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Environmental Effects on Dynamic Behavior of Moored Turret Ship Based on Numerical Simulations

Evgeny B. Karulin[1], Marina M. Karulina[1]
[1]Krylov State Research Centre, St.-Petersburg, Russia

ABSTRACT

This paper covers further efforts in a series of on-going numerical studies on dynamic behavior of a turret vessel exposed to simultaneous environmental effects like wind, current and broken ice as well loads from the turret mooring lines and own propulsion system. These studies are based on numerical integration of ship's horizontal motion equations. Broken ice impact on the turret vessel is estimated using the two-dimensional discrete element method (DEM), which proved to be an efficient tool in the studies on dynamics of moored structures as seen from earlier publications of the authors. This paper is a further extension of the DEM technique with adaptation of the model to cover new probable scenarios of the turret vessel operation: 1) turning of turret vessel in managed hummock ice; 2) impact of drifting ice on ship under circular tidal current and wind in compressed ice conditions. Broken ice is assumed to be 1 m thick. Typical ice floe sizes vary from 20 m to 40 m, and the initial ice concentration is 72%. The paper also presents the results of studies intended to examine how variations in the roughness of ship hull plating influence the ship motion characteristics, which is also an important operation factor.

KEY WORDS: Turret ship, Managed ice, Numerical simulation, External forces

INTRODUCTION

Moored floaters of various types like conical structures, semi-submersibles and turret vessels are platforms usually operated or planned to be operated for development of deep water oil and/or gas condensate fields, including those located in ice-covered waters. Investigation of dynamic behavior of moored floating structures under various external effects: winds, currents, ice as well as internal effects: own propulsion and mooring system responses is a challenging task. Some specific cases of vessel's behavior in ice are addressed based on analytic models (Onishchenko and Marchenko, 2015), as well as model tests (Bezzubik et al., 2004; Bruun et al., 2009). Numerical simulation of moored platforms in ice is an efficient method for investigations of this kind (Aksnes and Bonnemarie, 2009; Sayed and Barker, 2013; Sayed et al., 2015; Zhou et al., 2012).

In this study the numerical simulation is used as a tool to examine the behavior in ice of one type of the above-mentioned floaters – turret vessel. Distinctive feature of a turret vessel is availability of special structure – anchored turret enabling vessel rotation around a vertical axis. And horizontal ship displacements are dictated by stiffness of turret anchoring system. This structural feature of turret vessel gives it certain advantages over other platforms without turret regarding control of ice, wind and current load levels by rotation along the direction of impact of external force. As a rule, directions of impact of wind, current and ice drift do not coincide. At change of intensity or direction of impact of one of the above mentioned external factors a vessel starts to rotate to position providing it minimum level of total external load. For reducing the level of ice load on hull it is required to make a zone of managed ice around the ship.

The turret vessel under investigation is a FPSO option for the Shtockman field. The behavior of this vessel under some scenarios was examined by the authors earlier using a numerical model (Karulin and Karulina, 2016). The model is based on solution of equations describing vessel motion in horizontal plane under the impact of external forces. For the broken ice loads estimation we take a well-known discrete element model (DEM) approach fundamentals of which are presented in Hopkins (1998). This paper is a further extension of the DEM technique with adaptation of the model to cover new probable scenarios of the turret vessel operation: 1) turning of turret vessel in managed hummock ice; 2) impact of drifting ice on ship under tidal current in compressed ice conditions. Broken ice is assumed to be 1 m thick. Typical ice floe sizes vary from 20 m to 40 m, and the initial ice concentration is 72%.

THE NUMERICAL MODEL DESCRIPTION

Investigation into behaviour of a turret ship under wind, current and ice is based on composition and solution of differential equations for motion of such vessel in the horizontal plane. The problem statement is shown in Figure 1. Here, the following basic assumptions are introduced:

- no impact of roll and pitch on the ship motion in the horizontal plane;
- the ship gravity center is located in the midship frame plane, the vessel is assumed to be symmetrical against the centreline and midship plane;
- motion of the turret ship (horizontal offsets and yawing) is slow and the inertia of mooring system (MS) lines can be disregarded.

