



DYNAMIC POSITIONING CONFERENCE

October 9-10, 2012

ARCTIC/ICE OPERATIONS

Numerical Simulation of Dynamic Positioning in Ice

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1. Introduction

Numerical simulations have strong potential in a number of applications related to dynamic positioning (DP) in ice-covered waters, such as:

- modeling the effects of the physical ice environment on DP operations, i.e., assessing the feasibility of stationkeeping at a certain location;
- evaluating DP vessel concepts and studying the relationship between hull structures and ice loads;
- evaluating and comparing various DP control schemes—this may lead to, for example, an optimized thrust allocation strategy, reduced fuel consumption and overall greener operations;
- using high-fidelity models to validate simpler models for DP control development;
- using numerical models, integrated with training simulators, to develop operational procedures and educate personnel for Arctic offshore operations;
- analyzing multi-vessel operations, e.g., ice management concepts and strategies, or hydrocarbon offloading to shuttle tankers in icy waters;
- studying safety and reliability, i.e., modeling system failures numerically (e.g., global navigation satellite system failures or thruster failures). Such studies can be useful for risk assessment and DP capability analyses;
- interconnecting numerical simulators, coupled with aerial and underwater surveillance technologies, with onboard support systems for stationkeeping of Arctic offshore floaters;
- studying scale effects and sensitivity with respect to the physical modeling of the ice material, i.e., conducting scientific research.

Currently, numerical simulation of DP in ice is a novel research area. Very few off-the-shelf solutions exist on the market, and it is impossible to name a conventional approach or a standard model. One of the main reasons is that the physical ice environment is difficult to model and simulate. Section 2 of the paper elaborates on this topic and addresses the main challenges associated with numerical ice modeling in relation to DP.

Despite the challenges, several methodologies have been developed for simulating DP in ice. Section 3 of the paper reviews the state-of-the-art approaches and introduces their classification into three groups: empirical and statistical models, experimental data series methods, and physically based modeling. Each methodology is described and analyzed in terms of its strengths and weaknesses. In addition, recommendations are made for the use of a certain methodology at a particular design stage of a DP system.

This paper also presents a physically based dynamic ice load simulation model coupled with a DP controller. The theoretical and numerical details of the model, along with a series of numerical tests validated against experimental data, are presented in Section 4. Concluding remarks are made in Section 5.

2. Physical Ice Environment

Numerical simulation of DP in ice requires a mathematical model describing the behavior of a DP vessel in icy waters. The main challenge associated with the development of such a model is that the ice actions on a vessel depend on a vast multitude of physical parameters and properties related to the ice field, the vessel and the surrounding environment. Some important aspects of the ice-vessel interaction are summarized in Fig. 1. The definitions and discussion of the various elements from the figure can be found in Løset et al. (2006) and ISO (2010).

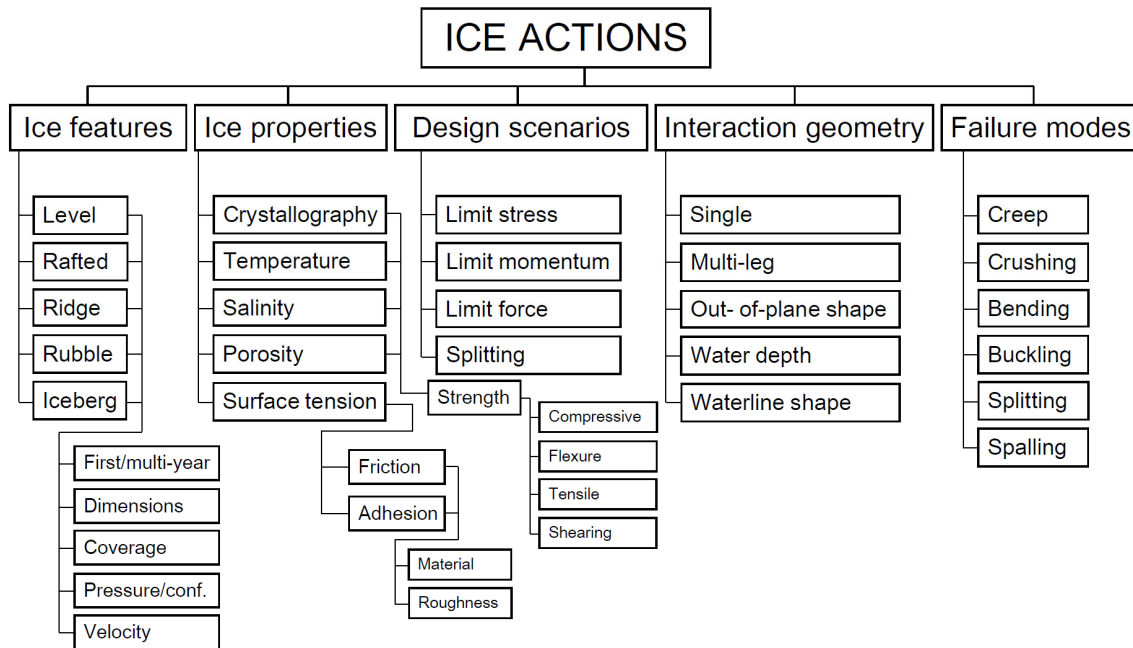


Fig. 1. Important aspects of ice actions on offshore structures. Courtesy Prof. S. Løset.

The complexity of the physical ice environment starts with the rich variety of ice features found in nature (Fig. 2). The likelihood of encountering a specific ice feature depends on the geographical location, time of the year, metocean conditions and the presence of ice management.



Fig. 2. Various ice conditions: managed ice, ice ridge and level ice (from left to right). Barents Sea, April 2012. Photos by Ivan Metrikin.

Ice management is especially important for DP, because it defines the performance and uptime of the whole operation (Gürtner et al., 2012; Hals and Efraimsson, 2011; Wilkman et al., 2009). Ice management is defined as the sum of all activities where the objective is to reduce or avoid actions from any kind of ice features (Eik, 2010). It includes physical ice breaking, which is usually performed by one or more icebreakers operating upstream of the vessel on DP. The result

of the ice breaking is the production of “managed ice,” which consists of ice floes of various shapes and sizes, brash ice (i.e., small chunks of ice less than 1 m across), and patches of open water. The managed ice environment can therefore be considered as the most likely setting for a DP operation in an ice-covered region.

