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Collaborative optimization for ring-stiffened composite pressure hull of underwater vehicle based on lamination parameters

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Abstract

A Collaborative Optimization (CO) methodology for ring-stiffened composite material pressure hull of underwater vehicle is proposed. Structural stability and material strength are both examined. Lamination parameters of laminated plates are introduced to improve the optimization efficiency. Approximation models are established based on the Ellipsoidal Basis Function (EBF) neural network to replace the finite element analysis in layout optimizers. On the basis of a two-level optimization, the simultaneous structure material collaborative optimization for the pressure vessel is implemented. The optimal configuration of metal liner and frames and composite material is obtained with the comprehensive consideration of structure and material performances. The weight of the composite pressure hull decreases by 30.3% after optimization and the validation is carried out. Collaborative optimization based on the lamination parameters can optimize the composite pressure hull effectively, as well as provide a solution for low efficiency and non-convergence of direct optimization with design variables.

Keywords: Underwater vehicle; Composite material; Ring-stiffened pressure hull; Lamination parameters; Collaborative optimization

1. Introduction

As a key device of ocean exploration and subsea operation the underwater vehicle is increasingly needed and is drawing more attention (Yoo et al., 2015). The pressure hull is one of the main structures of the underwater vehicle, which provides load capacity for electronic systems and buoyancy for the carrier structure (Fathallah et al., 2014). The ring-stiffened hulls have better structural performances and are widely used in underwater vehicles and submarines (Chen et al., 2015).

The pressure hull is subjected to external water pressure when the underwater vehicle dives in deep water. In order to increase effective load and endurance, composite materials have been adopted in the construction of underwater vehicles due to the light weight, high specific strength, high specific stiffness, resistance of corrosion and structural designability (Lee et al., 2013).

The composition of plies provides freedom for structure design. Laminate mechanical properties are determined by the configuration, such as fiber volume fraction, number of plies, ply thickness and fiber orientation angle, etc. (Pedersen, 2004; Setoodeh et al., 2005). Therefore, the maximum potential of structural performances can be stimulated by effective optimization. In conventional optimization design, the material properties of a single ply is always set first and the laminate plates are directly optimized by adjusting ply thickness and fiber orientation (Gurdal et al., 1999; Haftka and Gurdal, 1992; Le and Haftka, 1993). Due to the discrete variables and multiple-valued trigonometric functions, the optimization may be trapped into local optimal solution. A pressure hull of underwater vehicle demands materials with high strength and stiffness, and more plies are needed to meet the requirements.

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It will introduce too many design variables (including ply thickness and orientation, liner thickness and frame dimensions) to solve the corresponding optimal design problem.

The stiffness properties of laminates can be expressed by 12 lamination parameters representing the layup configuration of laminates. They are functions of ply orientations, thickness and number of plies (Jones, 1999). These 12 lamination parameters denote the in-plane, bending and shear stiffness according to the classic plate theory and Mindlin plate theory. Research has shown the feasibility of optimization design for laminated plates by lamination parameters, since the relationship between the stiffness properties and lamination parameters of laminated plates is convex (Durand, 2008; Foldager et al., 1998; Miki and Sugiyama, 1991). Compared to the direct optimization with ply parameters as design variables, it is easier to optimize the design according to the lamination parameters (Abdalla et al., 2007; Herencia et al., 2008; Setoodeh et al., 2006; Thuwis et al., 2010; Topal and Uzman, 2008).

In order to solve the optimal design problem of pressure hull the Collaborative Optimization (CO) is adopted which was proposed based on the optimization with compatibility constraints (Kroo et al., 1994; Braun et al., 1997; Gu and Renaud, 2001; Sobieski and Kroo, 1996). The method is a distributed optimization of multidisciplinary design optimization (MDO). The CO method is characterized by a two-level hierarchical structure which decomposes the optimization problem into system level and discipline level (Martins and Lambe, 2013). The system-level optimizer only provides system and coupling variables, and local design variables are treated exclusively in the discipline level. In the discipline level, optimizers process in parallel, while optimization is aimed at minimizing the incompatibility between design variables and coinciding with the system optimization direction. The system-level optimizer finds the system optimal solution while coordinating the incompatibility of discipline level. In conventional CO method the consistency equality constraints are sometimes so strict that the optimization is unable to converge. Sobieski and Kroo (2000) replaced the consistency equality constraints of system-level by an approximation model based on response surface estimation. Alexandrov and Lewis (2002) introduced the slack factor to change the equality constraints of system-level to inequality ones according to relaxation method. Vikrant and Shapour (2006) applied genetic algorithms to solve the CO problem. Li and Azarm (2008) provided a robust solution by employing concepts of interval uncertainty and its propagation.

Collaborative optimization has also been increasingly paid attention to in the field of marine engineering. Belegundu et al. (2000) presented a methodology for automated design synthesis using CO to solve the attribute-based optimization problem of underwater vehicles. Fu et al. (2012) proposed a CO model to optimize a container ship structure on static and dynamic responses. Luo and Lyu (2015) used the CO method for hydrodynamic performance optimization of underwater vehicles.

In this paper, according to the designability of composite materials, a layout-and-layup collaborative optimization scheme is established for minimizing the weight of a ring-stiffened pressure hull of an underwater vehicle with the lamination parameters as intermediate coordination variables. Aluminium alloy is combined with composite material to enhance the structure (Kim et al., 2010). Firstly, the lamination parameters of laminated plates are introduced. Secondly, a two-level optimization of the composite pressure hull is conducted, where the structural and material constraints are both met and the optimal solution provides initial value for collaborative optimization. Finally, the simultaneous structure and material collaborative optimization design for underwater vehicle pressure hull is implemented. Finite element analysis is conducted to validate the proposed optimization strategy and the results are presented.

2. Lamination parameters and stiffness invariants

Based on the laminated plate theory, constitution equations for a composite material laminated plate can be written as (Jones, 1999; Vasiliev and Morozov, 2007):

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} A_{11} \\ A_{22} \\ A_{12} \\ A_{66} \\ A_{16} \\ A_{26} \end{bmatrix} = t \begin{bmatrix} 1 & \xi_1^A & \xi_3^A & 0 & 0 \\ 1 & -\xi_1^A & \xi_3^A & 0 & 0 \\ 0 & 0 & -\xi_3^A & 1 & 0 \\ 0 & 0 & -\xi_3^A & 0 & 1 \\ 0 & \xi_2^A/2 & \xi_4^A & 0 & 0 \\ 0 & \xi_2^A/2 & -\xi_4^A & 0 & 0 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} B_{11} \\ B_{22} \\ B_{12} \\ B_{66} \\ B_{16} \\ B_{26} \end{bmatrix} = \frac{t^2}{4} \begin{bmatrix} 0 & \xi_1^B & \xi_3^B & 0 & 0 \\ 0 & -\xi_1^B & \xi_3^B & 0 & 0 \\ 0 & 0 & -\xi_3^B & 0 & 0 \\ 0 & 0 & -\xi_3^B & 0 & 0 \\ 0 & \xi_2^B/2 & \xi_4^B & 0 & 0 \\ 0 & \xi_2^B/2 & -\xi_4^B & 0 & 0 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ U_5 \end{bmatrix} \tag{4}$$