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# Lightweight hull surface self-design vertical parameterization method of based on NURBS

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**Abstract: [Objectives]** At present, conventional design is limited to parent ship design space, and cannot drive ship hull design using as few parameters as possible. In order to solve the above problems, **[Methods]** by combining the draught function with NURBS, a ship hull surface self-design method based on vertical parameterization is proposed. In this method, the waterline is designated as the basic design unit; the bottom flat end line, designed waterline, stem and stern contours, side flat end line and maximum section line are designated as the characteristic constraints of the ship hull; and the draught function values corresponding to the characteristic parameters are designated as the design objectives. In this way, a waterline approximation model is built, and an evolutionary algorithm can be used to solve the approximation model. Finally, the ship hull surface is generated on the basis of the waterline using the NURBS skinning technique. **[Results]** The design examples of the characteristic curves of the full-scale ship hull surface indicate the practicable and advanced nature of this method. **[Conclusions]** The hull surface can be designed with as few data as possible using this method, making it much more suitable for the self-design of new hull forms.

**Key words:** NURBS; hull surface; self-design; vertical parameterization; characteristic curves

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## 0 Introduction

Hull surface design is the basis of the following ship design, and Non-Uniform Rational B-Spline (NURBS) is the mainstream method of hull surface design. At present, the hull surface design is mainly the design based on data points. The process is that the interpolation of the data points generates the surface section line (B-spline curve), and then the hull surface is generated by the skin of the surface section line[1-4]. Wherein, determination of the data points is basically based on a parent form transformation method. Because most of the hull surface design methods based on NURBS do not consider the effect of weights, the section line will degenerate into B-spline, and the generated surface is interpolated surface. The inherent algorithm of interpolated surface will lead to excessive number of control points, which is not conducive to the subsequent surface fairing and modification. Lu et al.[5] considered the weights of NURBS, and used the real-coded genetic algorithm to approximate the hull waterline, and then the problem was further improved in Ref.[6]. But the above references basically belong to the expression of hull form, but have not involved the design. In hull form design, Yu et al.[7] proposed a new design

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method of hull surface parameterization, which is essentially a hull surface transformation method, namely, the parent form transformation method. Although the parent form transformation method makes the design ship inherit the advantages of parent ship, it also causes the hull surface to wander in the original design circle but difficult to innovate. Therefore, it is of great significance to study a hull self-design method with small data size and of which the design is not confined to the existing parent form. Zhang et al. [8] proposed a parameterization design technique of fair curve, and studied the parameterization design method of hull form based on the "centroid" of sectional area, but its design variables are the data points and the designed section line selects the section lines. Due to the difference in the convexity-concavity of the section lines, it is difficult to unify the number of design variables and the setting of initial values, which is not conducive to the construction of a unified optimal design framework. Therefore, based on the comprehensive comparison on the shape characteristics of the characteristic curves of hull, waterline was selected as the basic unit of parameterization design in this paper, and the curve design model of lightweight hull waterline and stem and stern contours was given. The draught function method[9] and NURBS method were combined to construct the parameterization self-design system based on the draught function.

# 1 NURBS

## 1.1 B-spline basis function

It is assumed that $\boldsymbol{U}=\{u_0, \cdots, u_m\}$ was a non-decreasing real sequence, i.e., $u_i < u_{i+1}$ ($i$=0,⋯, $m$−1), $u_i$ is denoted as knots, and $\boldsymbol{U}$ is knot vector. The $i^{\text{th}}$ B-spline basis function of $p$-degree $N_{i,p}(u)$ is defined as follows[10]:

$$\begin{cases} N_{i,0}(u)=\begin{cases}1, & u_i < u < u_{i+1} \\ 0, & \text{others}\end{cases} \\ N_{i,p}(u)=\dfrac{u-u_i}{u_{i+p}-u_i}N_{i,p-1}(u)+\dfrac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}}N_{i+1,p-1}(u) \\ 0/0=0 \end{cases} \tag{1}$$

