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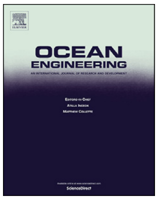

Multi-objective shape optimization of autonomous underwater glider based on fast elitist non-dominated sorting genetic algorithm

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ABSTRACT

Autonomous underwater glider (AUG) equips with limited battery capacity, and needs to optimize the shape of AUG to reduce power consumption and improve voyage. This paper presents a new method of the multi-objective optimization of AUG shape based on the fast elitist non-dominated sorting genetic algorithm (NSGA – II). The slender ellipsoid line is chosen as the reference model and the volume of the model is constrained to keep 100 L. The hull drag and the hull surface pressure are two key technical performance indicators. Variables are used for sensitivity analysis based on One-At-a-time (OAT) method. Comparisons between towing tank experiments and numerical simulation method is conducted to prove that this method is used for hydrodynamic analysis. The original shape, the NSGA-II optimization shape, the Spray shape and the multi-island genetic algorithm (MIGA) optimization shape are analyzed to verify the validity of the optimization method in this paper by comparing hydrodynamic performance and power conversion efficiency. The simulation results indicate that the NSGA-II shape obtains a better hydrodynamic performance than the others. At the same wing configuration and gliding depth, the voyage of the NSGA-II shape is more than the original shape 12%, which has great significance for reducing power consumption.

1. Introduction

Underwater glider has a fixed horizontal wing and tail, through the internal mass regulating device adjustment posture, through the buoyancy regulating device to move vertically and horizontally, in a saw tooth pattern through the water. Due to their ease of operation and low operational cost, some typical gliders have already been successfully used in ocean environmental survey and resource detection (Hussain et al., 2011), such as Slocum (Schofield et al., 2007), Spray (Sherman et al., 2001), Seaglider (Eriksen et al., 2001), and Deepglider (Osse and Eriksen, 2007). As the demand for ocean exploration increases, for some large-scale, longer-lasting ocean phenomena, the glider is required a long range and long time to continuously observe the oceanic phenomena and obtain more detailed and accurate data (Stuntz et al., 2016). Due to the limited internal volume of the glider, it is not enough to achieve this technical indicator only to increase the battery capacity, but also need to improve efficiency and reduce power consumption, shape optimization is an important way. This paper will study a multi-objective shape optimization of glider, which can provide technical support for the underwater glider with low drag, high efficiency, low power consumption and long voyage.

The traditional optimization method of the glider shape is mainly dependent on the experience of the designer based on the computational fluid dynamics (CFD). The slight change of glider shape parameters need to be re-modeling, meshing and numerical calculation, with the drawback is that the workload is large and the efficiency is low. S Yamaguchi et al. (2002) made calculations of the outflow field around the hull based on CFD and the shape was optimized to reduce the drag and to improve efficiency of the propeller. In contrast, some researchers have conducted a study of procedural design. Ting Gao et al. (2016) studied the Myring-type shape of hull by using the MIGA and the particle swarm optimization (PSO) method, only the drag was used as the optimization target, the results proved the MIGA method get the better hull shape. Sun et al. (2015) studied the parametric geometric model and shape optimization of a blended-wing-body underwater glider by using the Kriging-based genetic algorithm, and the maximum gliding range was used as the optimization. Some bionics research also has begun, Zhengxing et al. (2015) studied the shape of a dolphin which has a high mobility, high speed and long range according to the principle of bionics.

The drag of the glider reduction can ensure a larger voyage and higher speed, save the space occupied by the battery and increase the load capacity of the glider. The hull pressure curve tends to be flatter can reduce

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the pressure extremum, and postpone the boundary layer separation to avoid cavitation on the shell and reduce the form drag. The hull drag and the hull surface pressure are the key technical indicators of the glider shape optimization, which is a multi-objective optimization problem. In the traditional study of the optimal design of the glider shape, one of the optimization goals is usually set as the objective function, and the other as a constraint or multi-objective optimization problem is decomposed into multiple single objective functions. However, it is difficult to obtain satisfactory optimization effect (Coello et al., 2007; Dhanalakshmi et al., 2011). Since the 1980s, with the increasing demand for optimization of large-scale complex systems, the research and application of multi-objective genetic algorithm (MOGA) have been widely carried out. Schaffer (1985) proposed a multi-objective genetic algorithm which is called Vector Evaluated Genetic Algorithm (VEGA). Fonseca and Fleming (1993) proposed a multi-objective genetic algorithm (MOGA) based on Pareto rank ranking. Horn et al. (1994) proposed Niched Pareto Genetic Algorithm (NPGA) based on Pareto dominance. Deb et al. (2002) developed the idea of Goldberg, and proposed a non-dominated sorting genetic algorithm (NSGA), and put forward an improved version of NSGA, a classic algorithm which is named NSGA-II, combining the individual crowding distance (CD) and the non-dominant sorting which makes the whole algorithm more perfect and has more superior performance.

