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Rapidity and maneuverability optimization analysis of submersible vehicle based on particle swarm optimization

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Key Words: *AUV(Autonomous Underwater Vehicle); RSM (Response Surface Method); PSO(particle swarm optimization); optimized system.*

Abstract: Optimization is an important part of the design on submersible vehicles. In order to determine the influence of design variables, the study on the sensitivity of variables to optimized system is becoming important. In this paper, the AUV of AUTOSUB type is the object of research. The RSM method was used to construct response surface and establish a response surface equation between independent variables and dependent variable, which can provide basis for the establishment of optimization system. And, a mathematic model was conducted for rapidity and maneuverability of the AUV, which including design variables, objective function and constraint conditions. Then, optimization system was established using particle swarm optimization based on the response surface method. Six discrete design variables are selected to study their sensitivity to optimized system, which provides basis for the further optimization. The result shows that the effect of design variables sensitivity to the optimized system is different. The fluence of rapidity system to the overall system is biggest. And the optimized system has a high efficiency and the optimized results are reliable.

1 INTRODUCTION

AUV combines artificial intelligence, intelligent control, detection, identification, system integration and many other technologies. When a AUV navigates in a complex underwater environment, it can complete tasks by itself without the control of human[1]. Currently, AUVs are mainly used in the exploration of offshore oil and gas resources as well as military warfare[2].

The rapidity, maneuverability and endurance are the important aspects to evaluate the merits of AUV’s performance. Therefore, establishing a optimized system including rapidity and maneuverability is an important part in the design of AUVs. In the multidisciplinary optimization design, using the approximate model technology, which can also be called response surface, not only can reduce the amount of computational cost, but also can effectively ensure the accuracy of the calculation[3]. In order to establish the optimized system, three response surfaces have been established, which are the basis for solving the problems encountered in the design, and the final design of the optimized system can be realized by particle swarm optimization.

2 PSO

PSO is short for particle swarm optimization, which is a global random search algorithm simulating the process of birds' foraging[4]. As PSO has a good biological social background[5] to understand easier, easy to implement, without gradient information, fewer parameters and so on. Particle swarm optimization algorithm has more advantages in continuous optimization and discrete optimization problems[6-7].

The flow chart of the PSO is shown in the Fig.2-1. The optimization procedure of PSO is the process for many particles with a certain speed and direction to search optimal particle in a solution space[8].

Generally, the position and velocity of the particles are got in a continuous space of real numbers, and they change according to the following equations.

$$v_{iD}^{k+1} = \omega v_{iD}^{k} + c_1\xi(p_{iD}^{k} - x_{iD}^{k}) + c_2\eta(p_{gD}^{k} - x_{iD}^{k}) \tag{2-1}$$

$$x_{iD}^{k+1} = x_{iD}^{k} + v_{iD}^{k+1} \tag{2-2}$$

Where, ω is the inertia weight, which can make the particles have a balanced development ability (i.e., local search ability) and exploring ability (i.e., wide area search ability).

c_1 and c_2 are called learning factor or acceleration coefficient, which are positive constant generally and set as 2. $\xi, \eta \in U[0,1]$, which are pseudo random numbers uniformly distributed in the interval of 0 to 1. The velocities of particles are limited to a maximum speed.

