Multi-objective Optimal Design of Ship Propeller Considering Fluid-Structure Interaction

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ABSTRACT

This paper presents a multi-objective optimum program that applies the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) to propeller design, which takes into consideration the fluid-structure interaction based on the Panel Method (PM) and the Finite Element Method (FEM). The unsteady hydrodynamic performance and structure response are validated by comparing with experimental data. HSP, a highly-skewed propeller used on Seiun-Maru (a bulk freighter constructed in Japan), is studied as the case. Six parameters related to propeller geometry are chosen as design parameters: diameter, camber, pitch, rake, airfoil chord and thickness. Efficiency, unsteady force, and mass are chosen as optimum objectives under certain constraints of the hydrodynamic performance and the structure response, including natural frequency constraints. Optimizations take as a starting point from a nearly optimum propeller (HSP), in which the multi-objective optimum method improves all the objectives, and the results are analyzed. The multi-objective optimization program proposed in this study will be a prospective tool for propeller design in the future.

KEY WORDS: Multi-objective optimum of propeller; fluid-structure interaction

INTRODUCTION

The increasing demand for ship propellers meeting synthetical requirements has been putting great pressure on propeller designers. To meet these seemingly mutually exclusive objectives with higher efficiency and lower vibrations, less noise, etc, designers have been paying more attention to the concept of optimal design. Traditional designs consider only hydrodynamics in the optimization program, and check the strength of the preliminary optimal propeller. This paper proposed a multi-objective optimum program taking into consideration the fluid-structure interaction.

The ability to simultaneously estimate the hydrodynamic performance and structural response of the propeller has been the focus of research recently. Lin (1996) developed an iterative procedure, which coupled the FEM and the noncavitating lifting surface, but did not consider the fatigue strength of the propeller, to assess performance. Liu (2000) focused on investigating the physical nature of fluid-structure interaction problems by decomposing the system response into multiple frequency/wave number bands to obtain a better representation of the computed physics. Liu accomplished this by developing a multi-scale Reproducing Kernel Particle Method (RKPM) and applying it to 2-D airfoils. Haym and Timothy (2000) advanced the state-of-the-art understanding of the non-linear coupling between fluid and structural motions. Their efforts concentrated on accurately describing the response of structures to unsteady fluid loadings, sources of which include waves, currents and vortex shedding. Daron (2000) developed an automated fluid-structure interaction analysis procedure, which couples a steady-state CFD analysis using Fluent and a structural FEM using ABAQUS.

Optimization algorithms have been applied to propeller design by many researchers. Benini (2003) developed a multi-objective design program based on the evolutionary algorithm to optimize a B-screw propeller, while the open water performance is calculated using regression formulas. Han (2006) chose the Dynamic Hill Climbing method as the optimization mechanism to optimize both the efficiency and induced pressure fluctuation, while the structural response is not taken into consideration. Zhao Wei (2010) optimized pitch and camber distributions, obtaining the surface pressure distributions more uniformly without reducing the propeller efficiency. Cai Haopeng (2014) applied an improved particle swarm algorithm to optimize and analyze propeller skew distribution. Circulation distribution was optimized by Jan Klesa (2014) including the influence of viscosity. But they all focused on the aspect of hydrodynamics.

After reviewing previous similar work, we develop a multi-objective optimization procedure using NSGA-II optimization algorithms and taking fluid-structure interaction into consideration. The effect is considered as weak coupling, using PM and FEM to predict hydrodynamic performance and structure response. The final condition is the convergence of the iterations. The flow chart is shown in Fig.1.

![Flow chart of weak coupling of fluid-structure interaction](image)

Fig. 1: Flow chart of weak coupling of fluid-structure interaction

Theory

Panel Method

The panel method is used to predict the unsteady hydrodynamic performance of the propeller. The surface of propeller and the wake vortex are divided into a series of small units, and each unit is approximated by a hyperboloidal quadrilateral panel. Some assumptions are made for practicality.