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Comprehensive Optimization analysis of high-speed USV maneuver performance

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Abstract: In this paper ,we conducted the comprehensive optimization analysis for the maneuvering performance of the high-speed USV. Firstly, we established the high-speed USV synthesis optimization model. Secondly we developed a comprehensive optimization calculation procedures of sailing performance for high-speed USV which based on genetic algorithms .And finally we select a design speed of 26kn USV for an example , discuss the best design weights , analysis the effect of of the sensitive variables for the performance of the sailing performance of USV ,and probe into the optimization results for the overall objective function and maneuvering performance in both conditions of high speed and low speed by different optimization algorithms . By a large number of calculations indicating that the program is stable and reliable , we provides a reference platform for the preliminary design for the high-speed USV.

0 Introduction

The high-speed USV has lots advantage in high-speed ,excellent stealth and intelligent ,attaching importance of flexible fighting in the military aspect[1] ,thus catching eyes of States Navy and the shipbuilding industry.For civil applications, high-speed USV was applied in hydrologic meteorological monitoring, Patrol Search, Rescue and could hunt for surface float. Due to it’ s small weights, the issue of how to achieve an optimum sailing performance under the consideration and balance of its rapidity, maneuverability and many other sailing performance is a hot and difficult spot to research in this field .A lot of ship model tests in which deep and system research has been made to the maneuvering performance of water surface vessel in wave has been carried out in the America Davidson laboratory, where other series of experiments have also been made for the seakeeping performance of the prisms glider model in both ruled and irregular wave in the laboratory pool where influence law of the various main factor to the motion response in wave has been found[2~3]. In recent years, our country has achieved certain results in the research in the aspect of the glider resistance , wave resistance and stability . su-zhen Yang etc.of Huazhong university of science and technology studied the drag reduction effect of the air lubrication at the bottom of the glider , zhang kang wei of naval engineering university studied the heeling and stability problem while rotating and put forward the estimation formulas of heeling angle in rotation .Since the current research on the comprehensive optimization design for the sailing performance of the glider is very few, how to optimize the layout of the monomer unmanned craft is one of the hot spot for the time being.

1. The sailing performance comprehensive optimization mathematical model of surface high speed USV

1．1 The design variables

In the comprehensive optimization mathematical model for the sailing performance of high speed USV , the author set the power exponent product of the five performance indexes :speediness, linear stability, maneuvering quality, turn positive buoyancy and rollover stability as the optimization objective function, and set the buoyancy, the balance equation of the propeller provided thrust and torque with the drag and host provided torque , the restrictions of the principal element (parameters) of the ship type ,the propeller cavitation requirements as optimization constraints.so this form of comprehensive optimization calculating problem of the unmanned surface high-speed craft is more complicated, involving many ship form parameters. Through comprehensive analysis we choose the parameters in table 1 as design variables .

Tab．1 The design variables of high—speed USV sailing Performance integrated optimization

code	design variables	code	design variables
X1	The length of ship L	X18	Hydrofoil chord length B_H
X2	The molded breath of ship B	X19	Hydrofoil camber f_H
X3	The draft of ship T	X20	Hydrofoil deadrise angle β_H
X4	block coefficient C_B	X21	Hydrofoil initial angle of attack α_0
X5	Midship section coefficient C_M	X22	Hydrofoil installation location X_H
X6	Designed water plane coefficient C_W	X23	Hydrofoil pillar lateral spacing y_H
X7	The longitudinal position of barycenter L_{CP} (%)	X24	Hydrofoil dip deep h_0
X8	Propeller diameter D_P	X25	Rudder area A_d

X9	Propeller solidity ratio A_e/A_0	X26	Rudder aspect ratio λ
X10	Pitch ratio P/D_P	X27	The height between the center of gravity and the baseline Z_g
X11	Propeller rotational speed N	X28	The length of superstructure on top L_1
X12	Design speed V_S	X29	The width of superstructure on top B_1
X13	Half the water angle I_e	X30	The width of superstructure on bottom L_2
X14	Tailgate relatively wet area At/Am	X31	The width of superstructure on bottom B_2
X15	Sail trim angle α	X32	The height of part superstructure H_A
X16	Deadrise angle β	X33	High center of gravity after turning $\overline{Z_g}$
X17	Hydrofoil wingspan L_H		