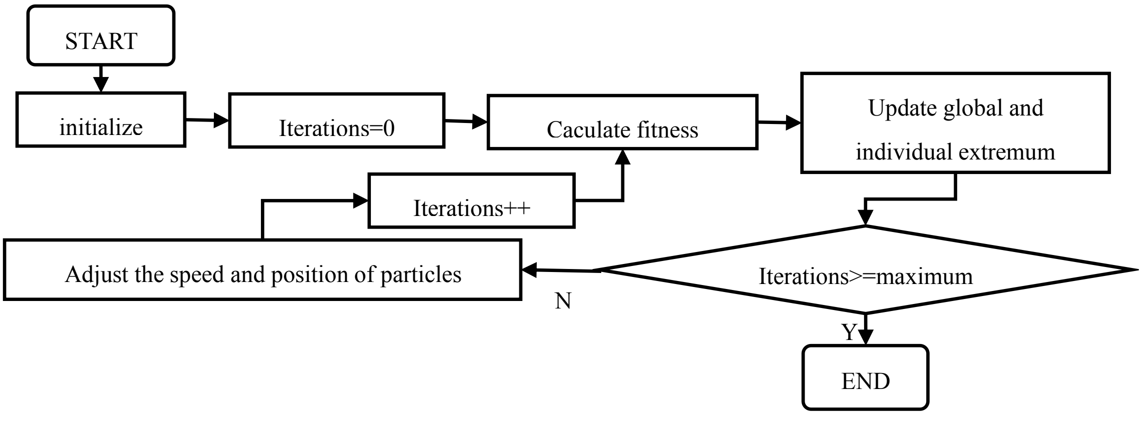

Fig.2-1 The flow chart of the PSO

3 RSM

RSM is a comprehensive optimization method. When analysing multi-factor numbers, the regression relationship between dependent variable and multiple independent variables can be constructed by this method[9]. Currently, the two commonly used global approximation methods are neural network method and polynomial response surface method[10].

3.1 Principle of RSM

There is a set of design variables: $x=(x_1,x_2,x_3,...,x_n)$, which are called design point values. A response value named y exists corresponding to these values. There are M groups of design variables and response values. And the function relation between design variables and dependent variable is : $\tilde{y}=f(x)$.

The approximate function called response surface function is obtained by the method of undetermined coefficients. And the function has cross quadratic polynomial, as follows:

$$\tilde{y}=\beta_0+\sum_{i=1}^{n}\beta_i x_i+\sum_{i=1}^{n}\beta_i x_i{}^2+\sum_{i<j}^{n}\sum_{i=0}^{j}\beta_{ij}x_i x_j \tag{3-1}$$

Where, x is the design variables; $\tilde{y}$ is the response surface function; $\beta=(\beta_0,\beta_1,\beta_2\cdots,\beta_{n(n+3)/2})$ is undetermined coefficient of constant term.

The number of items on the right of the equality can be calculated, as follows:

$$\mathrm{N}=1+n+n+C_n^2=1+n(n+3)/2 \tag{3-2}$$

Transform as follows:

$$\begin{cases} x_0=1 \\ x_1=x_1, x_2=x_2,\cdots,x_n=x_n \\ x_{n+1}=x_1^2, x_{n+2}=x_2^2,\cdots,x_{2n}=x_n^2 \\ x_{2n+1}=x_1x_2, x_{2n+2}=x_1x_3,\cdots,x_{n(n+3)/2}=x_{n-1}x_n \end{cases} \tag{3-3}$$

Response surface function can be expressed as follows:

$$\tilde{y}=\sum_{i=0}^{n(n+3)/2}\beta_i x_i \tag{3-4}$$

The matrix *G* of *M* rows and *N* columns and the matrices *β*, *Y* of *M* rows and one column, as follows:

$$G=\begin{bmatrix} 1 & x_1^{(0)} & x_2^{(0)}\cdots & x_{N-1}^{(0)} \\ 1 & x_1^{(1)} & x_2^{(1)}\cdots & x_{N-1}^{(1)} \\ & & \bullet & \\ & & \bullet & \\ & & \bullet & \\ 1 & x_1^{(M-1)} & x_2^{(M-1)}\cdots & x_{N-1}^{(M-1)} \end{bmatrix}, \quad Y=\begin{bmatrix} y_1 \\ y_2 \\ \bullet \\ \bullet \\ \bullet \\ y_M \end{bmatrix}, \quad \beta=\begin{bmatrix} \beta_0 \\ \beta_1 \\ \bullet \\ \bullet \\ \bullet \\ \beta_{N-1} \end{bmatrix}$$

The relationship between these three matrices can be expressed as follows:

$$G\beta = Y \tag{3-5}$$

$$G^T G\beta = G^T Y \tag{3-6}$$

The undetermined coefficient of constant term can be finally obtained by the transformation as follows:

$$\hat{\beta} = \left(G^T G\right)^{-1} G^T Y \tag{3-7}$$

The response surface equation can be finally obtained by putting the formular (3-7) into the formular (3-1).

