Performance Optimization Analysis of an USV Based on Improved Particle Swarm Optimization Algorithm

Man Liu[1], Songlin Yang[1], Shasha Gao[1], Yang Li[1]

[1] Jiangsu University of Science and Technology, Zhenjiang, China

Abstract: Rapidity, maneuverability, seakeeping and anti-overturning are important factors to evaluate unmanned surface vehicle's performance, which should be pay overall consideration to the impact of each performance to USV during the ship form design. In this paper, a new type of planning boat equipped with splash proof was selected as the object of research. Through the establishment of USV performance optimization mathematical model, a mathematical model was conducted for rapidity, maneuverability, seakeeping and anti-overturning of the USV, which including design variables, objective function and constraint conditions. Through the usage of particle swarm optimization (PSO) algorithm, comprehensive optimization software was compiled. Weighting design of the 4 system was set up and the influence of principal dimensions for USV performance was studied. Single PSO, hierarchical PSO and parallel PSO are adopted to calculate. And the optimal method suitable for the optimization model and the influence of each optimization system were obtained. The results showed that the optimization system based on the improved PSO was more efficient and the optimization results were more reliable.

Keywords: Unmanned Surface Vehicle (USV); PSO; Comprehensive Optimization; Hierarchical Strategy; Key Variables

1 Introduction

As the new type of water surface vehicle, USV has been more and more universal attention by the countries in the world for its numerous advantages such as its flexibility, small size, high speed and intelligence. Its other great virtue, of course, is it can substitute for people working in hazardous areas. At present, USV is widely used in civil areas in China, such as weather and hydrological forecasting, information collection, fishery breeding and so on.

As the applied fields of USV enlarged, more and more scholars began to study it both at home and abroad. The researches on USV include the study of its boat shape and hydrodynamic performance. Studying the 4 performance based on rapidity, maneuverability, seakeeping and anti-overturning of USV is an important step in the design of the boat type. It is of great importance to optimize and design of a USV with good performance. The traditional optimization of ship hydrodynamic performance was to take a key output as the optimized objective function, and considered other outputs in the form of constraints, and then the optimal solution of the system was obtained by solving the maximum value of the single objective function[1-2]. For example: The rapidity was optimized first, and then the seakeeping and maneuverability of the ship were checking and vibration; The method of target weighting was adopted to transform the multi-objective optimization problem into a single objective optimization problem. In this kind of mode, the design of the subsystems including rapidity, maneuverability and seakeeping were actually separated artificially. The synergy between the subsystems was not fully utilized to improve the hydrodynamic performance design of the ship. In this way, it is possible to lose the overall optimal solution of the system.

In recent years, many scholars both at home and abroad had put forward a comprehensive optimization design method[3-5]. Wei Zifan[6] established a comprehensive optimization mathematical model for high speed USV and she compiled optimization software by using intelligent optimization methods. Yu Ning[7] combined of three performance indexes including rapidity, maneuverability and seakeeping as the optimization objective functions of the comprehensive mathematical model for hydrodynamic performance optimization, and selected genetic algorithm as an optimization algorithm, compiled navigation performance optimization program of a high-speed monohul USV. In this paper, the comprehensive performance of USV was studied based on improved PSO algorithm, so as to realize the final design of the hull optimization system.

2 Particle Swarm Optimization

Because the PSO has many advantages, such as its simple algorithm, easy to implement, fewer parameters, no gradient information, fast convergence speed and so on, it had shown good results in the optimization problem and it had become the focus of intelligent optimization research in the world in recent years.

