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A numerical method for predicting the hydroelastic response of marine propellers

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ABSTRACT

This paper focuses on the development of a numerical model for predicting the hydroelastic responses of marine propellers oscillating in the wake of a submarine. The added-mass and -damping matrices due to strongly coupled fluid-structure interaction were considered. Three-dimensional panel methods in time and frequency domains combined with the finite element method were employed to study the hydrodynamic performance of the propeller. The panel methods were used to evaluate the hydrodynamic forces generated by the wake, and the finite element method was applied to determine the hydroelastic response of the propeller due to the pressure fluctuation. For predicting the structural responses, a mode superposition method combined with Wilson-θ method was employed to overcome the low numerical efficiency caused by the asymmetric added mass and damping matrices. The proposed numerical model was validated by comparing with other numerical solutions. The performance of the propellers was examined by considering one-way and two-way fluid-structure interactions.

1. Introduction

With the rotation of a propeller in a spatially non-uniform wake of a submarine, unsteady fluctuating forces may induce vibrations of the propeller itself or are transmitted to the submarine hull structure through the shaft and bearings. These forces include the thrust, torque, vertical and transversal forces and moments. Since these forces and moments may result in strong vibrations of the hull and underwater noise, a reliable method for predicting the hydroelastic response of marine propellers is of great importance.

In the last few decades, a number of analytical and numerical methods have been developed for predicting the hydrodynamic forces of underwater propellers, including the momentum or blade element method, lifting line method, lifting surface method and panel method. These methods assume that the blades of the propeller are rigid, and neglect the effect of blade deformation on the surrounding flow field. In general, these methods are computationally efficient, but in some cases, the accuracy of these methods for the prediction of hydrodynamics forces for propellers is not satisfactory. In recent years, flexible marine propellers have been employed in practical marine industries, and it is of crucial importance for the designers to have a deep insight into the hydrodynamic behaviors of elastic propellers. For analyzing the fluid-structure interaction problem of underwater propellers, two methods may be employed, namely the one-way method and the two-way method. In the first method, the hydrodynamic forces and the structural responses of the propeller are computed one after another. The governing equations of the fluid surrounding the propeller are solved first, and the resultant hydrodynamic forces acting on the propeller are computed, which are employed to calculate the structural responses of the propeller. In the two-way fluid-structure interactions, the fluid and structure are modeled as a coupled system. The structural motion of the propeller causes a change in the hydrodynamic forces acting on the wetted surface of the propeller, which in turn results in a change in the motion of the structure. Two major classes of two-way fluid-structure interaction (FSI) formulations exist in the literature [1,2], namely the loosely- and strongly-coupled methods, which may be employed for the analysis of FSI problems of underwater propellers. In loosely coupled approaches (also referred to as iterative approaches), the fluid and the structural equations are solved iteratively in uncoupled fashion, which enables the potential use of existing well-validated fluid and structural solvers. However, these methods may suffer form of lack of convergence, which have been noted in a number of situations, and considerable literature has been devoted to the

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discussion of these problems. In strongly-coupled methods (also referred to monolithic approaches), the fluid and the structural equations are solved simultaneously in fully-coupled manner. The main advantage is that monolithic methods tend to be more robust than the loosely-coupled methods.

Nomenclature

ν	Poisson's ratio
E	Young's modulus
ρ_s	Structural density
$\boldsymbol{M}$	Global mass matrix
$\boldsymbol{C}$	Global damping matrix
$\boldsymbol{K}$	Global stiffness matrix
$\boldsymbol{C}_\Omega$	Damping matrix caused by Coriolis forces
$\boldsymbol{K}_\Omega$	Stiffness matrix caused by centrifugal forces
$\ddot{\boldsymbol{u}}$	Nodal acceleration vector
$\dot{\boldsymbol{u}}$	Nodal velocity vector
$\boldsymbol{u}$	Nodal displacement vector
$\boldsymbol{F}_w$	Hydrodynamic force vector
$\boldsymbol{F}_\Omega$	Centrifugal force vector
$\boldsymbol{V}_{total}$	Total velocity of the flow
$\boldsymbol{V}$	Nonuniform inflow wake
ϕ	Perturbation velocity potential corresponding to the flow field induced by the propeller
$\boldsymbol{n}$	Outward unit normal vector on blade surface
$\frac{\partial\phi}{\partial\boldsymbol{n}}$	The derivative of ϕ with respect to the normal direction
$\boldsymbol{\delta}$	Displacement vector of the nodal points on the blade surface
$\boldsymbol{V}_0$	Uniform part of the wake
$\Delta\phi_W(\boldsymbol{R}_{wake}, t)$	The potential jump across the wake sheets
$\Delta\phi(\boldsymbol{R}_{re}, t-t')$	Potential jump across the blade surface at the trailing edge
t'	Time required for the fluid to travel along the wake surface from the blade trailing edge $\boldsymbol{R}_{re}$ to the wake point $\boldsymbol{R}_{wake}$
ρ	Density of the fluid
ϕ_r	The perturbation potential due to the rigid propeller advancing in the nonuniform inflow wake
ϕ_ν	The perturbation potential due to the elastic propeller vibrating in the uniform part of the wake
$\boldsymbol{F}_r$	Hydrodynamic forces generated by nonuniform wake
$\boldsymbol{F}_\nu$	Hydrodynamic forces generated by fluid-structure interaction (vibrating in uniform flow) resulting in the added mass and damping matrices of the fluid
Ω	Rotating speed of the propeller
$\Delta\boldsymbol{s}$	The area matrix,$\Delta\boldsymbol{s} = diag\left\{\Delta s_1, \Delta s_2, \ldots, \Delta s_N\right\}$
k	The frequency of hydrodynamic forces generated by nonuniform wake
i	$\mathrm{i} = \sqrt{-1}$
$\boldsymbol{U}$	$\boldsymbol{U} = \boldsymbol{C}_{k,\nu}^{-1}\boldsymbol{G}$, panel coefficient matrix
$\boldsymbol{E}$	Fluid structure interaction coefficient matrix caused by $\left(\left(\boldsymbol{\delta}\cdot\nabla\right)\boldsymbol{V}_0\right)\cdot\boldsymbol{n}$
$\boldsymbol{U}^{x_l}$	Panel coefficient matrices
$\boldsymbol{V}_0^{x_l}$	Velocity matrix constituted by $V_{0x_l}(\boldsymbol{R}_i)$
$V_{0x_l}(\boldsymbol{R}_i)$	Component of $\boldsymbol{V}_0$ in the x_i direction on point $\boldsymbol{R}_i$
$\boldsymbol{Z}_1, \boldsymbol{Z}_2$	Shape function matrices