1．2 The objective function

1．2．1 The objective function of the high-speed USV 's speed ability

We select the following formula for the ship fast optimization objective function to assess the drainage -speed ship rapidity pros and cons:

$$f_1(x) = C_{SP}{}^{\gamma_1} = \frac{\Delta V_S}{R_t / \eta_0 \eta_H \eta_B \eta_S} \text{。} \tag{1}$$

Where △ for displacement ; V_S for speed ; R_t for hull resistance ; η_0 for propeller open water efficiency ; η_H for hull efficiency ; η_R for relative rotation efficiency; η_S for shaft efficiency.

1．2．2The high-speed USV maneuvering performance objective function

Select the index of Linear stability and relative steady turning diameter to measure the ship handling performance. Which V_{arL} is the index of Linear stability and V_{arT} is the index of relative steady turning diameter. Objective function expression of maneuverability:

The formula of index of Linear stability as follow:

$$V_{ar_L} = Y_v' N_r' - N_v' \left(Y_r' - m' \right) \text{。} \quad (5)$$

Which Y_v', Y_r', N_v', N_r' for the dimensionless hydrodynamic and moment coefficients of the ship.which can be got according to the regression formula of the linear hydrodynamic derivatives settled by Clarke.

The formula of relative steady turning diameter:

$$V_{ar_T} = \frac{D}{L} \text{。} \quad (6)$$

Which D for constant diameter, L for the length of ship.

1.2.3 Surface high-speed USV anti overturning performance optimization objective function

Rollover resistance index $f_3(x)$ consists of the upright stability and the stability after turnover in the form of exponent ,GM for the metacentric height , $\overline{GM}$ for the metacentric height after turnover. The equation is as follows:

$$f_3(x) = GM^{\gamma_4} * \overline{GM}^{\gamma_5} \quad (7)$$

while

$$GM = BM - (Z_G - Z_B) \quad (8)$$

Where BM for transverse radius, Z_G , Z_B for the height of center of gravity and buoyancy.After the regression formula can get:

$$GM = {0.076LB^3} \big/ {\nabla} - (Z_G - 0.5T - 0.14B\tan\beta) \quad (9)$$

The expression of the metacentric height after turnover:

$$\overline{GM} = \left(\overline{Z_G} - \overline{Z_B} \right) - \overline{BM} \quad (10)$$

Where $\overline{BM}$ for transverse radius after turnover , $\overline{Z_G}$, $\overline{Z_B}$ for the height of center of gravity

And center of buoyancy after turnover.After the regression formula can get:

while，

$$\overline{BM}=\frac{0.937\left(B_{A1}+0.978\frac{(B_{A2}-B_{A1})\overline{T}}{H_A}\right)^3\left(L_{A1}+1.05\frac{(L_{A2}-L_{A1})\overline{T}}{H_A}\right)}{12\nabla}; \quad (11)$$

$$\overline{Z_B}=0.127\frac{H_A*B_{A2}}{(B_{A2}-B_{A1})*B_{A1}}\overline{T}。 \quad (12)$$

where $\overline{T}$, B_{A1}, B_{A2}、 L_{A1}、 L_{A2}、 H_A respectively are draught, the bottom width of superstructure, the top width of superstructure, the bottom length of superstructure, the top length of superstructure after turnover .

1．2．4 The overall objective function

The overall objective function of moving performance of high-speed USV :

$$F(x)=C_{SP}^{\gamma_1}*V_{ar_L}{}^{\gamma_2}*V_{ar_t}{}^{\gamma_3}*GM^{\gamma_4}*\overline{GM}^{\gamma_5} \quad (13)$$

Where $\gamma_1,\gamma_2,\gamma_3,\gamma_4,\gamma_5$ are weights for rapidity, linear stability ,maneuvering quality , upright stability, stability after turnover, each one of them is bigger than 0 and $\gamma_1*\gamma_2*\gamma_3*\gamma_4*\gamma_5=1$.

