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AN APPROACH TO TIME-DOMAIN STOCHASTIC SIMULATION OF ICE LOADS ON A SHIP HULL

Igor STEPANOV[1, 2], Sergey IVANOVSKY[3] and Nina KRUPINA[1]

[1] Arctic and Antarctic Research Institute, Saint Petersburg, Russia
[2] Saint Petersburg State Marine Technical University, Saint Petersburg, Russia
[3] Krylov Shipbuilding Research Institute, Saint Petersburg, Russia

ABSTRACT

An approach to numerical simulation of impact ice loads on a ship hull is presented. The ultimate objective of the study is to determine ice force and ice pressure distribution as a three-dimensional time-dependant random function and, in particular, to evaluate probability distributions of ice loads on ice belt structures along whole ship length. The objective is achieved by means of simulation of ship motion and her interaction with ice as a permanent continuous process. The simulation procedure is planned to be implemented in a computer software system.

The proposed approach includes:

- simulation of ice as a set of separate floes whose parameters are varied in accordance with prescribed probability distributions and/or regression dependencies;
- description of dynamics of a ship as a rigid body with six degrees of freedom;
- contact modelling aimed at calculation of time-dependent ice pressure distribution during each impact against ice floe(s);
- statistical processing and presentation of the simulation results.

1. INTRODUCTION

Determining the impact ice loads on the hull of a ship is one of the key questions for designing ice-strengthened ships and also for developing recommendations for providing safe navigation for these ships. This question was also given a great deal of attention while working on Harmonized International Polar Shipping Rules.

Practically all existed theoretical models for evaluation of these loads are based on the consideration of ship impact against a single separate floe. Such models do not allow proper implementation of a probabilistic approach and estimate of probability distributions of ice loads on a ship depending on hull area. Consequently, possibilities for adequate risk analysis, rational evaluation of the design load, comparison of simulated data with full-scale trial measurements are rather limited when these models are employed.

This was the reason why in the mid 1990s the Department of Ship Performance in Ice of Arctic and Antarctic Research Institute (AARI) started to develop a 3D model for time-domain stochastic simulation of ship behaviour in ice with application to prediction of impact ice loads on a ship's hull. This study is in progress; its ultimate goal is the creation of a computer software simulation system that can be a helpful tool not only for predicting ice loads on a ship's hull, but also for solving a wide range of other practical tasks.

In 1997 Transport Canada and National Research Council of Canada (NRC) initiated a project entitled "Software for Simulation of Ship Behavior in Ice". In the frame of this project, AARI was asked to describe its approach to modeling of ship/ice interaction. According to the contracts with NRC, AARI submitted a report on Stage 1 "System Definition" of the project in March 1998 and a draft report on Stage 2 "Mathematical Models for Prediction of Ice Loads" in December 1998. This paper contains a brief description of AARI's approach that was presented more comprehensively and specifically in the original reports (Stepanov, 1998) and (Stepanov et al, 1998).

2. GENERAL DESCRIPTION OF THE SIMULATION PROCEDURE

The simulation of ship behaviour in ice is carried out on the basis of **time-domain solution of a three-dimensional problem of ship dynamics in a general way**. The kinematic parameters of ship motion are represented as a time dependent vector with six components (longitudinal, lateral and vertical linear displacements of the centre of gravity of a ship and three angular displacements: rolling, pitching and yawing angles), as well as the first and second time derivatives of this vector (i.e. linear and angular velocities and accelerations). The ship dynamics is described with ordinary differential equations of ship motion, which link kinematic parameters and the principal vector of forces and the principal moment. Displacements, velocities and accelerations for sequential time moments are obtained as a result of numerical solution of the differential equations.

One should take into account that ship dynamics must be simulated not only at the time of impacts, but also during the intervals between them. This is particularly important for the adequate prediction of ice loads on the ship hull due to reflected impact. It should also be taken into account that in ice with high concentrations the ship can interact with several ice floes simultaneously, and these processes should be simulated. Motion of each ice floe that interacts with the ship, is described with six ordinary differential equations of the second order. The ice floes are considered motionless before impact with the ship.