For one-way fluid-structure interaction, Taylor [3] analyzed the strength of a propeller blade by considering the blade as a cantilever beam. The results of the structural responses of the blade were of limited applications due to the simple geometry of the blade. To improve the predictions for the stresses of the blade, a thin-shell theory was employed by Conolly [4]. This method has been successfully applied for the cases of wide blades, but the assumption of symmetrical forms and invariant normal deflection of a section limits the application of the approach. The finite element methods (FEMs) have also been developed for the analysis of blade strength as no additional assumptions about geometry of the blades are needed in such methods. Triangular plane elements were employed by Genalis [5] for the structural modeling of the blade. Atkinson [6] applied super-parametric thick shell elements in the analysis of the blade. Ma [7] employed 3-D quadratic isoperimetric brick elements for analyzing a highly skewed propeller. Triangular thin shell elements were used by Sontvedt [8] to analyze moderately skewed and highly skewed propellers. It should be noted that in all of these methods, the hydrodynamic loads acting on the surface of the blade were obtained by the quasi-steady method, the lifting line method or lifting surface method.

For two-way fluid-structure interactions, Kuo and Vorus [9] introduced a fully combined structural and hydrodynamic approach for the analysis of the blade stresses. A set of boundary conditions were established on the fluid-structure interaction, and a panel method on the camber surface was applied to determine the hydrodynamic blade loads, the added-mass and –damping matrices due to the elastic blade motion. The coupled problem was solved in the frequency domain using the FEM based on 3-D linear isoparametric brick elements. It is found that the skew of the blade has effect on the added damping- and mass-matrices and wet modes. Atkinson and Glover [10] investigated the dynamic behaviors of elastic propellers using an unsteady lifting surface method, which was coupled with a finite element model of the propeller based on thick shell elements. The results showed that the size and shape of the produced cavities can be greatly affected by the hydroelastic motions of the propeller. However, their analysis was limited to steady flow problems, and therefore the dynamic blade forces cannot be captured. Lin and Lin [11] analyzed the hydroelastic analysis of marine propellers based on a coupled 3-D non-linear FEM and a non-cavitating steady lifting surface method. Thrust, torque efficiency coefficients, and deflections were included in their calculation. It was found that the deflection of the blade is increased as the blade thickness is reduced. Young [12,13] presented a strongly coupled fluid-structure interaction analysis for predicting the hydroelastic behaviors of both metal and composite marine propellers in sub-cavitating and cavitating flows. A set of simplified boundary conditions were introduced on the interaction of the blade and the fluid. The fluid is modeled by using a 3-D boundary element method (BEM), which was combined with a finite element model of the blade. The change in influence coefficients due to the blade deformation was examined in the case of the flexible composite marine propeller. In order to save the computing resources required by the system equations, the asymmetric added matrices due to the fluid were made to symmetry matrices by using a HRZ-like lumping technique. It was found that for the analysis of the hydrodynamic behaviors of flexible composite propellers, the strongly coupled fluid-structure interaction must be considered. Neugebauer et al. [14] studied the fluid-structure interaction problems of propellers by using the method of computational fluid dynamics. The nodal displacements, velocities and accelerations near the propeller were included in their calculation, and the difference between the hydrodynamic pressures obtained by coupled and uncoupled method was examined. He et al. [15] developed a 3-D FEM/CFD coupling algorithm to investigate the hydroelastic behaviors of a highly skewed composite model propeller. The wet natural frequencies, mode shapes, hydrodynamic load coefficients and tip node displacements, etc., were examined. Lee et al. [16] introduced a BEM-FEM-based algorithm to predict the unsteady thrust and torque coefficients for flexible propellers. Maljaars and Kaminski [2] presented a review for the past research on