## 1.2 NURBS curve definition

The $p$-degree NURBS curve is defined as a piecewise rational parametric curve in the following form[10]:

$$C(u)=\frac{\sum_{i=0}^{n}N_{i,p}(u)\omega_i P_i}{\sum_{i=0}^{n}N_{i,p}(u)\omega_i}\ ;\quad 0 \leqslant u \leqslant 1 \tag{2}$$

where $\{P_i\}$ is the control point, and its connected lines form the control polygon of the curve; $\{\omega_i\}$ is the corresponding weight sequence; $\{N_{i,p}(u)\}$ is the $p$-degree B-spline basis function defined on the non-periodic nonuniform knot vector $\boldsymbol{U}=\{\underbrace{0,\cdots,0}_{p+1}, u_{p+1},\cdots,u_m,\underbrace{1,\cdots,1}_{p+1}\}$.

# 2 Characteristic curve of hull surface

As shown in Fig. 1, the side flat end line, the stem and stern contours, the bottom flat end line, the designed waterline and the maximum section line were selected as the characteristic curves of the hull surface design. Considering that the shape characteristics of the bottom flat end line, the designed waterline and other waterlines were similar, they can be unified as the design of one class of waterline in the vertical parameterization self-design system; and the stem and stern contours, the maximum section line and the side flat end line can be processed as feature point control line of waterline to be designed. Therefore, the parameterization design model of the waterline class was first given, and then the parameter control models of the stem and stern contours, the maximum section line and the side flat end line were given, which were described as follows.

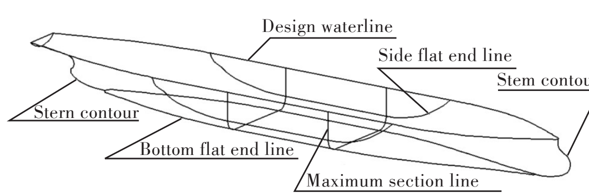


Fig.1 Characteristic curves of hull surface

## 2.1 Waterline design model

First, the design model was simplified. The hull waterline is usually composed of the fore and aft arcs (or straight lines), the fore and aft free curves and the middle straight section, as shown in Fig. 2.

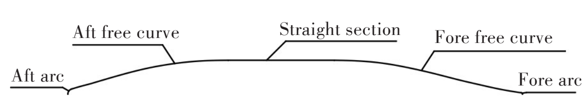


Fig.2 Waterline segmentation

We can see from Fig. 2, the feature points of the hull waterline were the fore and aft endpoints of the

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waterline, as well as the starting and ending points of the straight section, and these points can be defined by other characteristic curves such as the stem and stern contours and the side flat end line; the arc radius can be given preliminarily by the draught function in the initial design stage. In addition, taking into account that the shapes of the forebody and afterbody of hull waterline are similar, a unified parameterization design model can be built. Therefore, the origin of the coordinates was set at the intersection of the midship section and buttock line in center plane; $X$ axis was defined as the intersection of the longitudinal section in center plane and the base plane,pointing to the bow and stern as the positive direction; $Y$ axis was defined as the intersection of midship section and the base plane, pointing to the larboard as the positive direction; $Z$ axis was defined as the intersection of longitudinal section in center plane and the midship section, upward as the positive direction. In this coordinate system, the characteristic parameters of waterline forebody are given (for characteristic parameters of waterline afterbody, the subscript f was changed into a, thus no longer detailed below), as shown in Fig. 3.

