.

The vessel model comprises the core ship dynamics model and is expected to meet the following minimum functional specification:

- A six degree-of-freedom (6-DoF) state model of vessel surge, sway, yaw, heave, pitch, and roll, with emphasis on the fidelity of the former three states (and their coupling) for the DP control,
- The fidelity to adequately model the dynamic responses of in-scope vessels at zero to low speeds,
- The ability to receive control surfaces and actuator demands and calculate resulting forces and moments using characterization information from initialization, and,
- Well-defined state input/output variables for communication with Simulation Controller.

For ice floes, the discrete rigid body dynamic model provides the functionality of the motion solver. The typical equations of motion solved by DEM would be appropriate due to their simple geometry and mass properties. Although the ship is also treated as a rigid body subjected to external forces, due to its complexity in geometry and loading, a maneuvering motion solver for the ship specifically developed for slow speed maneuvering is more appropriate. As the primary component of the simulation engine, a motion solver has been developed to compute the motion response of the subject ship from external loads. This core ship maneuvering module computes the vessel's dynamic response from a set of external forces in the time domain, including hydrodynamic, ice, wind, wave, current, and propulsors/thrusters loads. The solver is also equipped with user specified conventional and azimuthing thrusters that can take arbitrary control from the operator. The performance of the thrusters can be modified to accommodate automatic-control by a DP system. The calculation is done in real-time simulation speed, but yet retains a satisfactory level of fidelity for accurate vessel states and response simulations.

The primary features of the motion solver may be summarized as follows:

- Standard equations of motion are used for surge-sway-yaw.
- Maneuvering coefficients are taken from Clarke et al. (1982), normalized to avoid singularities at low speed, using the "bis" system (Fossen, 2011).
- Wind and current forces are calculated using a cross-flow Morison formulation distributed along ship's length as discussion in Section 4.2.
- Uncoupled roll, pitch and heave motions due to regular wave actions are included using a Response Amplitude Operator (RAO) based approach as discussion in Section 4.3.
- Ice forces are provided by the ice model as discussed in Section 3.0.
- Rudder force is estimated using a first-order rudder model.
- Currently, the DP control is achieved using 2 coefficients for position and 2 coefficients for orientation. This will be replaced by OCRE-NRC's DP model (Millan, 2008) mentioned in Section 2.0.
- All coefficients are needed to be tuned: maneuvering coefficients, DP coefficients, rudder parameters, thruster parameters etc. Some simplified Planar Motion Mechanism (PMM) tests with the fully equipped drillship model (the same one used for DP in ice testing described in Section 5.0) will be beneficial to validate the manoeuvring coefficients used in the model.

### 4.2 Wind, Current and Tide Force Model.

These numerical models will be used to compute the force contribution of wind, current, and tide at every time step *t*. They utilize vessel state information, wind/current/tide environment state information (provided from the Current Provider via the Simulation Controller), and vessel sub-surface windage models provided by the Vessel Model. They produce the resultant force and moment on the vessel to be forwarded to the core Simulator to calculate vessel response. The wind and current forces are predicted using the cross-flow Morison formulation (strip theory approach) distributed along vessel's length (Raman-Nair, 2014). Tide force will be a simple coefficient based model.

### 4.3 Wave Force Model.

This numerical model is used to compute the force contribution of waves at every time step *t*. It utilizes vessel state information, wave environment state information (provided from the Wave Provider via the Simulation Controller), and vessel information provided by the Vessel Model. It will produce the resultant force and moment on the vessel to be forwarded to the core Simulator to calculate vessel response. This model is available to the Simulator for calculations. The wave force will be developed using a Response Amplitude Operator (RAO) based approach, including the 2$^{nd}$ order drift forces important for stationkeeping. For early development purposes, wave forces will be purely a function of the information provided by the Wave Provider, with no complex interactions from surrounding geography or bathymetry.

## 5.0 DP in Ice Model Experiments

The first phase of an extensive model experiments program has been carried out for a DP controlled generic drillship/FPSO (Floating Production, Storage and Offloading) vessel model in managed ice between February and April, 2015, in the ice basin of OCRE-NRC. The objectives of the model experimental program are:

- Assess the effect of physical and mechanical properties of managed ice field characteristics on the force and motion responses of a dynamically positioned floating structure;
- Use the test database to develop and validate an ice force model; and
- Assess the capabilities of a conventional open water, PID based DP system for stationkeeping of a floating structure in various managed ice conditions.

