Comprehensive Optimization Analysis of Rapidity, Maneuverability and Energy System for Flat Unmanned Underwater Vehicle

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Abstract
The design system of unmanned underwater vehicle involves multidisciplinary field, whose design process is rather complicated. The design of the traditional method is carried out according to the stage step by step, which can lead to low efficiency and high cost. And without considering the coupling relationship between different disciplines, the overall performance of the unmanned underwater vehicle designed by traditional method may not be optimal. In this paper, a flat unmanned underwater vehicle has been taken as a object to establish its comprehensive optimization mathematical model, including rapidity, maneuverability and energy system. And the optimization program has been written to accomplish the multidisciplinary comprehensive optimization computation on this unmanned underwater vehicle, according to hierarchical strategy improving genetic algorithm. The optimization results show that the maneuverability objective function and the total objective function have the same trend to some degree and the maneuverability optimization system has a great influence on the total optimization system. In addition, the influence and optimal values of some key design variables including the speed and propeller diameter have been obtained finally.
Keywords: *Unmanned underwater vehicle; Comprehensive optimization; Hierarchical strategy; Genetic algorithm.*

1. Introduction

Twenty-first Century is the century of the ocean, with the depletion of land resources and increasingly exhausted, the various countries have begun to invest a lot of money and manpower to explore the ocean and develop the marine technology. Underwater vehicle is attracting more and more attention because of its important role in ocean development [1-3]. At present, the domestic and foreign research on underwater vehicle are focused on the autonomous underwater vehicle (AUV) and autonomous underwater glider (AUG), they all have their own advantages. Among them, the AUV has high positioning accuracy and fast response, but poor endurance. while the AUG endurance is good, but the accuracy of the trajectory is lower. Therefore, AUV with the advantages of low resistance, wide range of activities, fast response, low noise, high positioning accuracy and no need to consider personnel safety, has caused wide attention in various countries.

Design of unmanned underwater vehicle is a complex system, the need to consider the relationship between multiple disciplines. The traditional design methods neglect the coupling relationship between the various disciplines, resulting in poor overall performance of AUV, while the independent design of each discipline will also lead to the problems of long design cycle and high cost. For the design of unmanned underwater vehicle, multidisciplinary design optimization (MDO) is the most representative method for designing such complex systems currently [4-6]. The MDO fully considers the coupling effect between various disciplines, it can be convenient and efficient to obtain the comprehensive optimal solution of complex system, and because the MDO is multiple discipline parallel design, the design cycle is greatly shortened and the design cost is significantly reduced [7].

In this paper, a flat unmanned underwater vehicle has been taken as a object to establish its comprehensive optimization mathematical model, including rapidity, maneuverability and energy system. And the optimization program has been written to accomplish the multidisciplinary comprehensive optimization computation on this unmanned underwater vehicle, according to hierarchical strategy improving genetic algorithm, and which has provide a reference for the future design of unmanned underwater vehicle.

2. Hierarchical strategy improving genetic algorithm

The basic idea of genetic algorithm is based on Darwin's theory of evolution, Weizmann's theory of species selection and Mendel's theory of population genetics. It is a algorithm that process to search the optimal solution by simulating the biological genetic mechanism and evolution in nature [8-9]. Genetic algorithm can find the global optimal solution in a very high probability, and it does not need the gradient information of the objective function and the constraint condition, which is suitable for engineering optimization design. The global search ability of genetic algorithm is strong, and can be close to the global optimum at a faster rate. But its local search ability is poor, to find the global optimum, a large number of the fitness value of the objective function is needed, and the amount of calculation increased significantly.

The basic idea of hierarchical strategy is to separate one time optimization into multiple steps, every step is carried out in the neighborhood of the many optimal solution of the last step optimization, and each time optimization is called a carrier [10]. The general genetic algorithm uses roulette mechanism, the main characteristics of the roulette mechanism are the large probability of the large individual's fitness value is chosen to be the next generation. Such mechanisms tend to result in a large number of repeat individuals in the next generation (individuals with large fitness values), so that the population in the process of evolution has lost the diversity. Taking into account the above reasons, the carrier mechanism was used in genetic algorithm, the improvement idea is, when the initial population is generated, the worst parts individuals of the next generation are randomly generated according to the characteristics of the several best individuals in the last generation in the neighborhood. This can not only ensure the evolution of the population towards the best individual, but also ensure that the population preserve the original features of individuals of the last generation. Of course, the accomplish of the improved algorithm involves three parameters: according to the characteristics of the number of individuals to produce a new individual, the range of the neighborhood and the number of the next generation of individuals to be eliminated.