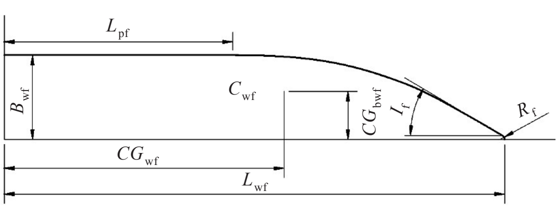


Fig.3 Characteristic parameter of waterline forebody

In the figure: $L_{wf}$ is the waterline forebody length from midship to bow, and its value can be determined by the stem contour; $L_{pf}$ is the length of the straight section of the waterline forebody measured from midship, and its value can be determined by the side flat end line; $B_{wf}$ is the half width value of the waterline forebody in midship, and its value is determined by the maximum section line; $C_{wf}$ is the area coefficient of the waterline forebody; $CG_{wf}$ is the distance from the centroid of waterline forebody to midship; $CG_{bwf}$ is the half width of the centroid of the waterline forebody; $I_f$ is the half entrance angle (here refers to the tangent vector at the starting point of waterline free curve); $R_f$ is the arc radius at the starting point of waterline. These values changed with the draught, and can be determined by the draught function in section 3. When these values were determined, the problem can be transformed into solving the approximation of curve that satisfies the given characteristic parameters. Next, the curve design model was established.

### 2.1.1 Design variables of design model

The number of design variables has great influence on the efficiency of the parameterization design program. In order to improve the operation efficiency of parameterization program, through repeated comparisons and analyses, it was proved that the design of waterline forebody using the 3 degree NURBS curve can meet the requirements of engineering accuracy and flexible modification. In addition, because the shape of fore arc can be determined by the fore endpoint and arc radius of waterline, the fore arc was not considered in the approximation model in this paper for the present, and the distribution of control points for the waterline forebody was set as shown in Fig. 4.

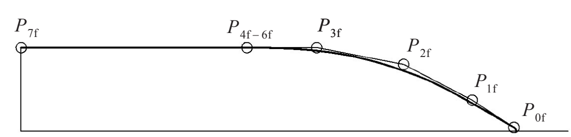


Fig.4 Control points setting for the waterline forebody

As shown in Fig. 4, there are 8 control points (6 independent positions) in the figure, which were divided into 3 categories:

1) Boundary control points $P_{0f}$, $P_{4f-6f}$ and $P_{7f}$, where $P_{0f}$ is the point of tangency between the fore arc and the free curve of waterline, $P_{4f-6f}$ is the fore endpoint of the straight section of the waterline forebody, and $P_{7f}$ is the intersection of waterline and midship section.

2) Tangent vector control points $P_{1f}$ and $P_{3f}$, where the line between $P_{1f}$ and $P_{0f}$ is tangent to the fore arc, and $P_{3f}$ is on the line determined by $P_{4f-6f}$ and $P_{7f}$, so as to achieve the purpose of smooth connection among the free curve, the straight section and the arc.

3) Shape control point $P_{2f}$, which is combined with $P_{1f}$ and $P_{3f}$ to control the shape of waterline.

It is assumed that $x_i, y_i, z_i$ and $\omega_i$ were the longitudinal coordinate, the horizontal coordinate, the vertical coordinate and the weights of control point $P_{if}$ ($i$ = 0, $\cdots$, 7), respectively. The value of $z_i$ was the draught height of the waterline to be designed. According to the distribution characteristics of control points, we can see: $y_7 = y_{4-6} = y_3 = B_{wf}$; $x_7 = 0$, $x_{4-6} = L_{pf}$; $\tan(I_f) = (y_1 - y_0)/(x_1 - x_0)$; $x_0 = L_{wf} - R_f(1-\sin(I_f))$, $y_0 = R_f \cdot \cos(I_f)$. The weights $\omega_0$,

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$\omega_{4-6}$ and $\omega_7$ were set to 1. Therefore, the design variables for the waterline forebody curve were $[x_1, x_2, x_3, y_2, \omega_1, \omega_2, \omega_3]$.

