The Optimization Analysis of Navigation Performance and Structural Properties of the High-Speed Monohull Ship in River

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Abstract

The authors use the weighting summation of rapidity and maneuverability as the sub-objective function of ship performances; By using the weighting summation of static and dynamic properties as the sub-objective function, The weighting summation of these 2 sub-objective functions is just the general objective function. In this paper, a parallel multi-processing genetic chaos algorithm (PM-C-FGA) has been put forward based on fuzzy method, genetic algorithm and chaos algorithm. This algorithm applied effectively to optimize the navigation performance and structural configuration of high-speed mono-hull ship in river.

Introduction

The most engineering design questions are the multi-objective issues. For example, when working on the mechanical system reliability design we hope the system has high reliability, low cost, light weight and so on. This question of demanding several design indexes reached optimum at the same time is called multi-objective optimization question. Meanwhile in the design process the fuzziness is inevitable. The ship design is the typical complex multi-objective design question with fuzziness. When we design a ship we should consider the navigation performance, structural configuration and arrangement characteristics. And their design parameters and constrained conditions have a certain boundary uncertainty.

In this paper, a parallel multi-processing genetic chaos algorithm (PM-C-FGA) has been put forward based on fuzzy method, genetic algorithm and chaos algorithm. This algorithm applied effectively to optimize the navigation performance and structural configuration of high-speed mono-hull ship in river.

**Pm-C-Fga**

PM-C-FGA is: According to the sensitivity of design variables, we divided variables into the most sensitive design variables, second-sensitive design variables, third-sensitive design variables and non-sensitive design variables, partition the search area those sensitive design variables scope by principle that high degree of sensitivity have many partition, then intersect and combine variables’ search scope zone. Those combination and remaining design variables search scope compose several optimization search scope. Optimization calculations have two steps. Firstly, search zone and short-algebra calculation of the parallel chaotic optimization at the same time. Second, selecting 3 or 5 groups of best optimal result, each group as a new optimization search zone, then do parallel fuzzy-GA calculation to obtain the optimal solution which is expected to efficiently for multi-objective, multi-discipline and multi-variable optimal solution of complex engineering problems.

**A. FGA’s Essential Procedure**

FGA is the algorithms based on delimitation search, which is to run genetic algorithms on special level when fuzzy optimization. It is explained with delimitation search method on fuzzy optimization and genetic algorithm. The delimitation search method that can present a distinct solution on fuzzy nonlinear programming is a common fuzzy optimization about engineering design. The book[6] is read about its step.

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

Coding: The chromosome coding is the floating data coding.

Selection: In this paper the comparatively common roulette method is employed.

Crossover: The crossover probability $p_c$ is selected as 0.85.

Mutation: The mutation probability $p_m$ is set as 0.05.

Fitness and Evaluation halt computing rule[4].

**B. Chaos Algorithm**

Chaos optimization is implemented by chaos variable. The authors choose a widely-used Logistic mapping to produce the chaos variable:

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

Where the time of iterative mapping $k=0,1,2, \ldots$.

It’s easy to prove that when $\mu=4$, 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. In this paper, the authors adopt twice-mapping chaos algorithm[5].

**Mathematical Model**

There’re 2 parts of synthetical optimization of ship performance and structure characteristic: navigation performances and structural mechanics properties. 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:

**C. Objective Function**

Suppose $P(X)$ is the general objective function, $P_N(X)$ is the sub-objective function of navigation performances, and $F(X)$ is the sub-objective function of structural mechanics properties. Then,

$$
P(X) = P_N(X) A \times F(X) B$$

$$P_N(X) = C_{sp} A \times M V B$$

Where $C_{sp}$ and $M_v$ are respectively normalized forms within [0,1] of rapidity criterion $C$ and maneuverability criterion $M$. $F(X)$ is gravity per meter of longitudinal member of midship section. Then,

$$C_{sp} = \frac{P_v}{\frac{2}{3}} \frac{V_s}{\eta_s \eta_R \eta_H}$$

Where $\Delta$—displacement; $P_v$—effective power; $\eta_s$—screw efficiency in the open; $\eta_R$—relative rotation efficiency.

$$M = V_{arl} \times V_{art} \times$$

Where $V_{arl}$—straight line stability coefficient; $V_{art}$—turning quality coefficient; $F(X) = (V_{ls} + \sum_{i=1}^{n} V_{tsi} + V_{tb}) / L$

Where, $M$ is the number of transverse frame of typical tank; $\rho$ is the density of material; $V_{ls}$ is the volume of longitudinal members of typical tank; $V_{tsi}$ is the volume of ith transverse frame of typical tank; $V_{tb}$ is the volume of single transverse bulkhead of typical tank; $L$ is the length of typical tank.

