Performance optimization analysis of the catamaran unmanned vehicle based on improved particle swarm optimization algorithm

Shi Yan, Yang Songling, Huang xiaoyu, Cai Chengqi, Cheng Zhanyuan

Abstract— The rapidity, maneuverability, seakeeping resistance and capsizing resistance of unmanned craft are important aspects for evaluating its performance. In the design of ship form, the influence degree of each performance should be considered comprehensively. In this paper a catamaran unmanned craft, determine the catamaran type unmanned craft performance (stability, quickness, maneuverability and seakeeping) evaluation function and comprehensive optimization objective function, the selected design variable and its scope and constraints, comprehensive optimization mathematical model is established, and the mathematical model and the four kinds of intelligent optimization algorithm, the combination of design and write a comprehensive optimization procedure is suitable for the catamaran unmanned craft, and a comprehensive optimization calculation and analysis. The optimal results are obtained by using a single particle swarm optimization algorithm with different computational algebra, fixed weight, maximum particle velocity and interval probability. Secondly, the particle swarm optimization algorithm was improved by using hierarchical and parallel strategies, and the hybrid algorithm and parallel computation of key design variables were carried out. By comparing the fitness function values, it is found that the optimization ability could be greatly improved by adding both hierarchical and parallel strategies. Finally, the optimal method and parameters of each system are obtained. The results show that the optimization system based on the improved particle swarm optimization algorithm is more efficient and the optimization results are reliable. The results can be used as a reference for solving the multi-objective, multi-variable and multi-constraint optimization problems of the performance optimization of the catamaran.

Index Terms— catamaran unmanned boat; optimization design; particle swarm optimization; hierarchical strategy; parallelism of key variables.

I. INTRODUCTION

Catamaran has become a hot research topic in recent years because of its stable navigation, good floating condition at high speed, large deck area, good maneuverability and maneuverability. More and more attention has been paid to the research of unmanned surface craft in various countries, and the research on its hydrodynamic performance, such as rapidity, maneuverability and seakeeping resistance, has become particularly important. The comprehensive optimization of surface unmanned boats [1] plays an important role in the design and development of unmanned boats. Therefore, China actively carries out the development

and performance research of unmanned surface craft and strives to achieve the strategic goal of maritime power and the great rejuvenation of the Chinese nation.

The research on the optimization of catamaran at home and abroad mainly uses SHIPFLOW, NASTRAN and other professional computing software to optimize the ship type or structure. Deng fang [2] et al. used Hullspeed software to calculate the hull resistance performance and proposed a digital optimization design method for catamarans based on the analysis of resistance performance, which can provide reference for the design of catamarans and multi-body ships. Zhang weiyi [3] et al. adopted the adaptive simulated annealing algorithm to optimize the large number of high-stress areas in the transverse bending condition of catamaran with small waterplane and obtained stable optimization results. Wei gang [4] et al. took the cabin model of the catamaran with small waterplane as the research object, optimized the topology, shape and size of NASTRAN with the goal of improving the overall rigidity of the cabin structure, combined with the process applicability, proposed a feasible optimization design close to the optimization results, and finally verified the effectiveness of the optimization method by direct calculation of the finite element method. The combination of genetic, chaotic and neural network optimization methods with ship type optimization can make up for the time consuming and low precision of determining basic ship parameters in the traditional method of mother type modification. Wei zifan [5] established the comprehensive performance optimization mathematical model of surface high-speed USV and wrote the optimization software with the intelligent optimization method. Yu ning [6] took the combination of three performance indexes of high-speed monomer USV, including rapidity, maneuverability and seakiness, as the optimization objective function of the comprehensive optimization mathematical model of hydrodynamic performance, and selected genetic algorithm as the optimization algorithm to compile the program of the comprehensive optimization of the navigation performance of high-speed monomer unmanned vehicle.

At present, there are more and more studies on catamaran, but most of them mainly focus on the resistance performance of catamaran. Therefore, it is important to optimize the maneuverability and Anti-Capsizing performance of catamaran. At present, compared with some shipbuilding powers, there is still a big gap in the application field of optimizing ship form in China, and how to apply the theoretical research results to the design and manufacture of ship form still needs a lot of research. On the other hand, it still needs to work hard to transform the theoretical research results into general software for design and manufacture.

