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Multi-objective optimization design for the multi-bubble pressure cabin in BWB underwater glider

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Abstract

In this paper, multi-objective optimization of a multi-bubble pressure cabin in the underwater glider with Blended-Wing-Body (BWB) is carried out using Kriging and the non-dominated Sorting Genetic Algorithm (NSGA-II). Two objective functions are considered: buoyancy-weight ratio and internal volume. Multi-bubble pressure cabin has a strong compressive capacity, and makes full use of the fuselage space. Parametric modeling of the multi-bubble pressure cabin structure is automatic generated using UG secondary development. Finite Element Analysis (FEA) is employed to study the structural performance using the commercial software ANSYS. The weight of the primary structure is determined from the volume of the Finite Element Structure (FES). The stress limit is taken into account as the constraint condition. Finally, Technique for Ordering Preferences by Similarity to Ideal Solution (TOPSIS) method is used to find some trade-off optimum design points from all non-dominated optimum design points represented by the Pareto fronts. The best solution is compared with the initial design results to prove the efficiency and applicability of this optimization method.

Keywords: Multi-objective optimization; Multi-bubble pressure cabin; Finite element analysis; Kriging; NSGA-II; TOPSIS

1. Introduction

Underwater glider (Javaid et al., 2014) is a new type of Autonomous Underwater Vehicles (AUV) which changes movement state by adjusting buoyancy and converts the lift on wings into propulsive force. Compared to the traditional propeller propulsion underwater vehicle, gliders have excellent hydrodynamic performance and cruising capacity which satisfies long-range and extended-duration deployments. BWB configuration was used to the design of underwater gliders in order to achieve higher hydrodynamic efficiency. This configuration has no clear dividing line between the wings and the main body of the craft, which provides higher maximum lift to drag ratio and lower wetted area to volume ratio. Jenkins et al. (2012) have fully studied the feasibility of BWB underwater gliders. ONR (Hildebrand et al., 2010) developed a BWB design model, “Liberdade X-Ray”, which is the world's largest known underwater glider. The Z-Ray underwater glider was a modified form of the X-Ray underwater glider which completed in March 2010.

In conventional torpedo-shaped underwater glider, circular fuselage can efficiently handle external pressure through hoop stress. Mukhopadhyay (1996) showed that in non-circular cross sections, such as those present in the BWB aircraft fuselage, large bending stresses are induced from internal pressure and present a critical loading condition. A wide variety of structural concepts have been proposed for the BWB aircraft fuselage. The first BWB designs proposed by Liebeck (2002) used traditional skin and stringer arrangements, two structural concepts were considered: (1) a thin arched pressure vessel above and below each cabin; (2) a thick sandwich structure for both the upper and lower wing surfaces. In order to take advantage of circular cross sections, later designs used

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pressures shells to contain the cabin pressure and a separate outer skin to handle the wing bending loads. Both light honeycomb material and cross-ribbed concepts have been proposed to connect the inner and outer skin. Another structural concept for the BWB fuselage uses flat sandwich panels where a deep sandwich shell with composite skins and honeycomb core simultaneously handle the internal pressure and wing bending loads.

Mukhopadhyay et al. (2012, 2016) developed a multi-bubble stiffened pressure vessel concept. In this design, the two merging bubble sections meet with the intercabin vertical wall at an angle so surface in-plane membrane forces are in self-equilibrium. This geometrical arrangement could reduce undue bending at these joints, thereby preserving the advantage of a cylindrical-section fuselage, under internal cabin pressure. Additional cross-ribbed outer shell structures appear to be quite effective to provide buckling stability and carry spanwise bending loads. The multi-bubble could reduce the overall weight by about 20–30% compared to using all flat surfaces. This result is ambiguous because the investigations were only based on finite element analyses of a section of the fuselage and it is unclear how the fuselage was designed nor integrated into the total structure.

