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Numerical Prediction of Hydroelastic Performance of the Flexible Propeller

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In this work, the numerical method for the prediction of unsteady behavior of the flexible propeller is presented. First, we use the boundary element method based on the lifting surface theory to solve the hydrodynamic problem around the flexible propeller and employ the finite element method (FEM) program for an analysis of the structural response. The FEM is formulated with 20-node isoparametric elements for the analysis of the structural response, and then results from two different methods are well arranged through the carefully designed interface scheme. In addition, we carry out dynamic analysis of the specific flexible propeller and validate the results by comparing them with the existing numerical data.

INTRODUCTION

Composite fiber-reinforced plastic (CFRP), which is lighter than and superior in performance to the existing copper alloy, is attracting attention not only in the automobile and aviation industries but also in the shipbuilding industry as a high strength and lightweight structural material. In particular, flexible propellers using CFRP can be significantly reduced in weight compared with the existing marine propellers that use copper alloys, reducing fuel consumption and increasing efficiency. It is also known to have advantages such as improved cavitation, improved erosion performance, and so on (Mouritz et al., 2001). Compared with the existing metallic propellers, where deformation is negligible under any operating condition, flexible propellers have a relatively large deformation under heavy loading conditions. Because of the flexibility of the composite propeller blade, it is necessary for a propeller designer to consider deformation of the blade in response to various hydrodynamic loading conditions at the initial design stage of the propeller. This is important because the performance of the propeller is directly related to its shape. In addition, it is necessary to design a shape capable of generating a desired load at a design point in consideration of a change in the shape of the propeller. To design it, we need to evaluate not only the hydrodynamic force around it but also the structural response of the flexible propeller according to its deformation. So it is necessary to develop a design tool that predicts the hydroelastic performance of the flexible propeller with deformation considering fluid–structure interactions and the special operating condition, and the design of an optimization tool for the flexible propeller using CFRP is required. An initial numerical model for a three-dimensional composite propeller was proposed by Lin (1991), who calculated and compared the stresses of conventional metallic propellers of the same shape with the composite propeller. Then, Lin and Lin (1996) proposed the three-dimensional finite element method/vortex lattice method (3-D FEM-VLM) that considers the nonlinear shape of the propeller by the elastic analysis method of the propeller. In the vortex lattice method (VLM), the elastic behavior of composite propellers under steady state conditions was calculated, and the authors successfully analyzed the propeller behavior according to the lamination method of composites (Lin and Lee, 2004; Lin et al., 2005). Chen et al. (2006) designed the rigid and flexible composite propellers and conducted a numerical analysis of it, and the model tests were carried out in a 36-inch water tunnel at the Naval Surface Warfare Center, Carderock Division (NSWCCD). As a result, they found out that the performance of the flexible propeller was superior to the rigid propeller in terms of efficiency and cavitation. Young (2008) presented a coupled boundary element method (BEM) and FEM approach to study the fluid–structure interaction of flexible composite propellers in subcavitating and cavitating flows. They also conducted experimental validation for composite propellers tested at the NSWCCD. More recently, they have studied to find out whether the bending–twisting coupling effects of anisotropic composites and load-dependent self-adaptation behavior of composite blades are the primary sources for the performance improvement of composite marine propellers, and they improved their design and analysis methodology for flexible composite propulsors (Motley et al., 2009, 2013; Motley and Young, 2011). Hong et al. (2012) proposed a hybrid method for predicting the structural damping of the composite blade. And they investigated the hydroelastic phenomena of the series of composite propeller using a 3-D FEM/CFD coupling algorithm (Hong et al., 2017). Lee et al. (2017) introduced steady and unsteady BEM-FEM fluid-structure interaction algorithms of a composite propeller blade and a simple finite element model that considered the lamination modulus of fiber materials.

To predict the hydroelastic performance for the flexible composite propeller, our research group has already developed the computer programs KPA4 and KPD4 based on the VLM of Kerwin and Lee (1978). And we also adopted the program ProSTEC

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KEY WORDS: Flexible propeller, composite propeller, fluid–structure interactive analysis, lifting surface theory, vortex lattice method, finite element method.