The following **modes of ship motion** may be simulated.

A. **Impact against a Separate Floe.** This mode is of most interest when comparing different models for computation of ice loads or deriving parametric dependencies (e.g. dependence of maximum ice pressure against size or thickness of the ice floe, ship displacement and others).

B. **Progressive Motion**. The ice cover is represented as a set of separate ice floes. Compensation for the ship going off course is achieved by the rudder; the rudder angle is determined from the equation of an automatic pilot. The computation in this mode is the simplest way of obtaining statistical characteristics of ice loads.

C. **"S-Motion"**. The ice cover is represented as a set of separate ice floes. The ship has constantly a curvilinear motion, changing from one turn to another. In her initial position the ship is at an angle of 90° with a line of general direction of motion. The ship motion with a predetermined rudder angle is simulated up to the time when the centre of gravity of the ship crosses the line of general direction of motion. Then the rudder is put over to the other side of the ship and she begins a turning circle on the other side. The system simulates all these manoeuvres automatically; the user should only introduce the input data. This mode enables assessment of the effect of curvilinear path of ship motion, as well as non-zero values of drift and yawing velocities on the ice loads.

D. **Arbitrary Manoeuvring**. The ice cover is represented as a set of separate ice floes. In contrast to all previous variants, in the present mode, the ship control during her motion is carried out by the user in the process of simulation. The thrust of propeller(s) (or shaft power) and rudder(s) angle can be changed at any moment; thus, the user has practically the same possibilities of influencing the ship motion during the simulation as a navigator does under actual conditions. The mode "Arbitrary Manoeuvring" is of interest for determining in what way the manoeuvring of the ship in ice affects the loads.

The determination of **ice conditions** depends on the simulated ship motion mode. When impacting against a separate ice floe, only the thickness of the ice floe and its diameter should be defined. In all other modes ice conditions are predetermined in exact accordance with the recommendations of the World Meteorological Organisation (WMO) – with the help of "egg codes". The difference from the general variant of the description of ice conditions is only that information of icebergs (an impact against an iceberg is not considered in the model) and of fast ice (in this case the initial task of determination of ice impact loads loses its meaning) is not perceived and, hence, processed.

3. ICE CONDITIONS

Generally, the ice cover can be considered as an outcome of a vector random function of three spatial co-ordinates and time; the components of this function are statistically dependent.

The basic characteristics of an ice cover (or in other words, the components of that vector function) may be combined into three groups:

- morphological characteristics of the ice cover i.e. the characteristics of the ice cover geometry (ice concentration, dimensions of ice floes, ice thickness etc.);
- physical-mechanical properties of ice (temperature, salinity of ice, ice strength etc.);
- kinematic and dynamic characteristics of the ice drift (velocity, direction of drift and others).

The parameters of the ice cover can be considered as time independent (in particular, the ice drift can be neglected) for the simulation of ship's motion in ice in many practical tasks. As a rule, the required information about the physical-mechanical properties of ice may be limited by data on ice strength. If so, the information about other properties of the ice (temperature, salinity etc.) may be useful to the extent that it can be applied in the evaluation of ice strength.

When simulating the morphological characteristics of the ice cover, the aim is to have an outcome in the form of a set of separate ice floes, which have statistical characteristics of thickness and shape coinciding with pre-described input distributions. Primarily it is necessary to determine the geometry of the ice floes in a horizontal plane. This can be achieved in different ways. An algorithm that is described below, seems one of the most appropriate.

Firstly, separate floes of ice are simulated ("generated") corresponding to specific requirements (if the simulation of the geometry of the cover is performed then these requirements come out of the distributions of thickness and plan dimensions of the natural ice floes, taking into consideration the interrelation of these parameters). Then the "generated" ice floes are placed in a given area, forming a simulated ice cover with the required concentration. The term "generation" is considered as it is used in the Monte Carlo method. For example, the generation of the ice thickness means that a data set is created, each figure in this data set is considered as the thickness of an individual ice floe; the statistical processing of this data set as a statistical sample should demonstrate that the generated thickness of the ice has the same probability distribution that was specified as input. The computational procedures for such a simulation which are suitable for simulating random values with arbitrary distribution laws are known and not described in the paper.

