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Propeller-ice contact modeling with peridynamics

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ABSTRACT

The ice contact loads pose a threat to safe operation of propellers. The propeller-ice contact process and the dynamic loads have been investigated numerically. Numerical method based on peridynamics and contact detection method has been introduced. Considering the difference of the mechanical properties of ice and propeller, the propeller is assumed as rigid body and the ice is treated as elastic brittle. To deal with the complicated surface of propeller, a continuous contact detection algorithm has been developed to detect the contact area between propeller body and ice particles. The brittle failure behavior of the ice during propeller-ice contact is simulated. The transient extreme contact loads have been investigated. It is concluded that the method can well capture the ice failure features, such as dynamic cracks and generation of ice pieces, and the calculated contact loads are reliable.

1. Introduction

When ice-going ships navigate in ice covered waters, the submerged piece or pieces of ice would act on their propellers. Especially during the propeller-ice contact, the propeller blades would suffer extremely ice contact loads. The dynamic forces on propeller will fluctuate significantly and change rapidly in amplitude as well as direction, resulting in problems such as noise, vibration etc. A reliable way to predict the propeller-ice contact loads accurately shows its importance both in the theoretical research and the design of ice class propeller. Nevertheless, the complexity of ice failure processes adds challenges to investigate the propeller-ice contact performance.

Propeller-ice contact has been studied by using experimental measurements and numerical methods. In most cases, these researches are based on experimental measurement, including full-scale and model-scale. Full-scale measurements have been carried out by several researchers (e.g. Laskow and Revill, 1986; Jussila and Koskinen, 1989; Keinonen et al., 1990; Williams et al., 1992; Newbury et al., 1993; Browne, 1997). Full scale measurements are valuable, which can help to understand the load magnitudes, the location of the ice loads and contact dynamics, but providing insufficient information, as well as tremendous spending makes it hardly to be an ideal approach. Model-scale tests (i.e. Veitch, 1995; Soininen, 1998; Searle et al., 1999; Moores, 2002; Wang et al., 2005, 2008; Hagesteijn et al., 2012) have been designed to overcome these shortcomings and can obtain more accurate information. Due to the complexity of propeller-ice contact process, numerical simulations of propeller-ice interaction have historically been based on some empirical interaction models (i.e. Kotras et al., 1985; Veitch, 1995; Jones et al., 1997; Soininen, 1998) without much consideration of detailed ice mechanics, so their applications were limited to specific conditions. With the development of computer technology and numerical techniques, Finite Element Method has been used to model the propeller-ice contact by scholars (Lee, 2007, 2008; Norhamo et al., 2009; Vroegrijk and Carlton, 2014), but it has not been fully developed. This is because Finite Element Method is based on continuum mechanics, so it is difficult in dealing with the fracture and damage mechanics of ice.

From above, it can be seen that certain mechanisms and dynamic fracture of ice during propeller-ice contact condition are not fully understood, further studies should be carried out. Predicting and analyzing propeller-ice contact by numerical method is nonetheless an effective method, so further studies should be carried out through advanced methods. It is practically significant and highly necessary to modeling propeller-ice contact based on meshfree methods for their independence on element grids. The peridynamic method, proposed firstly by Silling (2000), has its nature advantages in the fracture problems and is suitable for modeling the process from continuous to discontinuous (Zhao et al., 2016). The peridynamic method, based on the nonlocal continuum theory rather than the classical continuum theory, is an efficient and particle convergent method (Fan et al., 2016). Over the past more than a decade, the applications of the peridynamic method mainly focus on concrete structures and composite materials (Huang et al., 2015). But the application of the peridynamic method in simulating ice-structure interaction is limited.