**D. Constraints conditions**

**Equation constraints**

1) Balance between buoyancy and displaced weight: $\rho L B T C_B = \Delta$;
2) Balance between effective thrust $T_e$ and resistance $R$;
3) Balance between torque received by screw from main engine $M_d$ and torque from hydrodynamic resistance $M_p$.

4) Structure constraints: the stress of tank members are shown in the following Table 1.

**Inequality constraints**

1) Ranges of 49 design variables’ values;
2) Cavitation requirement for screw propeller according to Kelly formula;
3) Initial stability height $G_M > h$;
4) Maximal rolling angle $\phi_2 \leq \theta^o$;
5) Relative turning diameter $D_s < c$.

Table 1. Structure Constraints

<table>
<thead>
<tr>
<th>Member type</th>
<th>permissible stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner and bottom plate, side plate</td>
<td>$\sigma = 0.8\sigma_s$</td>
</tr>
<tr>
<td>Bottom plate longitudinal, side longitudinal</td>
<td>$\sigma = 0.8\sigma_s$</td>
</tr>
<tr>
<td>Transverse bulkhead, centreline bulkhead, knee</td>
<td>$\sigma = 0.7\sigma_s$</td>
</tr>
<tr>
<td>Deck and platform structure</td>
<td>$\sigma = 0.6\sigma_s$</td>
</tr>
<tr>
<td>Platform longitudinal, deck longitudinal, side longitudinal</td>
<td>$\sigma = 0.6\sigma_s$</td>
</tr>
<tr>
<td>Pillar</td>
<td>$\sigma = 0.42\sigma_s$</td>
</tr>
</tbody>
</table>

Ps: $\sigma_s$ is material buckling strength, MPa

E. Design variables

The synthetical optimization of mechanics properties for ships involves many factors. After analyzing and comparing their importance, 49 parameters (including 35 parameters of midship section) are selected as the main design variables: ship length L, ship breadth B, draft T, longitudinal prismatic coefficient Cp, mid-ship section coefficient CM, water plane coefficient CWP, longitudinal position of buoyancy center xCB, diameter of screw propeller DP, disk area ratio AE/AO, pitch ratio P/DP, rotation speed of propeller N, target velocity Vt, half angle of entrance ie, wetted surface area ratio of flap At/Am, thickness of upper deck 1, thickness of upper deck 2, type of upper deck longitudinal, thickness of upper deck girder, thickness of side plating 1, thickness of side plating 2, thickness of side plating 3, type of side longitudinal, thickness of side stringer, thickness of pillar, thickness of twin deck, type of twin deck longitudinal, thickness of twin deck girder, thickness of bilge strake 1, thickness of bilge strake 2, thickness of bilge strake 3, type of bilge longitudinal, thickness of inner bottom plating, type of inner bottom longitudinal, thickness of bottom plating, thickness of flat keel, type of bottom longitudinal, thickness of centre girder, thickness of side girder, longitudinal space of upper deck, side longitudinal space, longitudinal space of twin deck, longitudinal space of bulkhead, longitudinal space of bilge plating, longitudinal space between inner plating and bottom plating. Their vector is as follow:

$$X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}, x_{20}, x_{21}, x_{22}, x_{23}, x_{24}, x_{25}, x_{26}, x_{27}, x_{28}, x_{29}, x_{30}, x_{31}, x_{32}, x_{33}, x_{34}, x_{35}, x_{36}, x_{37}, x_{38}, x_{39}, x_{40}, x_{41}, x_{42}, x_{43}, x_{44}, x_{45}, x_{46}, x_{47}, x_{48}, x_{49}\}.$$  

Example Of Optimization Computation
F. Optimization Computation

The mathematic model shows that the synthetical optimization of mechanics properties for high-speed monohul ship in river involves at least 49 design variables, 9 equation constraints and 5 inequality constrains. Evidently, it’s a very complicated engineering optimization. the authors programme the solving software.

Here take a high-speed monohul ship in river for example. Its displacement is 4250t and it has double propellers. The ranges of its design variables’ values are listed in Table 3:

The authors assign values as: $A_p=1.0$, $B_p=1.25$; $A_{p1}=1.05$, $A_{p2}=1.0$; $pl=1.35$; $pt=1.55$.