2.1 The principle of PSO and its implementation flow

The basic description of PSO is as follows: A swarm group of *m* particles that travel at a certain speed in the *D* dimensional search space, each particle changes its position on the basis of taking into account the best points of its search history and the history of other particles within the swarm (or domain)[8]. The position and velocity of the particles vary with the following equation:

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

$$x_{iD}^{k+1} = x_{iD}^{k} + v_{iD}^{k+1}$$

Where, C_1 and C_2 are learning factors or acceleration coefficients which are normally a positive constant. And the values are 2. ξ and η are random values which uniformly distributed in the [0,1] interval. The velocity of the particle is limited to a range of maximum velocity $V_{\max}$. v_{iD}^{k} and x_{iD}^{k} are the velocity and position of the *D* dimensional variable of particle *i* for the *k* iteration point. p_{iD}^{k} and p_{gD}^{k} are the best positions and global wizard positions for the particle *i*.

2.2 Optimization strategy

2.2.1 Hierarchical strategy

The hierarchical strategy of the algorithm consists of internal hierarchical and external hierarchical. Internal layering is the introduction of hierarchical policies into a single algorithm, and external layering is applied between different algorithms.

Because PSO has the disadvantage of easy to fall into local optimum and slow convergence rate at the later stage, using the hierarchical strategy, individuals of each layer are inherited from the best particles of each group in the upper layer. For the internal hierarchical PSO, the relationship between each layer of particles and the optimum particles in each population a layer of each group of the best particle is not a direct replacement in the iterative process optimized PSO, instead, the best particle of good value can be replaced by a drop of particles corresponding to it by compare the best individuals in each layer with each group in terms of the best values of the particles corresponding to the previous iteration. This ensures that the updated particles have a better search location[9]. For external layering strategies, set the best values in the program in advance which means after the optimization calculation was completed, the upper and lower limits were updated according to the carrier probability, and the second optimization calculation was carried out. The external layering strategy can be used between different algorithms, and can be used many times in the same algorithm.

2.2.2 Parallel strategy

The idea of parallel strategy is to divide a task into multiple sub-tasks, and perform concurrent execution. In each sub-task, we find the optimal solution in turn, which is mainly used for solving the problem of easy falling into a local optimum.

Suppose there are M design variables and each design variable is divided into Q (Parallel time is Q-1). The number of calculations is N times, and then the number of calculations of the whole optimization system is $N*Q^M$. From this we can see that if the parallel space is too dense, it will increase the amount of computation of the computer traversing the parallel space. In practical calculation, in order to improve the efficiency of parallel computing, the sensitivity of each variable to the objective function can be considered. The variables with higher sensitivity to the objective function can be selected to be computed in parallel. The design space of these sensitive variables can be rationally divided which will reduce the amount of computer work and improve computing efficiency.

3 Establishment of optimization mathematical model

3.1 Design variables

As shown in Figure 3.1, in this paper, a new type of planning boat equipped with splash proof was selected as the object of research. And the bow was fitted with hydrofoil. Consider the factors that affect USV performance, the following 23 design variables were selected and their upper and lower bounds were determined.

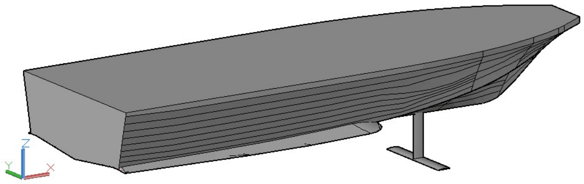


Figure 3.1 USV

Table 3.1 Design variables range

Number	Design variables	Symbols	Units	Lower limit	Upper limit
1	Ship length	L	m	5.8	6.2
2	Beam	B	m	1.9	1.94
3	Draft	T	m	0.36	0.38
4	Block coefficient	C_B	/	0.45	0.47
5	Mid-ship section coefficient	C_M	/	0.6	0.7
6	Design waterline coefficient	C_{WP}	/	0.88	0.96
7	Longitudinal position of center of	L_{cp}	m	-3	-2

