Comprehensive Optimization Method on Navigation Performance of the Planing-Hydrofoil USV

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***Abstract*—In this paper, a comprehensive optimization mathematical model of the planing-hydrofoil USV performance was established. A hierarchical parallel genetic-complex algorithm is advanced basing on parallel strategy, genetic algorithm and complex algorithm and it is called H-P-GA-C. The new algorithm for the optimization method study of performance of the planing-hydrofoil USV is very valuable. We use of VC++ into programming software. The calculation results of different solving methods show that compared with other methods such as H-P-GA-CA, H-P-C-GA, H-P-GA-C and parallel improved complex method, the paper also discussed the influence on total objective function、 two objective function and rapidity objective function caused by design variables such as the length of the hull and the speed, and determined the design variable sensitive degree. The composite algorithm is reliable and efficient so that it lays a solid foundation for hull form optimization design and evaluation analysis of the high-speed planing-hydrofoil USV.**

Keywords-synthetic optimization method; H-P-GA-C; planing-hydrofoil USV; navigation performance

I. INTRODUCTION

In order to solve the optimization problem vessels, for instance the design, major projects system in this field for the production and management. There are many optimization algorithms. However these methods are not fit in solving the problem with a lot of design variables and constraint conditions. It is essential that requires us developing a new optimization algorithm.

In 1993, Professor Xu Changwen[1] made a multi—objective optimization in structural engineering . The fuzzy optimization methods based on the different forms of fuzzy decision—making are presented， in which the fuzzy comprehensive assessment method with the ordered paired comparison technique is used to determine the tolerance values for the allowable limits of fuzzy constraints. In 2002, Zhang Huoming[2] made to Fuzzy—genetic Algorithm of Ship Navigation Performance Optimization. The bound search method, which can find a special vivid solution to fuzzy nonlinear programming, is employed to carry out the fuzzy optimization.

In 2007, the author[3] made up the fuzzy-chaos algorithm， which is composed of the fuzzy genetic algorithm of bound search and the chaos algorithm. This algorithm is applied to optimize，calculate and analyze large-scale ship performance or structural characteristics. The calculation results show that these optimization methods and the calculation software have a good correlation, which have practicability and applied to integrally optimize the ship performance or structural characteristics. It is worth using that design the large-scale ship project.

In 2013, Chen Peng[4] makes a multi-objective optimization analysis about UUV general optimization systems.

Based on genetic algorithm, chaos algorithm and parallel thought, some parallel optimization methods are constructed which are applied to solve the problem of calculation of synthetically optimization. The calculation results show that these methods which are constructed by parallel thought have an advantage better to solve such optimization problems. The best method is parallel genetic-chaos algorithm. which conducts reliable and high efficiency calculation.

The new algorithm H- P-GA-C constructed by the author which was based on delicate variables' segments, parallel thinking, genetic algorithm and complex method and succeeds in applying this method on sailing performance optimization for the planning-hydrofoil USV.

II. MATHEMATICAL MODEL

Due to a variable floating ship type, the ship hydrodynamic lift will rise with the increase of speed，and the ship will come into a half-planning state or totally planning state from drainage navigation state. The influence on the ship performance caused by hull type, propeller and related movement parameters has a great difference to conventional drainage ship, so the ship form design of planing craft is more complicated and difficult than the conventional drainage ship.

The design of the planning-hydrofoil USV should be analyzed comprehensively on the basis of general arrangement, resistance and propulsion performance, maneuverability， stability, the stability of rollover, airworthiness performance and other special requirements, choose the ship parameters accurately and reasonably and finally draw the graph. It is an indispensable progress to improve the design quality and efficiency through comprehensive optimum design.

There're three parts of synthetically optimization of performances of the planning-hydrofoil USV: rapidity, maneuverability, stability and rollover stability. Buoyancy and some other characteristics as well as limits of design variables form the constraint conditions. The mathematic model is described in detail as follows.

