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Optimization of autonomous underwater vehicle structure shape based on the characteristics of power flow distribution

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ABSTRACT

Power flow method (PFM) is firstly applied to the structural analysis of autonomous underwater vehicle (AUV). By finite element analysis, the numerical model of AUV is established. The propulsive force of the propeller is calculated and the dynamic responses of AUV are discussed. The characteristics of power flow distribution in AUV are studied, and the optimization of AUV shape by PFM is developed. The results show that the performances of AUV's anti-vibration are improved. The present work may lay the foundation for the propagation characteristics of structural vibration power flow under the multi-source load excitations, and also provide a novel optimization approach for AUV shape.

1. Introduction

Autonomous underwater vehicles (AUVs) are versatile submarine robots for maritime archaeology, oceanographic and marine biology researches [1]. In practical, AUVs are subjected to various dynamic loadings, from slowly varying hydrodynamic loadings to high frequency propeller induced forces, which results in unexpected vibration. Once the permissible vibration levels are exceeded, major issues are presented, such as fatigue failure in the structure, destruction of electronic/mechanical equipment and highly structural surface radiation noise. Hence, there are increasing demands on vibration mitigation of AUVs, which ensures its safety and standard performances. The vibration attenuation methods are mainly dependent on the nature of vibration, and thus it is of prime importance to predict the vibration characteristics of AUVs.

One relative new technique for vibration determination and analysis is based on power flow or structural intensity method [2]. The fundamental concept of structural power flow was firstly proposed by Goyder and White [3–5], and power flow is also denoted as energy flow [6]. Vibration of an elastic structure induces the propagation of vibratory energy through the structure and it is called vibrational or structural power flow [7]. Structural intensity, also known as power flow density, is defined as power flow per unit area in elastic medium, which is analogous to acoustic intensity in a fluid medium due to structural vibration or dynamic response [8]. Since the power flow method (PFM) could indicate the magnitude and direction of vibration and transient energy flow at any point of a structure, PFM is paid increasing attention to investigate structural vibration characteristics from a practical point of view [2].

Many scholars have utilized power flow analysis to study vibration performances of structures. Yang et al. [9] investigated the vibrational power flow of a two-degree-of-freedom nonlinear system and the steady-state responses were obtained by using the

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method of averaging and numerical integrations; the influences of system nonlinearities on power flow input, dissipation and transmission were revealed. Li et al. [10] studied the vibration characteristics of a finite plate under uniform force excitation by PFM using finite element analysis, and the surface mobility of a finite plate was predicted. The numerical simulation of power flow analysis was also validated by the theoretical predictions. Yan et al. [11] investigated the vibrational power flow propagation in an infinite periodic ring-stiffened cylindrical shell immersed in water. The numerical results showed that the characteristics of vibration power flow varied with different circumferential modes order and different frequencies. Xu et al. [8] conducted an energy flow analysis in stiffened plates of marine structures under point force and pressure excitations, and the vibration power flow propagation characteristics of the stiffener were studied. The results indicated the potential application of PFM towards structural design of marine structures. Tan et al. [12] established the power flow formulation in the general framework of multi-component mode synthesis and achieved additional computational efficiency by finding characteristic constraint modes. This multilevel, characteristic-mode-based approach provided a general framework for the efficient calculation of power flow in the low-to-mid frequency range. Qiao B [13] applied power flow combined with vibrational energy to assess the performances of active vibration isolation of rotating machinery, and the experimental investigation was provided. The vibration analysis by PFM has been also introduced to the structural crack detection [2,7,14].

PFM combines the effects of force, velocity amplitude and relative phase angles, and thus the vibration characteristics of structures could be accurately predicted, which is important for vibration attenuation. Compared with current investigations on dynamic performances of AUVs by conventional local physical quantities (such as force, displacement, velocity and acceleration) [15,16], PFM could globally describe the vibrational energy characteristics, which may provide a novel way to describe dynamic behaviors of complex structures [14]. In addition, some researches have been recently conducted on the structural optimization based on power flow analysis [17,18], and the optimal structure surfaces were achieved on the target of low vibration level. However, to the best of authors' knowledge, limited research has been conducted on utilizing PFM to study dynamic behaviors of AUVs [19], and the further optimization of AUVs for vibration attenuation by PFM was not explored.

This paper attempts to investigate the characteristics of vibration power flow distribution in AUV by PFM, and it is expected that the vibration characteristics provide a foundation to optimize AUV surface shape. In the content that follows, in section 2, the finite element model of AUV is established, and the propeller excitation force is obtained by hydrodynamic simulation; then the dynamic analysis of AUV is carried out to obtain vibration responses in the head, middle and tail sections; the power flow of AUV is derived by the frequency domain responses, and the power flow propagation characteristics of AUV are discussed. In section 3, the scheme of optimizing AUV shape by PFM is proposed. Section 4 summarizes the main conclusions and the innovation of the present work.

2. Characteristics of power flow distribution for AUV

2.1. Finite element model

In the present work, referred by GAVIA AUV [20], a small torpedo-shaped AUV is presented, which is the Myring profile of three-stage rotary body. The model is established by B-spline curve. In AUV model, the lengths of head, tail and middle sections are 310 mm, 690 mm and 1500 mm, respectively; the diameter of middle section is 300 mm; and the thickness of the AUV's shell is 6 mm. The material of GAVIA AUV [20] is stainless steel with an elastic modulus of 207 GPa, Poisson's ratio of 0.3, and a density of 7800 kg/m^3. The finite element model of AUV is shown in Fig. 1. The model is meshed by quadrilateral element (Quad 4) with 960 elements and 1214 nodes.

In working condition, the water depth of AUV is 80 m. The flow field in the present work is incompressible fluid and it belongs to turbulent flow field. For practical engineering calculations, the governing equations based on conservation laws of mass and momentum are generally expressed as,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial p}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial z_j} - \rho \overline{u_i' u_j'}\right) + \frac{\partial \sigma_{ij}}{\partial x_j} \tag{2}$$

where ρ is the density, u is the velocity vector, p is the pressure, σ_{ij} is the strain tensor. Eq. (1) is the continuity equation, and Eq. (2) is the Reynolds-averaged Navier-stokes equation. For obtaining unknown variables in Eqs. (1) and (2), the transport equations should be supplemented. Here, the standard k-ε model is introduced for solving turbulent kinetic energy k and turbulent dissipation ε, which

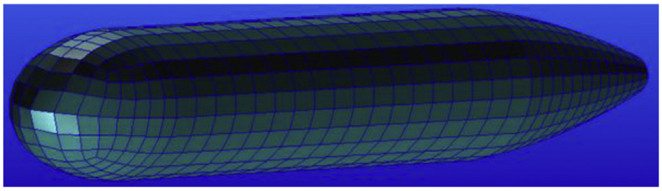

Fig. 1. Finite element model of AUV.