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In this paper, based on improved Particle Swarm Optimization, the comprehensive performance of catamaran is studied [7]. A set of multidisciplinary optimization design [8] analysis software with better comprehensive performance is developed, and the ship form optimization is studied, and the optimal principal dimensions and related parameters are obtained. It can not only provide important technical support for the overall design of the catamaran unmanned vehicle, but also provide some experience for further research, which has good practical benefits.

II. ESTABLISHMENTOFOPTIMIZED MATHEMATICALMODEL

A. .Design variables

In this paper, a common catamaran unmanned craft is taken as the research object. Considering the rapidity, maneuverability, seakeeping and capsizing resistance of the catamaran unmanned craft, the 16 design variables are selected, namely: draft T, propeller diameter D_P, area ratio A_{e0}, pitch ratio P_{DP}, speed N, speed V, vertical position of center of gravity to depth ratio δ_{ZD}, draft-to-depth ratio TD, rudder angle Rad, slice spacing C_0, total width of design water line B_0, The ratio of the length of the top superstructure to the length of the bottom δ_{L1}, the height of the top superstructure H1, the ratio of length to Captain of Bottom and Superstructure δ_{L2}, the height of the bottom superstructure H2, the width of the superstructure and the ship width ratio. The 16 design variables are combined and expressed as a vector Xsp:

$$\{X_{SP}=T,D_P,A_{e0},P_{DP},N,V,\delta_{ZD},TD,Rad,C_0,B_0,\delta_{L1},H_1,\delta_{L2},H_2,\delta_{Ba}\}$$

B. Objective function

1 Objective function of rapidity

The naval coefficient is an important parameter to measure the ship's rapidity, which includes both the ship's resistance and propulsion performance, and is a comprehensive evaluation factor of the ship's rapidity. In this paper, the criterion factor of rapidity, which is similar with the naval coefficient, is adopted as the objective function of rapidity optimization. The formula is as follows:

$$f_1(x) = C_{sp} = \frac{V^3\Delta^{2/3}}{p_E} = \frac{V^3\Delta^{2/3}(\eta_0\eta_H\eta_R\eta_S)}{R_tV*0.5144*1.35962*10^{-3}} \quad (1)$$

2 Manipulability objective function

Linear stability is the capability of a ship to recover its original straight sailing state after sudden disturbance by external forces, but the course changes. In this paper, linear stability is selected as the maneuverability [10] objective function of catamaran ships, and the stability criterion C is usually used to judge whether the catamaran has linear stability or not.

The stability of linear motion is determined by state variables v and variation characteristics r. The stability of the system is directly related to four acceleration hydrodynamic derivatives and four velocity hydrodynamic derivatives Y_v', Y_r', N_v', N_r'. If the stability criteria C are dimensionless, the maneuverability objective function is dimensionless stability criteria C'. The formula is as follows:

$$f_2(x) = C' = Y_v'N_r' - N_v'(Y_r' - m') \quad (2)$$

$$m' = m/(0.5\rho L^3) = \rho C_B LB_0 T/(0.5\rho L^3) = 2C_B\frac{B_0}{L}\frac{T}{L} \quad (3)$$

The dimensionless coefficients of hydrodynamic forces and moments in the formula can be derived from the regression formulas arranged by Clarke, D.

$$\begin{cases} (Y_v') = -\pi(T/L)^2(1+0.4C_BB_0/T) \\ (Y_r') = -\pi(T/L)^2(-0.5+2.2B_0/L-0.08B_0/T) \\ (N_v') = -\pi(T/L)^2(0.5+2.4T/L) \\ (N_r') = -\pi(T/L)^2(0.25+0.039B_0/T-0.56B_0/L) \end{cases} \quad (4)$$

3 Seakeeping objective function

Dimensionless attenuation coefficient μ is used to express the influence of ship rolling damping moment, rolling inertia moment and restoring moment on ship rolling. It is an important parameter to characterize ship rolling performance. The larger μ is, the faster ship rolling free attenuation is, the better ship rolling performance is. In this paper, the dimensionless roll attenuation index μ is selected as the objective function of seakeeping optimization. The formula is as follows:

$$f_3(x) = v/\omega_\phi = N/(I_{xx}'\omega_\phi) = \frac{N}{I_{xx}'}\sqrt{\frac{I_{xx}'}{\Delta H}} = \frac{N}{\sqrt{I_{xx}'\Delta H}} \quad (5)$$