Dashed line in Figure 1 shows position of the turret ship at the initial time moment $t = t_0$. We assume that following external forces start acting on the vessel at this moment – current, wind and ice (any combination of them or all together) causing the vessel to move in the horizontal plane. To describe the ship motion we apply two coordinate systems: immobile $\xi O_0 \eta$ and the vessel-fixed XOY. The origin of the vessel-fixed coordinate system lies in point of intersection of center plane and midship section, and axes OX and OY are directed to bow and starboard. At the initial moment of time $t = t_0$ both coordinate systems coincide. Thus, position of the turret ship and its kinematical parameters in an arbitrary moment of time can be found through integration of differential equations of the ship motion (Ship Theory Handbook, 1985) in the horizontal plane. Taking into account symmetry of the turret ship against the midframe plane, we can write the final differential equations in the vessel-fixed coordinate system in the following form:

$$
\begin{aligned}
& m(1+k_{11})\frac{dV_x}{dt} - m(1+k_{22})V_y\omega = X \\
& m(1+k_{22})\frac{dV_y}{dt} + m(1+k_{11})V_x\omega = Y \\
& I(1+k_{66})\frac{d\omega}{dt} = M
\end{aligned} \tag{1}
$$

where m, L, I are the ship weight, hull length, and inertia against the vertical axis running through the center of gravity (COG), accordingly; k_{11}, k_{22}, k_{66} are coefficients of the ship added water mass and added moment of inertia; V_x, V_y are projections of linear ship speed to axes of ship-fixed coordinate system; ω is angular velocity of the ship rotation; X, Y, M are projections of total external force and external torque acting on ship hull.

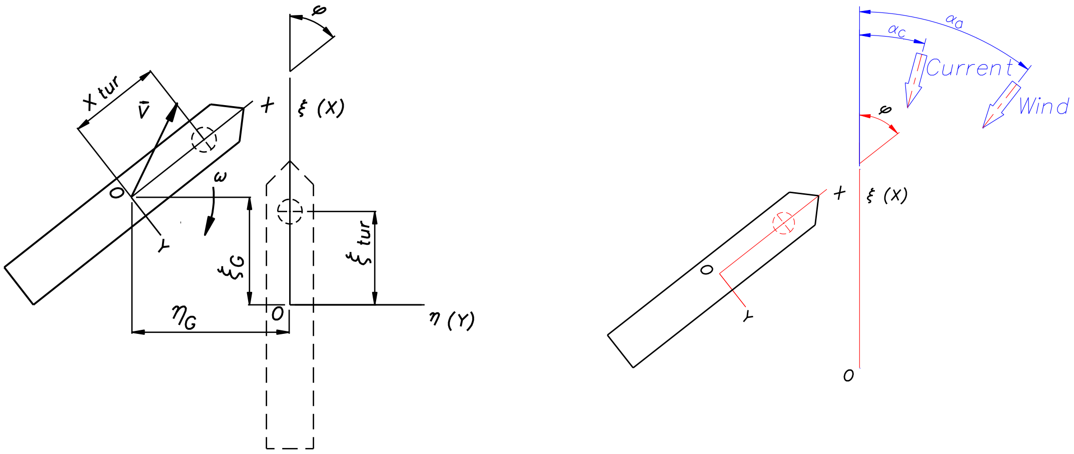


Figure 1. Problem statement. Coordinate systems and directions of external actions

Own ship inertia parameters are known. The total external load contains aero-, hydrodynamic and ice loads, forces and moments produced by the thrusters, and by mooring system. Formulas for determination of aero- and hydrodynamic loads are given in Karulin and Karulina (2011).

Loads caused by the broken ice field acting on floater hull are determined using 2D discrete element method (DEM). According to the method the broken ice is represented by a set of separate (discrete) floating bodies – disks of diameter corresponding to the typical geometrical dimension of separate floes. When the elements are interacting with each other or with the rigid boundaries (ship hull), it is supposed that there are contact forces on the contact zone. The detailed description of the DEM, as well as the contact forces calculation is given in Karulin and Karulina (2011). Additional assumptions have been made:

- disks do not raft – displacement occurs only in horizontal plane, two-dimensional problem is considered;
- ice discs are assumed to be destroyed due crushing when a certain pressure load level is achieved: as a result the ice discs diameters decrease;
- no turning of ice discs: ice blocks move incrementally;
- behaviour of broken ice can be described through the loose medium mechanics and characterized by its inherent features: angle of internal friction φ and cohesion c.