Numerical modeling of managed ice is challenging due to the apparent discrete-continuum nature of this material. On the one hand, managed ice is composed of distinct ice floes that can be described as separate independent bodies, i.e., a discrete system. On the other hand, during ice drift and ice-vessel interactions the ice floes can crush, split, buckle and fracture, producing new floes and brash ice. Such material behavior can be difficult to describe from a purely discrete perspective as it may require continuum modeling, possibly involving strength of materials, plasticity theory or fracture mechanics approaches (including detailed consideration of the material properties and microstructure). Moreover, the material properties of ice are highly dependent on the environmental conditions and interaction parameters listed in Fig. 1, leading to a spectrum of material behaviors ranging from “hard ice cream” for mild first-year ice to “concrete” for multi-year ice (Rohlén, 2009). A comprehensive review of the many ice properties, relevant for engineering calculations of ice loads, can be found in e.g. Timco and Weeks (2010).

Despite the aforementioned challenges, several techniques have been developed for modeling ice loads in DP simulations. These techniques are discussed in the following section.

3. Ice Loads Modeling for Numerical DP Simulations

Various approaches for modeling ice loads in DP simulations can be classified into three groups: empirical and statistical models, experimental data series methods, and physically based modeling. These groups are discussed in the following sub-sections.

3.1. Empirical and Statistical Models

Empirical models are based on observations and analysis of full-scale and model-scale trials. These models are expressed in formulas that calculate the ice loads based on a set of ice and vessel parameters and properties, including the following:

<u>Ice</u>	<u>Vessel</u>
Shapes and sizes of the ice features	Shape and size of the hull
Ice and water densities	Mass and inertia tensor
Ice material strength	Friction properties of the hull
Ice concentration	Hydrodynamics
Ice floe size distribution	Froude number
Ice confinement	Propulsion characteristics
Friction	
Presence of snow cover	
Hydrodynamics of the ice pieces	

The first empirical formula for ship resistance in broken ice conditions was apparently proposed by Nogid (1954) based on model testing data. Many improved and modified approaches have been developed subsequently. A comprehensive overview of the historical progress in this area can be found in Ionov and Gramuzov (2001), for example. Modern empirical formulations combine the knowledge gained from numerous full-scale trials and ice basin experiments with theoretical models based on the laws of physics. Due to this dualism, such methodologies are called “semi-empirical.” The state-of-the-art semi-empirical ice load formulations can be found in Liu (2009), Aksnes (2011) and Su (2011), for example. A pioneering implementation of a numerical DP model coupled with a semi-empirical ice load model was presented by Nguyen et al. (2009) for level ice conditions.

If an empirical formulation produces only one value of the ice load for a certain combination of ice-vessel parameters, it is possible to assign a certain statistical distribution to the empirical ice load (e.g., a Gaussian, Poisson, or Weibull distribution) in order to introduce dynamics into a time-domain DP simulation. This technique allows picking a new randomized value of the ice load at every time instant, i.e. performing a Monte Carlo simulation. However, to be realistic, the statistical and spectral distributions of the generated ice load signal should be based on either a physical model or experimental data, e.g. as reported by Frederking (2010).

In conclusion to this section it is possible to say that the main advantage of empirical and statistical models is their numerical efficiency, i.e. the ice load model adds almost no computational overhead to the DP simulator. The main weakness is the oversimplification of the ice-vessel interaction process, which may lead to unrealistic results. With respect to DP simulations, such models can be used for the initial testing of DP controllers and probing their reaction to ice load signals.

3.2. Experimental Data Series Methods

When ice model tests or full-scale trials are performed, the ice loads can be recorded in the form of data series. These data series can then be used as input to numerical DP simulators (Jenssen et al., 2009). Within the DYPIC (Dynamic Positioning in Ice) project (Jenssen et al., 2012), DP model tests were performed in various ice conditions and the recorded thrust forces were used to derive the ice loads acting on the vessel by subtracting the inertia effects. These ice loads were then fed into a DP simulator, whose structure is shown in Fig. 3.

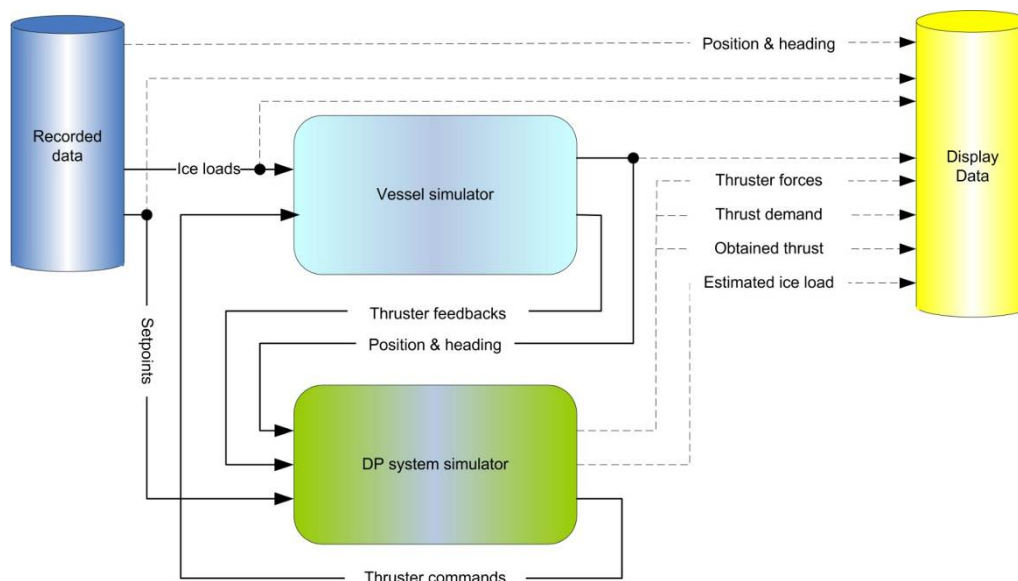


Fig. 3. Structure of a DP simulator that uses recorded experimental data.

The DP vessel was simulated in 3 DOF (surge, sway and yaw), taking into account the thrust, ice loads, fluid drag and inertia effects. The ice loads were fetched from the recorded experimental data, while the thruster commands (RPM and azimuth angles) were fetched from the DP system simulator (Fig. 3). Since the velocity of the vessel was close to zero, the Coriolis and centrifugal effects were not considered. Moreover, the simulator did not contain any dynamic inertia or damping effects from the ice field.

The DP system mimicked either a standard open-water DP control system or its ice-adapted version, and the Experimental Data Series simulation methodology has been used to identify the weaknesses of the conventional open-water DP control when exposed to ice loads. Experimental data from the DYPIC project has been used for this study and the results are shown in Figs. 4-5.