4 Anti-overturning objective function

In this paper, the inverse number of GM with high initial stability of positive buoyancy and $\overline{GM}$ with high post-capsizing stability is selected to construct the anti-capsizing optimization objective function. The formula is as follows:

$$f_4(x) = GM^{\gamma_1}*\overline{GM}^{\gamma_2} \quad (6)$$

5 Comprehensive optimization objective function

The objective functions of the four subsystems of the catamaran rapidity, maneuverability, seakeeping and anti-overturning, are formulated in the form of power exponential product.

$$F(x) = f_1(x)^{\varepsilon_1}*f_2(x)^{\varepsilon_2}*f_3(x)^{\varepsilon_3}*f_4(x)^{\varepsilon_4} \quad (7)$$

C. Constraint conditions

1 equality constraints

To satisfy the thrust constraint, the effective thrust of propeller is equal to the total drag of hull navigation, and its expression is as follows:

$$N_p K_T \rho N^2 D_P^4 (1-t) = R_t \quad (8)$$

To satisfy the torque constraint, the torque supplied by the main engine to the propeller should be equal to the hydrodynamic torque borne by the propeller. The expression is as follows:

$$\frac{\eta_R \eta_s P_s}{2\pi N} = K_Q \rho N^2 D_P^5 \quad (9)$$

2 Inequality Constraints

(1) The upper and lower limits of design variables should be satisfied;
(2) Propeller cavitation constraint:

$$A(x) = (1.3 + 0.3Z)T_e / ((P_0 - P_V)D_P^2) + K - (A_E / A_0) \leq 0 \quad (10)$$

In order to satisfy the stability criterion of ocean vessels, the high initial stability requirement of positive floating is more than 0.3:

$$GM > 0.3 \quad (11)$$

The draught after reversal is less than the total height of the superstructure:

$$T_1 < H_1 + H_2 \quad (12)$$

The inverse number of high initial stability defined in this paper needs to be greater than zero:

$$\overline{GM} > 0 \quad (13)$$

PARTICLESWARMOPTIMIZATIONS

Particle swarm optimization [11] (PSO) is a new optimization algorithm for simplified social model (bird foraging) simulation. It has the characteristics of easy realization, fast convergence and high precision. It starts from the stochastic solution and searches for the optimal solution by iteration of fitness value.

In the basic particle swarm optimization, the particle swarm is composed of M particles, each particle position represents the potential solution of the optimization problem in D-dimensional space, in which its particle is represented as a d-dimensional vector $x_i = (x_{i1}, x_{i2}, ..., x_{iD})$, i=1,2..., n. The fitness value can be obtained by substituting xi into the objective function. According to the fitness value, xi can be measured. The velocity of its particle can also be expressed as a d-dimensional vector $v_i = (v_{i1}, v_{i2}, ..., v_{iD})$, i=1,2..., n. The optimal position searched so far for its particle is: $P_i = (p_{i1}, p_{i2}, ..., p_{iD})$, i=1,2..., n. The optimal position searched by the whole particle swarm so far is: $P_g = (p_{g1}, p_{g2}, ..., p_{gD})$.

According to the particle swarm optimization (PSO) proposed by Eberhart and Kennedy, the position and velocity of particles are updated:

$$v_{iD}^{k+1} = v_{iD}^k + c_1\xi(p_{iD}^k - x_{iD}^k) + c_2\eta(p_{gD}^k - x_{iD}^k) \quad (14)$$

$$x_{iD}^{k+1} = x_{iD}^k + v_{iD}^{k+1} \quad (15)$$

Particle swarm optimization (PSO) usually sets the termination condition as a sufficiently good fitness value or the maximum number of iterations. Particle swarm optimization (PSO) algorithm includes the following related parameters: population size, learning factor, maximum velocity and inertia weight.

III. OPTIMALCALCULATIONANDANALYSIS

A. Single Particle Swarm Optimization

1 The influence of different Algebras
Population size: 200, fixed weight: 0.9-0.4, maximum particle flight speed and interval probability set as 0.12, and optimization algebra set as 2000-8000. The optimization results are summarized as shown in table 1:

Table 1 calculation results of different optimization algebras

Computation times	1000	2000	3000	4000	5000	6000	7000	8000
Fitness function value	112.25	114.26	115.95	113.74	113.68	115.21	115.92	115.99
Penalty function value	1	1	1	1	1	1	1	1