In current calculations, angle of internal friction is equal to 30° and cohesion is 2000 Pa.

These values are based on results of previous studies.

Apart from the described interaction forces each element in horizontal plane is subject to force of hydrodynamic and air resistance, which in general case do not coincide in direction. Force of disk hydrodynamic resistance is calculated under the formula:

$$\vec{F}_{HDdisk} = 0.5 c_{wdisk} \rho_w A_{disk} \left|\vec{V}_{disk}\right| \vec{V}_{disk} \quad (2)$$

where $A_{disk}, \vec{V}_{disk}$ are the disk area in plan and velocity in reference to water, accordingly; c_{wdisk} is coefficient of hydrodynamic resistance. Air resistance is determined under similar formula using corresponding values of air density and coefficient of air resistance. Coefficients of hydrodynamic and air resistance of ice floes are assumed c_{wdisk}=6·10-3 and c_{adisk}=3·10-3 according to Timokhov and Kheisin (1987). Added masses of water at disks motion in horizontal plane can be neglected.

After estimation of total force acting on each element, accelerations of each element are found, and differential equation of motion of each element is integrated and velocities and new coordinates of each element are computed. Summation of forces applied from discrete elements to the vessel contour enables obtaining components of ice load in vessel-fixed coordinate system – forces X_{ice}, Y_{ice} and moment M_{ice}

The model was validated by comparing numerical simulations of the Kulluk conical platform with full scale measurements, as well as numerical simulations of moored floater behaviour with ice model tests data (Hansen and Løset, 1999; Karulin and Karulina, 2011).

DESCRIPTION OF THE TURRET VESSEL AND MOORING SYSTEM

Main parameters of a turret vessel assumed to be an object of investigation are given in Table 1. In Figure 2, the vessel waterline with a turret position is shown.

Table 1. Main parameters of a turret vessel.

Parameter	Value
Length at waterline, m	235
Width at waterline, m	38.8
Draft at waterline, m	15.0
Displacement, m3	117000
Inertia, kg·m2	$552.3 \cdot 10^9$
Turret position fore of midship, m	85.0
Coefficient of water added mass k_{11}	0.0175
Coefficient of water added mass k_{22}	0.360
Coefficient of water added moment of inertia, k_{66}	0.290

In current studies, the turret MS consists of twelve chain lines (R5 114mm) of 2500 m length that are arranged strong radially. Break load of the chain line is 14.5 MN. The fair leads are located symmetrically along a turret circle of 30 m diameter at water depth 300 m. Stiffness of the anchoring system is assumed constant in various directions. Figure 2 illustrates turret MS restoring force depending on the offset.

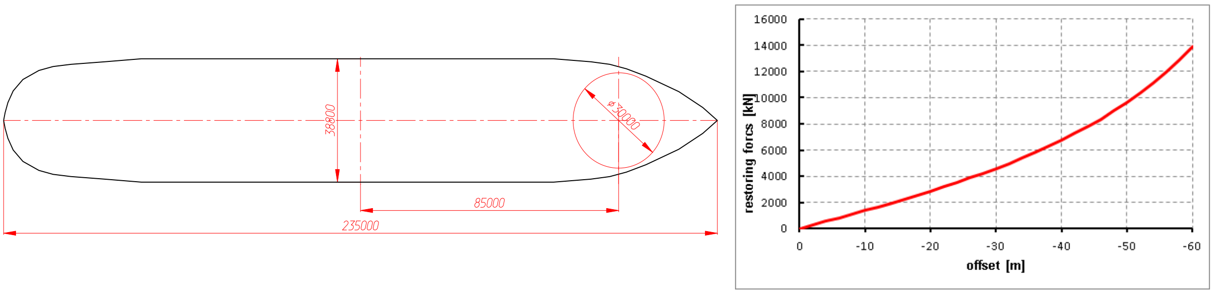


Figure 2. The turret ship waterline and the turret MS restoring force

TURRET SHIP TURNING IN IMMOVABLE MANAGED FIRST-YEAR ICE RIDGE

A zone of managed ice around the vessel is a pre-requisite for her safe operation in ice. If the vessel is operated in immovable ice field and it is predicted that the ice would drift in some direction, the vessel has to turn, under own propulsion or with assistance of ice management vessels, to meet the ice drift with the bow. The earlier studies of the authors for the same moored floater (Karulin and Karulina, 2016) showed that the turning maneuver of the turret vessel under own propulsion depends on ice parameters and managed ice area. At ice thickness 1 m, mean size of ice pieces 20 m and ice concentration 72% the vessel needs a managed ice zone of at least 900 m in diameter for effective turning maneuver. The same values are also assumed in this study, which examines a scenario of the ship turning about the turret using own thrusters in immovable managed first-year ice ridge.

