Ocean Engineering 156 (2018) 277–293

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Analysis of variable working conditions for propeller-ice interaction

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A R T I C L E I N F O

Keywords:
Propeller-ice contact
Peridynamics(PD)
Variable parameter
Comparatively analysing

A B S T R A C T

The propeller of a polar ship sailing in icy areas will quite likely be subjected to ice loads. Because of the various kinds of ice conditions and propeller working conditions, there are large differences in the types of ice loads acting on a propeller. In this paper, research has been done to investigate the propeller-ice contact and milling loads under different conditions. We established a numerical method for solving this propeller-ice contact problem based on the peridynamics method and the panel method, which numerically simulates the dynamic responses of single ice-blade collisions at different advance speed, contact positions, propeller rotational speeds, and ice sizes. With the help of a Fortran program, we conducted a comparative analysis of the thrust and torque of the blade sustained in six degrees by changing the specified factors, and finally obtained the changing regularity of the milling loads for the blade under different conditions.

1. Introduction

With the current opening of the Arctic passage, the research of polar ships is on the rise. When polar ships sail in icy areas, the propeller exposed to the stern is in direct contact with sea ice, which can easily cause damage. The problem of a collision occurring between sea ice and propeller blades is a structural problem between two solids. Compared with hydrodynamic loads, the loads of propeller-ice contact are larger by an order of magnitude, occupying a large proportion of the total propeller load. Hence, it is necessary to investigate propeller-ice contact.

Propeller-ice contact has been studied in 3ways: full-scale measurements, model tests, and numerical methods. In the 1990s, with the background of a joint project arrangement called JPRA6 conducted by Canada and Finland, several researchers carried out full-scale measurements (e.g. Keinonen et al., 1990; Williams et al., 1992; Browne, 1997), and obtained valuable data that could be used to explore the variation trend and the magnitude of ice loads. However, obvious shortcomings in these full-scale measurements, such as insufficient information and high cost, make this approach less than ideal. Therefore, with the advantages of requiring less labor and financial commitment, scale-model tests (Veitch, 1995; Searle et al., 1999; Wang et al., 2005) have been conducted in this research field, but more attention should be paid to the drawbacks caused by their complex scale effects. In recent years, with the development of computer technology and numerical calculation methods, numerical simulation has been used to solve these kinds of problem. Numerical simulation is a promising approach that can highly improve working efficiency and can be more appropriate in complex operating conditions. One study by Liu et al. (2000) simulated the blocking flow conditions under different ice conditions based on a propeller program. Two years later, the propeller program was improved to predict the hydrodynamic performance of the area between the propeller blade and an ice block. Hu(Hu and Gui, 2013) used the Smoothed Particle Hydrodynamics (SPH) method to calculate and analyze the loads of propeller-ice contact, and further investigation has summarized and analyzed the influence of different sizes and speeds of ice blocks acting on the contact loads. Ye et al. (2017) applied PD theory to establish a model of propeller-ice contact, applying a fresh approach to this research field.

Consistent with Ye, this paper investigates propeller-ice contact using the PD method, and focuses on analyzing the effect of factors influencing the contact load.

In this paper, to assess PD theory in modeling ice failure, we undertook a verification study by comparing a numerical model (established by PD theory) of an ice cylinder affecting a rigid flat panel with the uniaxial compression tests conducted by Carney et al. (2006). And to prove the accuracy of the propeller-ice contact model, we further carried out a verification study by comparing the prediction result of our contact model with the result of a propeller-ice interaction model test carried out at the ice tank of Institute for Ocean Technology (IOT) by Wang et al. (2005). We then studied the main factors influencing the contact process, mostly considering ice size, advance speed, propeller rotational speed,

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https://doi.org/10.1016/j.oceaneng.2018.02.026
Received 16 November 2017; Received in revised form 28 January 2018; Accepted 10 February 2018

Nomenclature

V	Velocity of the ice block
n	Propeller rotational speed
D	Propeller diameter
D_k	Diameter of the hub
R_0	Propeller radius
R_h	Radius of the hub
x	Position of a material point
u	Displacement vector of the material point
t	Time
Δt	Time step
ρ	Mass density
f	Pairwise force density function
ξ	Relative positon
η	Relative displacement
H_x	Horizon
δ	Positive number of Horizon
s	Bond stretch
s_0	Critical stretch
φ	Local damage
G_0	Critical energy release rate
κ	Bulk modulus
v	Velocity vector
μ	History-dependent scalar valued function
V_p	Volume of the material point
F	*Force*
M	Moment
E	Young's modulus
υ	Poission's ratio
Δx	Particle spacing value
P_k	Control point of the panel
F_x	Force in the direction of x-axis
F_y	Force in the direction of y-axis
F_z	Force in the direction of z-axis
M_x	Moment in the direction of x-axis
M_y	Moment in the direction of y-axis
M_z	Moment in the direction of z-axis
scr_1	Critical compression
scr_2	Critical stretch

and depth of cut. We summarized and analyzed the changes that occurred when varying the noted factors.