1．3 constraint condition

As the fundamental navigation performance, buoyancy must be met, thus the displacement delta should remain the same. In addition, the range of variation of the design variables should be within the constraint condition of a given line and meet the balance of forces at the same time . Constraints can be divided into 2 classes as equality constraints and inequality constraints.

1．3．1 Equation Constraints

1）Balance between static displacement and the summation of hull lift, hydrofoils lift and displacement when gliding:

$$\Delta=\Delta_1+C \quad (14)$$

Where Δ for displacement when USV is static, Δ_1 for displacement and C for the sum of dynamic lift and hydrofoil lift when USV is planing state.

2）Balance between effective thrust and hull resistance:

$$N_P K_T \rho n^2 D^4(1-t)-R_t=0 \quad (15)$$

Where N for number of propeller shaft, t for thrust deduction fraction, ρ for density of water.

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

$$\frac{\eta_R \eta_S P_S}{2\pi n} - K_Q \rho n^2 D_P^5 = 0 \tag{16}$$

Where P_S for host power, n for propeller revolutions, ρ for density of water.

1．3．2Inequality Constraints:

1）Ranges of values of 33 design variables;

2）According to the rules for sea going ships,the upright stability height GM>h;

3）The propeller must meet the demand of cavitation,calculated by the function of Keller:

$$\frac{1.3+0.3Z}{(P_0-P_v)D_P^2} + K - \frac{A_E}{A_0} \le 0 \tag{17}$$

4）Relative turning diameter $\Phi_\alpha = \Phi_\alpha(x) \le 10^0$

2 .The optimization calculation and the analysis of the results

2．1 Optimization calculation

Tab．2Range of design variables

code	lower limit	upper limit	code	lower limit	upper limit
L(m)	10.12	10.54	BH(m):	0.4	0.6
B(m)	3.03	3.21	fH(m):	0.02	0.04
T(m)	0.55	0.66	βH:	10	25
Cb	0.4	0.5	α0:	-1	1
Cm	0.86	0.89	XH(m):	2	2.8
Cwp	0.6	0.65	yH(m):	3.4	3.6
Lcb	-4	0	H0(m):	0.4	0.8
Dp(m)	0.45	0.5	Ad:	0.16	0.24
Ae/A0	0.4	0.5	λ:	1.5	3
P/Dp	0.6	0.8	Zg(m):	1	1.4
N(r/min)	2000	2700	L1(m):	4	6
Vs(kn)	26	26	B1(m):	2	2.4
ie	4	12	L2(m):	6	8
At/Am	0	0.18	B2(m):	3	3.2
α	2	5	HA(m):	2	3
β	10	30	$\overline{Z}_g$ (m):	2.8	3.4
LH(m)	1.8	2			

According to the scope of these variables and constraint conditions ,we initiall y set the weigh function on rapidity as 13/9, on linear stability as 15/11 , on ma neuvering quality ability as 11/13, on upright stability as 1, on rollover stability as 9/15.and calculate each of which three times the respective displacements of 8 t, 8.2 t, 8.4 t, 8.2 t, 8.8 t, 9 t, 9.2 t, 9.4 t, 9.6 t, 9.8 t, 10 t with the design speed of 26 kn and finally get the optimal results as shown in table 3.