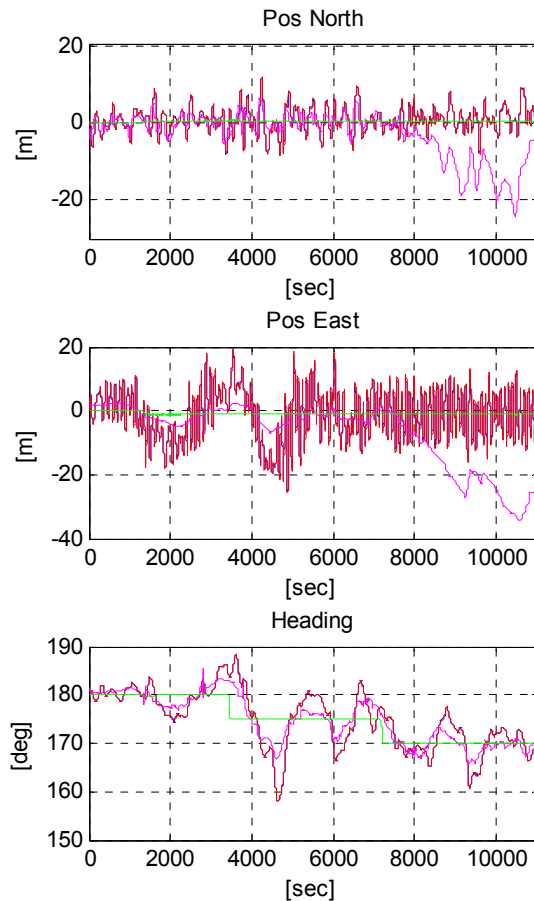


Fig. 4. Vessel motions with open-water DP.

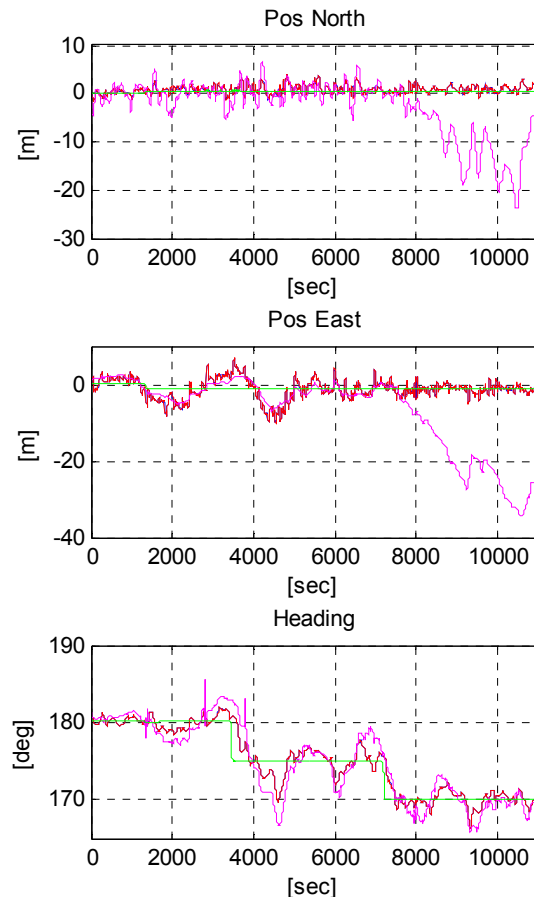


Fig. 5. Vessel motions with ice-adapted DP.

Legend: magenta – recorded values, red – simulated values, green – common setpoint values. All values are shown in full-scale.

The stationkeeping signal of the open-water DP is very oscillatory (Fig. 4), especially in the sway axis. The motions of the vessel with ice-adapted DP (Fig. 5) are clearly more stable due to improved ice load tracking. The general conclusion that can be drawn from this analysis is that the ice load tracking capability of the conventional DP control system is too weak for obtaining good stationkeeping performance in ice. However, with a modified external force tracker, improved performance is achievable.

Although the simulated heading response matches quite well with the experimental recordings in both Figs. 4 and 5, the position loss at a time of approximately 7500 seconds is not replicated in the simulation. Nevertheless, Fig. 5 shows a very good agreement between the motions, recorded during the model test, and the simulation results before the position loss. Still, the representativeness of such simulations can be questioned because the imposed ice loads do not depend on the motions of the simulated vessel, and the simulator does not consider any dynamic inertial or damping effects from the ice. However, if the simulated and the recorded motions of the vessel are quite similar, the loads may be said to be representative.

The experimental data series approach described in this section is useful for tuning DP systems to a particular set of conditions, i.e. a certain ice drift, ice concentration and a specific heading of the vessel. It is also reliable for estimating the ice load signal properties for that specific set of conditions and comparing open-water DP to ice-adapted DP. The limitation of this approach is that it can be difficult to extend it beyond the boundaries of a particular test (e.g. if the vessel uses another heading, the ice load signal will change). Moreover, the response of the vessel to the ice load and the coupled ice-vessel dynamics are not taken into account.

3.3. Physically Based Modeling

Physically based models are built on the fundamental laws of physics, and their main purpose is to simulate the system dynamics realistically. According to the classification of DP control system modeling (Sørensen, 2005), such models are process plant models, i.e. they contain comprehensive descriptions of the actual physical processes. Physically based models naturally produce time series of the ice loads, and they can be coupled with DP control systems in a closed loop. Therefore, such models can be used in numerical performance assessments, robustness analyses and testing of DP control systems. Modern physically based models of vessels in managed ice conditions are described in, for example, Kubat et al. (2010); Lau et al. (2011); Lobanov (2011); Wang and Derradji-Aouat (2010); Zhan and Molyneux (2012).

A common drawback of such models is their computational complexity which usually hinders real-time applications (Millan and Wang, 2011). However, recently, Lubbad and Løset (2011) presented a model that meets the real-time criterion by using novel computational software (a physics engine) and analytical closed-form solutions for the ice fracture modeling. The next section of this paper describes a physically based model for the numerical simulation of DP in managed ice that also uses a physics engine and therefore can perform in real-time under certain conditions.

4. NTNU Numerical Model

This section consists of two subsections. The first sub-section describes the high-fidelity numerical model developed by the Norwegian University of Science and Technology (NTNU). The second sub-section presents a series of numerical simulations, made with this model, and their comparison with experimental data obtained from the model testing of the DYPIC project.

4.1. Model Description

The numerical model is modular and can be represented by a block diagram shown in Fig. 6. The DP vessel is treated as a rigid body with 6 DOF. Its equations of motion are written as:

$$M(\bar{q})\ddot{\bar{u}} = \bar{g}(\bar{q}, \bar{u}, t) \quad (1)$$

where $M(\bar{q})$ is the generalized mass matrix defined as follows:

$$M = \begin{bmatrix} mI_{3 \times 3} & 0 \\ 0 & I(Q) \end{bmatrix} \quad (2)$$

m is the total mass of the vessel, $I(Q)$ is its 3×3 inertia matrix, Q is the orientation parameter (which can be expressed as a rotation matrix, a unit quaternion or a set of Euler angles) and $I_{3 \times 3}$ is the 3×3 identity matrix. Notably, this mathematical notation is fully compatible with that used by Fossen (2011), which is well-known in the field of DP.