In order to more intuitively see the influence of optimization algebra on fitness function value, the above results are drawn as shown in figure 1:
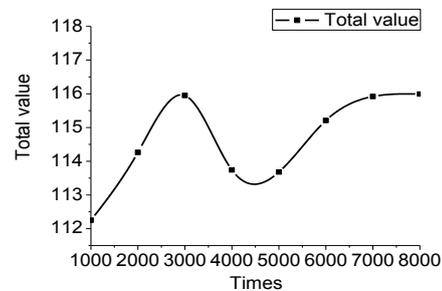

Fig. 1. The curve of the objective function value varying with the optimization algebra

As can be seen from Figure 2, the value of objective function fluctuates with the increase of optimization algebra, but the value of the objective function tends to be stable when a certain algebra is reached (the algebra in this paper is 7000 generations). Therefore, 7000 generation is regarded as the best algebra in the particle swarm optimization algorithm in this paper.

2 Influence of maximum particle flight speed and interval probability
A single particle swarm optimization algorithm was used, with 1000 times of calculation and variable weight of 0.9-0.4. The maximum particle flight speed and interval probability were calculated with the following six groups.

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Table 2 Calculations of different maximum particle velocities and interval probabilities

probability	0.1	0.12	0.14	0.16	0.18	0.2
Fitness function value	113.97	121.72	115.17	118.27	117.89	109.34
Penalty function value	1	1	1	1	1	1

As can be seen from table 2, all constraints are satisfied. With the increase of the maximum particle velocity and the interval probability, the fitness value calculated is changing constantly. When the maximum particle flying speed and interval probability are 0.12, there is the maximum fitness value, that is, the optimization effect is the best.

3 Influence of different fixed weights
The basic parameters of PSO are as follows: population size: 200, optimization algebra 7000, fixed weight is set to six groups. The maximum particle flight speed and interval probability are set as 0.12. The optimization results are summarized as shown in table 3:

Table 3 Calculations of different weights

weight	0.4	0.5	0.6	0.7	0.8	0.9
Fitness function value	117.13	122.73	114.41	122.19	121.42	118.88
Penalty function value	1	1	1	1	1	1

As can be seen from table 3, when the fixed weight changes, the fitness function value is the largest when the weight is 0.5, indicating that the optimization effect is better. In other words, for the optimization mathematical model in this paper, the optimization effect is better when the weight is set to 0.5 by particle swarm optimization algorithm.

B. Improved Particle Swarm Optimization

1 optimization calculation of hierarchical strategy
Firstly, the single particle swarm optimization algorithm is used to calculate and record the best five individual information. Then, according to the best five individual information, the external hierarchical strategy was used to initialize the new upper and lower limits, and the outer carrier probability was set as 0.005. Particle swarm optimization algorithm, chaotic algorithm, genetic algorithm and compound shape algorithm are selected for the second calculation [12]. The parameters are set as follows:

In the first calculation, the parameters of PSO are set as follows: population size is 200, variable weight is 0.9-0.4, maximum particle flying speed and interval probability is 0.12, optimization algebra is 7000, fixed weight is 0.5.
In the second calculation, the parameters of the chaotic algorithm are set as follows: the optimum algebra is 70000. The parameters of genetic algorithm are as follows: population size is 200, optimization algebra is 7000, genetic factor is 0.5, variable carrier probability is 0.0001-0.01, evolutionary weight is 0.5. Parameter setting of particle swarm optimization algorithm: population size is 200, variable weight is 0.9-0.4, maximum particle flight speed and interval probability is 0.12, optimization algebra is 7000, fixed weight

is 0.5. Parameter setting of compound shape algorithm: population size is 200, optimization algebra is 7000, mapping coefficient is 1.3, minimum mapping coefficient is 0.0001.

Table 4 external hybrid optimization results of different algorithms

Computing strategy	Single Particle Swarm	Particle swarm + particle swarm	particle swarm + genetic	particle swarm + chaos	particle swarm + complex
Fitness value	function 111.56	120.89	118.51	120.71	120.61
Penalty value	function 1	1	1	1	1

As can be seen from table 4, all constraints are satisfied. The results calculated by the external layering strategy are better than those calculated by the single particle swarm optimization algorithm, which shows that the external layering strategy can improve the optimization effect of the algorithm [13]. Through the comparison of the above optimization results, it can be concluded that the particle swarm optimization + particle swarm optimization algorithm has better optimization effect.