	buoyancy				
8	Propeller diameter	Dp	m	0.19	0.22
9	propeller area ratio	Ae/A0	/	0.55	1
10	Pitch ratio	P_{DP}	/	0.95	1.05
11	Propeller speed	N	r/min	5400	6000
12	Design speed	Vs	kn	22.5	23.5
13	Running pitch angle	α	/	3	7
14	Rise angle	β	/	10	30
15	The ratio of the vertical position of the center of gravity to the depth of the center of gravity	δ_{ZD}	/	0.58	0.68
16	The ratio of the distance between center of gravity and center of ship to length	δ_{GL}	/	0.05	0.08
17	The ratio of the length of wingspan to beam	δ_{LB}	/	0.45	0.55
18	The ratio of the top floor length to the bottom length	δ_{L1}	/	0.6	1
19	Superstructure height	H_1	m	0.2	0.5
20	The ratio of the bottom superstructure length to ship length	δ_{L2}	/	0.6	0.8
21	Bottom floor height	H_2	m	0.2	0.5
22	The ratio of the superstructure width to beam	δ_{Ba}	/	0.6	0.8
23	The ratio of draft to depth	δ_{TD}	/	0.45	0.48

3.2 Objective function

3.2.1 Rapidity objective function

Ship resistance and its propulsive performance are the main influencing factors of ship rapidity. All things considered, in this paper, we choosed rapidity weighting factor similar to the form of the admiralty coefficient as rapidity objective function. The formula for calculation is as follows:

$$f_1(x)=C_{sp}=\frac{V_s^2\Delta^{2/3}(\eta_R\eta_0\eta_s\eta_H)}{R_t} \qquad （3.1）$$

Where, V_s is design speed; Δ is displacement; η_R is relative rotation efficiency; η_0 is propeller open water efficiency; η_s is transmission efficiency of shafting; η_H is hull efficiency; R_t is total resistance of the hull by the water.

3.2.2 Maneuvering objective function

Ship maneuverability is an important index to evaluate ship performance. Taking into account the stopping performance prediction was difficult and the effect was comparatively smaller, in this paper, we mainly considered the straight line stability and turning performance. And finally the maneuvering objective function of USV was composed of the dimensionless dimensionless number of the straightline stability and the minimum relative tactical diameter.

(1) Straight line stability criterion is Q(x), with a α_1 weighting. In this paper, the dimensionless stability criterion was chosen, formulas are as follows:

$$Q(x) = Y'_v N'_r - N'_v (Y'_r - m') > 0 \qquad （3.2）$$

$$m' = m/(0.5\rho L^3) = \rho C_B LBT/(0.5\rho L^3) = 2C_B \frac{B}{L}\frac{T}{L}$$

Where, m' is dimensionless hull quality; Y'_v、N'_r、N'_v、Y'_r are hydrodynamic derivatives of ship, namely, force and moment. In this paper, the regression formula of linear hydrodynamic derivatives was given by Clarke，D.[10]:

$$\begin{cases} (Y'_v) = -\pi (T/L)^2 (1 + 0.4 C_B B/T) \\ (Y'_r) = -\pi (T/L)^2 (-0.5 + 2.2B/L - 0.08B/T) \\ (N'_v) = -\pi (T/L)^2 (0.5 + 2.4T/L) \\ (N'_r) = -\pi (T/L)^2 (0.25 + 0.039B/T - 0.56B/L) \end{cases}$$

Where, Q(x)>0 shows that ship has linear stability. Otherwise, the result is the reverse.

（2）The minimum relative tactical diameter is D_s, with a α_2 weighting.

$$D_S = \frac{L^2 T}{10 A_R} \text{ 且 } A_R = \mu L T \qquad （3.3）$$

Where, A_R is the flooded lateral area of the rudder, μ is coefficient.

The general objective function of maneuverability was establish as follows:

$$f_2(x) = Q(x)^{\alpha_1} / (D_S)^{\alpha_2}$$

Where, α_1，$\alpha_2 > 0$, $\alpha_1 * \alpha_2 = 1$.