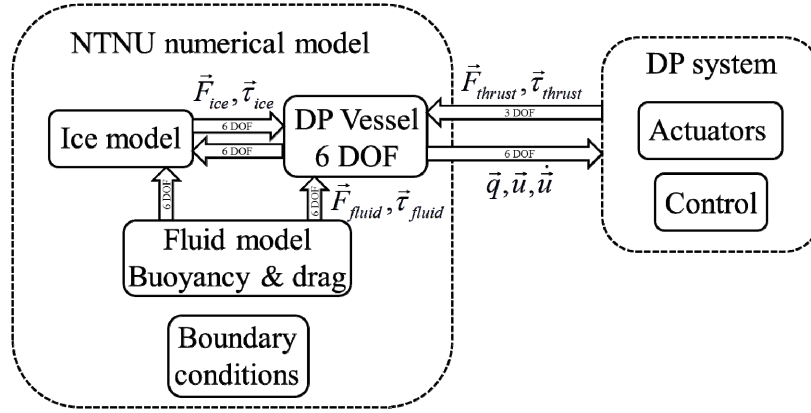


Fig. 6. Structure of the NTNU numerical model.

$$\bar{q} = (\bar{x}, Q) \quad (3)$$

is the tuple containing the position of the center of mass of the vessel $\bar{x} \in R^3$ and its orientation parameter Q .

$$\bar{u} = [\bar{v}^T \quad \bar{\omega}^T]^T \in \mathbb{R}^6 \quad (4)$$

is the generalized velocity of the vessel containing the translational \bar{v} and the rotational $\bar{\omega}$ velocities.

$$\bar{g}(\bar{q}, \bar{u}, t) = \begin{bmatrix} \bar{F} \\ \bar{\tau} - \bar{\omega} \times I(Q) \bar{\omega} \end{bmatrix} \quad (5)$$

is the vector of loads acting on the vessel, including the net applied force \bar{F} , net applied torque $\bar{\tau}$ and the gyroscopic torque $\bar{\omega} \times I(Q) \bar{\omega}$. t is time and upper dot in (1) denotes the time derivative.

$$\begin{bmatrix} \bar{F} \\ \bar{\tau} \end{bmatrix} = \begin{bmatrix} \bar{F}_{fluid} + \bar{F}_{ice} + \bar{F}_{thrust} \\ \bar{\tau}_{fluid} + \bar{\tau}_{ice} + \bar{\tau}_{thrust} \end{bmatrix} \quad (6)$$

\bar{F}_{ice} and $\bar{\tau}_{ice}$ are the ice force and torque, respectively; \bar{F}_{fluid} and $\bar{\tau}_{fluid}$ are the fluid force and torque, respectively; \bar{F}_{thrust} and $\bar{\tau}_{thrust}$ are the thrust force and torque, respectively.

The simulated DP vessel is a conceptual Arctic drillship (Fig. 7) equipped with six azimuth thrusters that in full-scale would generate approximately 5.4 MN thrust in total. The thrusters are modeled by the DP module (actuators in Fig. 6) and the NTNU numerical model receives the

resultant force and torque, which are then applied to the center of mass of the drillship. The shape of the DP vessel in simulation is based on its triangulated 3D geometry, which consists of 2956 vertices and 5908 faces that constitute the detailed structure of the hull. The main particulars of the drillship are specified in Table 1.

Table 1. Main particulars of the conceptual Arctic drillship (full-scale values).


Length between perpendiculars	184.00 m	Thruster arrangement 
Breadth, moulded	41.33 m	
Design draught	12.00 m	
Draught at aft perpendicular	12.00 m	
Draught at fwd. perpendicular	12.00 m	
Displacement volume	68457 m ³	
Centre of gravity from aft perp.	95.34 m	
Block coefficient	0.75	



Fig. 7. Artistic impression of the conceptual Arctic drillship. Courtesy Statoil ASA.

At every time step the numerical model receives \vec{F}_{thrust} and $\vec{\tau}_{thrust}$ in 3 DOF (surge, sway and yaw) from the DP system, calculates the ice and fluid loads in 6 DOF, and integrates the Newton-Euler equations (1) to yield the updated positions, velocities and accelerations of the DP vessel in 6 DOF. The new positions, velocities and accelerations are then transferred back to the DP control system, and a new cycle begins. In this manner, the DP system and the numerical model work in a closed loop, and the simulation advances at a prescribed time step.

Model tests of the DYPIC project (Jenssen et al., 2012) have been used to validate the numerical model. The ice basin experiments were performed in managed ice which was distributed over the surface of the HSVA basin. The large ice tank of HSVA is 72-m long and 10-m wide, but only a part of the total area was covered with ice in order to create a certain ice concentration (Fig. 8). The ice field consisted of floes with various shapes and sizes as well as some brash ice, so that the model ice cover closely imitated realistic managed ice conditions. These ice conditions were then reproduced numerically by generating multiple discrete ice pieces and distributing them randomly inside a virtual ice basin. Although the resulting numerical ice field appeared similar to the experimental ice field, the two were still different, because the exact positions of the ice floes in the model basin were not used for the initialization of the numerical model.

The equations of motions of each ice floe in the NTNU numerical simulator are the same as for the vessel (1), i.e. every ice piece is simulated in 6 DOF. However, the external forces in (6) obviously exclude the thrust loads. Furthermore, two assumptions are made in the ice modeling. First, although the simulation methodology allows simulating the ice fracture (Lubbad and Løset, 2011), all ice pieces are treated as unbreakable rigid bodies, and second, only the ice floes are simulated, i.e. the brash ice is not considered. Nevertheless, the contacts among all the bodies in the simulation (i.e., the ice floes, the vessel and the walls of the ice basin) are modeled and resolved. The ice pieces and the vessel are simulated as dynamic bodies that can move, while the walls of the ice basin are modeled as immovable static objects. Consequently, the basin walls serve as boundary conditions for the simulations. The implications of these assumptions are discussed in the following section of the paper.

The contact forces among the various simulated objects are decomposed into the normal and tangential components. In the normal direction, the stiffness, damping and restitution forces are modeled, while in the tangential direction, the static and dynamic friction forces are modeled. The contact rheology of the numerical model is summarized in

Table 2.