In the proposed approach, every floe of ice in a plan is represented as some geometrical figure, for example a circle, an ellipse or a polygon. If a real ice floe is substituted with a circle then the simulation algorithm will be quite simple. However the simulated ice cover does not appear sufficiently realistic. The representation of the ice floe as an ellipse is more acceptable. But a more general approach with which better results can be achieved is the representation of each floe of ice as an irregular convex polygon with a random number of vertexes.

The developed computing procedure has taken into account and provides for the simulation of the following characteristics of ice cover:

- ice concentration that can vary from 1 to 9 tenths (an algorithm based on the placement of a set of geometric figures that present ice floes does not work properly if the ice coverage of an area reaches close to 100%);
- plan dimensions and the peculiarities of the geometry of the ice floes; these parameters are specified by means of distributions of such basic geometrical characteristics of the ice floes such as their square areas, diameters, eccentricities; there are no constraints on the type of these distributions;
- ice thickness; correlation between ice thickness and plan dimensions of floes can be taken into account.

An example of simulated ice cover is given in Fig. 1. Input information is specified in terms of WMO "egg code" (Fig. 1a); ice floes are presented as irregular polygons.

The procedure provides coincidence with high accuracy of distributions of such basic parameters of natural and simulated ice cover as area, diameter, eccentricity of ice floe. This is not surprising as the developed algorithm guarantees such a result. More interesting is the fact that there is a coincidence between finer statistical characteristics of the morphology of the natural and simulated ice covers.

The surface of the sea, covered with the ice, was considered to be an outcome of a random scalar field, the value of which is equal to 1, if at that point there is ice, and it is equal to 0, if at that point there is open water. The spatial autocorrelation functions of the scalar fields corresponding to the natural and simulated ice cover were estimated. The values of these functions seen on the graphs in Figure 2 corresponded well. Such coincidence is valuable as the correlation function is a very sensitive characteristic allowing for the detection of even a negligible deviation of the geometry of the simulated cover as compared with the natural one.

The information about physical-mechanical properties required for the simulation of a ship's motion may usually be limited by the data regarding the strength of the ice. Ice compressive and bending strength is usually sufficient input data on ice properties to realise most models of ship/ice interaction. In addition to an explicit form of specification of the strength limits, it is worth providing for the possibility for the computation of these values as functions of parameters easily available for measurements and/or known from reference books on the geographical region concerned (temperature of air, salinity of water etc.). For such calculations the empirical formulas similar to the ones given in (Timco and Frederking, 1990) and (Timco and O'Brien, 1994) can be used.

For a number of the models, information on specific properties of the ice is needed. For example, the determination of ice loads on a ship hull by the hydrodynamic model requires values of the ice impact crushing strength. This value may be preliminary estimated using dependencies from (Likhomanov et al, 1998).