### 2.1.2 Constraint conditions

Because the waterline cannot generate the phenomenon of twists and turns, according to the convex-hull property of NURBS, the constraint conditions for the waterline forebody curve were set as follows:

$$\begin{cases} x_4 < x_3 < x_2 < x_1 < x_0 \\ y_0 < y_1 < y_2 < y_3 = y_4 \\ 0 < \omega_i < 50\ ; \quad i = 1, 2, 3 \\ \tan(I_{\mathrm{f}}) = (y_1 - y_0)/(x_1 - x_0) \end{cases} \tag{3}$$

### 2.1.3 Design objectives

It is assumed that $A_{\mathrm{wf}}$ was the area formed by the $x$ axis and the free curve of waterline forebody curve to be designed, $CG_{x\mathrm{f}}$ and $CG_{y\mathrm{f}}$ were $x$ and $y$ coordinates of the corresponding centroid (these values can be determined by the characteristic parameters of waterline), $A'_{\mathrm{wf}}$, $CG'_{x\mathrm{f}}$ and $CG'_{y\mathrm{f}}$ are respectively the corresponding parameters of free curve of the waterline forebody obtained by the proposed method. Then, the design objective function of waterline forebody is

$$\mathrm{Min}\, F(x) = \mathrm{Min}\left(\left|\left(A'_{\mathrm{wf}} - A_{\mathrm{wf}}\right)\big/A_{\mathrm{wf}}\right| + \left|\left(CG'_{y\mathrm{f}} - CG_{y\mathrm{f}}\right)/CG_{y\mathrm{f}}\right| + \left|\left(CG'_{x\mathrm{f}} - CG_{x\mathrm{f}}\right)/CG_{x\mathrm{f}}\right|\right) \tag{4}$$

As mentioned above, when the parameterization design of waterline was transformed into the curve approximation problem, the approximation problem can be solved by an evolutionary algorithm, such as the genetic algorithm with human-computer interaction[11] (for the waterline afterbody, subscript f was changed into a).

The method of preliminarily determining other characteristic curves was given, so that the characteristic parameters of the waterline to be designed can be obtained quickly in the initial design stage.

## 2.2 Control point distribution and control parameters of stem and stern contours

After repeated comparisons and analyses, the 3 degree NURBS curves approximating the stem and stern contours were determined, and the control points were set up as shown in Fig. 5 and Fig. 6, which can meet the requirements of engineering accuracy and flexible modification.

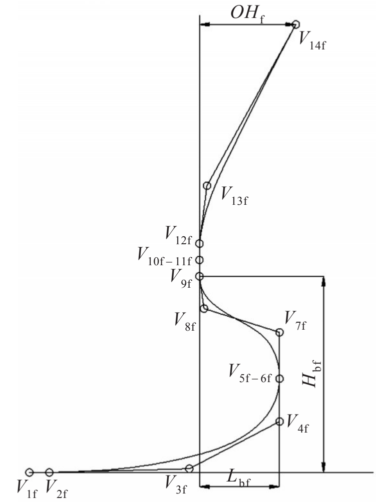


Fig.5 Control points setting for the stem contour

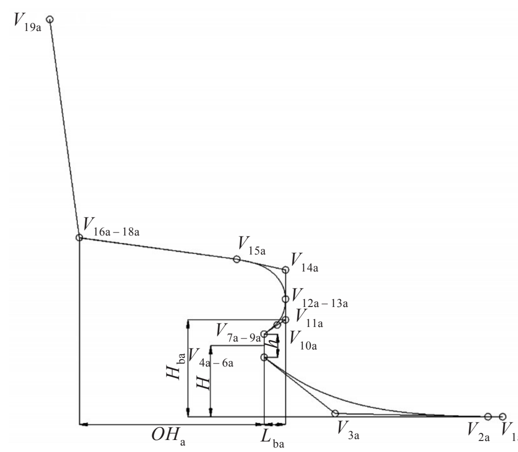


Fig.6 Control points setting for the stern contour

### 2.2.1 Control point distribution model of stem contour

As shown in Fig. 5, there are a total of 14 control points (12 independent positions) in the figure, which were divided into the following 3 categories:

1) Boundary control points $V_{1\mathrm{f}}$, $V_{5\mathrm{f}-6\mathrm{f}}$, $V_{10\mathrm{f}-11\mathrm{f}}$ and $V_{14\mathrm{f}}$, where, $V_{1\mathrm{f}}$ and the fore endpoint of the bottom flat end line coincided, $V_{14\mathrm{f}}$ and the fore endpoint of the deck center line coincided, $V_{5\mathrm{f}-6\mathrm{f}}$ controlled the extended length $L_{\mathrm{bf}}$ of the front end of bulbous bow, and $V_{10\mathrm{f}-11\mathrm{f}}$ controlled the connection between the bulbous bow and the overhang of stem contour. The latter two were the repeated control points, which controlled the tangent vector of the curve with the corresponding tangent vector control points in class 2). For a special stem contour with a flat front end of the bulbous bow, $V_{5\mathrm{f}-6\mathrm{f}}$ can be set separately and the connection line was made parallel to the $Z$ axis.

2) Tangent vector control points $V_{2\mathrm{f}}$, $V_{4\mathrm{f}}$, $V_{7\mathrm{f}}$, $V_{9\mathrm{f}}$ and $V_{12\mathrm{f}}$, where, the connection line between

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$V_{2f}$ and $V_{1f}$ determined the tangent vector at the bottom of the bulbous bow; $V_{4f}$, $V_{7f}$ and repeated control point $V_{5f-6f}$ were combined to control the tangent vector direction of the beak curve of the bulbous bow to be parallel to the $Z$ axis; similarly, $V_{9f}$, $V_{12f}$ and overlap point $V_{10f-11f}$ were combined to control the connection curve between the bulbous bow and the overhang of the stem contour so that a section was parallel to the $Z$ axis.

3) Shape control points $V_{3f}$, $V_{8f}$ and $V_{13f}$, where, $V_{3f}$ and $V_{8f}$ were combined with $V_{2f}$, $V_{4f}$, $V_{7f}$, $V_{9f}$, and a variety of bulbous bow contours can be obtained through adjustment; $V_{13f}$ was combined with $V_{12f}$ and $V_{14f}$ to control the shape of the overhang curve.

#### 2.2.2 Control point distribution model of stern contour

As shown in Fig. 6, there were 19 control points (12 independent positions) in the figure, which were divided into 4 categories:

1) Boundary control points $V_{1a}$, $V_{4a-6a}$, $V_{7a-9a}$, $V_{12a-13a}$ and $V_{19a}$, where, $V_{1a}$ and the aft endpoint of the bottom aft end line coincided, $V_{19a}$ coincided with the aft endpoint of the deck center line, $V_{4a-6a}$ and $V_{7a-9a}$ controlled the shape of stern shaft outlet, $V_{12a-13a}$ controlled the extended length $L_{ba}$ at the end of the bulbous stern, and controlled the connection between the bulbous stern and the overhang of the stern contour.

2) Tangent vector control points $V_{2a}$, $V_{11a}$ and $V_{14a}$, where, the connection between $V_{1a}$ and $V_{2a}$ determined the tangent vector of the bottom of the bulbous stern; $V_{11a}$ and $V_{14a}$ were combined with $V_{12a-13a}$ to control the connection curve between the bulbous stern and the overhang of stern contour, so that a section was parallel to the $Z$ axis.

3) Shape control points $V_{3a}$, $V_{10a}$ and $V_{15a}$, where, $V_{3a}$ and $V_{10a}$ were combined with $V_{2a}$, $V_{4a-6a}$, $V_{7a-9a}$, and $V_{11a}$; a variety of shapes of the bulbous stern contour can be obtained through adjustment; $V_{14a}$ and $V_{15a}$ were combined with $V_{16a-18a}$ to control the shape of the overhang curve.

4) Plane control points $V_{16a-18a}$ and $V_{19a}$ of stern transom plate. The triplex control points $V_{16a-18a}$ coincided with the lowest point of the stern transom plate, which, with $V_{19a}$, determined that the contour of the part above the lowest point of the stern transom plate was a straight line, and the purpose was to ensure that the stern transom plate was a plane when the hull surface was designed.