3.2 Application of RSM in Mathematic Model

1) The displacement volume and wet area of a hull change with the main dimensions. So, considering that the local dimensions of a hull have a high impact on the displacement volume and wet area, the response surface function can be established as follows.

$$V = f_1(L_h, L_m, L_a, B, H, \lambda) \qquad S = f_2(L_h, L_m, L_a, B, H, \lambda) \tag{3-8}$$

Where V is volume of displacement; S is wet area; L_h is the length of bow; L_m is the length of middle body; L_a is the length of stern; B is molded breadth; H is molded depth; L is the length of hull; λ is the aspect ratio of rudder;

The dimensionless form of the response surface function can be calculated as follows.

$$\frac{V}{D^3} = f_1\left(\frac{L_h}{D}, \frac{L_m}{D}, \frac{L_a}{D}, \lambda\right) \qquad \frac{S}{D^2} = f_2\left(\frac{L_h}{D}, \frac{L_m}{D}, \frac{L_a}{D}, \lambda\right) \tag{3-9}$$

Where $D=(B+H)/2$;

2) The frictional resistance of the hull can be calculated by the formula ITTC. The viscous pressure resistance can be calculated through total resistance minus the frictional resistance. Considering the factors influencing the viscous pressure resistance, a response surface function can be established as follows.

$$R_{pv} = f_3(L_h, L_m, L_a, B, H, V_s, \lambda) \tag{3-10}$$

Where R_{pv} is the viscous pressure resistance; Vs is the design speed; The dimensionless form of the response surface function can be calculated as follows.

$$\frac{R_{pv}}{\Delta} = f_3\left(\frac{L}{D}, \mathrm{Re}, \lambda\right) \tag{3-11}$$

4 MATHEMATIC MODEL

4.1 Design Variables

In this paper, the AUV of AUTOSUB type was chosen to study, it is shown in Fig. 4-1.

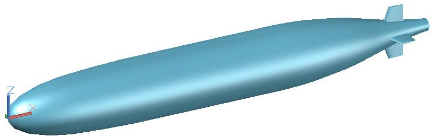

Fig.4-1 The schematic diagram of AUV optimization model

Considering the impact of various factors on the hull performance, several design variables have been selected and shown in Table 1.

Table1. The range of design variables

No.	Design variables	Symbol	Unit	Lower limit	Upper limit
1	The length of bow	L_h	m	0.920	1.125
2	The length of middle body	L_m	m	2.682	3.278
3	The length of stern	L_a	m	1.362	1.531
4	molded breadth	B	m	0.738	0.902
5	molded depth	H	m	0.738	0.902
6	The longitudinal position of barycenter	X_g	m	-0.03	-0.04
7	The longitudinal position of buoyant center	X_f	m	-0.22	-0.23
8	Propeller diameter	D_p	m	0.45	0.55
9	Propeller solidity ratio	A_e/A_0		0.062	0.07
10	Propeller rotational speed	N	r/min	300	500
11	Design speed	V_s	kn	2.9	3.100
12	The outer end length of the horizontal rudder	d_{oh}	m	0.1	0.2
13	The inner end length of the horizontal rudder	d_{ih}	m	0.1	0.2
14	The height of the horizontal rudder	Z_h	m	0.25	0.3
15	The outer end length of the vertical rudder	d_{ov}	m	0.1	0.2
16	The inner end length of the vertical rudder	d_{iv}	m	0.1	0.2
17	The height of the vertical rudder	Z_v	m	0.25	0.3
18	Longitudinal coordinate of forward looking sonar	X_h	m	2.415	2.425
19	Longitudinal coordinate of communication sonar	X_e	m	2.15	2.16
20	Longitudinal coordinate of lifting GPS	X_{Gps}	m	0.365	0.375
21	Longitudinal coordinate of communication antenna	X_l	m	0.075	0.077
22	Longitudinal coordinate of emergency communication sonar	X_y	m	-0.840	-0.850
23	Longitudinal coordinate of front rings	X_{d1}	m	1.99	2.00