A. Objective Function

Suppose G(X) is the general objective function, Csp(X) is the sub-objective function of rapidity criterion, Mv (X) is the sub-objective function of maneuverability criterion, and Sv (X) is the sub-objective function of Stability and rollover stability:

$$G(X) = Csp^{A_{P1}} * Mv^{A_{P2}} * Sv^{A_{P3}} \quad (1)$$

Where AP1≥0, AP2≥0, AP3≥0, AP1*AP2*AP3=1; Then, the Csp (X) is show as follows.

$$Csp = \Delta Vs^2 \eta_o \eta_R \eta_H / P_E \quad (2)$$

Where Δ—displacement;
P_E—the power of effective;
η_o—screw efficiency in the open;
η_H—the efficiency of hull;
η_R—relative rotation efficiency.

$$Mv = V_{arL}^{pL} * V_{arT}^{pT} \quad (3)$$

Where V_{arL}—straight line stability coefficient;
V_{arT}—turning quality coefficient;
p_L, p_T — weight numbers;
$p_L * p_T = A_{P2}$.

$$Sv = GM^{c1} * \overline{GM}^{c2} \quad (4)$$

Where GM—High stability of nomal floating
$\overline{GM}$—Flip the stability of high
c1*c2= A_{P3}

B. Constraints Conditions[5]~[6]

There are two constraints that one is the equation constraints and another is inequality constraints.

C. Design Variables

The synthetically optimization of mechanics properties for ships involves many factors. After analyzing and comparing their importance, 33 parameters are selected as table I.

III. The New Algorithm

Optimization methods can be divided into conventional and modern. The former usually can't avoid falling into local optimization so that it's not suitable for complicated optimization of multi-variable, multi-constraint and multi-objective function. Genetic algorithm, one of modern optimization methods, has strong global optimization ability so that it has been applied to complicated optimization of ship engineering. But to those optimizations which have many design variables, it'll take a long time for GA to compute and if cutting down the GA generation, it' s very likely to develop premature convergence. So the authors use of the ideas of parallel and hierarchical (The ideas of parallel ideological is substance of the range of segmentation and the calculation of space is reduced; therefore, it can greatly increase the probability of optimization.) to construct many different of algorithm (The algorithm is divided into two calculation that it is the first layer of the parallel *** algorithms and the second layer use *** algorithm) in this paper. For example: H-P-GA-C, H-P-GA-CA, H-P-C-GA.

H -P -GA -C solves the optimization in such a way: We need choose several best results of GA (usually half of the first step) then compute them again by complex algorithm. After these works, we can figure out the global best solution.

There are the same process above described H -P -GA -CA algorithm in the H-P-GA-CA and H-P-C-GA. But the difference is that new chaos algorithm of the second step is chosen in the H-P-GA-CA while Genetic algorithm is chosen in the first step.

Complex algorithm is chosen in the first step, while the second step is Genetic algorithm in the H-P-C-GA algorithm. H -P -GA –C is established exchanging the algorithms of the two steps.

A. Chaos Algorithm

New chaos optimization is implemented by chaos variable. The authors choose a widely-used logistic mapping to produce the chaos variable,

$$z_{k+1} = \mu z_k (1 - z_k). \quad (5)$$

where the time of iterative mapping k=0,1,2, etc.

It's easy to prove that when μ=4, above equation is fully in chaos state, which means by iterative mapping, the equation can randomly produce all values within (0, 1) except 0.25, 0.5 and 0.75. Because chaos algorithm is sensitive to initial value, n different chaos variables can be obtained by assigning n different initial values within (0, 1) to the equation except 0.25, 0.5 and 0.75.

B. GA's Essential Procedure[7]

Genetic algorithm is widely used in the field of automatic control, computing science, pattern recognition, engineering design, intelligent fault diagnosis management science and social sciences. It is applicable to solve complex nonlinear and multi-dimensional optimization problem.

The genetic algorithm's key steps adopted in this article are as follows:

1) Coding;
2) Selection;
3) Crossover;
4) Mutation;

5) Evaluation halt computing rule: If we track the searching procedure of GA, it is found that it would approach a steady optimum solution quickly. In this way, we can assume a largest number for searching, such as 600 or 6000 generations, as the halt computing rule.

C. Complex algorithms

Complex method is derived from solving unconstrained of non - linear optimization problems Optimization - simplex method, which is simply made in the development of constrained optimization problems. Complex refers to the n-dimensional of designing space feasible region, which is formed by K> n +1 vertices of the polyhedron. This method is continuous circulation process of the iterative optimization.