Table 3 The objective function values at different weights

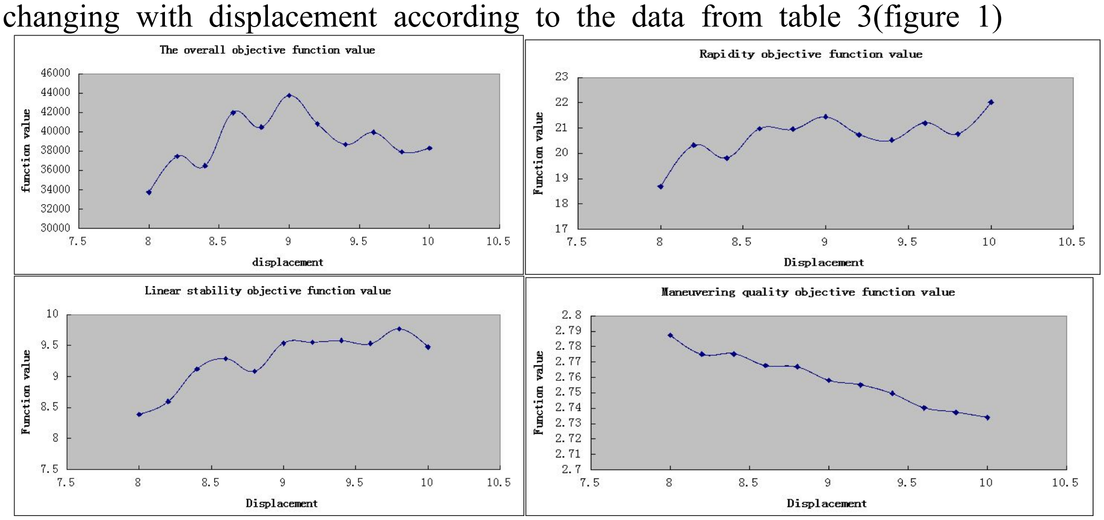
Design displacement	8	8.2	8.4	8.6	8.8	9	9.2	9.4	9.6	9.8	10
Comprehensive objective function value	33733	37459.1	36488.7	41949.6	40470.5	43755.8	40815.6	38690.8	39934.7	37915.9	38309.2
Fast optimization objective function value	18.6941	20.3257	19.8089	20.9797	20.9582	21.4477	20.7358	20.524	21.1959	20.7683	22.0262
Linear stability value	8.38863	8.59487	9.121	9.28745	9.08339	9.53777	9.55384	9.57877	9.53462	9.76937	9.4768
Minimum of relative steady turning diameter value	2.78746	2.77511	2.77517	2.76773	2.76689	2.75816	2.75503	2.74955	2.74019	2.73735	2.73394
Metacentric height	2.81685	2.70102	2.41116	2.56404	2.52904	2.47414	2.42474	2.31667	2.2994	2.21557	2.11541
Metacentric height after turnover	1.72381	1.6956	1.7774	1.75887	1.77219	1.78953	1.74318	1.70125	1.70253	1.58167	1.57801

when design speed at 26kn

2.2 Optimization Analysis

2.2.1 The influence of the Designed displacement to the overall objective function and each navigation performance indicator

The curve of the overall objective function and the navigation performance index changing with displacement according to the data from table 3(figure 1)



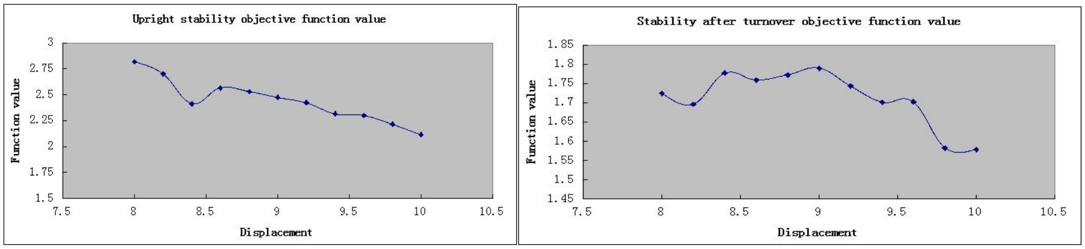
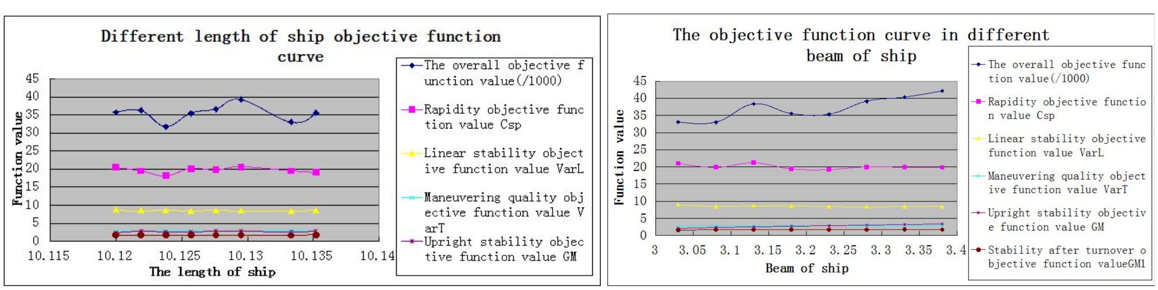