A brief discussion on the test setup, conditions, managed ice field modeling, test results and discussions is presented in the following sub-sections.

**5.1 Phase I Test Setup and Conditions.**
A simplified generic drillship/FPSO model with length overall (LOA) of 206 m and displacement of 102000 tonnes at 1:40 scale was tested in multiple managed ice configurations, see **Figure 7**. A total of 372 test runs were carried out in 17 ice sheets to evaluate the ice forces and motion responses of the hull in various managed ice conditions. Test variables included ice thickness, ice strength, ice concentration, ice floe size, drift speed, and ice encroachment direction. Additionally, a number of tests were completed in managed ice conditions with the presence of ridge fragments, in various vessel operation modes (DP or manual), in ridges and in 0.625 m thick level ice. Azimuthing angles and propeller rotational speeds from each of the six podded propulsors were measured and the vessel's 6-DOF motion/trajectory was recorded using an optical tracking system. Each of the tests was run for at least four hull lengths for each of the drift speeds in the basin. Additional measurements were made on the linear accelerations and rotational rate of the model. Multiple camera systems were also used to record detailed ice movements in various locations.

For each of the tests in managed ice, the DP system of the vessel is set to track and maintain pre-determined position and heading set points relative to the main carriage of the ice basin. Ice drift is simulated by allowing the vessel to move through a stationary ice field while following the setpoint fixed on the main carriage moving through the ice tank. Changes in the ice drift angle are simulated by changing the heading of the vessel through the DP interface. The overall setup of the DP in managed ice conditions is presented in Figure 8. The scope of the testing campaign with the boundaries of the test parameters is presented in Table 2. Details of the vessel characteristics, measurement instrument, and basin overall setup conditions are presented in Wang et al. (2016).