1) In the design variables of the feasible region, K vertex are selected as the initial complex vertices.

2) By comparing objective function values of vertices, the minimum corresponding to the worst point is removed (in the paper optimization of objective is the maximum of the objective function value, if the minimum of the objective function value problems may be a negative sign in front of F(X)).

3) Replace the worst point of the mapping points (In the worst point of the composite shape of the outside of the center of each point is the center of the mapping point of the obtained mapping) composing of the new complex.

4) Repeat the above process, which complex continuously deformed, transfer, narrows, gradually approaching of the most advantages point. When the complex objective functions value of the vertices is little difference or in close proximity of each vertex, the maximum vertex of objective function value is to the most advantages point.

IV. Optimization Computation

A. Computation

The mathematic model shows that the synthetically optimization of mechanics properties for the planning-hydrofoil USV involves at least 33 design variables, 3 equation constraints and 70 inequality constrains. Evidently, it's a very complicated engineering optimization. In this paper, the authors apply H-P-GA-CA, H-P-C-GA, H-P-GA-C, parallel improved complex method and use of the c++ to programme the solving software.

Here take the planning-hydrofoil for example. It's displacement is 1.4t and it has single propellers. The ranges of its design variables' values are listed in table I:

The authors assign values as: A_{P1}=13/7,p_L=1,p_T=11/13,c1=9/11,c2=7/9.The authors adopt four different of algorithms, such as: H-P-GA-CA, H-P-C-GA, H-P-GA-C and parallel improved complex method, the results are as table I.

TABLE I. Calculation Results Of Different Methods & Design Variables

Items				H-P-C-GA	parallel improved complex method	H-P-GA-CA	H-P-GA-C
General objective function value				2.75493	2.84914	3.12004	3.27324
Displacement (t)				1.39931	1.4012	1.40792	1.40138
T_E (kN)				2.11012	2.11623	2.16041	1.97645
Resistance (kN)				2.10851	2.11831	2.1584	1.97463
Mp (kN·m)				0.097888	0.098681	0.102977	0.088116
Md (kN·m)				0.097813	0.098777	0.102882	0.088035
P_E (kW)				25.4547	25.6894	27.324	23.5277
Main engine power (kW)				36.1976	36.5616	39.4456	33.8902
Froude number (Fr)				1.61511	1.62258	1.69275	1.5941
Wetted surface				7.79908	7.84012	7.73205	7.73446
Friction drag modulus C_f				0.002258	0.002257	0.00224192	0.002263
Re				5.79E+07	5.82E+07	6.08E+07	5.72E+07
Items	variables	Lower limit	Upper limit				
X_1	Ship length L	5.7	5.9	5.70103	5.70019	5.7071	5.70068
X_2	Ship breadth B	1.65	1.85	1.67842	1.7001	1.654	1.67672
X_3	Draft T	0.3	0.4	0.352857	0.349778	0.3618	0.356793
X_4	Longitudinal prismatic coefficient C_B	0.4	0.5	0.40394	0.402899	0.4018	0.400501
X_5	Mid-ship section coefficient C_M	0.86	0.89	0.860077	0.860031	0.87794	0.886081
X_6	Water plane coefficient C_{WP}	0.6	0.65	0.601622	0.602879	0.64215	0.635644
X_7	Longitudinal position of buoyancy center x_{CB}	-1	0	-0.959	-0.90978	-0.379	-0.91088
X_8	Diameter of screw propeller D_P	0.25	0.275	0.267273	0.268218	0.27035	0.257962
X_9	Disk area ratio A_E/A_O	0.4	0.5	0.500191	0.499805	0.4828	0.480501