The authors run chaos algorithm, GA of 7000 generations, parallel GA of 500 generations and PM-C-FGA. The results are as Table 2&3 shows:

<table>
<thead>
<tr>
<th>Items</th>
<th>Chaos algorithm</th>
<th>GA (7000 generations)</th>
<th>Parallel GA (500 generations)</th>
<th>PM-C-FGA (300 generations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General objective function value</td>
<td>0.577523</td>
<td>0.622116</td>
<td>0.8259</td>
<td>0.704408</td>
</tr>
<tr>
<td>Displacement</td>
<td>4247.85</td>
<td>4251.77</td>
<td>4242.93</td>
<td>4252.32</td>
</tr>
<tr>
<td>$T_E$ (kN)</td>
<td>4124.36</td>
<td>3945.84</td>
<td>3939.39</td>
<td>3944.81</td>
</tr>
<tr>
<td>Resistance</td>
<td>4115.07</td>
<td>3943.51</td>
<td>3941.14</td>
<td>3940</td>
</tr>
<tr>
<td>$M_p$ (kN·m)</td>
<td>2306.54</td>
<td>2050.89</td>
<td>2175.89</td>
<td>2168.24</td>
</tr>
<tr>
<td>$M_d$ (kN·m)</td>
<td>2301.35</td>
<td>2049.68</td>
<td>2176.86</td>
<td>2165.6</td>
</tr>
<tr>
<td>$\eta_e$</td>
<td>0.687395</td>
<td>0.730334</td>
<td>0.744664</td>
<td>0.69291</td>
</tr>
<tr>
<td>$P_E$ (kW)</td>
<td>102801</td>
<td>99103.3</td>
<td>99085.3</td>
<td>98351.5</td>
</tr>
<tr>
<td>Main engine power (kW)</td>
<td>157310</td>
<td>140468</td>
<td>142812</td>
<td>149070</td>
</tr>
<tr>
<td>Froude number (Fr)</td>
<td>0.67817</td>
<td>0.685875</td>
<td>0.686002</td>
<td>0.687324</td>
</tr>
<tr>
<td>Initial stability height (m)</td>
<td>0.739906</td>
<td>0.72131</td>
<td>0.837217</td>
<td>0.790517</td>
</tr>
<tr>
<td>Relative turning diameter Ds</td>
<td>7.0266</td>
<td>6.80503</td>
<td>7.18528</td>
<td>7.08429</td>
</tr>
<tr>
<td>Friction drag modulus $C_f$</td>
<td>0.0013462/2</td>
<td>0.0013469/6</td>
<td>0.0013468/2</td>
<td>0.001350/79</td>
</tr>
<tr>
<td>Re</td>
<td>2.9109e+009</td>
<td>2.89715e+009</td>
<td>2.89972e+009</td>
<td>2.82731e+009</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Items</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_i$ (m)</td>
<td>134</td>
<td>150</td>
<td>138.464</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>136.992</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>137.056</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>134.592</td>
</tr>
</tbody>
</table>
From the results, we can see that inequality constraints are all satisfied to a degree of 100%. These indicate that this solving method is reliable.

**G. Analysis**

From the table 32 we can gain the satisfaction of condition of equality constraints on ship performances. The results are shown in the following table 3.

From the table 2, we can see that the satisfaction of condition of equality constraints on ship performances is higher than 99.77%. These indicate that the penalty strategy is efficient.

3 points of conclusions are drawn after comparing and analyzing those different solving methods from table 3.

a. The values of chaos algorithm’s and 7000-generationed GA’s algorithm’s general objective functions are respectively 0.5775 and 0.6221. The former is lower than the latter by 7.17%, which means parallel algorithm is more efficient.

b. The values of 7000-generationed GA’s and 500-generationed parallel GA’s general objective functions are respectively 0.6221 and 0.6882. The former is lower than the latter by 9.60%, which means obvious premature convergence of GA.

c. PM-C-FGA’s general objective function is 0.7044. It’s higher than those of parallel GA algorithm and GA by 2.35% and 13.23%. These 2 data tell us that PM-C-FGA based on delicate variables’ segments is the best among these methods in solving complicated engineering optimizations of multi-objectives, multi-constraints and multi-variables.

**Conclusion**

In this paper, PM-C-FGA has been put forward to applying to synthetic optimization of ship performance and structure characteristic for high speed monohull ship in river. Computation results show
that this method is of high efficiency. It lays on a solid foundation for overall evaluation of high speed monohull ship in river design and integrated decision of ship parameter. Using this software can provide the condition to integrate evaluation of the ship design project and the integrate decision-making of ship parameters.

References


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