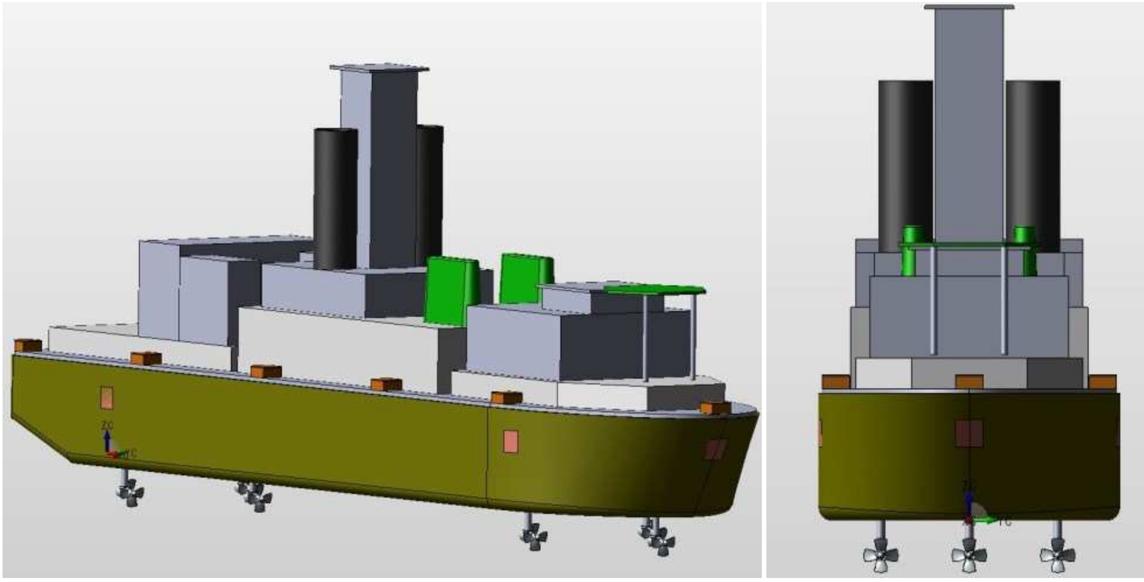

**Figure 7: The Solidworks™ model showing the off-axis and front views of the hull**

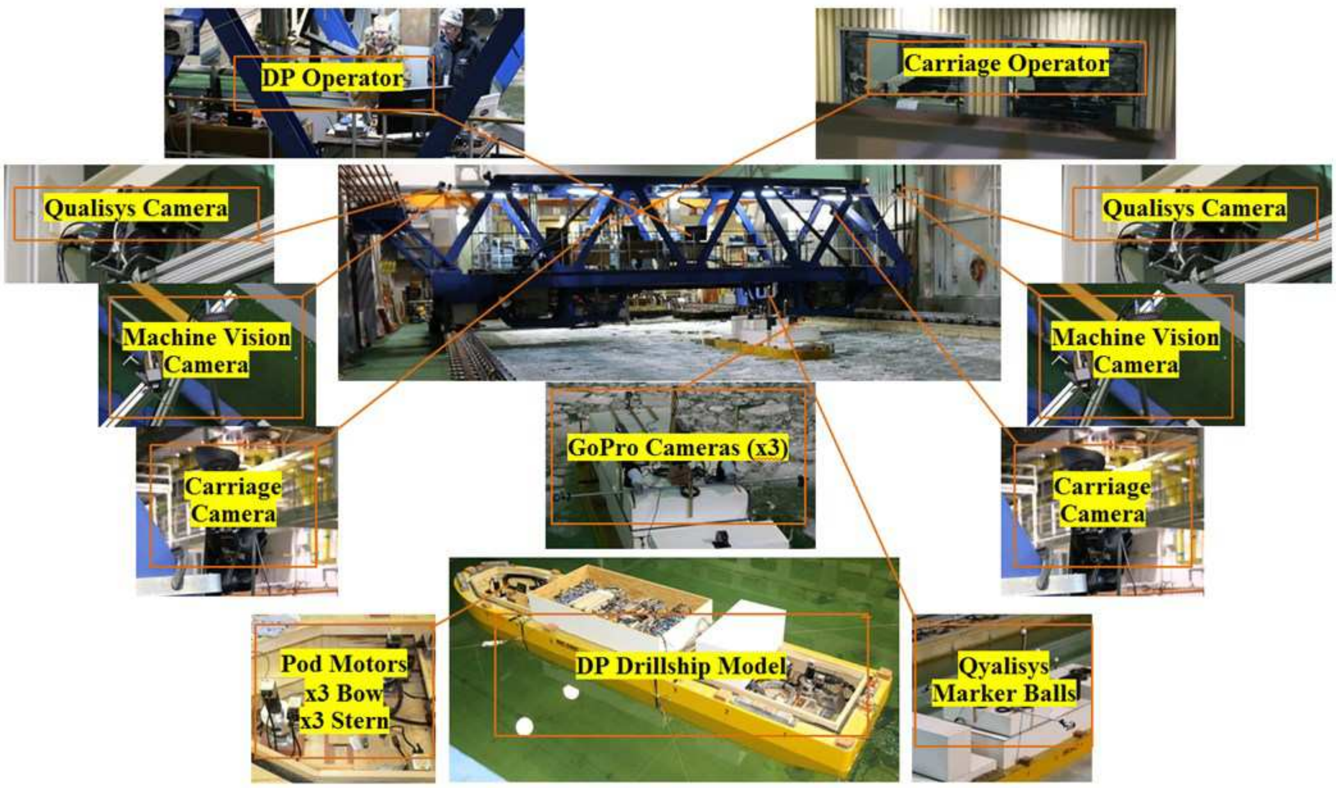


**Figure 8: DP in Managed Ice Testing Setup**

**Table 2: Details of the Scope of the Model Test I (Parameters in Full Scale)**

| *Parameter* | *Variable* | *Value* | *Unit* | *Parameter* | *Variable* | *Value* | *Comment* |
|---|---|---|---|---|---|---|---|
| Ice thickness (FS) | T1 | 0.6 | m | Brash/small ice pieces inclusion | B1 | 34% | A mixture of brash ice and small ice pieces |
| | T2 | 1.3 | m | | | | |
| | T3 | 2 | m | | | | |
| | | | | Shape of ice | Square with rounded corners for 100m floes first then manually break for smaller ice floes (50m and 25m floes) | | |
| Size of ice (FS) | S1 | 100 | m | | | | |
| | S2 | 50 | m | | | | |
| | S3 | 25 | m | | | | |
| | | | | Concentration | C1 | 90+ % | Initial set up |
| Drift Speed (FS)* | V1 | 0.2 | kts | | C2 (repeat) | 90+ % | More brash ice |
| | V2 | 0.5 | kts | | C3 (One floe interaction) | | individual floe interaction if time permitted |
| | V3 | 1.2 | kts | | C4 | 70% | Initial set up |
| | | | | | C5 (repeat) | 70% | More brash ice |
| * Note that number of speeds will be reduced if speed effect is negligible. | | | | | | | |

