Journal of Sound and Vibration 432 (2018) 602–620

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Investigation of added mass and damping coefficients of underwater rotating propeller using a frequency-domain panel method

Jiasheng Li [a], [b], [*], Yegao Qu [a], [**], Yong Chen [a], [b], Hongxing Hua [a], [b], [***]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai, 200240, PR China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai Jiao Tong University, Shanghai, 200240, PR China

ARTICLE INFO

Article history:
Received 25 October 2017
Received in revised form 1 June 2018
Accepted 26 June 2018

Handling Editor: S. Ilanko

Keywords:
Fluid–structure interaction
Hydroelastic responses
Propeller
Added mass and damping
Vibration

ABSTRACT

For a propeller vibrating in a fluid, the added mass and damping coefficients characterize the hydrodynamic forces and moments acting on the propeller, which are of great importance for evaluation of the vibration behaviors of submerged propellers. The present paper is concerned with the development of a numerical method for predicting the added mass and damping coefficients of a rotating marine propeller immersed in water. The three-dimensional panel method in frequency-domain is employed to establish the strongly coupled fluid-structure interaction models of the propellers to compute the added mass and damping coefficients. The relationship between the added mass and damping matrices due to the whole vibration of a rotating propeller and the local vibrations of the propeller blades is considered. Results of the present method are compared with those experimental and numerical data available in the literature. Very good agreement is achieved. The differences of the added mass and damping coefficients due to propeller vibrations of two types are analyzed. The results show that the added mass and damping coefficients of a submerged rotating propeller are functions of the ratio of oscillation frequency of rigid propeller f_v to the blade frequency f_b, and the advance ratio. In addition, the non-penetration boundary conditions should be imposed on the deformed blade surface for predicting the added mass and damping coefficients m_{32}, m_{62}, c_{32} and c_{62}, where $m_{32}(c_{32})$ and $m_{62}(c_{62})$ denote mass (damping) coefficients related to the lateral force and bending moment in the z direction induced by the transversal vibration in the y direction. Absolute values of all coefficients in the added mass matrix decrease as the ratio f_v/f_b is increased, and the absolute values of the coefficients in the added damping matrix increases with an increase in the advance ratio.

1. Introduction

Propellers play an important role in the vibration and noise reduction of underwater vehicles and ships. The knowledge of the vibration behaviors of a propeller is of great importance for successful design of the propulsion system. For a submerged

---

[*] Corresponding author. No. 800 Dongchuan Road, Minhang District, School of Mechanical Engineering, Shanghai Jiao Tong University, PR China.

[**] Corresponding author. No. 800 Dongchuan Road, Minhang District, School of Mechanical Engineering, Shanghai Jiao Tong University, PR China.

[***] Corresponding author. No. 800 Dongchuan Road, Minhang District, School of Mechanical Engineering, Shanghai Jiao Tong University, PR China.

E-mail addresses: Jiashenglee@sjtu.edu.cn (J. Li), quyegao@sjtu.edu.cn (Y. Qu), hhx@sjtu.edu.cn (H. Hua).

https://doi.org/10.1016/j.jsv.2018.06.060
0022-460X/

elastic propeller, the presence of water around the propeller vibrating as a part of the system changes the dynamic characteristics of the propeller, and therefore fluid-structure interactions must be taken into account in the vibration analysis of the propeller. In general, the fluid-induced reaction forces (i.e., the hydrodynamic forces) acting on a fully immersed propeller include the added mass and damping forces, which are proportional to the acceleration and the velocity of the propeller. Since the added mass and damping can be of the same order of magnitude or even higher than the structural inertia and damping of the propeller, the knowledge of the added mass and damping are of great importance for accurate evaluation of the vibration characteristics of lightweight and flexible propellers.

A submerged marine propeller may vibrate in different ways, and these vibrations may results in different added mass and damping matrices. The most important vibration modes of the propeller may be categorized into two main types [1]. The first type of vibration mode of a propeller is characterized by whole vibration of the propeller in six degrees of freedom, including surge, sway, heave, roll, pitch and yaw motions. This type of vibration mode is caused by the vibration of the shafting system. In this case, the propeller may be treated as a component of the line shafting and modeled as a rigid body. The second type of propeller vibration is characterized by the local vibrations of the blades, which is induced by time-varying hydrodynamic forces acting on the blades. For this case, the propeller has to be considered as an elastic body. The added mass and damping coefficients due to the first type of propeller vibration can be represented by two 6×6 matrices, which are key design parameters for practical shaft design of ships and underwater vehicles. On the contrary, high-dimensional matrices have to be employed to represent the added mass and damping coefficients due to the second type of propeller vibrations. These matrices are of primary importance for the design of the propeller, which determine the frequencies of the wet modes of the propeller, and affect the amplitudes of the bearing forces near wet mode frequencies. The determination of the fluid-induced forces for above mentioned two types of propeller vibrations fall within the research field of hydroelasticity of propeller.