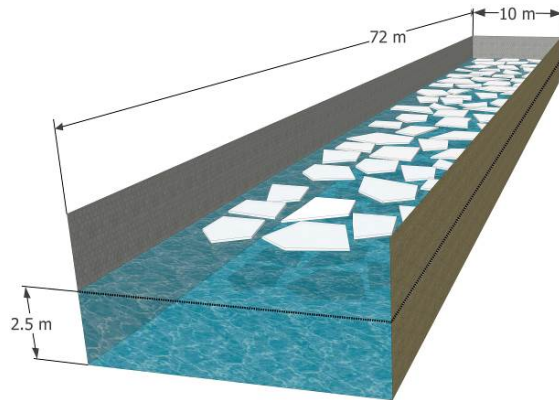


Fig. 8. Sketch of the HSVA large ice model basin with managed ice inside.

Table 2. Contact rheology.

Vessel-ice friction (dyn/stat)	0.0976/0.11
Ice-ice friction (dyn/stat)	0.05/0.1
Ice-basin wall friction (dyn/stat)	0.05/0.15
Coefficient of restitution	0.5
Contact stiffness	10^{10} kg/s^2
Contact damping	$8.3 \cdot 10^8$

The fluid is simulated as a static water plane. The hydrostatic loads on the DP vessel and the ice floes are calculated according to the following formulae (buoyancy force and torque):

$$\begin{aligned}\vec{F}_b &= -\rho V \vec{g} \\ \vec{T}_b &= \vec{r}_b \times \vec{F}_b\end{aligned}\quad (7)$$

where $\rho = 1000 \text{ kg/m}^3$ is the water density, V is the submerged volume of a body, $g = 9.807 \text{ m/s}^2$ is the acceleration of gravity, and \vec{r}_b is the vector directed from the center of mass of a body to its center of buoyancy. The ice density in the simulation is $\rho_{ice} = 880 \text{ kg/m}^3$.

The following resistance force is applied to the bodies moving through the simulated fluid (the DP vessel and the ice floes):

$$\vec{F}_R = -\frac{1}{2} \rho A (\vec{v} \cdot \vec{n})^2 \vec{n} \quad (8)$$

where A is a submerged surface area element on a body with unit outer normal \vec{n} and \vec{v} is the velocity of that element relative to the fluid. The total resistance force on a body is equal to the

sum of the resistance forces on its submerged surface area elements facing the flow. As the bodies move through the fluid, the resistance and hydrostatic loads are computed and applied at every time step. The hydrodynamic effects, such as the added mass, damping and ventilation, are not modeled. Finally, the current, wind and wave loads are not considered, because the goal of the numerical model was to reproduce ice basin trials in which none of those environmental phenomena were present.

As mentioned in Section 3.3, a physics engine is used to implement the numerical simulation. A preliminary technical comparison of various physics engines for simulating a vessel in broken ice was performed by Metrikin et al. (2012). However, a clear winner was not identified at that time. Later it has been discovered that the Vortex physics engine (CMLabs, 2012) appears to be the only one that provides the required fluid simulation capabilities out of the box. Therefore, Vortex v. 5.1.0 has been selected for this study. Additionally, Vortex provides a convenient visualization interface which was used to monitor the simulation and extract screenshots.

4.2. DP Simulations with the NTNU Numerical Model

Model tests of the DYPIC project (Jenssen et al., 2012) have been reproduced with the numerical model described in Section 4.1. The DP control system, connected to the numerical model, was the same as in the model testing, and the tuning of the DP parameters was strictly the same as in the ice basin during the trials. Therefore, the results of the numerical modeling can be compared directly to the experimental data. The DP system, considered in this study, was built by DCNS Research/Sirehna for HSVA (dal Santo and Jochmann, 2012).

The simulations were performed in 0.75-m-thick managed ice with a linear ice drift velocity of 0.5 knots full-scale. Both in the ice basin and in the numerical model the ice drift was simulated by moving the vessel forward at the prescribed velocity. The ice drift angle was simulated by changing the heading set point in the DP while the ship was moving through the ice (both in the simulation and in the physical experiments). The tested ice drift angles were 0° , 5° and 10° . Detailed description of the model testing setup can be found in Haase et al. (2012).

Figs. 9-10 illustrate the DP performance in the numerical simulation. Fig. 9 shows the trace of the ship in the northeast plane, while Fig. 10 shows the time history of the vessel's heading. Fig. 11 illustrates the time series of the vessel's motions for each ice drift angle. All values are presented in full-scale units.

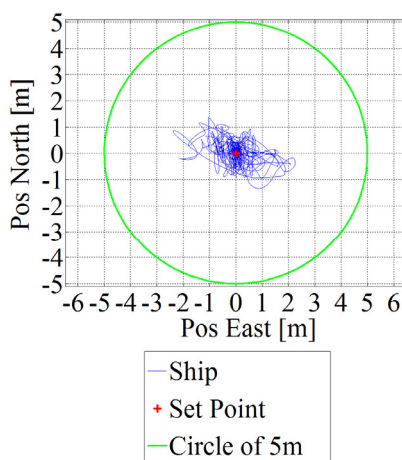


Fig. 9. Trace of the DP vessel in the numerical simulation.

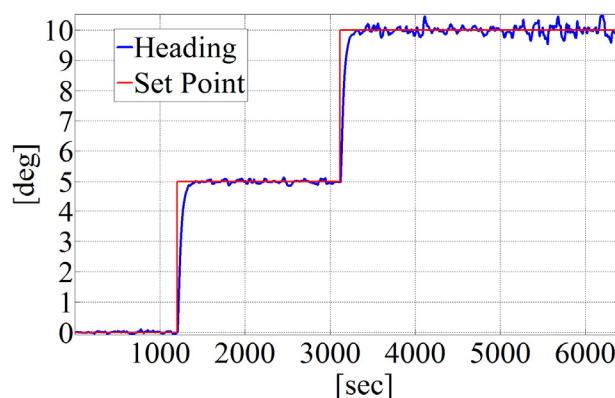


Fig. 10. Heading of the DP vessel in the numerical simulation.