## 5.2 Managed Ice Field Modeling.

In the Phase I model testing program, the ice field was prepared such that it composed of dominant size ice floes with approximately 34% of brash ice and small ice pieces. The sketch of the ice field preparation procedure is shown in Figure 9 (Left). Once all cuts were finished, ice floes were re-arranged as shown in Figure 9 (Right). Once 100 m floe tests were done, the ice floes were cut in half as 50 m and manual rearranged. After 50 m floe tests, the ice floes were cut again for 25 m floe tests. Once the model moved down the tank and came back, the ice field was re-arranged manually. Some of the tests in managed ice include ridge fragments in 25 m ice floes. A number of tests were carried out with the DP model in level ice. Level ice at 0.6 m thick with a flexural strength of approximately 700 kPa was prepared and tested. First year ridge was also built and ridge penetration tests were carried out, see **Figure 10**. The level ice tests were completed in three ice drift speeds and in both dynamically positioning and manual control modes.

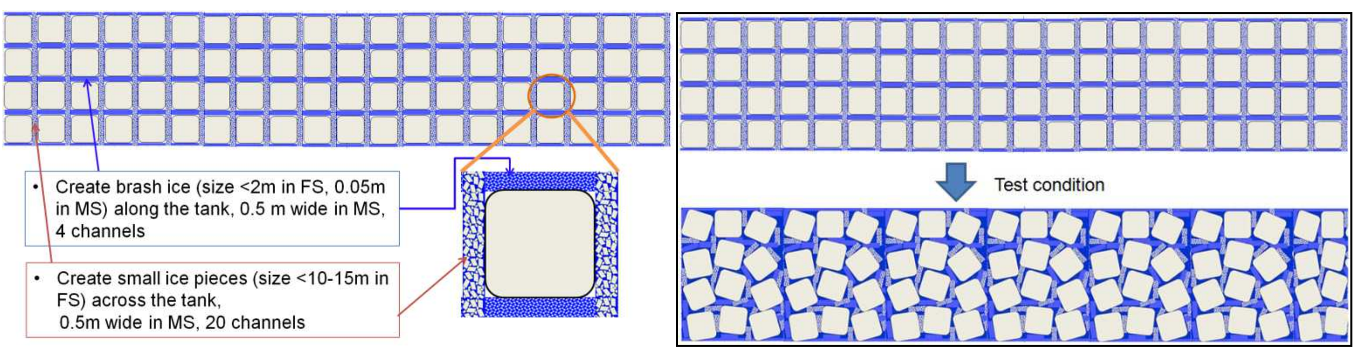


**Figure 9: Left – 100 m Floe Cut with Brash/Small Piece Inclusion; Right - Rearrangement of Ice Floes for Test**

With a given scale ratio, four 100 m floes were made across the tank, see **Figure 10**. It was the minimum number that could be modeled in the basin such that the vessel could move through at light concentration. For the heavy concentration, multiple 100 m floes were compacting and the vessel was not easily operable. In most 100 m floe ice tests, the initial position of the vessel was always between ice floes. During the tests, especially repeat runs, ice floes were rearranged and more realistic ice conditions were made. For 50 m and 25 m floe, the vessel didn't have many challenges regardless of the initial position, see **Figure 10**.

**Figure 10: Top-Left - DP Vessel Testing in 100 m Floe; Top-Right - DP Vessel Testing in 50 m Floe; Bottom-Left - DP Vessel Testing in 25 m Floe; Bottom-Right - DP Vessel Testing in Ice Ridge**

### 5.3 Model Test Results and Discussions.

Analysis on the test data in managed ice condition was conducted to evaluate the effect of various ice field parameters on the loads imposed on the hull due to its deviation from the target set point. Analysis reveals that each of the ice parameters under investigation has moderate to strong effect on surge load. Clear trends are not seen on the effect of the parameters on the sway load and yaw moments. The effect of the ice parameters on both surge and sway loads are seen for the oblique ice tests. The analyses of the physical ice-vessel interaction processes observed during the tests indicate that the DP stationkeeping of a vessel in managed ice involves intricate ice mechanics, with multiple physical processes that are non-linearly interlinked contributing to the ice-hull interactions.