In this paper, hierarchical strategy improving genetic algorithm is used for optimization calculation. The ratio of the number of original individuals of the next generation according to their characteristics and the total population is called genetic factor, the ratio of the number of the next generation of individuals to be eliminated and the total population is called evolutionary weight, and the ratio of neighborhood size of a single optimal individual and the whole optimization interval is called carrier probability. Here, the genetic optimization algebra is 8000, the population size is 200, the crossover probability is 0.75, the mutation probability is 0.015, the genetic factor is 0.15, and the evolutionary weight is 0.5. In this paper, the carrier probability is changed, that is, with the increase of the optimization algebra, the carrier probability is reduced, make the neighborhood of the optimal value of the evolution of the population decreased with the increase of algebra. If the carrier probability is 0.01 in the second generation and 0.001 in the last generation, then the linear change curve is:

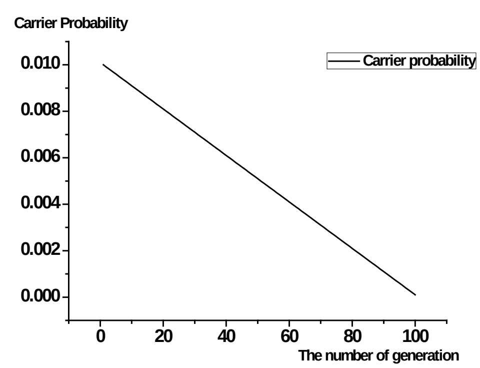

Fig. 1 The curve of carrier probability varying with algebraic change.

3. Establish the optimization mathematical model of unmanned underwater vehicle

In this paper, the optimization of flat unmanned underwater vehicle including rapidity, maneuverability and energy system. According to the optimal principle, the optimization mathematical model mainly includes the following three parts:

design variable, objective function and constraint condition. We choose the performance of larger influence as its corresponding index, and then construct an optimization total objective function by the way of power exponent multiply with each index, while the limitation of the buoyancy, stability and other performance and design variable are used as the constraint conditions.

3.1 Design variable

The research object of this paper is a flat unmanned underwater vehicle, it' s geometric model of bare hull as shown below:

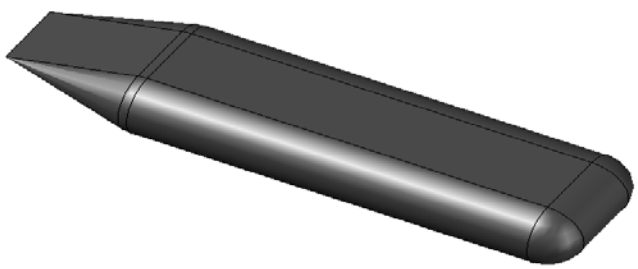

Fig. 2 The geometric model of bare hull of flat unmanned underwater vehicle.

There are many factors affecting the rapidity, maneuverability and energy system of unmanned underwater vehicle. By comprehensive consideration, 28 parameters are selected as design variables of the optimization mathematical model of flat unmanned underwater vehicle, shown in the following table:

Table 1: The range of design variable

NO.	Design variable	Unit	Upper and lower limit
1	The length of bow(L_h)	m	0.5013~0.6127
2	The length of middle hull(L_m)	m	5.4819~6.7001
3	The length of stern(La)	m	1.9368~2.3672
4	The width of the hull(B)	m	2.0772~2.5388
5	The height of the hull(H)	m	1.014~1.114
6	The longitudinal position of barycenter(X_g)	m	-0.04~-0.03
7	The longitudinal position of buoyant center(X_f)	m	-0.23~-0.21
8	Propeller diameter(D_p)	m	0.36~0.42
9	Propeller solidity ratio(A_e/A_0)		0.62~0.7
10	Propeller rotational speed(N)	r/min	340~360
11	Pitch ratio(γ)		0.85~1.05
12	Design speed(V_s)	kn	2.9~3.1
13	The outer end length of the horizontal rudder(d_{oh})	m	0.2~0.4
14	The inner end length of the horizontal rudder(d_{ih})	m	0.3~0.43
15	The height of the horizontal rudder(Z_h)	m	0.6~0.72
16	The outer end length of the vertical rudder(d_{ov})	m	0.2~0.4
17	The inner end length of the vertical rudder(d_{iv})	m	0.3~0.43
18	The inner end length of the vertical rudder(Z_v)	m	0.5~0.75
19	Longitudinal position of the rudder(X_r)	m	-4.05~-4
20	The sailing time of design speed(x)	h	150~250
21	Propeller rotational speed at the speed of V_1(N_1)	r/min	100~500
22	Propeller rotational speed at the speed of V_2(N_2)	r/min	500~1000
23	The reduction coefficient of height(β)		0.7~0.8
24	The ratio of the length of energy tank and the length of middle hull(ζ)		0.35~0.5
25	The number of battery box in the direction of coxswain(m)		5~9
26	The number of battery box in the direction of the wide of boat(n)		2~5
27	The number of battery cassette in the battery box(v)		7~11
28	The number of battery in the battery cassette(u)		2~6