2 parallel strategy optimization calculation

In this paper, we use particle swarm optimization (PSO) to do parallel computation. Its basic parameters are: population size: 200, fixed weight: 0.5, maximum particle velocity and interval probability: 0.12, iteration times 7000 generations. In this paper, two key design variables, speed N and speed V, are selected for parallel calculation [14], and the parallel times are 1-2 times respectively. The parallel calculation results are summarized as shown in table 5:

Table 5 Parallel strategy optimization results

Computing strategy	Not parallel	Parallel 1 times N	Parallel 1 times V	Parallel 2 times N	Parallel 2 times V	Parallel 1 times N+V	Parallel 2 times N+V
Fitness value	function 113.86	117.87	113.95	118.75	116.72	120.49	120.73
Penalty value	function 1	1	1	1	1	1	1

From Table 5, it can be concluded that the optimization result with parallel strategy is better than that without parallel strategy, that is, parallel strategy can effectively improve the optimization effect of the algorithm. At the same time, it is obvious that parallel multiple key design variables and multiple parallel can get better optimization results.

C. determine the best optimization method

By comprehensive comparison of the above calculation results, it can be concluded that both parallel and hierarchical optimization strategies can improve the optimization effect of the algorithm for the optimization mathematical model in this paper, and the optimization effect is the best when the two optimization strategies are adopted at the same time, and the maximum fitness function value obtained is 122.02. The values of the design variables and objective functions obtained are shown in table 6 and 7 respectively:

Table 6 Values of design variables for optimal results

number	design variable	Lower Limit	Upper Limit	Optimization value
1	draft(m)	0.85	1.04	0.86
2	Propeller diameter(m)	0.6	0.68	0.629
3	Disk ratio	0.65	0.75	0.683
4	Pitch ratio	0.75	0.8	0.792
5	Propeller speed(rpm)	1200	1350	1212.524
6	Design speed(kn)	13	16	13.001
7	Vertical position of center of gravity and depth ratio	0.7	0.8	0.72
8	Draft to mold depth ratio	0.4	0.6	0.447
9	Rudder angle	32	36	34.09
10	The ratio of the top length to the bottom length	0	0.1	0.08
11	Top height of superstructure	0.5	1	0.803
12	Ratio of the length of the upper base to the captain	0	0.08	0.06
13	Bottom Height of Upper Building	0.5	1	0.997
14	Ratio of the width of the upper part to the ship	0	0.8	0.079
15	Slice spacing(m)	2.9	3.3	3.293
16	Design total waterline width(m)	9.3	10	9.93

Table 7 objective function values of the optimal results

Optimization results of each objective function value	
Fitness value	122.02
Total objective function value	122.02
Rapidity objective function value	6.25
Manipulability objective function value	1.15
Seakeeping objective function value	1.00
Anti-overturning objective function value	6.28
Penalty function value	1

IV. CONCLUSION

In this paper, by establishing optimization mathematical model [15], four optimization algorithms are selected to compile the performance comprehensive optimization software system of the catamaran unmanned vehicle. Sixteen design variables are selected and constraints are determined. Four sub-objective functions, namely, rapidity, maneuverability, seakeeping and anti-overturning, are established to form a comprehensive optimization objective function, and the weights of each objective function are set. Finally, the evaluation index of the optimization system is established. Particle swarm optimization algorithm [16] is used to compile the optimization system. By calculating different algebras, different weights and different maximum particle flight velocities and interval probabilities under single particle swarm optimization, the optimal calculation algebra, fixed weight and maximum particle flight velocities and interval probabilities are obtained. At the same time, the particle swarm optimization algorithm is improved, and internal and external hierarchical strategy calculations are carried out on the particle swarm optimization algorithm to obtain the maximum fitness function value of the particle swarm optimization + particle swarm optimization algorithm, indicating the best optimization effect. Speed and speed are selected as the key design variables for 1-2 times of parallel calculation, and it is found that multiple key design variables and multiple times of parallel can get better optimization results. Finally, the optimization results of the single particle swarm optimization algorithm and the layered parallel improvement strategy are compared. It is shown that the layered and parallel strategies can effectively improve the optimization effect of the particle swarm optimization algorithm, and the optimization effect of the layered and parallel strategies is the best. Finally, the optimal main scale and related kinematics parameters of the catamaran are obtained. The research results provide a reference for further improving the comprehensive optimization theory [17] and the calculation software of the catamaran unmanned craft.

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