figure 1. the overall objective function and each navigation performance indicator curve in different Designed displacement

With the increase of the displacement, velocity and linear stability index is on the rise, whereas rotary, positive buoyancy and rollover stability index is on the decline. Therefore,we can see from it that the high-speed unmanned craft with the small displacement design has good rotary, upright stability and rollover stability, while the craft with the large displacement design has good quickness and linear stability. The general objective function curve in the figure shows that the genera l objective function increases first to up to 9 tons as the biggest value and then decreases with the increase of displacement . Therefore, within the scope of the d esign variables in table 2, the unmanned surface vessel will achieve the optimally comprehensive sailing performance with the displacement of 9 tons.

2.2.2 The influence of key variables to the overall objective function and each seagoing performance

In order to discuss the effectiveness of key variables to the sailing performance of unmanned surface vessel in the preliminary design stage , the authors select the four key variables of captain L, the beam B, propeller diameter D and screw rotational speed N as the sensitive variables and carry out the discrete optimization of these four sensitive variables under the condition of design speed of 26kn, and the displacement of 9 tons as the optimization result for the best navigation performance. And finally draw the curves of the most sensitive variables of the objective function by the ultimate optimization results as shown in figure 2:



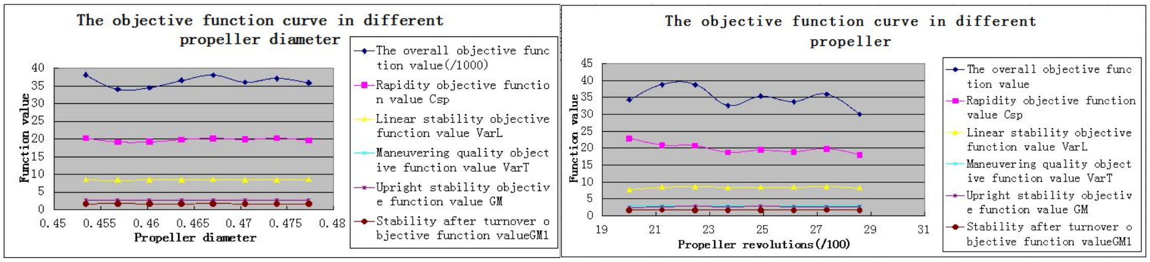


figure 2. The objective function curve in different key variables

It can been seen from the comparison of the four figures that with the increase of the captain, the beam B, propeller diameter D, screw rotational speed N , the changes of the quickness index and general objective function tend to close, so the speediness index had the greatest influence on total objective function, which is reasonable for the selected ship form of the the designed calculated unmanned ship vechile is high speed featured. Below is the fluctuation influence of the four variables to the overall objective function and each sub-objective function .

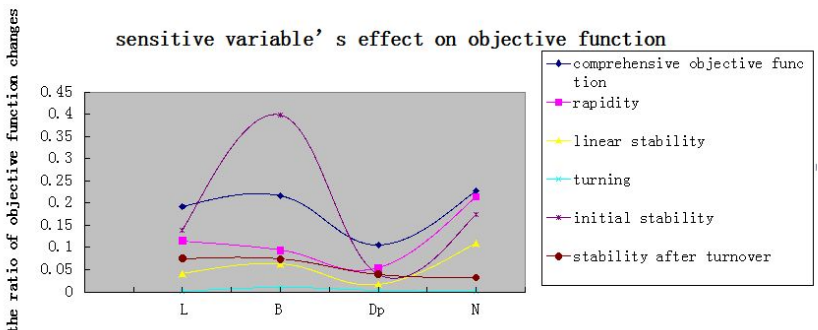


figure 3. Sensitive variable to the overall objective function and each sailing performance curve