X_{10}	Pitch ratio P/D_P	0.6	0.8	0.799163	0.796957	0.775	0.783523
X_{11}	Rotation speed of propeller N	3500	4000	3530.78	3530.96	3655	3672.02
X_{12}	Target velocity Vs	23	28	23.4687	23.5756	24.61	23.1628
X_{13}	Half angle of entrance ie	4	12	4.39929	4.25648	4.68	7.4921
X_{14}	Wetted surface area ratio of flap At/Am	0	0.18	0.067833	0.065974	0.00846	0.024846
X_{15}	Trim angle α	2	7	6.67377	6.5511	2.67	6.245
X_{16}	Ramp angle β	10	30	29.7487	29.9417	28.78	21.4518
X_{17}	Hydrofoil semispan L_H	0.9	1	0.981386	0.988813	0.997	0.997319
X_{18}	Hydrofoil chord length C_H	0.2	0.3	0.299352	0.3	0.299	0.297797
X_{19}	Hydrofoil degree of crown f_H	0.01	0.02	0.010783	0.010409	0.01004	0.010042
X_{20}	Hydrofoil ramp of angle β_H	10	25	23.579	23.7599	24.64	20.5846
X_{21}	Hydrofoil longitudinal mounting position x_H	1	1.4	1.14966	1.22073	1.3748	1.39909
X_{22}	Hydrofoil pillars of transverse distance y_H	1.7	1.8	1.70568	1.70667	1.7037	1.7001
X_{23}	Hydrofoil immersion h_0	0.2	0.4	0.387518	0.379404	0.3374	0.367101
X_{24}	The initial angle of attack hydrofoil α_0	0.04	0.06	0.059978	0.06	0.05994	0.059936
X_{25}	Area of rudder A_d	1.5	3	2.99179	2.99977	2.6655	2.65465
X_{26}	Rudder aspect ratio λ	0.5	0.7	0.527017	0.566742	0.6906	0.673132
X_{27}	Height of center of gravity away from the baseline Z_g	2	3	2.95198	2.96278	2.017	2.163
X_{28}	Building on top of the length of LA_1	1	1.2	1.02437	1.02569	1.087	1.10815
X_{29}	Building on top of width B_{A1}	3	4	3.08257	3.18457	3.841	3.40273
X_{30}	Building on the bottom of the length L_{A2}	1.5	1.6	1.52854	1.52511	1.5011	1.55313
X_{31}	Building on the width of the bottom B_{A2}	1	1.5	1.16545	1.12847	1.3445	1.25978
X_{32}	Building on highly H_A	1.4	1.7	1.52375	1.5378	1.4189	1.4721
X_{33}	Flip the the center of gravity height Z_g'	-1	1	-0.97605	-0.9606	-0.982	-1.00142

B. Analysis

1) The satisfaction of condition of equality constraints. From the table I, we can see that inequality constraints are all satisfied to a degree of 100%. The satisfaction of condition of equality constraints on ship performances are shown in the following table II.

TABLE II. SATISFACTION OF MAIN EQUALITY CONSTRAINTS CONDITION

Items	H-P-C-GA	parallel improved	H-P-GA-CA	H-P-GA-C
1	99.95%	99.91%	99.43%	99.90%
2	99.92%	99.90%	99.90%	99.90%
3	99.92%	99.90%	99.90%	99.90%

From the table II, we can see that the satisfaction of condition of equality constraints on ship performances is higher than 99.90%. These indicate that the penalty strategy is efficient and this solving method is reliable.

2) Analysis of the calculation results. Two points of conclusions are drawn after comparing and analyzing those different solving methods from table I. The values of H-P-GA-CA's and H-P-C-GA's general objective functions are respectively 3.12004 and 2.75493. The former is higher than the latter by 11.7%; which means P-GA-PCA is more efficient. b. H-P-GA-C's and parallel improved complex method's general objective function is 3.27324 and 2.84914.Thus，H-P-GA-C is better than parallel improved complex method. What's more, H-P-GA-C is higher than that of H-P-GA-CA by 4.6%. The above data tell us that H-P-GA -C based on delicate variables' segments is the best among these methods in solving complicated engineering optimizations of multi-objectives, multi-constraints and multi-variables.

3) The feasibility distribution function of general objective value. The authors attained the feasibility distribution function of general objective value basing on a lot of calculation results, the curve of distribution functions are shown in Fig.1-4. What's more, the author received rapidity and maneuverability of the overall objective function values also, the curve of distribution functions are shown in Fig.5-8.