It is assumed that after ice management an ice ridge is broken and some ice blocks from the ridge keel and its consolidated layer have formed a zone (stretch) of broken ice. It is also assumed that the width of this zone is equal to 180 m, while the maximum ice thickness along central axis is 10 m. Ice thickness is linearly reduced to the zone edges reaching the surrounding ice thickness. It is assumed that the propulsion unit generates a thrust of 900 kN applied normally to the ship centreline at the point with the coordinates $x=-102.0$ m, $y=0$ m. The calculation domain is a managed ice area of regular polygon shape inscribed in a circle of 900 m diameter. The calculation domain boundaries are solid walls simulating edges of unbroken ice sheet. In the initial instant the turret center coincides with the circumscribed circle origin. Three initial positions of the ice ridge axis with respect to the ship hull are considered. The results obtained from modeling the ship turn in ice ridge are compared with the ship turn in managed ice of constant thickness. All types of calculation domains at the initial instant and in time after 180° turn are shown in Figure 3. Color gradations reflect different thickness of ice blocks: black color refers to the maximum thickness of 10m.

Some calculation results are shown in Figures 4 and in Table 2. Fluctuations of the restoring force of turret mooring system (Figure 4) are caused by periodical action of ice floes and by compliance of the mooring system itself.

Table 2. Calculation results for the ship turning in managed ice conditions

Ice conditions	Managed ice	Managed ridge 1	Managed ridge 2	Managed ridge 3
Time of turning at 180° [s]	1700	1970	2970	3080
Turret maximal offset [m]	6.9	6.6	5.5	7.3
Maximal restoring force [MN]	1.00	0.95	0.80	1.06