#### 2.2.3 Control parameters of the stem and stern contours

The main control parameters of the stem contour are as follows:

| | |
|---|---|
| Length of bulbous bow | $L_{bf}$ |
| Height of bulbous bow | $H_{bf}$ |
| Length of the overhang of the stem contour | $OH_f$ |

The main control parameters of the stern contour are as follows:

| | |
|---|---|
| Height of the center line of stern shaft | $H$ |
| Height of propeller post bossing | $h$ |
| Length of bulbous stern | $L_{ba}$ |
| Height of bulbous stern | $H_{ba}$ |
| Length of the overhang of the stern contour | $OH_a$ |

#### 2.2.4 Method for determining the stem and stern contours

Firstly, the positions of the boundary control points of the contours were determined according to the control parameters of the stem and stern contours, and then the distribution of the tangent vector and shape control points was adjusted to obtain the stem and stern contours satisfying the design intent. After the stem and stern contours were determined, the characteristic parameter $L_{wf}$ of the waterline to be designed was also determined.

### 2.3 Maximum section line

The most common form of maximum section line is divided into round bilge type, inclined bottom + round bilge type and elliptic bilge type according to different shapes of the bilge. Their shapes are simple, which can be determined by first determining their shape parameters, and then giving the piecewise function according to the shape feature with draught as a variable. The maximum section line of round bilge type was taken as an example as below to illustrate the form of the function, as shown in Fig. 7.

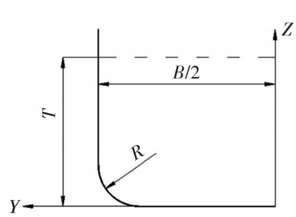


Fig.7 Round bilge type of midship section

There is only one shape parameter for the maximum section line of round bilge type, which is the arc radius $R$ shown in Fig. 7. The function of its half width relative to the draught can be written as

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$$B_{\text{wf}}(z)=\begin{cases}B/2 & , \quad R\leqslant z\leqslant T\\ \sqrt{2Rz-z^2}+(B/2)-R, & 0\leqslant z<R\end{cases} \quad (5)$$

In the formula: $B$ is molded breadth; $T$ is design draught. The maximum section lines of other forms can also determine $B_{\text{wf}}$ by giving the function with draught as an independent variable, which is no longer detailed here.

### 2.4 Side flat end line

The intersection of the side flat end line and the waterline forebody corresponds to the straight section $L_{\text{pf}}$ of the waterline forebody. The length of the straight section has little influence on the fairing of the hull form. Therefore, in the initial design stage, according to the parameter polynomial, it can be expressed as[9]

$$L_{\text{pf}}(z)=L_{\text{pf0}}+0.5(L_{\text{pfd}}-L_{\text{pf0}})(3(z/T)-2(z/T)^3+(z/T)^4) \quad (6)$$

The shape parameters are as follows: the length of the parallel middle body $L_{\text{pf0}}$ at the fore of the bottom flat end line, and the length of the parallel middle body $L_{\text{pfd}}$ at the fore of the designed waterline. In the design, the side flat end line can be drawn first according to the formula values, and then the side flat end line is gradually adjusted to meet the design requirements.

## 3 Draught function

The selection of draught function has a great influence on the fairing of the hull form. The draught function in Ref. [9] was extended on the basis of Ref. [12]. In this paper, first, the value of the draught function designed in Ref. [9] was used as the basic value to draw the draught function curve, and on this basis, the shape of the draught function curve was repeatedly adjusted according to the shape characteristics of hull lines to be designed, until the satisfactory molded lines were obtained. The mathematical formula of the draught function is as follows.