3.2.3 Seakeeping objective function

Considering that sway motions have a great effect on seakeeping of ship, this paper selected the dimensionless attenuation index of roll, pitching index and heave index form the optimization objective function of seakeeping of USV, formulas are as follows:

Dimensionless attenuation index of roll is μ, with a β_1 weighting:

$$\mu = \nu / \omega_\phi = N/(I'_{xx}\omega_\phi) = \frac{N}{I'_{xx}}\sqrt{\frac{I'_{xx}}{\Delta h}} = \frac{N}{\sqrt{I'_{xx}\Delta h}} \qquad (3.4)$$

Where, h is initial metacentric height; N is the coefficient of roll damping moment; I'_{xx} is total moment of inertia of ship.

$$f_3(x)=\frac{\mu^{\beta_1}}{(\psi_{1/10})^{\beta_2}*(Z_{1/10})^{\beta_3}}$$

Where, pitching index $\psi_{1/10}$ and heave index $Z_{1/10}$ selected Wei Zifan’s prediction formula which was based on the Fridsma test data that obtained by polynomial response surface fitting. β_1，β_2，$\beta_3>0$, β_1，β_2，β_3 were the weights for three subsystems of roll, pitch and heave, respectively, and $\beta_1*\beta_2*\beta_3=1$.

3.2.4 Anti-overturing objective function

Anti-overturing objective function was composed of initial metacentric height of upright floating GM and initial metacentric height of capsizing GM_1. The general objective function of the mathematical model of anti-overturning is as follows:

$$f_4(x)=GM^{\gamma_1}*GM_1^{\gamma_2} \tag{3.5}$$

Where, γ_1,γ_2 are the weights of initial metacentric height of upright floating and initial metacentric height of capsizing, and $\gamma_1*\gamma_2=1$.

3.2.5 Integrated optimization objective function

Performance optimization objective function of USV had been constructed in the form of a power exponential product based on rapidity, seakeeping, maneuverability and anti-overturing stability.

$$F(x)=f_1(x)^{\varepsilon_1}*f_2(x)^{\varepsilon_2}*f_3(x)^{\varepsilon_3}*f_4(x)^{\varepsilon_4} \tag{3.6}$$

Where, $\varepsilon_1,\varepsilon_2,\varepsilon_3,\varepsilon_4>0$, which are the weights of rapidity and maneuverability, seakeeping and anti-overturing stability, and $\varepsilon_1*\varepsilon_2*\varepsilon_3*\varepsilon_4=1$. Here, the greater the overall optimization objective function, the better the value.

3.3 Constraint condition

3.3.1 Equality constraints

Equality constraints include floating condition, thrust constraint and torque balance constraint. All document as follows:

1) Satisfy the floating constraint, namely, the optimized drainage volume agrees with the drainage volume obtained by the given formula:

$$\nabla=LBHC_B \tag{3.7}$$

2) Meet thrust constraint that the effective thrust of the propeller hull is equal to the resistance of navigation:

$$N_pK_T\rho N^2D_P^4(1-t)=R_t \tag{3.8}$$

3) Satisfy torque constraint, that is the torque supplied by the main engine to the propeller is equal to the hydrodynamic torque that the propeller receives:

$$\frac{\eta_R\eta_sP_s}{2\pi N}=K_Q\rho N^2D_P^5 \tag{3.9}$$

3.3.2 Inequality constraints

1) The upper and lower bound of design variables should be satisfied.

2) Propeller cavitation constraint should be met.

$$(1.3+0.3Z)T_e/((P_0-P_V)D_P^2)+K-(A_E/A_0)\leq 0 \tag{3.10}$$

3) Minimum relative rotary diameter constraint should be content with:

$$D_S<D \tag{3.11}$$

In this paper, D was set to10.

4) The draft was less than the total height of the ship superstructure:

$$T_1<H_1+H_2 \tag{3.12}$$

5) Initial metacentric height of capsizing should be greater than 0.3:

$$GM_1>0.3 \tag{3.13}$$

4 Optimization calculation and analysis

We set a group of initial weights for each of the optimization subsystems, as shown in the following table.