3.2 Objective function

In this system, there are three speed: design speed Vs, balance speed V1 and balance speed V2. V1 was 2 kn and V2 was 5 kn. The ratio of the V1 navigation time and Vs navigation time is k1, the ratio of the V1 navigation time and Vs navigation time is k2, here k1, k2 are taken 0.1. In this paper, the combination of unmanned underwater vehicle rapidity, maneuverability and energy system three performance index as the optimization objective function of the comprehensive optimization mathematical model, and the specific composition by the way of power exponent multiply with each index.

3.2.1 Objective function of rapidity

Considering the resistance and propulsion performance, ensure unmanned underwater vehicle keep high speed in the case of less consumption of the main engine power. Here is the navy coefficient as a measure of rapidity performance index of unmanned underwater vehicle.

The formula of Navy coefficient is:

$$C_{sp} = \frac{V^2 \Delta^{2/3} (\eta_R \eta_0 \eta_s \eta_H)}{R_t} \quad (1)$$

The rapidity objective function is as follows:

$$C_S = \frac{1}{1+k_1+k_2} C_{sp1} + \frac{k_1}{1+k_1+k_2} C_{sp2} + \frac{k_2}{1+k_1+k_2} C_{sp3}$$

(2)

Where C_{sp1} 、 C_{sp2} 、 C_{sp3} respectively are navy coefficient of design speed V_s, balance speed V_1 and balance speed V_2; V is the speed; Δ is the displacement; R_t is the total resistance; η_0 is the propeller open water efficiency; η_H is the hull efficiency; η_R is the relative rotation efficiency; η_S is the shafting transfer efficiency.

3.2.2 Objective function of maneuverability

The maneuverability of the unmanned underwater vehicle should be considered from the horizontal and vertical movement. In this paper, 6 sub-objective functions are selected to form the performance index of maneuverability, and the specific composition by the way of power exponent multiply with each index.

1.Static stability coefficient index of incidence angle (Lalfa)

$$Lalfa = l'_\alpha = \frac{l_\alpha}{L} = -\frac{M'_w}{Z'_w} \quad (3)$$

Where M'_w is the derivative of the longitudinal moment on the heave speed; Z'_w is the derivative of the vertical force on the heave speed.

2.Trim angle index of depth-keeping linear with balance navigation (Ta)

$$Ta = \alpha = \theta = \frac{M'_{\delta_h} Z'_0 - M'_0 Z'_{\delta_h}}{(M'_w + M'_\theta) Z'_{\delta_h} - M'_{\delta_h} Z'_w} \quad (4)$$

Where M'_{δ_h} is the derivative of the longitudinal moment on the rudder angle of the horizontal rudder; Z'_{δ_h} is the derivative of the vertical force on the rudder angle of the horizontal rudder; Z'_0 is the coefficient of zero lift; M'_0 is the torque coefficient of zero lift; M'_θ is the derivative of the longitudinal moment on the trim angle.

3.Rudder angle index of depth-keeping linear with balance navigation (Ra)

$$Ra = \delta_h = \frac{M'_0 Z'_w - (M'_w + M'_\theta) Z'_0}{(M'_w + M'_\theta) Z'_{\delta_h} - M'_{\delta_h} Z'_w} \quad (5)$$

4.Index of rise rate (Rra)

$$Rra = \frac{\partial V_{x'}}{\partial \delta_h} = -\frac{V^3}{m'gh} \left[\frac{M'_{\delta_h}}{Z'_{\delta_h}} - \frac{M'_w}{Z'_w} - \frac{M'_\theta}{Z'_w}\right] Z'_{\delta_h} \quad (6)$$

Where m' is the dimensionless value of quality.