24	Longitudinal coordinate of back-end rings	X_{d2}	m	-0.965	-0.985
25	Longitudinal position of the rudder	X_r	m	-2.61	-2.63
26	Longitudinal coordinate of rudder's steady wing	X_w	m	-2.1	-2.3

4.2 Objective Function

4.2.1 Rapidity Index

Admiralty coefficient contains the information about the resistance and propulsion performance of the ship and can be used to measure the rapidity performance of a ship. Admiralty coefficient can be calculated by the formular as follows.

$$C_{sp} = \frac{V_s^2 \Delta^{2/3} (\eta_R \eta_0 \eta_s \eta_H)}{R_t} \tag{4-1}$$

Where R_t is the total resistance; Δ is the displacement; Vs is the design speed; 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.

4.2.2 Maneuverability Index

Considering the horizontal and vertical motions of the AUV, seven indexes has been selected as follows.

1) Vertical dynamic stability criterion numeral: C_v, the weight is shown as β_1;

$$C_v = \left[1 - \frac{M_w^{'}(m^{'} + Z_q^{'})}{M_q^{'} Z_w^{'}} \right] > 0 \tag{4-2}$$

2) Trim angle of a certain depth movement: T_a, the weight is shown as β_2;

$$T_a = 57.3 \frac{-(M_w^{'} + M_0)(Z_0^{'} + P^{'}) + (M_0^{'} + M_p^{'}) Z_\delta^{'}}{(M_w^{'} + M_\theta^{'}) Z_\delta^{'} - M_\delta^{'} Z_w^{'}} \tag{4-3}$$

3) Horizontal rudder angle of a certain depth movement: R_a, the weight is shown as β_3;

$$R_a = 57.3 \frac{-(M_0^{'} + M_p^{'}) Z_0^{'} + (Z_0^{'} + P^{'}) M_\delta^{'}}{(M_w^{'} + M_\theta^{'}) Z_\delta^{'} - M_\delta^{'} Z_w^{'}} \tag{4-4}$$

4) The rate of vertical movement: R_{ra}, the weight is shown as β_4;

$$R_{ra} = \frac{\partial V_\zeta}{\partial \delta_h} = \frac{V^3}{57.3 m^{'} g h} \left[\frac{M_{\delta_h}^{'}}{Z_{\delta_h}^{'}} - \frac{M_\delta^{'}}{Z_\delta^{'}} - \frac{M_\theta^{'}}{Z_w^{'}} \right] Z_{\delta_h}^{'} \tag{4-5}$$

5) The inverse velocity of vertical movement: I_v, the weight is shown as β_5;

$$I_v = \sqrt{\frac{m^{'} g h Z_{\delta_h}^{'}}{Z_{\delta_h}^{'} M_w^{'} - Z_w^{'} M_{\delta_h}^{'}}} \tag{4-6}$$

6) The stability criterion of horizontal linear motion: C_H, the weight is shown as β_6;

$$C_H = 1 + \frac{N_v^{'}(m^{'} - Y_r^{'})}{N_r^{'} Y_v^{'}} > 0 \tag{4-7}$$

7) Rudder effectiveness index: V_T, the weight is shown as β_7;

$$V_T = \frac{Y_{\delta_v}^{'}(m^{'} - Y_v^{'}) + N_r^{'} Y_\delta^{'}}{N_v^{'}(m^{'} - Y_v^{'}) + N_r^{'} Y_w^{'}} \tag{4-8}$$

In summary, maneuvering index:

$$C_{ma} = \frac{C_v^{\beta_1} R_{ra}^{\beta_4} C_H^{\beta_6} V_T^{\beta_7}}{T_a^{\beta_2} R_a^{\beta_3} I_v^{\beta_5}} \tag{4-9}$$

