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Interaction of waves with a body floating on polynya between two semi-infinite ice sheets

Z.F. Li [a], Y.Y. Shi [b], G.X. Wu [a,c,*]

[a] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China
[b] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[c] Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

HIGHLIGHTS

- A hybrid method for interaction of waves with a body floating on polynya between two semi-infinite ice sheets is proposed.
- Test case studies have shown that the method is effective and efficient for both submerged and floating bodies.
- Numerical simulations show that there may be multiple natural frequencies within a relatively small range, and very large resonant motions can be excited by the incident wave.

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ABSTRACT

The interaction of waves with a two-dimensional body floating on polynya between two semi-infinite ice sheets is investigated, based on a hybrid method utilizing a simple source function and eigenfunction matching. The ice sheet is modelled as a continuous thin elastic plate with uniform properties, while the fluid flow is described by the velocity potential. In the polynya, an integral equation is established by using the simple source function. In the two exterior ice covered regions, the potential is expanded in terms of eigenfunctions which satisfy the governing equation and all boundary conditions apart from that on the interface with the inner region. The unknown coefficients in the expansion and the boundary integral equation in the inner region are solved together by enforcing the continuity conditions of the pressure and normal velocity on the interface. The effectiveness and accuracy of the hybrid method is demonstrated through comparison with published results for a submerged cylinder and a floating rectangular body. Simulations are then carried out for a floating elliptical cylinder. Extensive results for the hydrodynamic force and motion response are provided, and the effects of ice draught as well as the body shape are investigated.

1. Introduction

The latest developments in Arctic engineering motivated by possible new routes for shipping and sources for resource extraction have led to an increased interest in wave/body/ice interactions. A typical case is that a ship navigates across the ice covered region, in a channel opened by an icebreaker (Appolonov et al., 2013). In such a case, the ship is floating on a strip of water surface confined between two semi-infinite ice sheets. Due to the wave reflection and transmission when propagating

* Corresponding author at: Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK.
E-mail address: g.wu@ucl.ac.uk (G.X. Wu).

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across the ice covered region (Fox and Squire, 1990), highly complex behaviour of the ship motion can be expected. Thus, an efficient numerical tool is adopted to investigate the characteristics of the motion.

There has been strong interest in wave/ice sheet interaction problems. Much of the early work was concerned with marginal sea, as reviewed by Squire et al. (1995), and more recently Squire (2007, 2011). Fox and Squire (1990) considered the reflection and transmission of free surface waves impinging the ice sheet in the normal direction based on the eigenfunction method. This was extended to the case of an oblique incident wave by Fox and Squire (1994). Sahoo et al. (2001) solved similar problems through defining an inner product with orthogonality in the eigenfunction expansion method, and the influence of edge conditions was analysed. Linton and Chung (2003) used the residue calculus technique and solved the problem in which the oblique incident wave was from the open sea into the ice covered region or the other way round. Porter and Evans (2007) solved the problem of a water surface covered by an elastic sheet with parallel finite straight cracks. Meylan and Sturova (2009) considered the transient problem of a finite elastic plate on the free surface. Williams and Porter (2009) studied the problem of wave propagation through the ice sheets with non uniform draught. Mohapatra et al. (2013) analysed the effects of compressive force on the wave/elastic sheet interactions. The Wiener–Hopf method was also widely used to solve this type of problem. Typical work includes those by Evans and Davies (1968), Balmforth and Craster (1999), Tkacheva (2001), Chung and Fox (2002) and Tkacheva (2004).

There has also been increasing interest in wave/body/ice interaction. Sturova (2015) used the boundary element method together with Green functions for a submerged body. Ren et al. (2016) used a semi analytical solution for a rectangular body floating on the water surface. The obtained explicit equations provided some insight into this kind of problem, but the method was limited to this particular body shape only.

The velocity potential problem related to body/free surface interaction is usually solved by the boundary element method. It converts the governing Laplace equation in the fluid domain into an integral equation over its boundary together with the Green function. When the free surface motion and the body motion are small, linearization of the boundary condition can be applied and it can be imposed on the mean surface of the fluid domain. As adding a harmonic function which satisfies the governing Laplace equation into the Green function will not change its nature, the Green function adopted in the boundary integral equation can be chosen in such a way that it satisfies all the boundary conditions apart from that on the body surface (Wehausen and Laitone, 1960), which is commonly called the free surface Green function. As a result, the boundary integral equation needs to be applied only to the body surface (Newman, 1977). This can significantly reduce the effort required in surface discretization and surface integration. However, the Green function is in an integral form, which, in the three dimensional problem, can be either a double integral or has an integrand involving complex special functions. The calculation of the Green function itself can be very time consuming. This led to the development of the hybrid method.

Yeung (1975) and Yeung and Bouger (1979) developed a hybrid method in which the velocity potential away from the body was expanded into an orthogonal series of eigenfunctions. Near the body, the simple source function $\ln(r)$ was used, where r is the distance between the source point and the field point. This avoided extensive discretization while it retained the advantage of the boundary element method. Related methods adopted a localized finite element method while the boundary integral was performed on the outer surface of the finite element mesh. Although the free surface Green function was still used, the surface integration was performed on a much simpler rectangular shape. Typical work includes those by Bai and Yeung (1974) and Eatock Taylor and Zietsman (1981) for wave radiation and diffraction without forward speed, and by Wu and Eatock Taylor (1987) and Wu (1991) for problems with forward speed. A near field boundary element method coupled with the finite element method in the far field was also used for the nonlinear wave/body interaction problems (Wu and Eatock Taylor, 2003).

With the developments in computer power and numerical algorithms for the free surface Green function, it is more common nowadays to adopt the boundary element method directly on the body surface for the linear radiation and diffraction problems. However, the latest developments in Arctic engineering have led to renewed interest in the hybrid method. In such a case, the water surface is no longer entirely 'free' everywhere and part of it is covered by the ice sheet. The Green function which satisfies both boundary conditions on the free surface and ice sheet is less straightforward to obtain than the free surface only problem (Wehausen and Laitone, 1960) or the ice cover only problem (Sturova, 2013). Usually it is obtained from the matched eigenfunction method. Different series are used in each sub-domain. The unknown coefficients in each series are found by imposing a continuity condition at the interface. Sturova (2015) solved the problem for the Green function with two ice sheets of zero draught. This was then used for a submerged body in polynya and only the body surface discretization was needed. Unlike the free surface only problem, the Green function would have to be found for a different polynya or a different ice sheet thickness.

Therefore, the hybrid method will be reintroduced in this work, and be applied to the interaction of waves with a horizontal cylinder of arbitrary shape floating on polynya. The total fluid domain is divided into three sub-regions, i.e. one interior region with the free surface, two exterior regions with the ice sheet. In the interior region, the simple source function is used to construct the boundary integral equation over its boundary. In the two exterior regions, the potential is expanded in terms of the eigenfunctions which satisfy all the boundary conditions apart from that on the interface with the interior region. The unknown coefficients in the expansion and the integral equation are solved together through enforcing continuity of pressure and normal velocity on the interface. The effectiveness and accuracy of the proposed numerical scheme is demonstrated through two typical cases, i.e. a submerged cylinder and a floating rectangular body. Comparison is made with the published results and very good agreement is achieved. Simulations are then carried out for a floating elliptical cylinder. Extensive results are provided through the hydrodynamic force and motion response, and the effects of ice draught as well as the body shape are investigated.