This paper is divided into five sections. Section 2 briefly introduces the multi - objective optimization problem of the AUG shape. Section 3 describes the design and implementation of NSGA-II algorithm. Section 4 verifies the accuracy of the numerical simulation method by comparing with the towing tank experiments, and compares the hydrodynamic performance and power conversion efficiency of the four shapes. Section 5 provides the conclusion.

2. Multi - objective optimization problem for AUG shape

2.1. Parametric model of slender elliptical line

The slender ellipsoid line is widely used in underwater vehicles because of its good hydrodynamic performance and manufacture characteristics, such as the Spray (Stephen, 2009). Fig. 1 shows the parametric model of the slender ellipsoid line, which is divided into three lengthsL_b, L_c, L_t, for bow, central and tail part and d is the diameter at the central part and two shape exponents $n_p$and n_q. The origin of the coordinate system is located at the head of the glider. The X-axis coincides with the glider axis and points to the tail, the Z-axis points vertically upwards and the Y-axis follows the right-handed system. The bow, the central and the tail radius follow from (Alvarez et al., 2009):

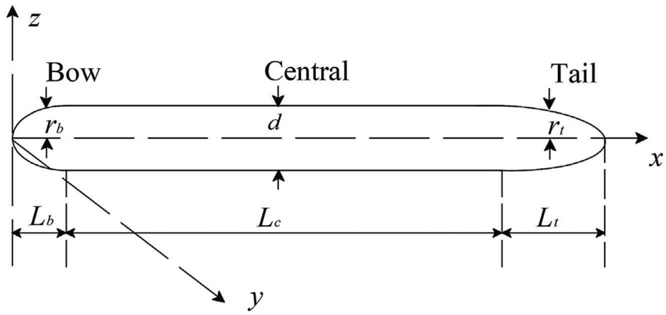

Fig. 1. Parametric model of slender elliptical line.

Table 1
Variation range of decision variables.

Decision variables	Lower limit	Upper limit
d/m	0	0.5
L_b/m	0	1
L_c/m	0	1.5
L_t/m	0	1
n_{p1}, n_{p2}	1	3
n_{q1}, n_{q2}	1	3

$$\begin{cases} r_b = \frac{d}{2}\left(1 - \left(\frac{L_b - x}{L_b}\right)^{n_{p1}}\right)^{\frac{1}{n_{q1}}} \\ r_c = \frac{d}{2} \\ r_t = \frac{d}{2}\left(1 - \left(\frac{x - L_b - L_c}{L_t}\right)^{n_{p2}}\right)^{\frac{1}{n_{q2}}} \end{cases} \tag{1}$$

where, r_b is the Y-axis coordinate at the bow position$x$, r_c is the Y-axis coordinate at the central part, r_t is the Y-axis coordinate at the tail position$x$.

2.2. Optimization objective and decision variables

The volume of the glider is kept at 100 L at the optimization processing. Because the glider internal energy load is limited, hull drag should be as small as possible to achieve the long range, this is the primary optimization target. Hull surface pressure on the glider power consumption will also have great impact, in which too fast change of bow pressure will lead to premature separation of the boundary layer and fast change of tail pressure will produce a flow separation and finally produce tail vortex. The distribution of the hull surface pressure should be flatter.

When sailing underwater, the glider produces a pressure extremum in the bow and tail part, which forms the pressure bipolar structure. The optimization of glider shape should reduce the curvature of the line, so that the pressure extremum position is delayed and the hull pressure distribution tends to be flat. n_p, n_q determine the curvature of the line, which mainly affects the hull pressure distribution. Usually, $1 \le n_p \le 3$, $1 \le n_q \le 3$.

The glider geometry model contains many parameters, and these parameters affect hydrodynamic performance, and navigation characteristics. Considering the advantages and disadvantages, the following eight controlled parameters are selected as decision variables, Table 1 lists the boundaries of this variables.

3. Design and implementation of NSGA-II genetic algorithm

The basic idea and operation method of NSGA-II genetic algorithm has been very standardized. However, the multi-objective optimization problem of the AUG shape needs to center around the initial parameter setting and the object function design.

3.1. Initial parameters

The population size and iteration times of the NSGA-II algorithm affect the optimization performance and optimization efficiency. The small number of populations and the smaller number of iterations lead to the poor performance of the algorithm, and tend to get the local optimal solution and error solution. The large number of populations and iterations can increase the optimization performance, and also lead to the increase of the calculation and reduce the computational efficiency. Determining the appropriate population size and number of iterations is crucial to the optimization results and optimization efficiency of the algorithm. In this paper, the population size is 300 and the number of iterations is 180.

Because genetic operators are the means of population optimized, the selection of better genetic operators can speed up the convergence rate of genetic algorithm and improve the quality of solving. Genetic operators mainly include three categories: selection operator, crossover operator and mutation operator. The selection operator using competitive-game