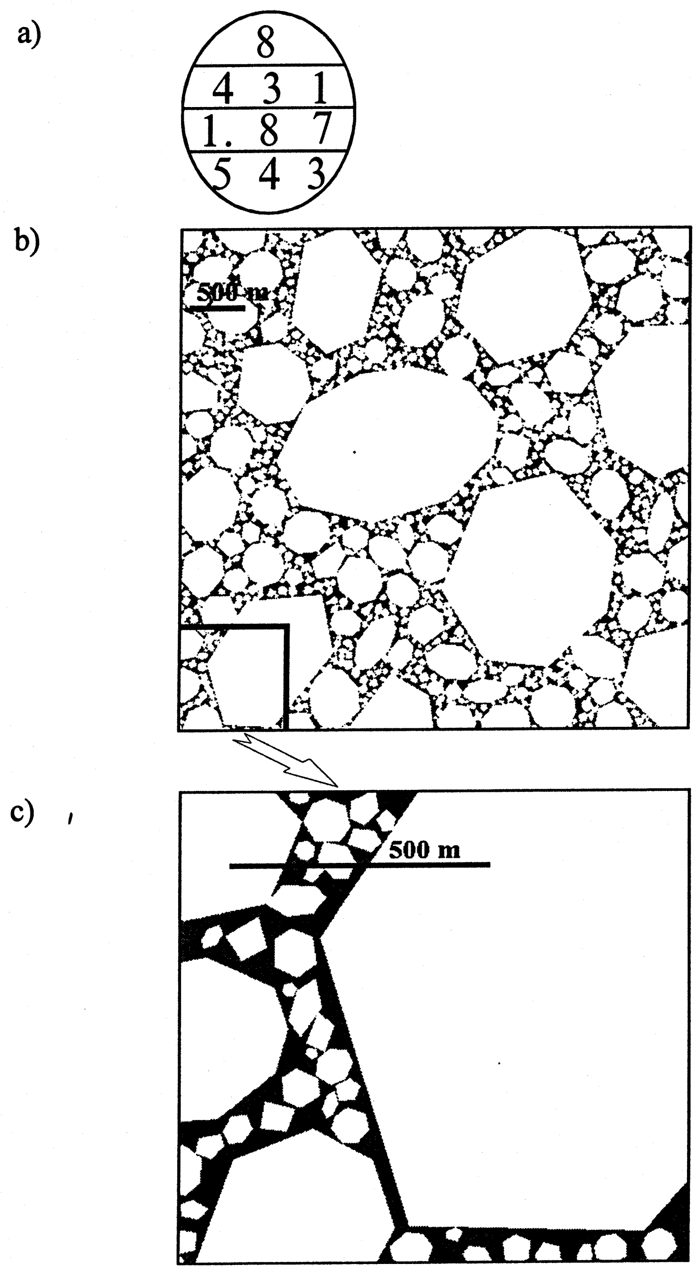

Figure 1. An example of the simulated ice cover: "egg code" as input information (a), general plan view of the cover (b) and its fragment in a larger scale (c); total concentration - 8 tenths, including 4 tenths of big floes, 3 tenths of medium floes and 1 tenth of small floes.

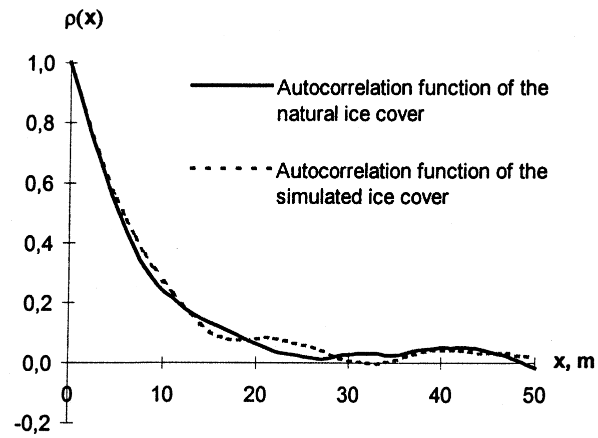

Figure 2. The autocorrelation functions of the natural and simulated ice covers

4. CONTACT MODELLING

The determination of ice pressure on a hull of a ship under her interaction with ice and the evaluation of the ice force and moment acting on the ship consist of the sequential solutions of the following tasks:

(a) establishing the initiation of the interaction between a ship and an ice floe;

(b) finding the boundaries of a contact zone and determining those geometrical characteristics of the zone which are required for computation of the ice pressure (square area, orientation in space etc.);

(c) computing the vector of the relative velocity of indentation of the contact zone of the ship's hull into the ice;

(d) finding the spatial distribution of ice pressure over the range of the contact zone;

(e) determining the vectors of ice forces and moment acting upon a ship from the side of the ice;

(f) establishing the end of the interaction between the ship and the ice floe.

After establishing the fact that the interaction has began (task (a)), tasks (b) -(e) are solved on every time step as the ship's hull enters an ice field.