5.Static stability index of drift angle ($Lbelta$)

$$Lbelta = l'_\beta = \frac{l_\beta}{L} = \frac{N'_v}{Y'_v} \quad (7)$$

Where N'_v is the derivative of yawing moment on the sway speed; Y'_v is the derivative of drifting force on the sway speed.

6.Weight dimensionless number index of horizontal line stability (C_H)

$$C_H = 1 + \frac{N'_v (m' - Y'_r)}{N'_r Y'_v} > 0 \quad (8)$$

Where N'_r is the derivative of yawing moment on the heave speed; Y'_r is the derivative of drifting force on the heave speed.

In summary, the objective function of maneuverability is as follows:

$$C_M = \text{Lalfa}^{\alpha 1} * \text{Ta}^{\alpha 2} * \text{Ra}^{\alpha 3} * \text{Rra}^{\alpha 4} * \text{Lbelta}^{\alpha 5} * \text{CH}^{\alpha 6} \quad (9)$$

Where $\alpha 1$、$\alpha 2$、$\alpha 3$、$\alpha 4$、$\alpha 5$、$\alpha 6$ respectively are weight of each sub-objective function, $\alpha 1$、$\alpha 2$、$\alpha 3$、$\alpha 4$、$\alpha 5$、$\alpha 6$ are greater than 0, and $\alpha 1 * \alpha 2 * \alpha 3 * \alpha 4 * \alpha 5 * \alpha 6 = 1$, their values respectively are 7/5, 3/7, 7/5, 5/3, 5/3, 3/7.

3.2.3 Objective function of energy system

In the energy system, taking into account the performance of the energy tank is determined by the power supplied by the unit weight, and need to have a high circuit efficiency. So the selection of power circuit efficiency, equipment circuit efficiency and energy weight ratio as 3 sub-objective function, and then the distribution of weight, using the way of power exponent multiply with each index to obtain the objective function of energy system.

The objective function of energy system is as follows:

$$C_N = \eta_M^{\beta 1} * \eta_E^{\beta 2} * \mu^{\beta 3} \quad (10)$$

Where η_M is the power circuit efficiency, $\eta_M = \frac{P_E}{P_t} = \frac{(E - Ir)I}{EI} = \frac{U}{E} = \frac{145}{3.2uvw_1}$; η_E is the equipment circuit efficiency, $\eta_E = \frac{P_E}{P_t} = \frac{(E - Ir)I}{EI} = \frac{U}{E} = \frac{24}{3.2uvw_2}$; μ is the energy weight ratio, $\mu = \frac{0.16uv}{1.5uv + 0.2v + 0.3}$; w_1 and w_2 are the number of battery box that provide power circuit and equipment circuit; $\beta 1$、$\beta 2$、$\beta 3$ respectively are weight of each sub-objective function, $\beta 1$、$\beta 2$、$\beta 3$ are greater than 0, and $\beta 1 * \beta 2 * \beta 3 = 1$, their values respectively are 9/7、11/9、7/11.

3.2.4 Total optimization objective function of unmanned underwater vehicle

The index of unmanned underwater vehicle rapidity, maneuverability and energy system are combined, using the way of power exponent multiply with each index to obtain the total optimization objective function.

The total optimization objective function is as follows:

$$C = C_S^{\gamma 1} * C_M^{\gamma 2} * C_N^{\gamma 3} \quad (11)$$

Where $\gamma 1$、$\gamma 2$、$\gamma 3$ respectively are weight of rapidity, maneuverability and energy system, $\gamma 1$、$\gamma 2$、$\gamma 3$ are greater than 0, and $\gamma 1 * \gamma 2 * \gamma 3 = 1$, their values respectively are 7/5、10/9、9/14.

3.3 Constraints conditions

3.3.1 Equation constraints

1) Meet the buoyancy constraints, balance between optimized displacement and designed displacement: $\rho V = \Delta_0$;

2) Meet the force balance constraints: $T_E = R_t$;

3) Meet the torque balance constraints: $\frac{\eta_R \eta_S P_s}{2\pi N} = K_Q \rho N^2 D_p^5$;

4) Meet the power supply constraints of energy tank, W_M and W_E respectively are the power consumption of power circuit and equipment circuit: $W = W_M + W_E = 0.16 * u * v * m * n * 0.95$.