2. Ice material model and discretization in propeller blade

2.1. Ice material model and its discretization

Traditional continuum mechanics theory is based on the continuum hypothesis, and it has singularities when solving discontinuous problems of differential equations in abstract spaces. Thus, it is not suitable to solve the propeller-ice contact problem because of the many discontinuities that occur during the ice-crushing process, such as damage, fracture, and cracks. PD (Silling and Askari, 2005; Madenci and Oterkus, 2014; Huang et al., 2015) is a new meshless method based on continuous medium theory, which discretizes a continuum into a series of material points with finite volume and mass. The method considers only the affecting force of the material points in the near-field range and disregards whether the displacement field is continuous, showing great adaptability to many discontinuous problems. PD theory places a greater focus on the interaction between the two material points, to understand the link between two material points better, you might imagine the effect between the two material points to be a bond, or somewhat like a spring. In PD theory, we use the horizon of H_x to describe the near-field range of a material point x, which is a sphere with a radius ofδ and its sphere center is set as the location of material point$x$as shown in Fig. 1.

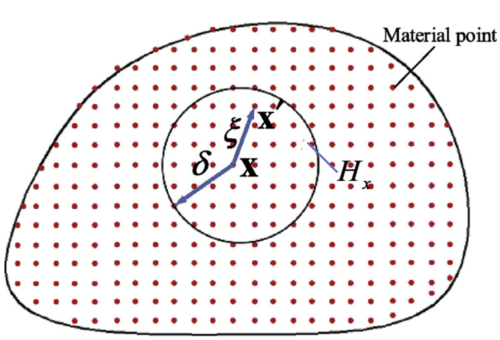

Fig. 1. Material point interacts with those in the sphere through bonds.

To describe the mechanical properties of the material points in the domain, the relative positions between the two material points are defined as $\xi = x' - x$, and the relative displacements at time t are defined as $\eta = u(x', t) - u(x, t)$, so the vector$\xi + \eta$ is the relative position of the two interacting points at$t$. The action of the bond between the material points changes with the deformation of the material, which is indicated by the elongation of the bonds:

$$s = \frac{|\xi + \eta| - |\xi|}{|\xi|} = \frac{y - |\xi|}{|\xi|} \tag{1}$$

The key aspect of PD theory is the basic equation representing the displacement and force of the material points. All of the formulas in PD theory are transformed to solve the following equation:

$$\rho\ddot{u}(x, t) = \int_{H_x} (f(u(x', t) - u(x, t)),\ x' - x) dV_{x'} + b(x, t) \tag{2}$$

Where H_x is the domain of integration within the horizon of the material point x,u is the displacement vector of the material point x, and $\rho$is the mass density. The vector is a pairwise force density function defined as the force per unit volume that the material point at exerts on the material point at x. For an object composed of micro-elastic materials, the constitutive function of PD can be expressed as follows:

$$f(\eta, \xi) = \frac{\xi + \eta}{|\xi + \eta|} f(|\xi + \eta|, \xi) \quad \forall \eta, \xi \tag{3}$$

The pairwise forces are regarded as interactions between pairs of material points as a continuum. To ensure a function does not violate Newton's third law of motion, the pairwise force density function must obey the linear and angular admissibility conditions, which are as follows:

$$f(-\eta, -\xi) = -f(\eta, \xi) \quad \forall \eta, \xi \tag{4}$$

When a bond is deformed beyond a predetermined value, it is judged to be a failure and can never be recovered. For the Prototype Micro-elastic Brittle (PMB) material, the bond force can be expressed as follows:

$$f(y(t), \xi) = g(s(t, \xi))\mu(t, \xi) \tag{5}$$

where g is the linear scalar-valued function defined by

$$g(s) = cs \quad \forall s \tag{6}$$