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An energy-based formulation for vibro-acoustic analysis of submerged submarine hull structures

Guoyong Jin[a,*], Xianglong Ma[b], Wenyao Wang[a], Zhigang Liu[a]

[a] College of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, PR China
[b] Shanghai Marine Equipment Research Institute, Shanghai, 200031, PR China

A R T I C L E I N F O

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A B S T R A C T

An energy-based formulation is developed to investigate the vibro-acoustic behaviors of the submarine hull immersed in heavy fluid in the present paper. The conical-cylindrical-hemispherical coupled shell with bulkheads and ring stiffeners is considered as the theoretical model of the hull structure, which is discretized into a number of spectral elements according to the structure type. Displacement components of each spectral element are invariably expressed by a set of modified Fourier series. The external acoustic field is described by one-dimensional Helmholtz integral formulation that can be solved by the means of discretization along the generator line of the hull structure. Subsequently, the full vibro-acoustic model for the submerged hull is established by taking into account the energy of the acoustic field acting on the hull surface. The reliability and accuracy of the present method is validated by comparison of vibration and acoustic responses with those from the commercial softwares. Several examples are conducted to understand the effects of bulkheads, ring stiffeners and coupling stiffnesses on the vibro-acoustic behavior of the submerged hull, which provides some helpful information in the design of underwater hull structures.

1. Introduction

The hull is the key structure of submarines to directly face the external fluid, of which the vibration transmitted from the internal power machine and the propeller-shafting system can result in a high level of radiated noise. In practice, the detectable noise may raise security problems for submarines. In this regard, the radiated sound from the hull structure must be reduced in an adequately low level. Indeed, the sound radiated to the external fluid and the vibration of the hull structure influences each other for the submerged hull structure. Thus, thoroughly understanding the dynamic behavior of the submerged hull depends greatly on the formulation of the fully coupled vibro-acoustic system.

The acoustic problems of elastic structures reported in the literature are generally solved by the means of the Helmholtz equations or the Helmholtz integral formulation. Since the analytical solutions greatly depends on the geometry, considerable attention in the related literature is just devoted to a small number of simple structures such as infinite circular cylinders and spherical shells (Junger and Feit, 1986; Skelton and James, 1997; Ding and Chen, 1998; Fahy and Gardonio, 2007) rather than the shells with complex geometry and coupled structures. The literature concerning the sound radiation of elementary shells with complex geometry is rather limited to conical shells and elliptical cylindrical shells (Caresta and Kessissoglou, 2008; Li et al., 2014). As far as a coupled structure under water is concerned, the approximate method that provides a possible solution attracts increasing attentions recently. The finite element method (FEM) and the boundary element (BEM) method are two popular approaches to describe radiated sound field from submerged structures in early papers (Alfredson, 1973; Arlett et al., 1968; Chien et al., 1990). Without regard to the structural geometry, the submerged structure is discretized into a number of elements by these two approaches to describe its vibro-acoustic behavior. In order to reduce the modeling cost, the coupled BEM/BEM method has been developed by Jeans and Mathews (Mathews, 1986; Jeans and Mathews, 1990, 1993; Peters et al., 2014) to investigate the dynamic behavior of structures immersed in an infinite fluid medium, in which the structure and the acoustic field are described by finite elements and boundary elements respectively. Although commercial software such as ANSYS and Virtual. lab popularize these two numerical methods, the accuracy of them highly depends on element meshing especially for high-frequency analysis, which limits the use of these two methods to predict vibro-acoustic behavior for the case with large size. Besides, the variational principle is also usually used to predict the acoustic characteristics of submerged structures (Gladwell, 1966; Wu,

* Corresponding author.
E-mail address: guoyongjin@hrbeu.edu.cn (G. Jin).

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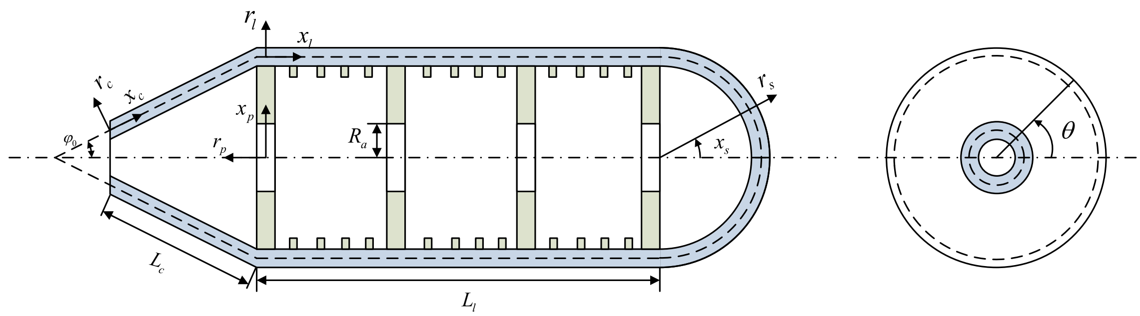

Fig. 1. Geometrical model and coordinate system of the hull structure.

1989; Chen and Ginsberg, 1993; Bjarnason et al., 1994; Choi et al., 1995).