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Nomenclature

V_{ice}	Velocity of the ice block
D	Propeller diameter
R_0	Propeller radius
x_r	Rake value
P	Propeller Pitch
N_r	Grid number in the radial direction
s_1	Distance between the point and the leading edge
c_1	Distance between leading edge and the generatrix
y_b	Distance from a point on the back section to a chord line
y_f	Distance from a point on the face section to a chord line
$\mathbf{x}$	Position of a material point
t	Time
ρ	Mass density
$\boldsymbol{\xi}$	Relative positon
H_x	Horizon
s	Bond stretch
φ	Local damage
κ	Bulk modulus
μ	History-dependent scalar valued function
$\mathbf{F}$	*Force*
E	Young's modulus
Δx	Particle spacing value
F_x	Force in the direction of x-axis
F_z	Force in the direction of z-axis
M_y	Moment in the direction of y-axis
n	Propeller rotational speed
D_h	Diameter of the hub
R_h	Radius of the hub
θ_s	Skew angular
β	Propeller pitch angle
N_c	Grid number in chordwise direction
$\mathbf{u}$	Displacement vector of the material point
Δt	Time step
$\mathbf{f}$	Pairwise force density function
$\boldsymbol{\eta}$	Relative displacement
δ	Positive number of Horizon
s_0	Critical stretch
G_0	Critical energy release rate
$\mathbf{v}$	Velocity vector
V_p	Volume of the material point
$\mathbf{M}$	Moment
υ	Poission's ratio
$\mathbf{P}_k$	Control point of the panel
F_y	Force in the direction of y-axis
M_x	Moment in the direction of x-axis
M_z	Moment in the direction of z-axis

To find an accurate and efficient numerical method to simulate propeller-ice contact, this paper develops a peridynamic model. The basic peridynamic theory has been briefly reviewed, including the peridynamic model and the description of failure. Because of the geometric complexity of propeller surface and the high rotational speed of propeller, it's difficult to deal with the problem that how to detect the interpenetration between a propeller and ice while modeling contact. To address this issue, the surface of a propeller is discretized into small quadrilateral panels with the idea of panel method. Thus, for each panel, it is easy to derive whether interpenetration between a propeller and ice particles occurs and to determine value of the contact loads at each time step. The current method not only offers practical solution to propeller-ice contact modeling, but also provides another thinking way for the contact modeling of other bodies in case that the surface of the impactor is complex.

2. The mathematical model for propeller-ice contact

In this paper, the implementation of the current method to model propeller-ice contact will be illustrated with the case that the propeller operates in milling condition, and the general idea is as follows: First, the ice region will be discretized into a great number of material particles, and the surface of propeller is discretized into small quadrilateral panels; Then, the acceleration, velocity and displacement of each material particle can be calculated based on peridynamics at each time step; a continuous contact detection algorithm is applied to detect the contact between a propeller and ice material particles at each time step; Considering the contact effect, the acceleration, velocity and displacement of the ice material particles that contact with the propeller are updated and the contact forces can also be calculated at each time step.

2.1. Basic assumptions

There's a real possibility that the submerged piece or pieces of ice shall contact with propellers during icebreaking process of icebreaker. For the large pieces of ice, the milling process will occur. Fig. 1 shows the comparison of the reality and the numerical model of propeller-ice contact process. To facilitate the study, the ice block is usually treated as a cuboid moving to the propeller with a certain velocity of V_{ice}, and the propeller is treated as a rigid body rotating with an rotational speed of n. Since the properties of ice behave as elastic brittle in operation condition, the PMB material model of peridynamics is suitable for modeling ice failure. Given that the ice contact force produced by

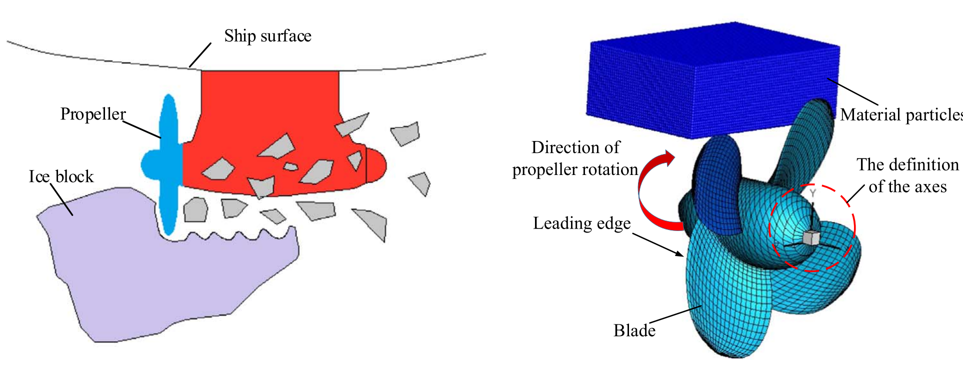

Fig. 1. Illustration of the propeller-ice contact problem. (a) Propeller-ice contact process. (b) The numerical model.