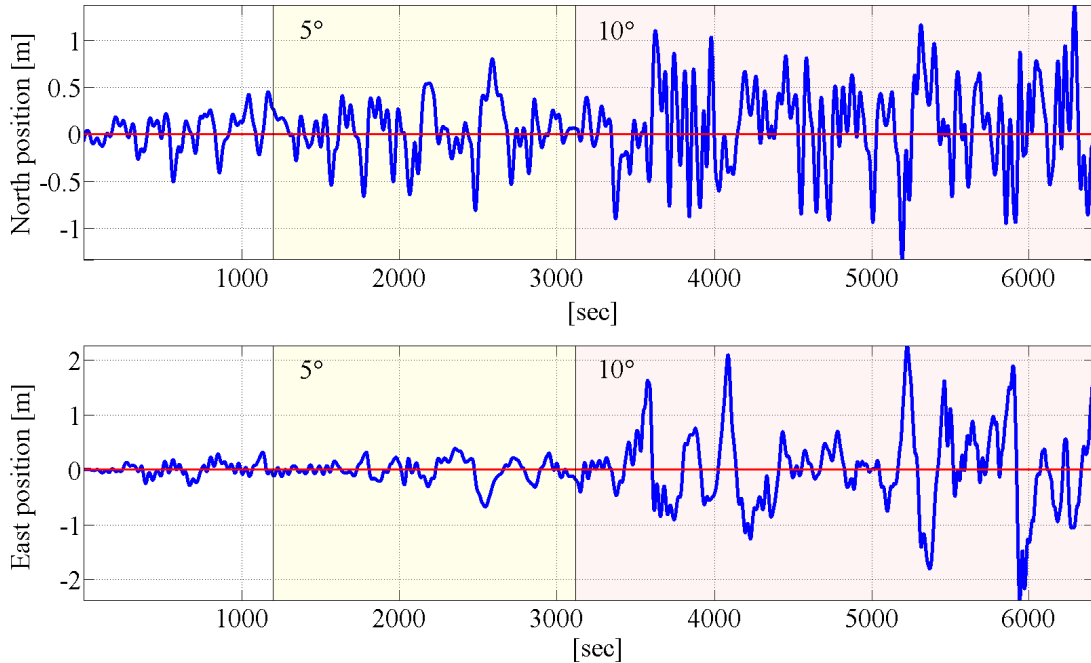


Fig. 11. Motions of the DP vessel in the numerical simulation.

The DP system maintained the vessel in a circle of approximately 2.5 m during the whole simulation, which is similar to the performance observed in the model basin. Furthermore, the displacements in surge were generally smaller than the displacements in sway, what can be explained by the lateral confinement in the ice field produced by the ice basin walls and the hull of the vessel. Furthermore, the DP performance decreased (and the oscillations in all controlled DOF increased) when the ice drift angle increased. All these observations indicate that the simulator behaved in a reasonable and expected manner.

Figs. 12-14 show graphical comparisons of the numerical simulation results with the experimental data for 0°, 5° and 10° ice drift angles, respectively. The time histories of the vessel’s displacements and heading are presented for each ice drift angle in the figures, along with the data series of the ice loads in surge, sway and yaw DOF (all values in full-scale).

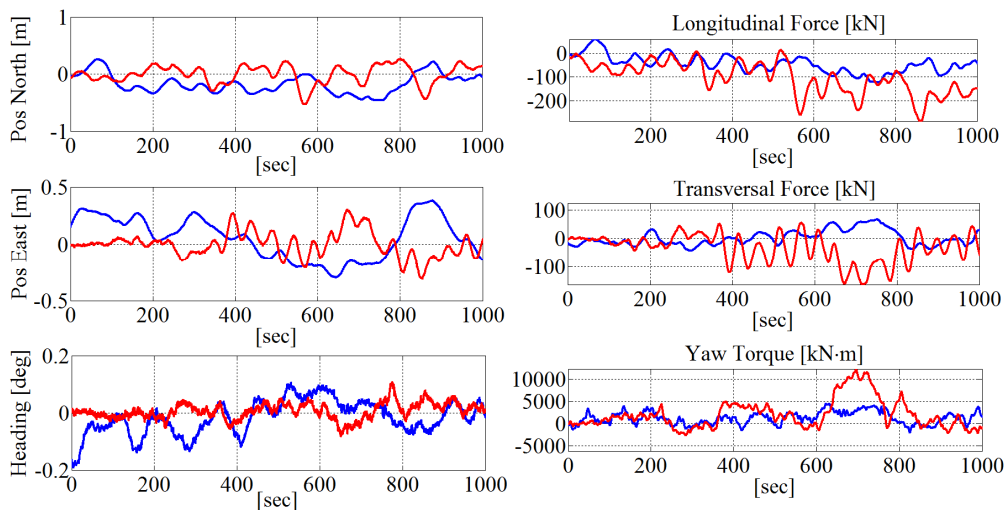


Fig. 12. Comparison of the numerical simulation results with the ice tank trial at 0° ice drift angle. Legend: red = numerical simulation, blue = ice tank experiment.

Table 3. Signal analysis of the data series from Fig. 12, 0° ice drift angle.

	Standard deviation		Median value	
	Ice Basin	Simulation	Ice Basin	Simulation
Pos North [m]	0.17	0.18	-0.17	0.04
Pos East [m]	0.18	0.12	-0.04	~0.0
Heading [°]	0.06	0.03	-0.01	-0.0
Longitudinal Force [kN]	36.8	66.4	-48.4	-92.5
Transversal Force [kN]	28.1	53.5	7.55	16.8
Yaw Torque [kN·m]	3742.3	3319.4	1072.2	910.1

Tables 3–5 contain the signal properties of the time series from Figs. 12-14. The ice loads were estimated by the DP system using the Kalman filtering approach. As mentioned in Section 3.2, the estimation of external loads in ice requires improvements over the traditional open-water algorithms. Such improvements have been successfully implemented within the framework of the DYPIC project and have been tested in the ice model basin. The estimated ice loads in the numerical simulation were obtained using the same algorithm as that used in the ice tank.

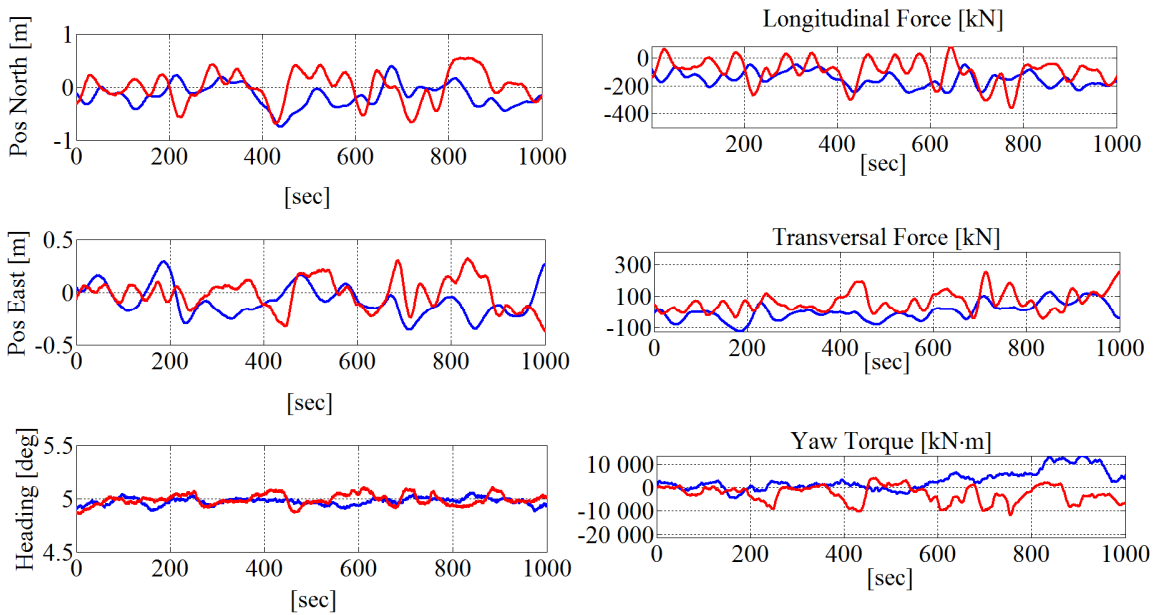


Fig. 13. Comparison of the numerical simulation results with the ice tank trial at 5° ice drift angle. Legend: red = numerical simulation, blue = ice tank experiment

Table 4. Signal analysis of the data series from Fig. 13, 5° ice drift angle.