The length of ship, the molded breath of ship, propeller diameter ,propeller rotational speed have effect on comprehensive objective function and each navigation performance index,and with a sensitivity analysis ,the comprehensive objective function is the most sensitive of these four ,among of them , the molded breath of ship has the greatest sensitive influences of comprehensive.objective function changes while the maneuvering quality index is on the contrary .Propeller rotational speed was effect the changes of rapidity index, linear stability index ,maneuvering quality index, upright stability index, stability after turnover index mostly, whereas the propeller diameter with minimal impact .

2.2.3 The overall objective function by different optimization algorithm under different speed and Each sailing performance indicators value analysis

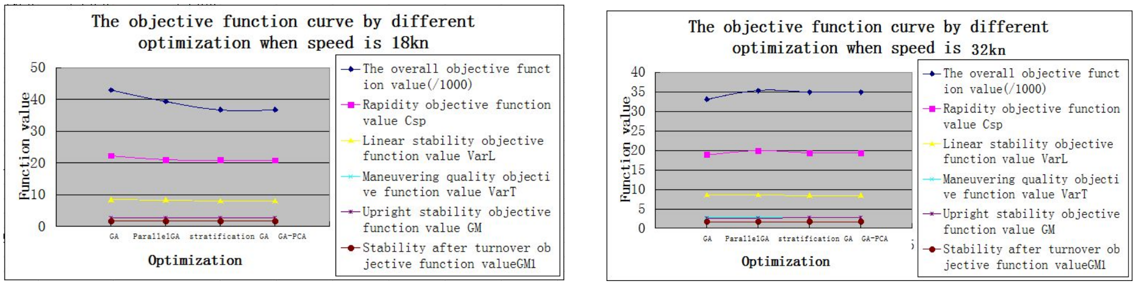


figure 3. The objective function curve by different optimization algorithm under different speed

It can be known from comparative analysis of figure 4 that at low speed , the general objective function value GA > IPGA > GA - PCA > LGA, the GA's general objective function value is the largest, the GA - PCA differs 0.166% with the LGA's general objective function values .The discrepancy of the maximum total objective function value and the minimum objective function value (GA differ with GA - PCA) is 14.45%; At high speed , the total objective function values IPGA > LGA >GA - PCA > GA, the discrepancy of the maximum total objective function value and the minimum objective function value (LGA differ with GA)is 6.68%, GA -PCA differs 0.132% with the LGA's general objective function value. With the increase of speed, the general objective function of the simple genetic algorithm (GA) is reduced in comparison with other kinds of optimization algorithm , the values of the general objective functions between LGA and GA - PCA are closest , whose relative difference decreased first and then increase , and reach the minimum at 26kn.So adopting the single genetic algorithm is better for design at low speed while the parallel genetic algorithms fits better for design of high speed.

3 End

This paper studies the high-speed USV's rapidity l, and at the same time get the specific form of high-speed USV sailing performance objective function and its specific constraints according to the atlas interpolation of the maneuverability index and stability index of monomer high-speed USV by reference to the relevant material .Take the USV which design speed is 26kn for an example , we had researched the variation of overall objective function value and each navigation performance index changes with he displacement and determined the optimum displacement of the high-speed USV.Then in condition of the optimum displacement as design displacement ,we discussed the influence of the four main variables :length of ship L, beam of ship B, the propeller diameter D, propeller speed N to the high-speed USV's overall objective function value and index of each sailing performance, and concluded that the great of influence has been made of the beam of ship to The overall objective function,and propeller speed to each sailing performance index, while the minimum of influence of propeller on the contrary. At last, the paper determines the effect of different optimization algorithms to optimize for specification design in the high or low speed condition,which would have a certain influence to the selection of optimization algorithm, and it has important significance meaning to further comprehensive optimization study of the high-speed USV .

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