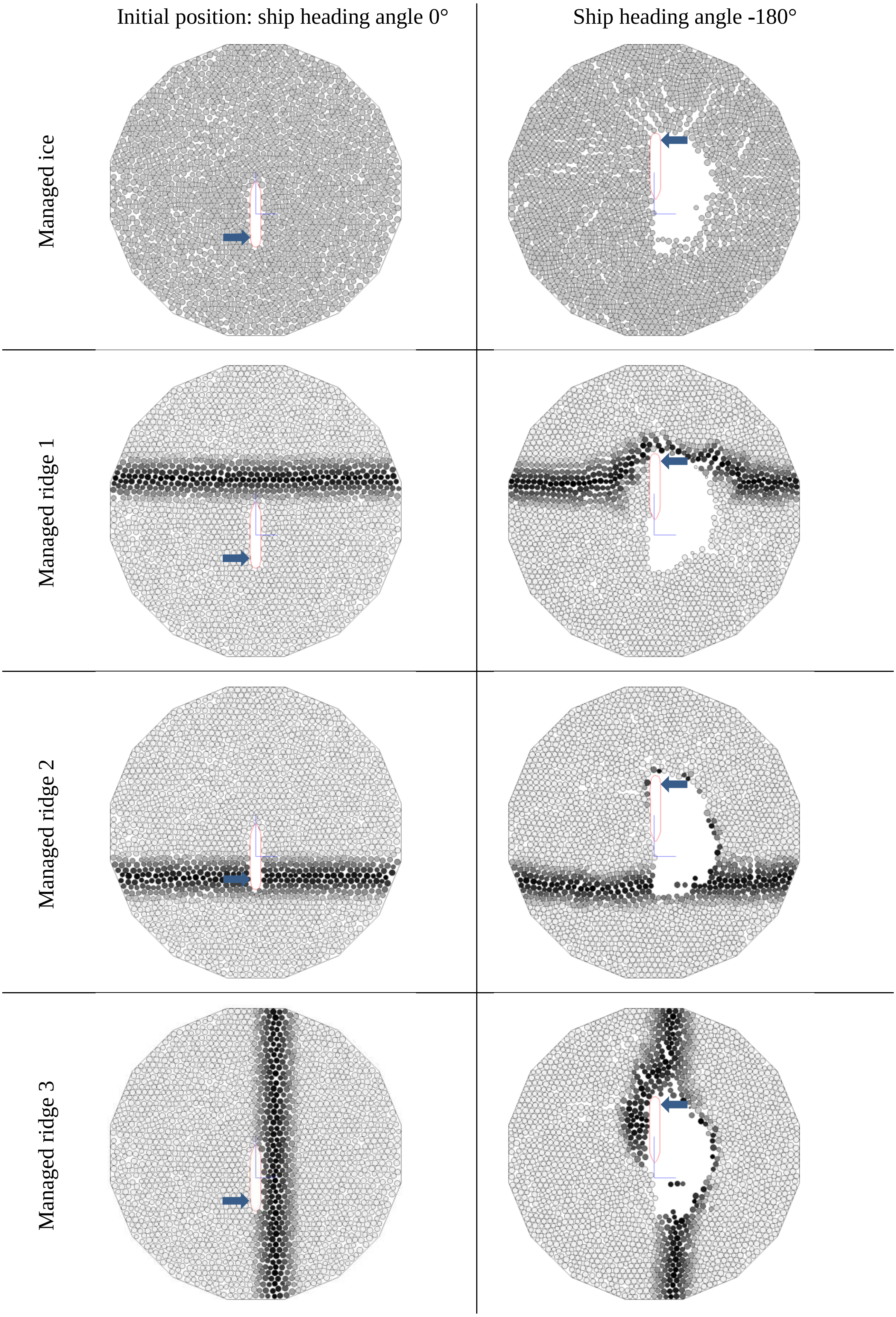


Figure 3. Snapshots of calculation domain (blue arrow shows the thruster action)

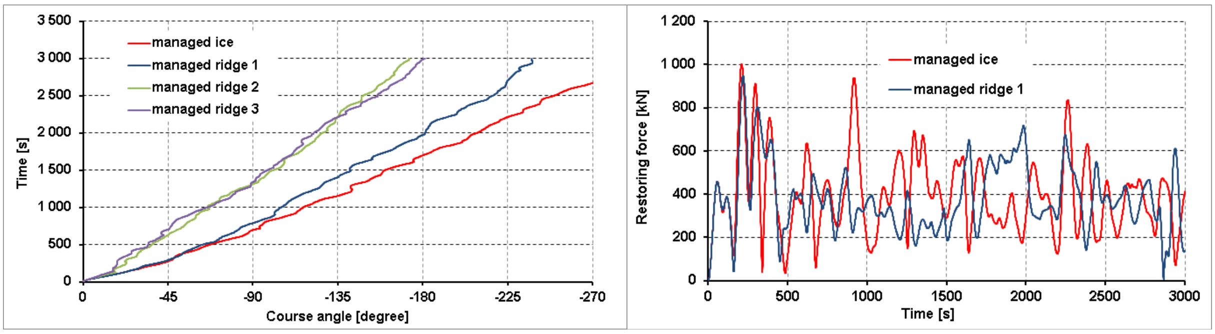


Figure 4. Time histories of the ship heeding angle and the turret MS restoring force

Analysis of computations based on this numerical model indicates the following:

- Turret vessel is able to turn safely under own propulsion in the managed ice ridge of given configuration at different initial orientation of the ridge axis with respect to the hull, while ship's turning speed in this case is lower than that in the managed ice of constant thickness.
- The time required by the ship to change the heading by 180° shows that the turning maneuver in ridge 1 is performed faster than in ridges 2 and 3 with a different initial axis orientation.
- In considered cases of the ship turning the turret excursions and restoring forces are practically the same as in managed ice.

THE TURRET SHIP BEHAVIOUR UNDER ACTION OF SVERDRUP TIDAL WAVE

Earlier the authors studied the turret vessel behavior under Sverdrup tidal wave effects (Karulin and Karulina, 2016). It was shown that the ship slowly turns when there is a zone of managed ice with an average size of ice flows 40 m. In this case the turret excursion and restoring force are small and the ship may safely turn under own propulsion. This result was obtained without ice compression or wind. In this study the Sverdrup wave scenario is consecutively added with two additional external effects: ice compression and wind. In addition, it is examined how the ice/hull friction coefficient influences ice load.

