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A three-dimensional sono-elastic method of ships in finite depth water with experimental validation

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ABSTRACT

In order to conduct the comprehensive analysis of fluid-structure interactions, acoustic radiation and acoustic propagation, a three-dimensional sono-elastic method in the frequency domain is proposed in this paper. In this method, the three-dimensional hydroelasticity theory of floating structures is incorporated with the hydro-acoustic propagation theory by introducing frequency domain Green's functions appropriate to the ocean hydro-acoustic waveguide environment. The simple source boundary integral approach is adopted to obtain the sono-elastic response in the frequency domain. In order to deal with the irregular frequency problem in this approach, a Closed Virtual Impedance Surface (CVIS) method is put forward. At last, the sono-elastic method is validated by calculating the acoustic radiation of a floating elastic spherical shell and an experiment of the underwater acoustic radiation of two ring-stiffened cylindrical shell models.

1. Introduction

For a long time, the issue of floating structures' vibration in the water along with the acoustic radiation and scattering has been studied separately from the issue of acoustic waves' propagation in the ocean waveguide environment. In the former issue, the sea water is modelled as ideal acoustic medium, and the influence of free surface and seabed boundary was often ignored. As for the latter issue, the investigations of the transmission of acoustic waves mainly focused on the monopole point source. In practice, these are two interrelated issues that need to be considered simultaneously. With the development of theoretical methods and computational techniques, it will be possible to perform an integrated calculation and analysis for problems in both of these two aspects, including the floating structures' fluid-structure interactions, the acoustic radiation and the acoustic propagation in the ocean waveguide environment. In a broad sense, this issue belongs to the category of hydroelasticity. But the water here must be treated as compressible acoustic medium, which differs from the conventional hydroelasticity studies (Wu, 1984; Bishop et al., 1986; Chen et al., 2006; Gao et al., 2011).

During the past few decades, researchers have developed various methods to deal with the problem of floating structures' acoustic radiation and scattering in the ideal acoustic medium. For instance, some analytical methods are established to evaluate the acoustic radiation of structures with regular shapes, such as the elastic spherical shell, the cylindrical shell and the equidistantly stiffened single or double cylindrical shell (Burroughs, 1984; Junger and Feit, 1986; Skelton and James, 1997). The approaches appropriate for the structures with complex shapes include the finite element/finite element method (FEM/FEM) (Hunt et al., 1974, 1975), the finite element/finite element/infinite element method (FEM/FEM/IEM) (Astley and Macaulay, 1994; Burnett and Holford, 1998) and the finite element/boundary element method (FEM/BEM) (Chen and Schweikert, 1963; Everstine and Henderson, 1990; Giordano and Koopmann, 1995; Tong et al., 2007; Peters et al., 2014). According to the finite element/finite element method (FEM/FEM), both of the floating structure and the water medium are modelled with discrete finite elements. Artificial absorbing boundary conditions are set at the edge of the water area. When it comes to acoustic radiation problems in broad water areas, the finite element method cost a large amount of computation; thus only the sound field near the structure can be calculated and given. When using the finite element/finite element/infinite element method (FEM/FEM/IEM), the floating structure and the near-field acoustic medium are modelled with finite elements, while the far-field acoustic medium is modelled with infinite elements. At present, the research on this method is still inadequate. The strategy of the FEM/BEM method is modelling the floating structures with finite elements and the fluid field with boundary elements on the wetted surface based on the boundary

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integral equation. In this method, the Green's functions used to describe the acoustic propagation in the fluid field are often expressed in analytical forms. As a consequence, this method has the advantage of high precision and effectiveness when it's used to deal with the acoustic problems in the infinite or half-infinite fluid field. The FEM/BEM method, which avoids the deficiencies of the FEM/FEM method, is the most commonly used method to solve the complex structures' sono-elasticity problem in the low frequency band. Everstine and Henderson (1990) regard the FEM/BEM method as the most practical way to calculate the large-scale structures' acoustic radiation with high precision.

Historically, there are mainly two kinds of boundary element methods (BEM) in the study of acoustics: the Helmholtz integral method and the simple source method. When using these two kinds of methods in practice, there is an irregular frequency problem, i.e., the results near the irregular frequencies are often significantly distorted. Strictly speaking, the irregular frequencies are of purely numerical problem with no physical explanation. It has been proved in a mathematical manner that there is no solution at the irregular frequencies in the simple source method while the solution is not unique at the irregular frequencies in the Helmholtz integral method (Schenck, 1968). Since the 1970s, the Helmholtz integral method has been widely used in acoustics, for the reason that various methods are created to solve the problem of irregular frequencies in this method (Schenck, 1968; Burton and Miller, 1971; Wu and Seybert, 1991). On the contrary, improvement is still needed to deal with the irregular frequency problem in the simple source method.