Geuskens et al. (2008, 2011, 2012) presented the interior configuration of multi-bubble pressure cabin used in BWB aircraft in detail. The multi-bubble composed of cylindrical, spherical, toroidal and tapered membrane elements was analyzed under internal pressure about 0.08 MPa. Linear membrane theory was used to assess the membrane forces and deformations in the pressurized structure. The structural efficiency was defined as the ratio of the mass and the pressurized volume of the pressure vessel. Multi-bubble pressure cabin is also suitable for BWB underwater glider. The structural performance of multi-bubble pressure cabin can be obtained by the FEA.

The effective area is defined as the ratio of the inscribed rectangle by the frontal area as shown in as Fig. 1. The structural efficiency is defined as the ratio of the pressurized volume and the mass of the pressure vessel. Compared to the single pressure hull, multi-bubble pressure cabin has higher effective area and lower structural efficiency. In addition, multi-bubble pressure cabin can takes full use of the underwater glider's geometrical space. Therefore, multi-bubble pressure cabin is particularly interesting for underwater glider applications.

For the multi-objective problems which involve a large number of function evaluations, the optimization algorithms based on community intelligence, such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm, have been widely applied and the good performances have been validated (Chen et al., 2012). Some Multi-Objective Optimizations (MOO) in modern design problems often involve intensive computation and costly simulation, such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). So the huge computational overhead is the main challenge in the application of these community based optimization methods to deal with the MOO problems involving costly simulations.

One effective way to reduce the number of expensive computational evaluations in global optimization is to employ the efficient Surrogate-Based Optimization (SBO) technology (Queipo et al., 2005). The SBO search process includes three steps: (a) select sample points; (b) construct a surrogate model (SM); and (c) resample promising points. To get a better initial SM with fewer sample points, a variety of Design Of Experiments (DOE) methods have been introduced, including Latin Hypercube Sampling (LHS) (Iman, 2008), Optimal Latin Hypercube Sampling (OLHS) (Jin et al., 2005), uniform design method (Liao et al., 2008) etc. Common SM methods include Polynomial Response Surface (PRS) (Viswamurthy and Ganguli, 2007), Radial Basis Function (RBF) (Myers et al., 2016), Kriging (Forrester and Keane, 2009), Support Vector Regression (SVR) (Yang et al., 2002), multivariate adaptive regression spline (MARS) (Friedman, 1991), Adaptive and Interactive Modeling System (AIMS) (Yang et al., 2005), neural network (Saijal et al., 2011) etc.

In problems with at least two conflicting objectives, a set of optimal solutions exists as a result of the trade-offs between these objectives. Different versions of multi-objective evolutionary and metaheuristic algorithms have been successfully used to develop Pareto fronts, including Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Chang et al., 2005); Ant Colony Optimization (ACO) (Jalali et al., 2007); Honey Bees Mating Optimization (HBMO) (Haddad et al., 2006); Particle Swarm Optimization (PSO) (Fallah-Mehdipour et al., 2011); Ant Lion Optimizer (ALO) (Mirjalili, 2015).

Rajagopal and Ganguli (2008) processed a conceptual design of UAV using Kriging based multi-objective genetic algorithm. Li et al. (2008) presented a new multi-objective design optimization approach in which the Kriging-based metamodeling is embedded within a MOGA. Chen et al. (2015) discussed multi-objective optimization of the vehicle ride comfort based on Kriging approximate model and NSGA-

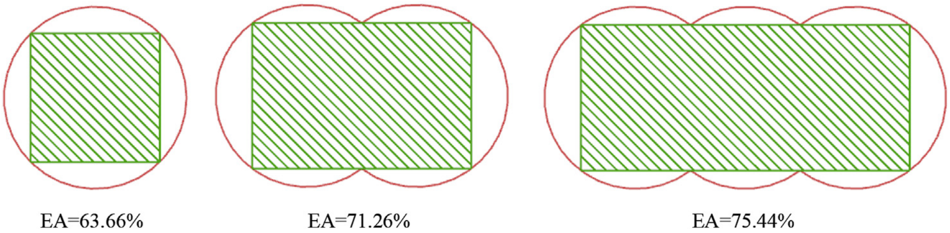

Fig. 1. Effective area (EA) for different cylinder configurations.

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