The input information for calculating ice force, exerted on the ship hull by the ice floe during impact, is the dependence of ice pressure spatial distribution in the contact area depending on the depth of penetration in ice (or on time). In principle, any formula or numerical procedure can be used in the system. For example, the following variants can be include:

A. **Constant pressure**. It is supposed that ice pressure is constant and equals to the ice confined compressive strength (it can be assumed that this value is equal to ice uniaxial compressive strength multiplied by a constant coefficient). It is evident that in this case the force acting on the ship from ice will be in direct proportion to the contact area.

B. **Hydrodynamic model**. The pressure is considered as a function of the velocity of ship penetration and geometric characteristics of contact area (pressure reaches maximum in the middle of contact area and decreases to zero to the edges of the area).

C. **Pressure-area model.** It is accepted that ice pressure is uniformly distributed on contact zone; pressure value depends only on contact area and can be defined by equation $p(A) = k \cdot A^{-n}$, where p - ice pressure, A - contact area, k and n - a coefficient and an exponent, values of which are considered as known.

At every time step a check is done to see whether the interaction between the ship and an ice floe is on-going or has ceased (task (f)). Two criteria are used for this purpose:

- Kinematic criterion. It is natural to take as a criterion the direction (actually, the sign) of the normal component of the relative velocity of the indentation of the ship into ice. After starting the interaction the normal component of the velocity coincides in direction with the vector of the average external normal to the surface of the contact area. In the process of the interaction the value of that velocity begins to decrease. If ice sheet does not failure by bending or buckling (only ice crushing/flaking take place) then the indentation velocity drops to zero, and the sign of velocity changes. The interaction with the given ice floe is considered to have stopped when this occurred.
- Failure criterion. If the force exerted on the ice floe by the indenting ship's hull causes ice floe to fail by bending or buckling then the interaction event is assumed terminated.

5. EQUATIONS OF MOTION

The equations of motion establish the interconnection between kinematic parameters of motion of an object considered as a solid body (linear and angular displacements, velocities and accelerations) and the external forces acting upon a body and the moments of these forces. In the given problem it is necessary to write down and to solve numerically both equations of the ship's motion and equations of motions of all those ice floes that are interacting with a ship at a particular moment of time. In the general approach used by the authors, when every object (ship or ice floe) is assumed as a rigid body with 6 degrees of freedom, the motion of every object is described by six ordinary differential equations of the second order. To solve the equations numerically it is expedient to transform each equation of the second order into two equations of the first order by means of a replacement of variables. The equations may be written in the following generalised way:

$$d\vec{P}/dt = \vec{Q}(t, \vec{P}),$$

where

$\vec{P} = \left\{P_1, P_2, \ldots, P_{12(1+n_i)}\right\}$ - a vector of the kinematic parameters of a motion; its components are liner and angular displacements, velocities and accelerations of a ship and ice floes interacting with the ship;

$\vec{Q} = \left\{Q_1, Q_2, \ldots, Q_{12(1+n_i)}\right\}$ - a known vector function of time and of the kinematic parameters of motion;

n_i - number of ice floes that interact with a ship at the considered moment of time; n_i may be equal to 0, 1, 2, ...

Particular expression for the vector function $\mathbf{Q}$ may be written using dependencies from the theories of ship manoeuvrability and oscillations in waves with additional components of forces and moments due to ship/floe(s) interaction. These additional components are obtained by means of the contact modelling. Hydrodynamic inertial forces are taken into account by means of introducing added masses and moments of inertia of the ship and the interacting ice floes in a conventional way. Ship motion damping is also considered. Due to impact nature of the ship/floe interaction, damping of floe motion may be neglected.

It is principally possible to simulate movement of not only those floes that directly impact with the ship hull, but also of those floes that start to move due to floe/floe contact. The main problem is that this would result in a significantly more time-consuming modelling procedure. Such increasing of the required computer time does not look justified. Ice impact load during each interaction event reaches its maximum quite rapidly (usually not more than in 1-2 s), i.e. when forces between floes are rather small. Consequently, influence of interaction between separate floes on maximum ice loads on a ship hull may be ignored.