In this paper, the three-dimensional hydroelasticity of floating structures (Wu, 1984; Bishop et al., 1986) is incorporated with the hydro-acoustic propagation theory to gain a three-dimensional sono-elastic analysis method in the frequency domain by introducing a frequency domain Green's function appropriate to the hydro-acoustic waveguide environment. This method makes it possible to implement a unified analysis of fluid-structure interaction, acoustic radiation and sound propagation. The details are given about how the simple source boundary integral equation is theoretically derived from Helmholtz boundary integral equation. It's pointed out that the irregular frequencies in the simple source method are induced by the resonances of imaginary inner fluid field. Taking this principle into consideration, a closed virtual impedance surface is introduced in the imaginary inner fluid domain to absorb the energy of acoustic vibration, thus eliminating the resonances and irregular frequencies. This method is named as the Closed Virtual Impedance Surface (CVIS) method. According to the simple source method, the acoustic field is obtained by the superposition of a series of monopole point sources with different amplitudes and phases distributed on the wetted surface of the floating structures. Since the monopole source's acoustic propagation in the ocean waveguide environment has been widely studied (Jensen et al., 2011), lots of existing results can be directly introduced into the calculation of Green's functions used in this work.

According to classic method of three-dimensional hydroelasticity (Wu, 1984; Bishop et al., 1986), the dry modals (the structure vibration modals in vacuum) are selected as the generalized basis functions because they are orthogonal, complete and easy to solve. The effect of fluid-structure interaction is reflected in the corresponding added mass, radiation damping and generalized restoring coefficients. This approach has the advantage of high calculation efficiency and clear physical meaning. Besides, it can separate the principal modes that make a significant contribution to the vibration and acoustic radiation. The advantages of this method are inherited in this work. With reference to the general definition of hydroelasticity (Heller and Abramson, 1959), the sono-elasticity mentioned in this work is defined as a discipline that deals with the interactions between the inertia force, the acoustic pressure in the water and the elastic force in the structures.

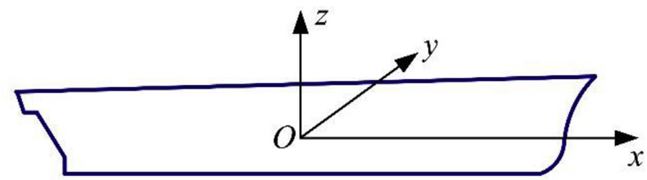

Fig. 1. The equilibrium coordinate system.

2. The sono-elasticity theory of ships in frequency domain

For the zero forward speed case, the fluid motion and responses of a floating body are defined in an equilibrium coordinate system *Oxyz* with the *x*-axis pointing towards the bow, the *z*-axis pointing upwards, as shown in Fig. 1. The ship structure is assumed to be linear with small motions and distortions about its equilibrium position. The displacement at any point of the structure may be expressed as the superposition of the principal modes in vacuum (Bishop et al., 1986):

$$\mathbf{u}(t) = \sum_{r=1}^{m} \mathbf{D}_r q_r(t) \tag{1}$$

where $\mathbf{D}_r$ and $q_r(t)$ $(r = 1,2, \cdots, m)$ are respectively the principal modes and principal coordinates, with the first six $(r = 1,2, \cdots, 6)$ being the rigid body modes.

During the process of structural vibration and acoustic radiation the fluid restoring force is rather small and negligible. The generalized equations of motion of the ship structure may be written in matrix form as:

$$\mathbf{a}\ddot{\mathbf{q}} + \mathbf{b}\dot{\mathbf{q}} + \mathbf{c}\mathbf{q} = \Xi(t) + \mathbf{G}(t) \tag{2}$$

where $\mathbf{a}$, $\mathbf{b}$ and $\mathbf{c}$ are matrices of generalized mass, generalized damping and generalized stiffness of the dry modes. $\mathbf{q}$ is a column vector of the principal coordinate. If there is no incident acoustic waves, and only mechanical excitations are concerned in the present analysis of structural vibration and acoustic radiation problems, there exists generalized radiation wave force $\Xi(t)$ and generalized mechanical exciting force $\mathbf{G}(t)$.

If the fluid is inviscid and compressible, its flow is irrotational, the fluid density is uniformly distributed and the amplitudes of acoustic waves are small, there exists a velocity potential function Φ for description of the acoustic field caused by structural vibrations of a ship. The total velocity potential Φ can be represented as the linear superposition of the acoustic wave radiation velocity potential of each order:

$$\Phi(x, y, z, t) = \sum_{r=1}^{m} \varphi_r(x, y, z, t) \tag{3}$$

where $\varphi_r(x, y, z, t)$ is the r-th order acoustic wave radiation velocity potential which is induced from the ship's vibration excited by the external loads.

The velocity of fluid is expressed as

$$\vec{v} = \nabla\Phi \tag{4}$$

where $\nabla = \frac{\partial}{\partial x}\vec{\mathrm{i}} + \frac{\partial}{\partial y}\vec{\mathrm{j}} + \frac{\partial}{\partial z}\vec{\mathrm{k}}$ is the Hamilton differential operator, $\vec{\mathrm{i}}$, $\vec{\mathrm{j}}$ and $\vec{\mathrm{k}}$ are the unit vectors corresponding to the x, y, and z axis respectively.

The sound pressure in the fluid field can be written as

$$p(x, y, z, t) = -\rho_0 \frac{\partial \Phi}{\partial t} \tag{5}$$

where ρ_0 is the fluid density.

Assuming a time harmonic dependence in the form of $e^{i\omega t}$ in frequency domain, the corresponding r-th radiation wave potential may be represented as

$$\varphi_r(x, y, z, t) = \varphi_r(x, y, z)q_r(t) = \varphi_r(x, y, z)q_r(\omega)e^{i\omega t} \tag{6}$$