Where $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7 > 0$, and $\beta_1 \beta_2 \beta_3 \beta_4 \beta_5 \beta_6 \beta_7 = \beta$; β is the weight of the maneuverability index;

4.2.3 Comprehensive Objective Function

The synthetical optimization objective function has been established as follows, including rapidity, maneuverability system.

$$f(x) = C_{sp}^{\alpha} \times C_{ma}^{\beta} \tag{4-10}$$

Where α is the weight of rapidity index; β is the weight of maneuverability index; And $\alpha * \beta = 1$.

4.3 Constraints Conditions

4.3.1 Equation Constraints

1) Balance between buoyancy and displaced weight.

$$\nabla = LBHC_B \tag{4-11}$$

2) Balance between effective thrust and resistance .

$$N_p K_T \rho N^2 D_P^4 (1 - t) = R_t \tag{4-12}$$

3) Balance between torque received by screw from main engine and torque from hydrodynamic resistance.

$$\frac{\eta_R \eta_s P_s}{2\pi N} = K_Q \rho N^2 D_P^5 \tag{4-13}$$

4.3.2 Inequality Constraints

1) Ranges of values of 26 design variables.

2) The trim angle should be less than 10 degrees:

$$T_a = \frac{-(M_w^{'} + M_0)(Z_0^{'} + P^{'}) + (M_0^{'} + M_p^{'}) Z_\delta^{'}}{(M_w^{'} + M_\theta^{'}) Z_\delta^{'} - M_\delta^{'} Z_w^{'}} < 10^o \tag{4-14}$$

3) The rudder angle should be less than 5 degrees:

$$R_a = 57.3\frac{-(M_0^{'}+M_p^{'})Z_0^{'}+(Z_0^{'}+P^{'})M_\delta^{'}}{(M_w^{'}+M_\theta^{'})Z_\delta^{'}-M_\delta^{'}Z_w^{'}} < 5^o \tag{4-15}$$

5 OPTIMIZATION CALCULATION AND ANALYSIS

5.1 Optimization Calculation

1) The weights of each objective function have been defined as follows.
$\alpha=7/3$, $\beta=3/7$; $\beta_1=47/55$, $\beta_2=33/47$, $\beta_3=21/31$, $\beta_4=55/49$, $\beta_5=1$, $\beta_6=31/33$, $\beta_7=1$;
2) The main dimensions have influence on the resistance coefficient and the wet area of a hull, which affects the total resistance of the hull directly. In the system of maneuverability, main dimensions impact the calculation of hydrodynamic derivatives and zero lift. The diameter and rotational speed of propeller mainly affect the open water efficiency of the propeller, which should have a high value in the case of meeting all the constraint. And the other design variables mainly affect the subsystem. Considering the characteristic of each variable, six variables have been selected to take a research on the sensitivity of these variables to the optimized system.
3) Six discrete design variables have been selected to optimize, including the length of bow, the length of middle body, the length of stern, the molded breadth, the molded depth, the propeller diameter and rotational speed of propeller, when the design speed is 3kn.
4) The optimized method is the particle swarm optimization based on RSM and the algorithm runs 8000 times for one optimization.

5.2 Results And Analysis

The rapidity objective function is shown as C_{sp}, the maneuverability objective function is shown as C_{ma} and the overall objective function is shown as Goal. And the corresponding graphs are shown in Fig.5.

