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An application of multidisciplinary design optimization to the hydrodynamic performances of underwater robots

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ABSTRACT

Multidisciplinary Design Optimization (MDO) is proposed for the design of the lines of an underwater robot. Hydrodynamic performances of the underwater robot are concerned about in the design, including the resistance and the manoeuvrability. A method of MDO, Collaborative Optimization (CO), is adopted. To improve the efficiency of optimization, approximate models are established in sub-disciplines. Also, an artificial intelligent technique, Particle Swarm Optimization (PSO), is incorporated into the CO framework. The optimization design of the lines of the underwater robot is carried out on an Isight platform, an automatic integration optimization platform. Through the platform, the optimization design of the lines and the analysis of the hydrodynamic performances can be achieved automatically with high efficiency. An autonomous underwater vehicle (AUV), SUBOFF, is taken as a verification model. For different lines, CFD calculation is performed to analyze the resistance and manoeuvrability. By comparison, the optimal lines of the hull and the fairwater are determined.

1. Introduction

Usually, the overall design of an underwater robot observes three steps, i.e. the schematic design, the preliminary design and the detailed design (Cui and Ma, 2009). At the stage of schematic design, the hydrostatic balance and hydrodynamic performances are mainly concerned about, especially for the determination of hydrodynamic coefficients and the efficiency of propulsion. Compared with the other two stages, the stage of schematic design offers a designer the highest design freedom due to less demand for design knowledge. At this stage, optimization design is commonly used. Traditionally, the optimization design is conducted step by step, and the hydrodynamic performances are separately paid attention to at each step. At the first step, only the rapidity (including resistance and propulsion) is focused on. While at the next step, only the manoeuvrability and seakeeping are cared about. The coupling effect of different hydrodynamic performances is not taken into account. As a result, the efficiency of optimization design is seriously degraded. Furthermore, the global optimization solution cannot be guaranteed. As pointed out (Liu et al., 2002; Xue, 2007), the solitary disciplinary optimization design is not appropriate for the optimization of hydrodynamic performances.

For complex engineering systems involving multiobjective, multivariable and multiple constraints, Multidisciplinary Design Optimization (MDO) provides a practical and effective way. During last decades, studies on MDO have been performed widely, especially in the field of aerospace. For example, Braun and Kroo (1997) developed a collaborative architecture of MDO and applied it into the design of a large-scale aerospace vehicle. MacMillin et al. (1997) presented a MDO procedure to illustrate the effects of numerous trim, control, and performance requirement for high speed civil transports. Gundlach et al. (2000) used MDO to achieve a design of Strut-BRACED wing, with less fuel cost and weight, smaller engine as well. Nigam and Kroo (2008) designed multiple unmanned air vehicles by using a MDO based system-of-system (SoS) architecture. Roth and Kroo (2008) applied MDO methods to an aircraft family design and reduced the computational burden substantially.

In the field of marine engineering, MDO has also been increasingly paid attention to in recent years. Belegundu et al. (2000) presented an attribute design approach for the design of undersea exploratory vehicles. Yukish et al. (2000) cast the conceptual design problem for undersea vehicles in a MDO framework. Neu et al. (2000) addressed the application of MDO in the surface ships' design. McAllister et al. (2002) introduced MDO to the design of an autonomous underwater vehicle. Liu (2007) proposed

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a BLH (Bi-Level Hierarchic) approach to a 7000 m HOV (Human Occupied Vehicle) general design. Cao (2008) explored the MDO application to the design of a HOV. Pan et al. (2009) established a MDO model for the conceptual design of a practical ship. Vlahopoulos and Hart (2010) addressed the MDO framework for a conceptual submarine design study. Yang (2012) studied the MDO application to design of an underwater robot, while Campana et al. (2012) proposed a survey of MDO formulations for ship design, where penalty approaches were investigated.

This paper presents an application of MDO to the optimization of hydrodynamic performances of an underwater robot. Two disciplines, rapidity and manoeuvrability, are concerned about. The design of lines is based on the optimization results. Often in applications of MDO to underwater robots, the rapidity was cared about more than manoeuvrability (e.g. McAllister et al., 2002; Cao, 2008). An approach of MDO, Collaborative Optimization (CO), is employed to execute the parallel analysis of disciplines. The hull resistance, transverse force and yaw moment are taken as optimization goals. The design variables consist of the length of parallel middle body, the maximum body radius, the after-body's minimum radius, the sail's position, the height of the sail, and the edge curve slopes of sail's fore and aft. The constraints include the hull longitudinal area, the cross-sectional area, the wetted surface area and the hull volume. By using Isight software, an automatic integration optimization platform is set up to run the multidisciplinary design optimization. To guarantee the convergence of CO and the global optimization solution, Particle Swarm Optimization (PSO) is incorporated into the CO framework. To improve the efficiency of solution-searching, an approximate model is taken to substitute the traditional subject analysis model. An autonomous underwater vehicle (AUV), SUBOFF, is used for verification. Rather than the empirical formula commonly used in analyzing the hydrodynamics (e.g. Pan et al., 2009; Vlahopoulos and Hart, 2010; Yang, 2012), CFD numerical simulation is performed to analyze the hydrodynamic performances. Numerical results demonstrate the validity of the proposed optimization strategy.