Velocity vector components $U_{S,x}$ and $U_{S,y}$ in the Sverdrup tidal current are as follows:

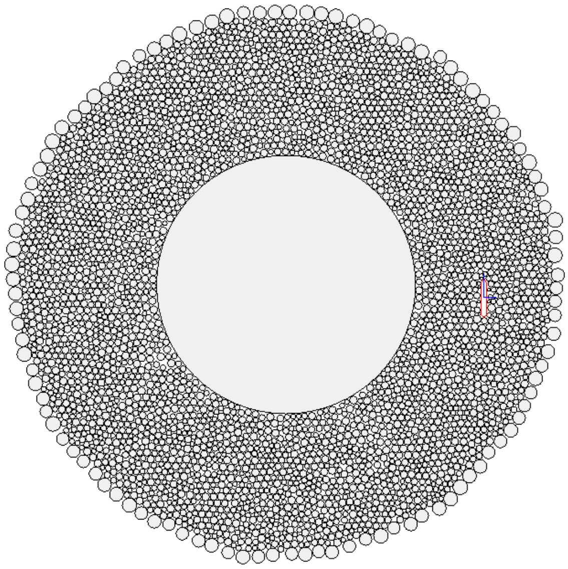
$$U_{S,x} = \frac{a\omega_S}{k_S H}\cos\theta, \quad U_{S,y} = \frac{af}{k_S H} sin\theta, \qquad \theta = k_S x - \omega_S t, \tag{3}$$

where a– wave amplitude, ω_S and k_S – frequency and wave number of Sverdrup tidal current, respectively, H – water depth and f – Coriolis parameter. In current study, the typical parameters of 74°N were used: a =0.1, k_S = 2.583·10-7, f = 1.398·10-4, ω_S =1.405·10-4, H =3.000·102 (Marchenko, 2015).

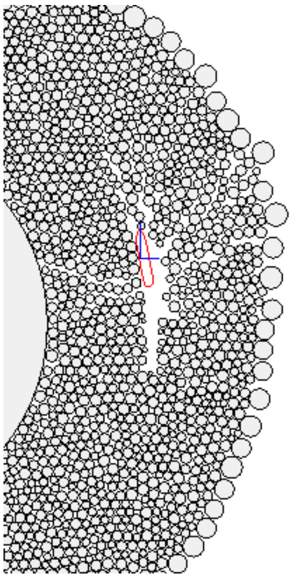
The calculation domain of special configuration is generated taking into consideration a circular motion of ice floes drifting due to Sverdrup tidal current. The circle-shaped calculation domain consists of three parts: a central circle and two concentric rings (Figure 5, left). The central circle of 1583 m in diameter is an intact part of the ice field with 1 m thickness. The middle ring, which circles the ship under study, is filled up with ice floes with an average diameter of 40 m and concentration of 72%. The ring outer diameter is 3190 m. For reducing the number of ice floes in calculations the outer ring is represented by a layer of ice floes with an average diameter of 85 m. The calculation domain has free boundary.

Initially the Sverdrup tide wave impact is not accompanied with ice compression and wind effects. The vessel slowly turns under the tide wave action with small spaces of open water being formed around the hull (Figure 5, middle). Approximately 33 minutes after such turning is initiated, the ship is exposed to ice compression. The numerical model simulates ice compressions with additional pressures applied to ice blocks on the periphery of the calculation domain acting towards the center of this domain. The pressure magnitudes depend on the specified compression grade. Calculations are done for ice compression grades 1 and 2 characterized by 10 кPa and 30 kPa, respectively (Timokhov and Kheisin, 1987). Calculations based on the described model indicate that ice compression quickly closes the channel behind the ship: the ice channel was totally closed after about 1.5 min subject to ice compression of grade 1 (Figure 5, right). Exposure to ice compression gives considerable increase in average and amplitude values of ice loads transmitted to the turret mooring system (Table 3 and Figure 6.). Compression level variations within grades 1 and 2 have practically no effect on average ice load values.