Table 4.1 Initial weight setting of each optimization system

Rapidity	2		
Maneuverability	1.6	Straight line stability	1.6
		Turning quality	0.625
Seakeeping	0.625	Dimensionless attenuation coefficient	0.625
		Significant height of pitch	1.6
		Significant number of heaving	1
Overturning resistance	0.5	Initial metacentric height of upright floating	1.6
		Initial metacentric height of capsizing	0.625

4.1 PSO algorithm optimization calculation

Set the basic parameters as follows: population size was 200; Variable weight was 0.4-0.9; The maximum particle velocity and interval probability are 0.15.

4.1.1 Discuss the influence of different algebra in PSO

Table 4.2 Computational results of PSO with different optimization algebra

Optimized algebra	1000	2000	3000	4000	5000	6000	7000
Fitness value	1714.9241	1731.066	1812.2647	1847.3805	2072.3825	2097.1574	1969.7023
Penalty function	1	1	1	1	1	1	1

value

Conclusions can be drawn from table 4.2: All penalty function value were 1, which means that the constraints were all satisfied. When the optimization algebra was set to 5000 or 6000, the fitness values obtained by PSO were larger and the optimization effect was the best. Considering the computational time and efficiency, we choosed 5000 as optimized algebra to calculate.

4.1.2 The influence of maximum particle velocity and interval probability

In order to discuss the influence of the maximum particle velocity and the interval probability on the optimization results in PSO algorithm, we set the parameters as follows: Population size was 200; Variable weight was 0.4-0.9; The optimized algebra was 5000.

Table 4.3 Calculation results of different maximum particle velocity and interval probability

Probability	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
Fitness value	1839.4515	1904.6893	2213.1063	1966.5011	1949.0372	2258.8674	1681.2393	1390.7559	1996.9618	1546.426	1974.5047
Penalty function value	1	1	1	1	1	1	1	1	1	1	1

As observed on the table, all the constraints were satisfied. With the increase of the maximum particle velocity and the interval probability, the calculated fitness values were also changing. When the maximum particle velocity and the interval probability were 0.15, there was the maximum fitness value, which means the optimization effect was the best under this circumstances. For the mathematical model of this paper, we set the maximum particle velocity and the interval probability were 0.15.

4.2 Optimization calculation of modified PSO algorithm

4.2.1 Hierarchical strategy optimization calculation

In this paper, we choosed the external hierarchy strategy, which was based on the best results obtained by the PSO algorithm, and then proceed the next optimization calculation. The second calculation was based on PSO, chaos algorithm (CA) and genetic algorithm (GA), and the parameters were set as follows:

When the first calculation was done, the parameters of the particle swarm algorithm were set to the following form: Population size was 200; Variable weight was 0.4-0.9; The optimized algebra was 5000; The maximum particle velocity and interval probability were 0.15.

For second calculations, parameter setting of chaotic algorithm was that the optimized algebra was 5000. Parameters setting of genetic algorithm: Population size was 200; The optimized algebra was 4000; Genetic factor was 0.09; Variable carrier probability was 0.0001-0.01; Evolutionary weight was 0.8. Parameters setting of PSO: Population size was 200; Variable weight was 0.4-0.9; The optimized algebra was 5000; The maximum particle velocity and interval probability were 0.15.

Among them, probability of external hierarchical strategy was set to 0.005.

Table 4.4 Optimize calculation results of external hierarchical strategy

Calculation strategy	PSO	PSO+CA	PSO+GA	PSO+PSO

Fitness value	2165.9812	2231.0501	2254.9924	2416.514
Penalty function value	1	1	1	1

As you can see from table 4.4, all constraints were satisfied. The results of the external hierarchical strategy were better than that of the single PSO algorithm, and this shows that the external hierarchical strategy can improve the optimization effect of the algorithm.

4.2.2 Parallel strategy optimization calculation

PSO algorithm was used to do parallel computation, its parameters were set as follows: Population size was 200; The optimized algebra was 5000; Variable weight was 0.4-0.9; The maximum particle velocity and interval probability were 0.15. Three key design variables including ship length, beam and draft were selected for parallel calculation, and the number of parallel time was setting to 1-2. The calculation results were shown in table 4.5.