It is consistently observed that large ice floes tend to be broken by flexural bending. Ice floes are pushed by the vessel relatively freely and when the floe is constrained due to interacted ice pieces, it is slightly tilted due to the bow shape. Consequently flexural bending events were observed. When the ice piece is broken, relatively large drop in surge force was observed. This is due to relatively easier surge correction of the DP controller, which means reduced thruster shaft speed or turning of azimuthing angle. This is different from what is observed in the level ice condition, where flexural failure is more dominant and frequent. When the ice floes were larger and the concentration was higher, the model was more easily trapped due to interlocking, jamming, compacting and possibly side walls effect, see **Figure 11**. When the multiple large ice floes are aligned and move against the vessel, the vessel couldn't keep position for most cases, especially for sway and yaw due to the larger ice mass and contact area (impacting portion or whole side of the vessel). Due to the ice mass, even in real life, if multiple 100 m ice floes approach a DP vessel for any length of time, similar results are expected.

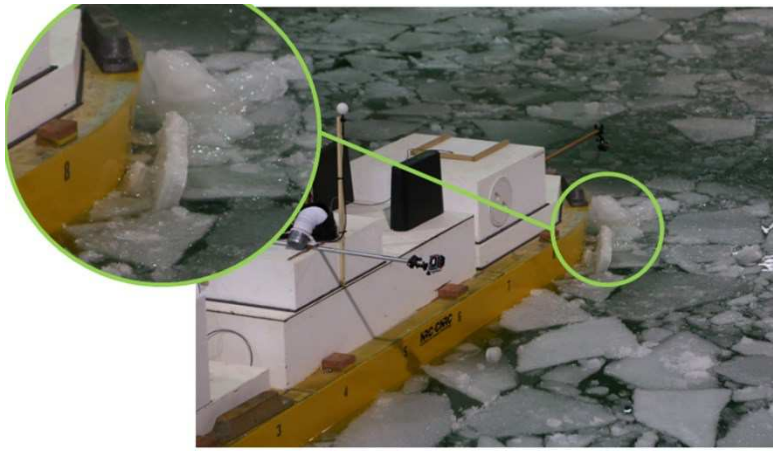

**Figure 11: Video Image Showing Ice Event of Floe Turning, Sliding and Jamming**

Overall, the open water DP controller appeared sufficient for the model to hold its station for the initial vessel heading close to zero. However, for some of the cases, especially with non-zero initial vessel heading and in heavy ice condition, the model couldn’t keep the position using DP mode and the operator had to control the model manually. In manual control mode, the maximum power was used to move the model to a desired area where the least ice force is expected. In some cases the model operated under partially manual control. This means the model hull could be operated in DP mode for most of the time during the test run but needed manual control to complete the entire run.

In the oblique ice tests, the vessel was set at a certain oblique angle either during the entire test run or for a certain duration before it is changed to another oblique angle. These tests were completed for various oblique angles, ice concentration, floe size and drift speeds. It was found that for the majority of cases, the DP system was unable to maintain its station if the oblique angle exceeds 15°, especially for 2.0 m ice, 9/10th concentration and 100 m floes. Further details of the observations on the videos and the data regarding the effects of various ice parameters on vessel loads are presented in Wang et al. (2016).

## 6.0 Concluding Remarks

This paper presents a general overview of the DP in Ice Environment project currently being carried out in Canada. This is a five-year collaborative initiative between CMS-MI, OCRE-NRC, KMS and some industry partners aiming to contribute significantly in the knowledge and understanding of safe DP operations in managed ice conditions.

Within the project scope, design and implementation of a Dynamic Positioning in Ice Validation Platform (DPIVP) concept has been realized. This will be used to develop a proof of concept for potential commercial DP applications and for an educational tool to train DP operators in realistically simulated managed ice environment on DP operations and critical dynamic ship-ice interaction scenarios. The critical prototypes include a slow speed vessel maneuvering model, ice force model and other environment force models. An extensive model test program with a fully DP controlled vessel has been carried out in various managed ice scenarios to generate a database for developing an ice force model, which is the core to the DP in Ice Control System prototype. Another model test program is currently being developed to augment the ice-hull interaction load database.

Brief discussions on methodologies and implementation on the ice and other environment force models, vessel model and overall framework of the DPIVP and its major components are presented in the article. The knowledge and understanding gathered on the ice-hull interactions during model test one is presented. The knowledge will be used in planning and designing the next model test.

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