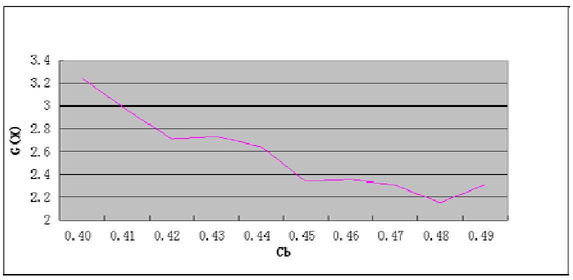

Figure 1. General objective function values G(x) of the curve with the change of block coefficient Cb

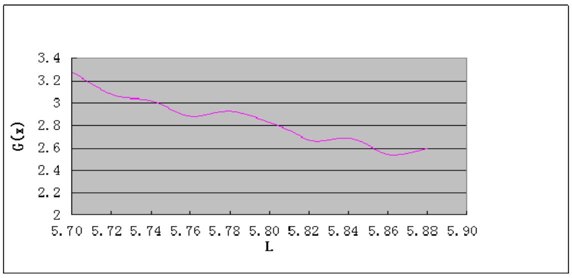

Figure 2. General objective function values G(x) of the curve with the change of captain L

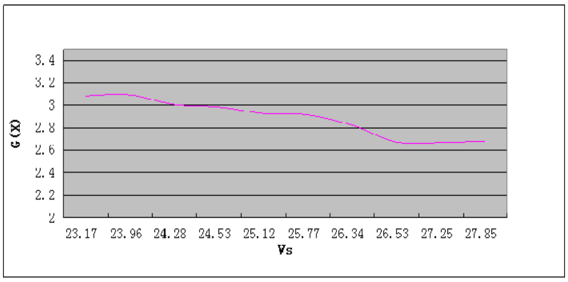

Figure 3. General objective function values G(x) of the curve with the change of craft speed Vs

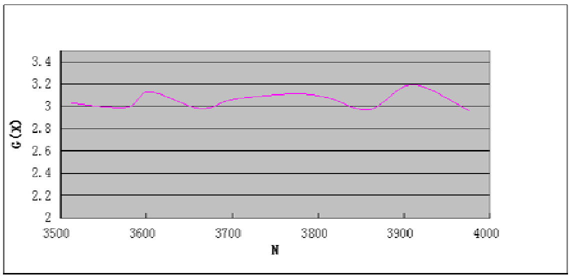

Figure 4. General objective function values G(x) of the curve with the change of propeller speed N

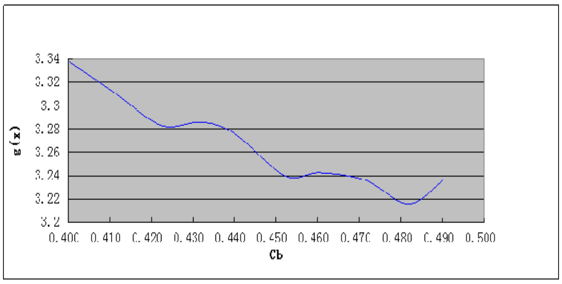

Figure 5. The curve of rapidity and maneuverability of the overall objective function values g(x) with the change of block coefficient Cb

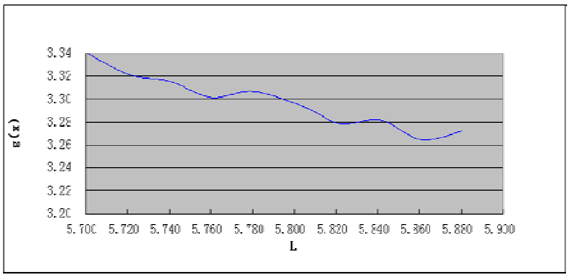

Figure 6. The curve of rapidity and maneuverability of the overall objective function values g(x) with the change of captain L

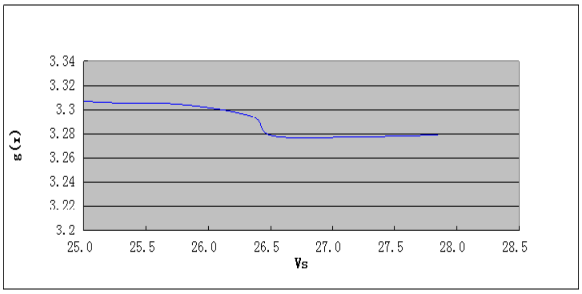

Figure 7. The curve of rapidity and maneuverability of the overall objective function values g(x) with the change of craft speed V