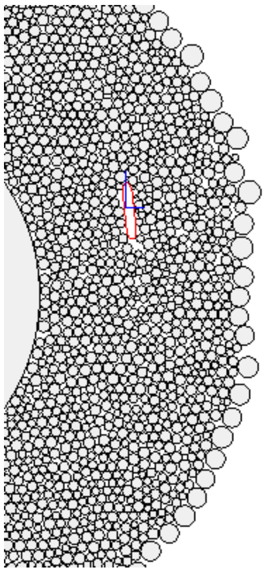
It is seen from computations that the ice load significantly depends on hull plating conditions: an increase in ice/hull friction coefficient from 0.09 to 0.36 has increased the average restoring force from 1.7 MN to 2.8 MN under compression of grade 2. (Table 3).



Time step=0 s
initial position



Time step=1980 s
beginning of ice
compression



Time step =2070 s
closure of
the channel

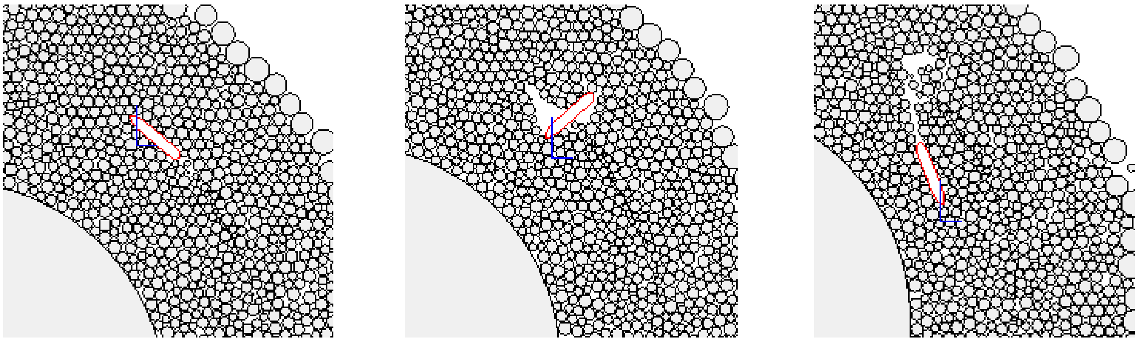
Figure 5. Snapshots of the calculation domain under ice compression action.

Table 3. Average restoring forces on ship exposed to Sverdrup tidal wave

Friction coefficient ice/hull	Restoring force, MN		
	Without ice compression	Ice compression 1 grade	Ice compression 2 grade
0.09	0.7	1.7	1.7
0.36			2.8

In one of the scenarios, the ship in addition to tide wave and ice compression of grade 1 is subjected to wind of 15 m/s at 135° angle at time instant t= 7020 s (117 min). Trajectories of ice blocks are governed by joint actions of current and wind. Calculations and full scale observations of ice drift in the Pechora Sea suggest that wind speeds higher than 10 m/s govern ice drift directions (Zubakin et all., 2004). Direct wind effects are also observed in view of a large wind exposed area of the vessel under consideration.

Wind onset causes intensive rotation of the vessel, which tends to minimize her windage. Figure 6 shows calculation domains at the wind onset and ship turning instants as well as ship's equilibrium position under joint effects of all factors considered: Sverdrup tide wave, ice compression, wind and managed drifting ice. As it is seen from Figure 7, the equilibrium heading angle is about 196° with small excursions around it. It means that the hull is not aligned exactly into wind due to other environmental factors. Figure 8 shows that the wind onset did not cause any noticeable change in maximal values of the restoring force.



Time step=7020 s beginning of wind action | Ship turning under wind action | Equilibrium position of turret ship

Figure 6. Snapshots of the calculation domain under ice compression and wind action.