For the first type of propeller vibration, MacPherson et al. [2] proposed a semi-empirical model for predicting the added mass coefficient and the torsional moment due to the axial vibration of the propeller. Their model was established based on experimental data for propellers of the Wageningen B-series and the KCA series, which may limit the application of their model for other propellers. Hutchison et al. [3] analyzed the added mass of a ducted propeller using the WADAM program of the commercial DNV software HydroD. The results showed that the hydroelastic responses of the propeller can be significantly affected by the presence of the duct. Van Esch et al. [4] studied the add mass and damping coefficients due to the torsional and axial vibrations of ship propellers by using computational fluid dynamics (CFD) method. The results showed that the wakes shed from the blades can affect both the magnitude and phase of the damping forces. Gaschler and Abdel-Maksoud [5] analyzed the added mass and damping coefficients for heaving motion of a marine propeller by using a three-dimensional (3-D) panel method, and both the non-cavitating and cavitating conditions were considered. They found that the hydrodynamic mass and damping coefficients are insignificantly affected by the unsteady sheet cavitation. Martio et al. [6] calculated the added mass and damping coefficients by prescribing sinusoidal translational and rotational motions of the propeller. For investigating the effect of the viscosity on the vibration coefficients, unsteady Reynolds Averaged Navier-Stokes simulations were employed in their work. Later, Martio et al. [7] extended their method to analyze the added mass and damping coefficients for open and ducted propellers in straight and oblique flows. The viscosity was found to have certain effects on some coefficients. Yari and Ghassemi [8] calculated the added mass coefficients based on the boundary element method. The results showed that the diameter, expanded area ratio, and thickness of the propeller have significant effects on the added mass coefficients. A 3-D curved lifting line model coupled with a 2-D unsteady thin foil theory was employed by Mao and Young [9] for predicting the added mass and damping coefficients. They found that the skew of the propeller can affect the added mass and damping matrices due to the coupling of the sway, heave, pitch, and yaw motions of the propeller, but the influence of the skew on the surge and roll motions is negligible.

Regarding the second type of propeller vibration, Maljaars and Kaminski [10] presented a review for hydroelastic analyses of flexible propellers, and they indicated that the majority of the developed methods were limited to the analyses of steady performance of flexible propellers. Tsushima and Sevik [11] used the lift surface theory and finite element method to analyze the fluid-structure interaction problem of underwater propellers. Experiments were carried out to validate their numerical model, and the results showed that hydroelastic effects should be considered for analyzing fluid-structure interactions of high skew propellers. Kuo and Vorus [12] introduced a fully coupled structural and hydrodynamic method for analyzing the blade stresses. It was found that the skew of the blade may affect the added mass and damping matrices as well as the wet modes of the propeller. Suo and Guo [13] analyzed the hydroelastic behaviors of 3-D rotating structures by using the theory of potential flow and the finite element method, and the general expressions for the added mass, damping and stiffness matrices of the structure were obtained. Lin and Tsai [14] investigated the free vibration problems of an underwater composite propeller blade based on the finite element method and the panel method. The effects of the added mass were considered. Their results showed that the natural frequencies of the blade in wet condition were much lower than those of the blade in dry condition, but the mode shapes are almost the same for the blade either in wet or dry conditions. Young [15,16] carried out a strongly coupled fluid-structure interaction analysis to analyze the hydroelastic behaviors of marine propellers made of metal/composite materials and subjected to sub-cavitating and cavitating flows. The fluid was modeled by using a 3-D boundary element method, which was combined with a finite element model of the blade. Neugebauer et al. [17] studied the fluid-structure interaction problems of propellers based on the CFD method. He et al. [18] developed a 3-D FEM/CFD coupling algorithm to investigate the hydroelastic behaviors of a highly skewed composite model propeller. The natural frequencies, mode shapes, hydrodynamic load coefficients and deformation of blade tip were analyzed. Lee et al. [19] introduced a coupled BEM/FEM algorithm for predicting the unsteady thrust and torque coefficients of flexible propellers. Zou et al. [20] carried out