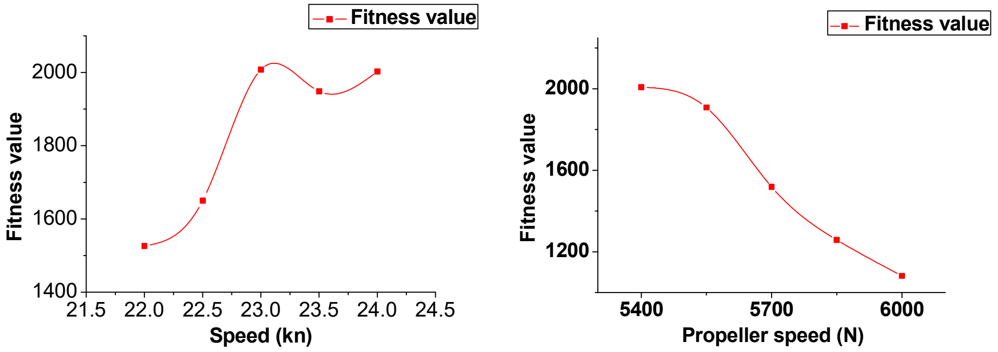
Table 4.5 Optimization calculation results of parallel strategy

Calculation strategy	unparallel	1 times parallel computation (length)	1 times parallel computation (beam)	1 times parallel computation (length+beam)	2 times parallel computation (length+beam)
Fitness value	1989.0023	2377.1409	2013.7619	2320.9584	2167.7294
Penalty function value	1	1	1	1	1
Calculation strategy	1 times parallel computation (draft)	1 times parallel computation (length+draft)	1 times parallel computation (beam+draft)	1 times parallel computation (length+beam+draft)	2 times parallel computation (length+beam+draft)
Fitness value	2081.6274	2283.3463	2215.4464	2247.7205	2377.6984
Penalty function value	1	1	1	1	1

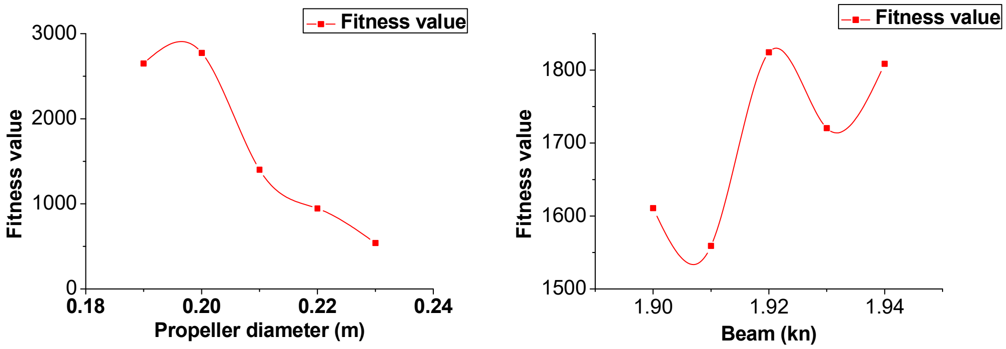
The constraints were satisfied by the results computed in table 4.5. The result of using parallel strategy was better than that of without, which showed that parallel strategy could improve the optimization effect of the algorithm. At the same time, several optimized design variables and multiple parallel operations could achieve better optimization results.

4.3 Analyze the influence of key variables on the optimization system

The parameter settings of PSO were the same as 4.2.2. The optimal design variables, such as speed and propeller speed, were optimized respectively, and their fitness values were obtained. The change curve was shown in the following figure.