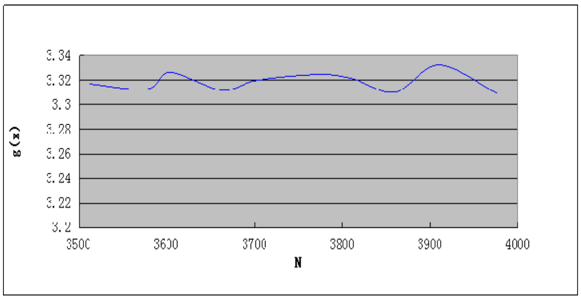

Figure 8. The curve of rapidity and maneuverability of the overall objective function values g(x) with the change of propeller speed N

It can be shown in Figure 1-4, the general objective function values, based on Cb, L, N and Vs, showing the overall trend of gradually decreases. Also, when N changes constantly, the general objective function values appear in three peaks. All

these proved that this kind of optimization problem is an exceptionally complex multimodal optimization problem. From Table III, we can see that the design variables N is not sensitive variables, Vs are a slightly sensitive variable, Cb and L are sensitive variables. However, L is a particularly sensitive variable.

It can be seen from Figure 5-8 and Table IV, relative to the rapidity and maneuverability of the overall objective function, we can see that the design variables Vs and N are not sensitive variables, Cb is slight sensitive variables, L are sensitive variables. However, L are particularly sensitive variables.

TABLE III. RELATIVE WAVE RATIO OF GENERAL OBJECTIVE FUNCTION

Item	*Wave ratio of the feasibility distribution function of general objective value (①)*	*The relative ranges of its design variables (②)*	*Relative wave ratio of General Objective Function (①/②)*
The Feasibility Distribution Function of General Objective Value (Cb)	51.16%	22.50%	227.38%
The Feasibility Distribution Function of General Objective Value (L)	29.25%	3.50%	835.71%
The Feasibility Distribution Function of General Objective Value (Vs)	15.73%	20.20%	77.87%
The Feasibility Distribution Function of General Objective Value (N)	5.74%	13.18%	43.55%

TABLE IV. RELATIVE WAVE RATIO OF RAPIDITY AND MANEUVERABILITY OF THE OVERALL OBJECTIVE FUNCTION

Item	*Wave ratio of the feasibility distribution function of general objective value (①)*	*The relative ranges of its design variables (②)*	*Relative wave ratio of General Objective Function (①/②)*
The Feasibility Distribution Function of Rapidity and maneuverability of the overall Objective Value (Cb)	4.05%	25.00%	16.20%
The Feasibility Distribution Function of Rapidity and maneuverability of the overall Objective Value (L)	2.45%	3.50%	70.00%
The Feasibility Distribution Function of Rapidity and maneuverability of the overall Objective Value (Vs)	1.22%	20.20%	6.04%
The Feasibility Distribution Function of Rapidity and maneuverability of the overall Objective Value (N)	0.60%	13.18%	4.55%

V. CONCLUSION

In this paper, H-P-GA-C based on delicate variables' segments principle has been proposed to applying to synthetic optimization of sailing performance optimization of the planning-hydrofoil USV. The authors had discussed on H-P-GA-NCA, H-P-C-GA, H-P-GA-C and parallel improved complex method, Computation results show that H-P-GA-C is the highest efficiency about navigation performance of the planning-hydrofoil USV. That inequality constraint on ship performances are all satisfied to a degree of 100% and the equality constraints are higher than 99.90%, these indicate that the penalty strategy is efficient; this new optimization algorithm (H-P-GA-C) is suitable for optimization performance of the planning-hydrofoil USV. Based on H-P-GA-C, the author makes a lot of calculation. According to the results of the calculation, the author draw the curves of the general objective, rapidity and maneuverability of the overall function's feasibility distribution function, with the change of breadth, block coefficient, captain, ship speed, propeller speed and propeller diameter, and discussed the sensitivity of design variables. It lays on a solid foundation for overall evaluation of the planning-hydrofoil USV design and integrated decision of the planning-hydrofoil USV parameter. With using of this software can provide the condition to integrate evaluation of the planning-hydrofoil USV design project.

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