	Standard deviation		Median value	
	Ice Basin	Simulation	Ice Basin	Simulation
Pos North [m]	0.24	0.32	-0.16	0.03
Pos East [m]	0.17	0.21	0.12	~0
Heading [°]	0.03	0.06	-0.02	-0.001
Longitudinal Force [kN]	60.56	98.1	-165.9	-88.3
Transversal Force [kN]	65.9	93.5	13.7	58.2
Yaw Torque [kN·m]	3742.3	4314.1	2818.3	-2583.9

For 0° ice drift angle the results indicate that the simulator reproduces the experiment reasonably well and that the signals are comparable, especially for the surge and the yaw motions. However, the numerical simulation produces more oscillations than the basin test. The authors believe that

this is mainly because no brash ice was modeled and because the ice floes were simulated as unbreakable bodies.

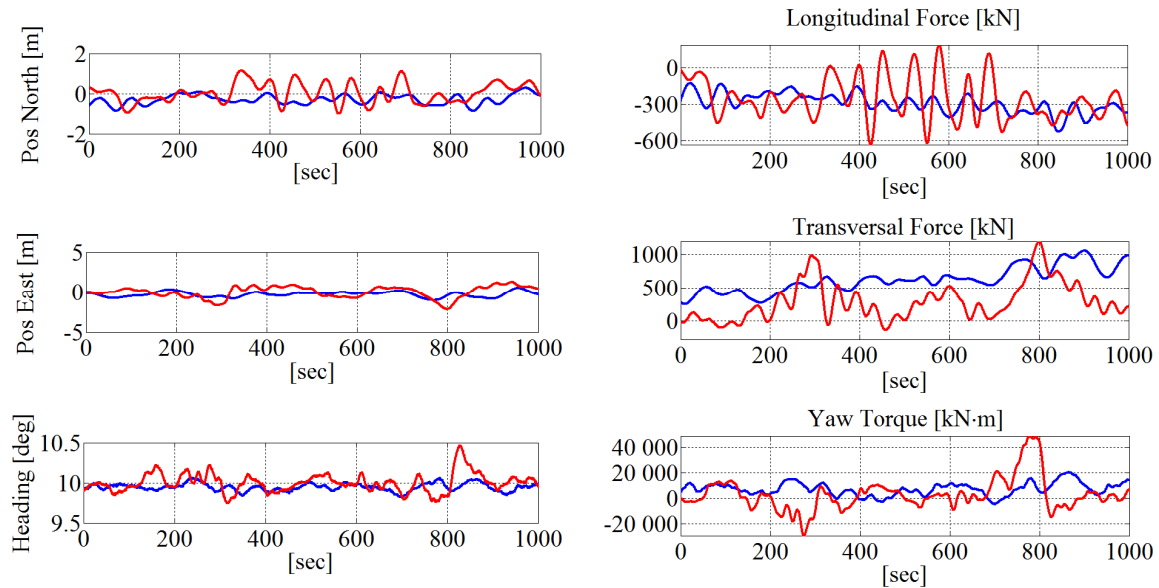


Fig. 14. Comparison of the numerical simulation results with the ice tank trial at 10° ice drift angle. Legend: red = numerical simulation, blue = ice tank experiment.

Table 5. Signal analysis of the data series from Fig. 14, 10° ice drift angle.

	Standard deviation		Median value	
	Ice Basin	Simulation	Ice Basin	Simulation
Pos North [m]	0.27	0.47	-0.22	0.08
Pos East [m]	0.48	0.68	0.16	-0.08
Heading [$^\circ$]	0.047	0.110	-0.053	-0.003
Longitudinal Force [kN]	73.2	165.6	-294.1	-269.7
Transversal Force [kN]	197.1	278.0	600.2	159.9
Yaw Torque [kN·m]	5794.7	11802.6	8726.5	2859.6

For 5° ice drift angle the surge and the yaw are quite well simulated. However, the median values of the yaw torque from the basin test and from the simulation are opposite in sign. The most likely reason for this discrepancy is the presence of unbreakable floes that accumulate and produce pressure on one side of the DP vessel. This aspect should be improved in future versions of the simulator, i.e. ice floe breaking and splitting should be introduced.

Finally, for 10° ice drift angle the general trend in the surge force level is relatively representative, but the oscillations of the signal are too high. Moreover, the sway forces are significantly different.

Both in the ice tank and in the numerical simulation, the 0° , 5° , and 10° trials were performed within one single basin test. This test consisted of 3 segments with equal testing length of 510 m full-scale. The first segment was performed with a 0° ice drift angle, the middle segment with a 5° and the final segment with a 10° ice drift angle. In the physical experiment it was observed that the ice field was strongly compacted against the end wall of the ice tank at the end of the test, i.e. at 10° ice drift angle. A significant amount of ice breaking events were then observed in the compacted part of the ice field. Therefore, since the ice breaking was not modeled numerically, the differences between the numerical simulation and the experimental results are especially high for the 10° case (in terms of absolute values). Another possible reason for the observed

discrepancies is that the wake of the azimuth thrusters has not been modeled numerically. In the physical experiments extensive ice clearing with the propeller wash was observed, and this could have had a considerable effect on the measured ice loads. Finally, in the physical tests it was observed that after breaking a significant amount of ice was going under the hull of the drillship. However, in simulation with unbreakable ice floes this phenomenon was not reproduced.

Finally, several screenshots comparing the numerical simulation with the ice basin trials are shown in Fig. 15. It is evident that the numerical model captures the ice rafting phenomenon quite well, because the ice floes are sometimes pushed up on top of each other. This phenomenon has also been observed in the physical experiments. Such phenomenological agreement is a consequence of the 3D numerical modeling and would not be possible in 2D simulations.