(a)Variation of fitness value with speed (b)Variation of fitness value with propeller speed



(c)Variation of fitness value with propeller diameter (d)Variation of fitness value with beam

Figure 4.2 The change curve of fitness value with the key variable

As can be seen from the above 4 diagrams, the variation of the fitness values of several key design variables, such as speed, was obvious, which indicating that they were sensitive to the overall optimization system. Figure (a)-(c) standed for fast system parameters. The variation trend of their fitness value was that the speed increased first, then decreased, then increased, and the optimum speed was 23kn; With the increased of propeller speed, it basically decreased, and the optimal propeller speed was 5400r/min; The diameter of the propeller increased first, then decreased, then increased, and finally decreased, and the optimum diameter of the propeller was 0.196m. The fitness value with increasing beam first decreases, then increased, and then decreased, and finally increased, the best hull width was 1.922m.

4.4 Determine the best method of optimization

Based on the above results, it can be concluded that the optimization effect of the algorithm can be improved by using the parallel and hierarchical optimization strategies, and the optimization effect was best when the two optimization strategies were used together. The best result was when the length, breadth and draft were calculated by parallel strategy and combined with hierarchical strategy. The results of the optimization of the design variables and the results of all the sub objective function values were shown in table 4.6 and table 4.7, respectively.

Table 4.6 Design variable values for optimal results

Number	Design variables	Lower limit	Upper limit	Optimal value

1	Length	5.8	6.2	5.998
2	Beam	1.9	1.94	1.925
3	Draft	0.36	0.38	0.368
4	Block coefficient	0.45	0.47	0.457
5	Mid-ship section coefficient	0.6	0.7	0.645
6	Design waterline coefficient	0.88	0.96	0.95
7	Longitudinal position of center of buoyancy	-3	-2	-2.117
8	Propeller diameter	0.19	0.22	0.206
9	Propeller area ratio	0.55	1	0.87
10	Pitch ratio	0.95	1.05	0.953
11	Propeller speed	5400	6000	5425.375
12	Design speed	22.5	23.5	23.484
13	Running pitch angle	3	7	4.001
14	Rise angle	10	30	19.077
15	The ratio of the vertical position of the center of gravity to the depth of the center of gravity	0.58	0.68	0.627
16	The ratio of the distance between center of gravity and center of ship to length	0.05	0.08	0.066
17	The ratio of the length of wingspan to beam	0.45	0.55	0.523
18	The ratio of the top floor length to the bottom length	0.6	1	0.797
19	Superstructure height	0.2	0.5	0.355
20	The ratio of the bottom superstructure length to ship length	0.6	0.8	0.705
21	Bottom floor height	0.2	0.5	0.284
22	The ratio of the superstructure width to beam	0.6	0.8	0.68
23	The ratio of draft to depth	0.45	0.48	0.46

Table 4.7 The objective function values of the optimal results

Optimization results of objective function values	
Fitness value	2471.055
Total objective function value	2471.055
Objective function value of Rapidity	13.0449

Objective function value of maneuverability	1.7569
Objective function value of seakeeping	3.2518
Objective function value of Overturning resistance	5.2385
Objective function value of straightline stability	1.4064
Objective function value of turning quality	3.8433
Objective function value of rolling	1.4652
Objective function value of pitching	10.6622
Objective function value of heaving	1.2253
Objective function value of upright floating	1.5316
Objective function value of capsizing	0.3123
Penalty function value	1

5 Conclusion

In this paper, a comprehensive optimization system of USV performance was established by setting up mathematical model and optimizing algorithm. We selected 23 design variables and constraint conditions, and further established comprehensive optimization objective function based on 4 sub objective function including rapidity, maneuverability, seakeeping and anti-overturning. Then we set up each objective function weights and designed the evaluation index of the optimization system. PSO was used to construct the optimization system. The optimization results of single PSO and improved PSO with hierarchical and parallel strategies were compared, and the influence of several key variables such as speed on the total system was analyzed. The optimization results showed that the hierarchical and parallel strategies could effectively improve the optimization effect of PSO and the optimization effect was the best by using hierarchical and parallel strategies jointly. The research results could provide a reference for further improving the integrated optimization theory and calculation software of USV. In addition, by analyzing the influence of the key variables on the USV total optimization system, we got the parameters which have great influence on the performance of USV and reached the optimal solution. The calculation results are helpful to the overall design of USV.

Acknowledgments

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