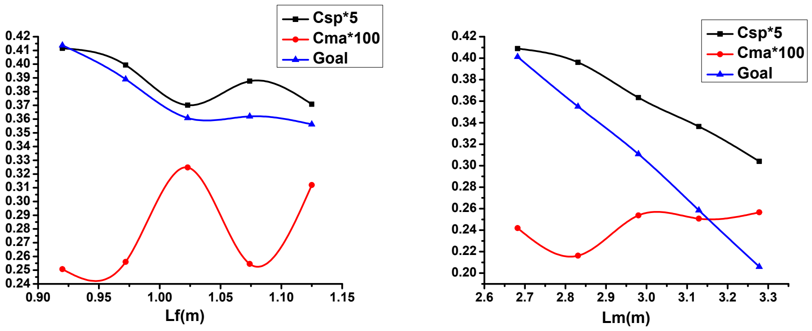

Fig.5-1 the objective function curves with the change of length of bow(left)and middle body(right)

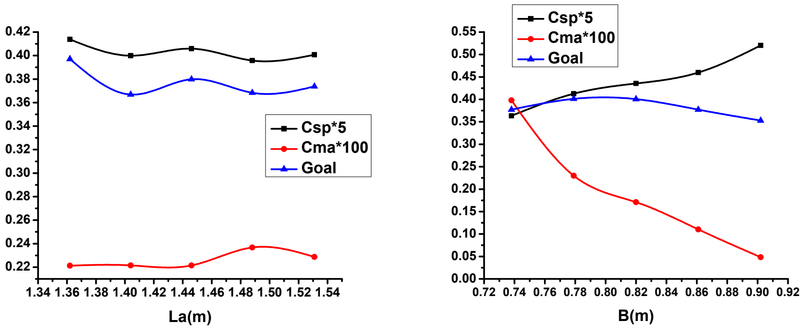

Fig.5-2 the objective function curves with the change of length of stern(left)and molded breadth(right)

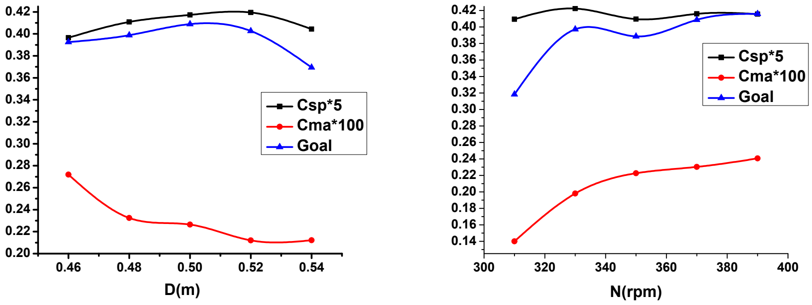

Fig.5-3 the objective function curves with the change of diameter (left) and rotational speed (right) of propeller

Analyzing from the Fig.5, the length of bow, length of middle body and the molded breadth have a higher sensitivity and the length of stern have a low sensitivity on the rapidity system. Similarly, the length of bow , molded breath, the diameter of propeller and the rotational speed have a higher sensitivity on the maneuverability system. Comparing the overall objective function, the lengths of bow and middle body have a higher sensitivity on the overall optimized system. So, the accuracy can be improved further through selecting the sensitive variables to parallelly divide and optimizing further.

Analyzing the results, the rapidity objective function account for a higher percentage of the overall objective function, which reflects that the design of the rapidity system is the key part of the design of the optimized system. And the curves also reflect that the overall objective function and the rapidity objective function have the same trends to some extend, which expresses that the rapidity system has a bigger influence on the overall system.

When the design speed is 3kn and the diameter of propeller is in the range of 0.48m to 0.52m and the rotational speed is in the range of 320rpm to 340rpm, the ship have a better propulsion and maneuverability performance.

6 CONCLUSION

In this paper, a comprehensive optimization system of rapidity and maneuverability has been established through constructing mathematic model and writing optimization algorithm. Twenty-six design variables have been selected and six constraint conditions have be established in this paper. The overall objective function has been established by eight sub-objective functions, which include the parts of rapidity and maneuverability. The particle swarm optimization algorithm based on the response surface method has been constructed to study the sensitivity of six design variables, which provides reference for the further optimization. And the results show that different design variables have different sensitivity to the optimized systems. On the other hand, using response surface method simplifies the optimized system, which can provide an idea for solving the optimized problems of multiple objectives, multiple variables and multiple constraints.

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