2. Multidisciplinary design optimization

MDO was put forward in the late 1980s (Sobieszczanski-Sobieski, 1987). By MDO, one can organize all relevant disciplines simultaneously in a design, and exploit the interactions between different disciplines. Many approaches have been developed for the MDO applications during last decades. For example, Multi-disciplinary Feasible Method (MDF) was proposed for the analysis and integration of disciplines (Adelman and Mantay, 1991). Simultaneous Analysis and Design (SAND) (Lavelle and Plencner, 1992) and Individual Discipline Feasible (IDF) (Cramer et al., 1994) were proposed for the parallel analysis of disciplines and data management. For complex engineering systems, an expert system based MDO was developed, including Concurrent Subspace Optimization (CSSO) (Wujek et al., 1996), Collaborative Optimization (CO) (Braun et al., 1997) and Bi-level Integrated System Synthesis (BLISS) (Sobieszczanski-Sobieski and Kodiyalam, 2001). Among them, CO is very promising for large-scale engineering systems. First of all, its framework is consistent with the mechanism of engineering design. Second, the integration of software is easy. Finally, the parallel processing is possible. In consideration of the complexity of the underwater robot system, in this paper the CO method is adopted.

2.1. CO methodology

CO is a distributed optimization method, characterized by consistency constraints and a two-level hierarchical structure (Kroo et al., 1994; Martins and Lambe, 2013). Fig. 1 depicts the framework of CO. Each optimizer has its own design variables and constraints. At the system level, the goal is to achieve the overall performance of design. While at the sub-discipline level, the goal is to minimize the interdisciplinary inconsistency (Liu and Cui, 2004). The sub-discipline optimizers can be executed in parallel. The solution information circulates throughout this hierarchical structure.

The mathematical models adopted at the system level and sub-discipline level can be described as follows, respectively.

For system-level optimization problem, it follows:

$$\text{Minimize}: \left\{J_{sys}(z)\right\} \tag{1}$$

$$\text{Subject to}: d_i^*(z^s, z^c) = 0 \quad (i = 1, 2, 3, \ldots, N) \tag{2}$$

$$\text{Design variable}: z = [z^s, z^c]$$

where z^s is the global design vector, z^c is the coupling state vector which represents the coupling among sub-disciplines. Both z^s and z^c are the system-level optimization design vectors and can be defined in the original optimization space. The constraint d_i^* is used to make the ith discipline coordinate with the system.

For sub-discipline optimization problem, one has

$$\textit{Given}: z_i^s, z_i^c$$

$$\text{Minimize}: d_i = \|x_{si} - z_i^s\|^2 + \|y_i - z_i^{out}\|^2 + \|x_{auxi} - z_i^{aux}\|^2, \quad (z_i^c = z_i^{out} \cup z_i^{aux}) \tag{3}$$

$$\text{Subject to}: g_i(x_i, x_{si}, y_i, x_{auxi}) \le 0 \tag{4}$$

$$\text{Design variable}: x = [x_{si}, x_i, x_{auxi}]$$

where the z_i^s and z_i^c denote the expectation values of the global design variable and the state variable respectively, derived from the system level. Design variables in disciplinary optimization involve the global design variable x_{si}, local design variable x_i and auxiliary design variable x_{auxi}.y_i is a state vector in the ith sub-discipline. The analysis and optimization of sub-disciplines are carried out under the condition of the discipline's constraints.

Usually, finding the overall optimal solution needs switching frequently between the system level and the sub-discipline level. The solving steps of CO can be described as follows.

(1) Initialize the design variables;
(2) Solve the optimal solution in each discipline, then create the system-level optimization mathematical model;
(3) Solve the system-level optimization mathematical model to achieve the initial coordinate values of the system variables that consist of sharing design variables and related variables;

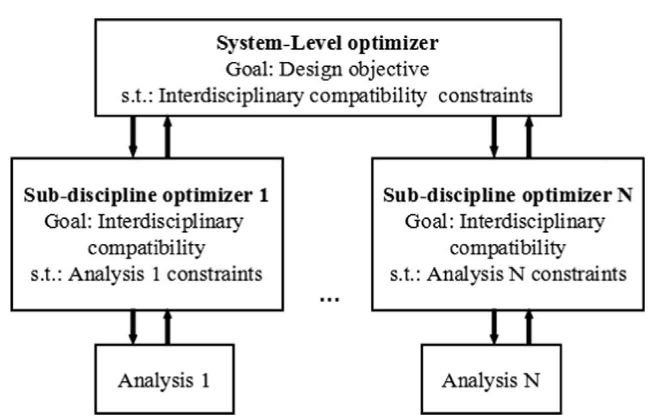

Fig. 1. The framework of CO.