Recently, the semi-analytical method attracts increasingly more attention to dynamic analysis of submerged shells of revolution (Soenarko, 1993; Wang et al., 1997; Wright et al., 2009), in which the displacement function in the circumferential direction is expanded by the Fourier series due to axisymmetrical properties. In this way, only the discretization along the generator line of the shell is needed resulting in one-dimensional Helmholtz integral instead of the traditional two-dimensional integral, which can reduce much efforts to solve acoustic problems of submerged shell structures. The fully vibro-acoustic system for the submarine hull structure is established by Caresta and Kessissoglou (2010), in which the structural responses of the hull are calculated through solving dynamic equations for each substructures while the direct boundary element method is introduced to solve the one-dimensional Helmholtz integral formulations. In Ref. (Caresta and Kessissoglou, 2010), the submarine hull is simplified as a cylindrical shell closed by truncated conical shells with internal bulkheads and ring stiffeners. The semi-analytical method is developed by Qu et al. (2015) to investigate the vibro-acoustic behavior of submerged coupled spherical-cylindrical-spherical shells reinforced by ring stiffeners and longitudinal stringers. In this study, the modified variational method is used to formulate the coupled stiffened shell whereas the collocation approach is introduced to solve the Helmholtz integral formulation. Chen et al. (Chen et al., 2015; Xie et al., 2017) developed an analytical method to analyze free and forced vibration characteristics of ring-stiffened combined conical-cylindrical shells, in which Power series, wave functions and Bessel functions are used to express the displacement functions of conical segment, cylindrical segment and annular plate, respectively. Wang (2016) developed a semi-analytical method to analyze the vibration response of submerged stiffened combined shells by coupling the precise transfer matrix method (PTMM) and wave superposition method (WSM).

From the review of the literature, the modeling accuracy of vibro-acoustic system depends on descriptions of both the structure and the external acoustic fluid. In practice, the submarine hull generally consists of the truncated conical shell, the cylindrical shell, the hemispherical shell, the bulkheads and the reinforcement. In particular, there are usually some structural types repeated involved in the whole structure such as the bulkhead and ring stiffeners. Subsequently, developing a more efficient and accurate method for such complex coupled structure is also of great significance to investigate the vibro-acoustic behavior for the submerged cases. The modified Fourier series-spectral element approach is developed by Jin et al. (2017) to formulate such hull structures as mentioned. The modified Fourier series proposed originally by Li (2000) is composed of a Fourier series and auxiliary functions, which can adapt arbitrary boundary and coupling conditions. In Ref. (Jin et al., 2017), the built-up structure including repeated substructures is discretized as a number of spectral elements according to the structure type while the modified Fourier series is invariably used to describe displacement components of each spectral element.

In the present work, an energy-based formulation is developed to analyze the vibro-acoustic behaviors of submerged submarine hull structure which is simplified and modeled as a conical-cylindrical-hemispherical coupled shell with bulkheads and ring stiffeners. For such complicated structures immersed in a heavy fluid medium, the modified Fourier series-spectral element method is used to formulate the structural model, while the external acoustic field is described by one-dimensional Helmholtz integral formulation that can be solved by the means of discretization into the system of linear equations. The work done by the external acoustic field acting on the hull surface is considered to formulate the strong coupling relationship between the structural response and radiated sound pressure. The accuracy of the present method is validated by comparison of vibration and acoustic responses with those from the commercial software. Several examples are conducted to investigate the effects of the bulkhead, ring stiffener and coupling stiffness on the vibro-acoustic behaviors of the submerged hull.

2. Theoretical formulation

2.1. Model description

The hull structure considered in the presented paper is a circular cylindrical shell closed at ends with truncated conical and hemispherical caps respectively as shown in Fig. 1. The cylindrical shell is reinforced by N_r ring stiffeners that can be arbitrary in number, size and space arrangement. Besides, the internal space of the coupled shell is separated by bulkheads that are uniformly modeled as thin annular plates with inner radius R_a. The conical shell is truncated with left radius R_0, semi-vertex angle φ_0 and length L_c along the generator line, whereas L_l represents the length of the cylindrical shell with radius R as the spherical shell. Generally, the truncated conical, cylindrical and hemispherical shells as well as bulkheads are independently described by orthogonal coordinate systems (x_i, θ_i, r_i), in which the subscript $i = c, l, s, p$ respectively. Specifically, x_i is measured along the generator line, where as θ_i represents the circumferential direction and r_i is the normal direction of the middle surface.

The displacement components of these shells in the x_i, θ_i and r_i directions are respectively denoted by u_i, v_i and w_i, which can be written as

$$u_i = U(x_i,\theta_i)e^{j\omega t} \tag{1}$$

$$v_i = V(x_i,\theta_i)e^{j\omega t} \tag{2}$$

$$w_i = W(x_i,\theta_i)e^{j\omega t} \tag{3}$$

where $j = \sqrt{-1}$, ω is the frequency and t represents the time.

The thickness of the shell components and annular plates is assumed to be uniform and adequately small compared to other geometrical parameters, which makes the thin plate and shell theories applicable. Furthermore, it is assumed that all the shell sub-structures, annular plates and ring stiffeners are made of same materials with Young's