6. PRESENTATION OF THE RESULTS

The volume of information received as a result of modelling is so large that a selection and a rational interpretation of the output data may become rather difficult. Therefore a post-processing of the simulation output should be one of the functions fulfilled by the modelling system. In order to take into account the interests of the potentials users of this system, at the system development stage the list of output values should be specified and the most appropriate form of data presentation should be found.

The problems, the solution of which may be of interest for potential users, can be relatively divided into “research” and “applied” ones. For example, an objective of research can be establishing correlation between ice conditions, hull shape of the vessel and her operational mode and ice loads on a ship hull, their spatial and temporal distributions, etc. A quite comprehensive output information should be provided by the modelling system to a user for further data processing by means of computer software for statistic analysis, computer spreadsheets, etc.

The “applied” tasks may include a structural design of a ship’s hull, analysis of structural strength of an earlier designed ship (for example, if a ship-owner considers the possibility of ship navigation in ice conditions in which the ship has not operated before and for which it had not been previously designed), etc. For solving such problems it is desirable to get a “maximum” (design) value of the ice load depending on location of ship’s hull area.

For research purposes, the most appropriate form of presenting the results of modelling seems to be an ASCII/ANSI format computer file containing instant values for sequential time moments of the following parameters:

- liner and angular displacements, velocities and accelerations of a ship motion;
- co-ordinates of the centre of a hull/ice contact zone (this and further parameters from the list are calculated and presented as output only for the moments of time when there is a direct interaction of a ship with ice floe(s); if a ship simultaneously interacts with several floes then the information listed below is given for each ice floe and, consequently, for each contact zone);
- dimensions (length, height) and area of a contact zone;

- spatial average of ice pressure on contact area and maximum ice pressure within this area;
- ice force (normal and tangential components);
- thickness and plan dimensions of the impacted ice floe;
- ice failure mode (by crushing, by bending etc.).

A user has the opportunity of specifying the frequency (or a time step), with which the information will be saved in a file (this time step may be equal or more than the time step used for numerical solving of the differential equations of ship motion), as well as to select parameters from the total list which will be given as an output. Obviously the saving of data in a file can be simultaneously accompanied with the displaying of the results of simulation in a graphic form on a computer monitor screen.

7. CONCLUSIONS

A. The described approach to 3D time-domain stochastic simulation of ship motion and her interaction with ice floes has the following main features.

- The ice cover is represented as a set of separate ice floes of random shape and randomly allocated.
- A ship and the ice floe(s) interacting with her are assumed as bodies with 6 degrees of freedom. The problem is considered in nonlinear formulation.
- A ship's motion is simulated as a continuous process. The model describes both a rectilinear movement of a ship and her arbitrary maneuvers.
- The possibility of a simultaneous interaction of a ship with several ice floes is accounted for. The model includes all possible scenarios of impact interaction of a ship with ice including an oblique impact, a reflected impact, ramming and others.
- The ice pressure on a ship's hull due to impact is considered as a function of time and three spatial coordinates. In particular, the change of dimensions of a contact area and its centre shift in the process of impact with an ice floe, taking into account the actual shape of a ship's hull and ice floe in the region of the contact, relative linear and angular displacements of a ship and ice floe, are accounted for.
- The output of the simulation procedure is the dependencies on time of linear and angular displacements, velocities and accelerations of a ship, ice pressure and ice force, geometrical characteristics of a ship/ice contact zone and location of these zones as well as the probabilities distributions of ice loads on the ice belt structures including the structures in the midbody and stern area.

B. The key question for further development of the model consists in a more precise and comprehensive understanding of the processes which occur in a ship/ice contact zone and, in particular, the description of the spatial and temporal distribution of ice pressure during the impact. This problem may be solved on the basis of the analyses of the available results, both experimental investigations (including data of measurements on ships) and the numerical modelling of ice deformation and failure during the interaction with a structure. The execution of such investigations in this direction may become a source of new and valuable practical information.

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