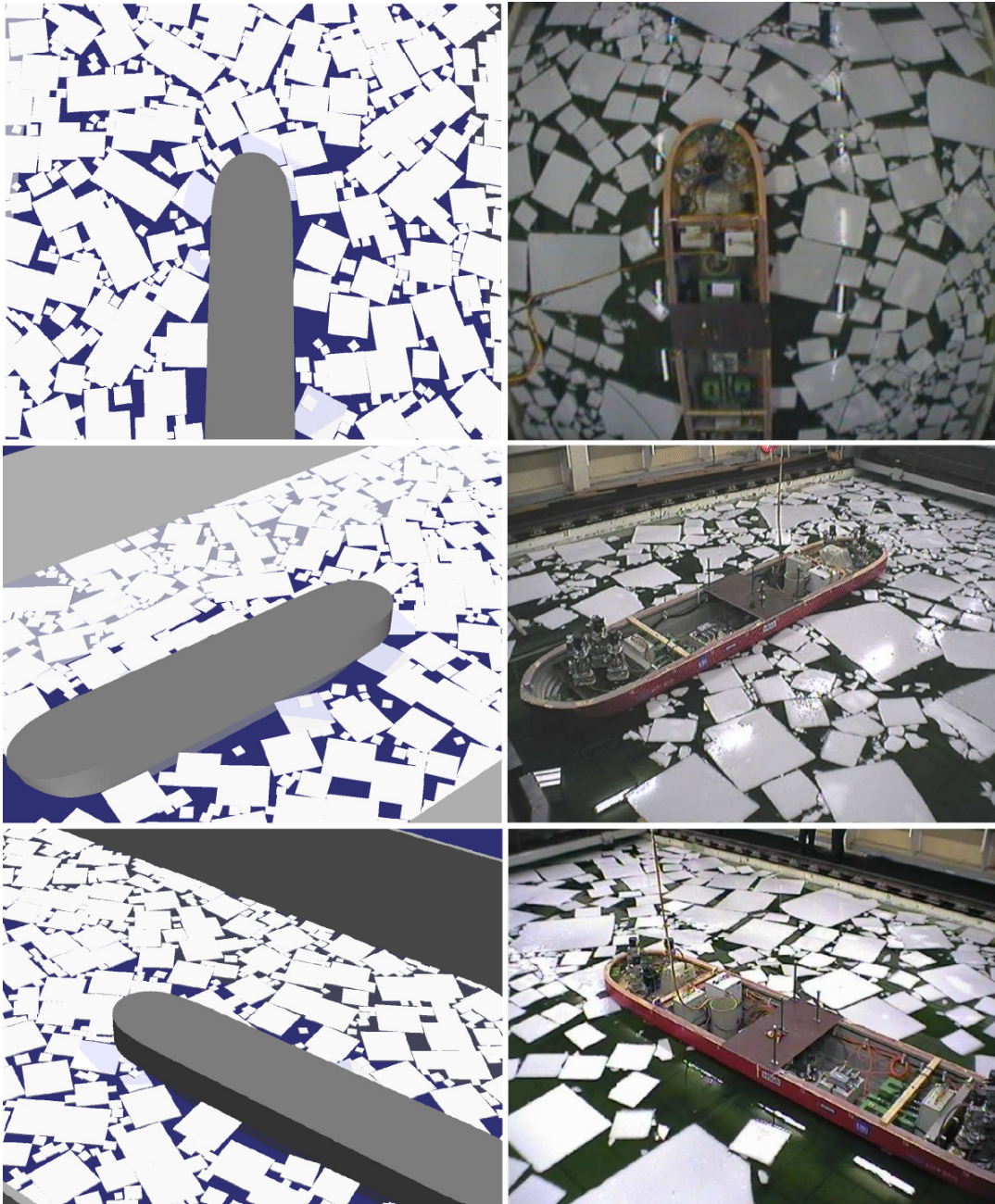


Fig. 15. Visual comparison of the numerical simulation (left) with the ice basin trials (right).

5. Conclusions

Numerical simulation of dynamic positioning (DP) in ice is a novel research topic that has potential in many industrial and scientific applications. This paper reviewed and summarized the main challenges associated with the numerical ice modeling and proposed a classification of approaches for modeling the ice loads in DP simulations. The approaches have been classified into the following three groups: empirical and statistical models, experimental data series methods, and physically based modeling.

Empirical and statistical models are based on observations and analysis of experimental data. The main advantage of this approach is its numerical efficiency, that is, the ice load model adds almost no computational overhead to the DP simulator. The main weakness is the oversimplification of the ice-vessel interaction process, which may lead to unrealistic results. With respect to DP simulations, such models can be used for the initial testing of DP controllers and probing their reaction to ice load signals.

Experimental data series methods use data, recorded in model tests or full-scale trials, as input to numerical DP simulators. This approach is useful for tuning DP systems to a particular set of conditions, i.e. a certain ice drift angle, velocity and concentration, and a specific heading of the vessel against the ice drift. The approach is also reliable for assessing the signal properties of the ice loading in that specific set of conditions. The limitation of this approach is that it can be difficult to extend it beyond the boundaries of a particular case. Moreover, the response of the vessel to the ice load and the coupled ice-vessel dynamics are not taken into account. Therefore, the results will not be valid unless the simulated and the recorded responses correspond well.

Physically based models are built on the fundamental laws of physics. These models contain comprehensive descriptions of the actual physical processes and can therefore closely reproduce the reality. The main drawback of such models is their computational complexity, which can prohibit real-time applications.

Finally, this paper presented a physically based model of DP in ice. The model was used to perform a multibody simulation of a model test with a conceptual drillship on DP in managed ice using the commercial physics engine Vortex. The simulation modeled the ice basin, the DP vessel, the ice, the surrounding fluid and their mutual interactions. Validation of the model against model testing data demonstrated that in certain conditions the simulator reproduced the experiment reasonably well. However, for high oblique angles the discrepancies were high. The reasons for the discrepancies have been proposed and discussed in the paper.

Acknowledgements

The authors would like to thank the Research Council of Norway (RCN) for the financial support of the MARTEC ERA-NET project “DYPIIC - Dynamic positioning in ice covered waters” (RCN Project No. 196897) and the Arctic DP project (RCN Project No. 199567/I40). The authors would also like to thank the Ministry of Ecology, Sustainable Development, Transport and Housing (France) and the Federal Ministry of Economics and Technology (Germany) for their financial support of the MARTEC ERA-NET project “DYPIIC–Dynamic positioning in ice covered waters.” Additionally, the authors would like to thank their industry sponsor, Statoil ASA, their project partners, Det Norske Veritas and Hamburg Ship Model Basin, and the authors’ affiliated companies for the permission to publish this paper. Finally, the authors are thankful to Mr. Dmitry Sapelnikov (NTNU) for his efforts in implementing the NTNU numerical simulator.

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