3.3.2 Inequality constraints

1) Ranges of values of 28 design variables;

2) Meet the trim angle constraints of depth-keeping linear with balance navigation: the trim angle must be less than 10°;

3) Meet the rudder angle constraints of depth-keeping linear with balance navigation: the balance rudder angle control within the range of ±5°;

4) Meet the length constraint of energy tank: $L_E = 0.284m + 0.05(m - 1) < \varsigma L_m$;

5) Meet the width constraint of energy tank: $B_E = 0.21n + 0.05(n - 1) < B - 2b$;

6) Meet the height constraint of energy tank: $h = (0.015u + 0.003)v + 0.065 < \beta H$.

4. Optimization calculation and result analysis

The designed displacement of the flat unmanned underwater vehicle is 16t, all kinds of parameters in the mathematical model are given. In this paper, a large number of optimization calculation is carried out for the key design variables such as speed, propeller diameter and so on.

4.1 The influence of key design variables on the value of the total optimization objective function

The optimization calculation is carried out on the different speed, different propeller diameter, different boat wide and different ratio of the length of energy tank and the length of middle hull a total of 4 key design variables. The calculation results of the total objective function values are shown in the following figure:

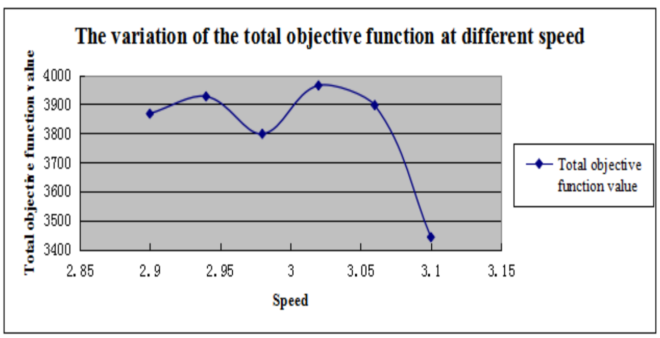

Fig. 3 The variation of the total objective function at different speed.

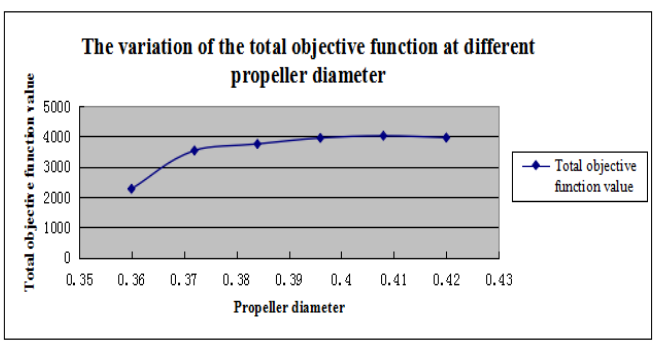

Fig. 4 The variation of the total objective function at different propeller diameter.

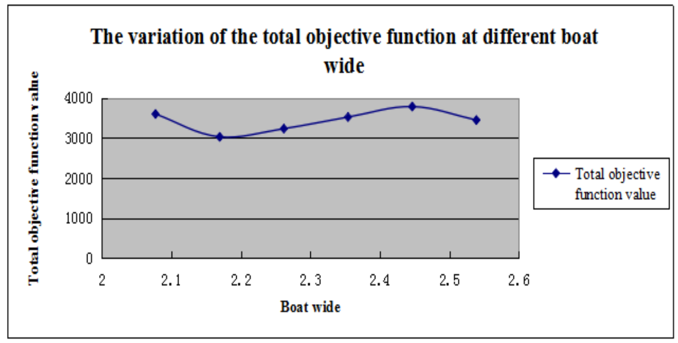

Fig. 5 The variation of the total objective function at different boat wide.

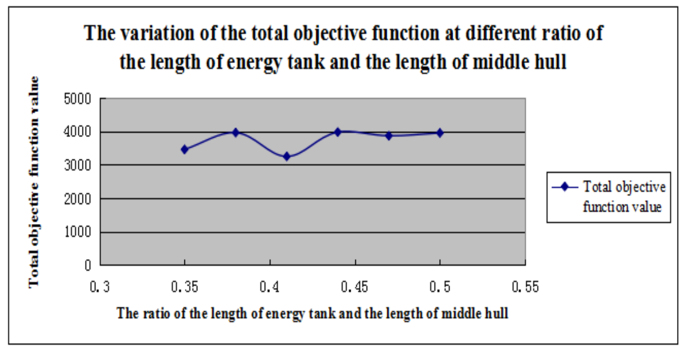

Fig. 6 The variation of the total objective function at different ratio of the length of energy tank and the length of middle hull.