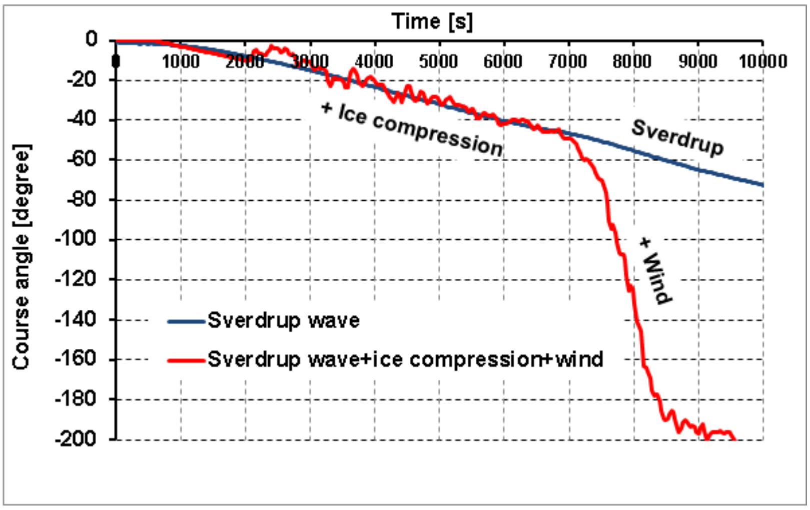


Figure 7. Time histories of the ship heeding angle.

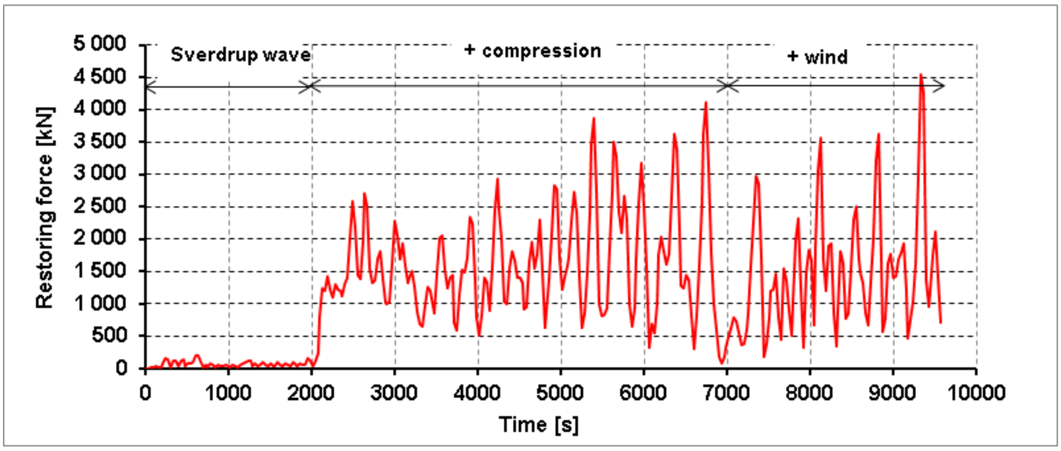


Figure 8. Time histories of the MS restoring force.

CONCLUSIONS

This study examined some scenarios of environmental effects (wind, current and ice) on a turret vessel which may occur during operation of a real vessel in freezing deep-water seas, e.g. at Shtokman field. The numerical model presented in the paper enabled the authors to identify the ship responses under given external effects and determine kinematic parameters of ship's dynamic behavior and forces transmitted to the turret mooring system.

Calculations show that the turret vessel is able to turn safely under own propulsion in the managed first-year ice ridge with a keel up to 10 m. The ship turning speed in the managed ice ridge is slower than in the managed ice of uniform thickness, and it takes more time to perform the turning maneuver. Time estimates are required for operational planning to turn the vessel well in advance into the right position based on weather forecasts to ensure minimum or safe level of environmental loads.

Investigations of ship's dynamics in managed ice under Sverdrup tide wave are complemented with the analysis of ice compression and wind effects. The results of numerical simulations show that ice compressions of grades 1 and 2 have practically no effect on ship dynamics under Sverdrup tide wave effects, but loads on the turret mooring system increase significantly (by an order of magnitude). If an additional wind factor comes into play with a speed higher than 10 m/s, then the circle ice drift trajectory changes, and additional aerodynamic loads are applied to ship hull, which significantly changes the turret ship dynamics during the turning maneuver.

It should be noted that the obtained results are influenced by specific features of the applied numerical model and boundary conditions. The conclusions drawn from these results are valid for the range of external action parameters and specific floater features covered by this study. Therefore, extrapolation of the results and conclusions outside this range should be made with caution and validated by appropriate full-scale or model tests data.

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