From the above 4 pictures, we can see that the change trend of the total optimization objective function value is that with the speed (from 2.9kn to 3.1kn) first increases, then decreases, then increases, and finally decreases; with the propeller diameter (from 0.36m to 0.42m) has been increased; with the boat wide (from 2.0772m to 2.5388m) first decreases, then increases, and finally decreases; with the ratio of the length of energy tank and the length of middle hull (from 0.35 to 0.5) first increases, then decreases, then increases, and finally tends to be stable. And their optimal values respectively are 3.02kn, 0.41m, 2.45m and 0.44.

Analysis and comparison of the change trend of the total optimization objective function value, can be found in Figure 3 and Figure 4 greater volatility, and figure 5 and Figure 6 is relatively stable, it can be concluded that the speed and propeller diameter is more sensitive to the optimization system.

4.2 The influence of each subsystem on the total optimization system

In order to analyze the effect of rapidity system, maneuverability system and energy system of three subsystems to the total optimization system, the optimization calculation of different speed and different middle hull length is carried out. The total objective function value and the sub-objective function value are obtained, and the results are as follows:

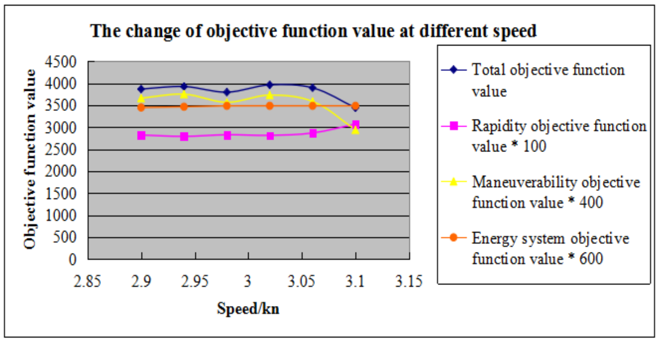

Fig. 7 The change of objective function value at different speed.

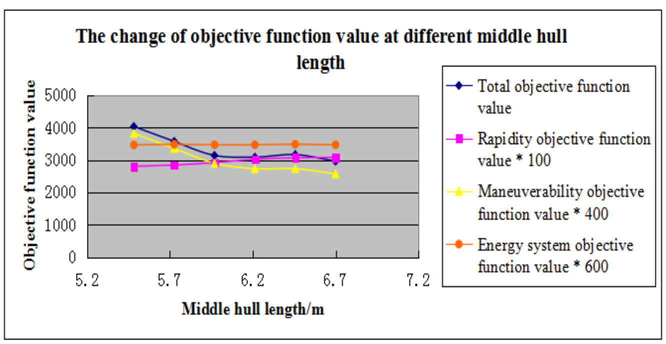

Fig. 8 The change of objective function value at different middle hull length.

Observation figure 7 and figure 8, we can get that the sensitivity of each subsystem to the total optimization system is maneuverability > rapidity > energy system, and the change of energy system objective function value is not obvious. The maneuverability objective function and the total objective function have the same trend to some degree, and it can be concluded that the maneuverability optimization system has a great influence on the total optimization system.

5. Conclusion

In summary, in this paper, taking into account rapidity, maneuverability and energy system, 28 design variables are selected, and 9 constraint conditions are determined. Established the comprehensive optimization mathematical model, and the optimization program has been written to accomplish the multidisciplinary comprehensive optimization computation on this unmanned underwater vehicle, according to hierarchical strategy improving genetic algorithm. The optimization results show that the sensitivity of each subsystem to the total optimization system is maneuverability > rapidity > energy system. The maneuverability objective function and the total objective function have the same trend to some degree, and it can be concluded that the maneuverability optimization system has a great influence on the total optimization system. And the optimal value of each key design variable is obtained through optimization calculation. Among them, the hierarchical strategy to improve genetic algorithm has provides a new optimization ideas for the optimization algorithm. In this paper, the comprehensive optimization of unmanned underwater vehicle has provides a basis for solving the optimization design problem of multi-objective, multi-variable and multi-constraint.

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