### 3.1 Entrance and exit angles *i*

The vertical function for entrance and exit angles adopts the quadratic polynomial equation [9]:

$$i(z)=c_1+c_2(z/T)+c_3(z/T)^2 \quad (7)$$

The shape control parameters of coefficients $c_1$, $c_2$, $c_3$ were determined: $i=i_j$ ($j$ = 1, 2, 3), and $i(z)=(L_{\text{wf}}(z)-L_{\text{pf}}(z))I_{\text{f}}(z)/B_{\text{wf}}(z)$.

### 3.2 Arc radius *r*

The vertical function of fore arc radius curve adopts cubic polynomial equation[9]:

$$r(z)=c_1+c_2(z/T)+c_3(z/T)^2+c_4(z/T)^3 \quad (8)$$

The shape control parameters of coefficients $c_1$, $c_2$, $c_3$, $c_4$ were determined: $r=r_j$ ($j$ = 1, 2, 3, 4), and $r(z)=(L_{\text{wf}}(z)-L_{\text{pf}}(z))R_{\text{f}}(z)/B^2_{\text{wf}}(z)$.

### 3.3 Waterplane coefficient $C_{\text{w}}$

The vertical function of the waterplane coefficient is a draught function which has a great influence on the fairing performance, and can be roughly dealt with according to the following equation[9]:

$$C_{\text{wf}}(z)=c_1+c_2(z/T)+c_3(z/T)^2 \quad (9)$$

The shape control parameters of coefficients $c_1$, $c_2$ and $c_3$ were determined as follows: the waterplane coefficient $C_{\text{wf0}}$ of the bottom flat end line, and the waterplane coefficient $C_{\text{wfd}}$ of the designed waterline, as well as

$$C_{\text{bf}}=\int_0^T\frac{2C_{\text{wf}}(z)L_{\text{wf}}(z)B_{\text{wf}}(z)}{L_{\text{ppf}}BT}\text{d}z \quad (10)$$

where $C_{\text{bf}}$ is block coefficient of ship forebody; $L_{\text{ppf}}$ is the distance from fore perpendicular to the midship.

### 3.4 Centroid position of waterplane

1) Distance from the waterplane centroid to the midship.

The vertical function of the waterplane centroid is a draught function which has a great influence on the fairing performance, and it can be roughly dealt with according to the following equation[9]:

$$cg_{\text{wf}}(z)=c_1+c_2(z/T)+c_3(z/T)^2 \quad (11)$$

The shape control parameters of coefficients $c_1$, $c_2$, $c_3$ were determined: distance $CG_{\text{f0}}$ from centroid of the bottom flat end line to the midship, and distance $CG_{\text{fd}}$ from centroid of the designed waterline to the midship, as well as

$$L_{\text{cbf}}=\frac{1}{C_{\text{bf}}}\int_0^T\frac{2cg_{\text{wf}}(z)C_{\text{wf}}(z)L^2_{\text{wf}}(z)B_{\text{wf}}(z)}{L^2_{\text{ppf}}BT}\text{d}z \quad (12)$$

where $L_{\text{cbf}}$ is the distance from buoyant center of the ship forebody to the midship divided by the distance $L_{\text{ppf}}$ from fore perpendicular to the midship, and $cg_{\text{wf}}(z)=CG_{\text{wf}}(z)/L_{\text{wf}}(z)$.

2) Distance between the centroid of half waterplane and the center line.

The vertical function of the centroid of half waterplane is a draught function which has a great influence on the fairing performance, and it can be roughly dealt with according to the following equation:

$$cg_{\text{bwf}}(z)=c_1+c_2(z/T)+c_3(z/T)^2 \quad (13)$$

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The shape control parameters of coefficients $c_1$, $c_2$ and $c_3$ were determined as follows: half width $CG_{\mathrm{bwf0}}$ of the centroid of the bottom flat end line, half width $CG_{\mathrm{bwfd}}$ of the centroid of the designed waterline, and half width of the centroid of any waterline. In addition, $cg_{\mathrm{bwf}}(z)=CG_{\mathrm{bwf}}(z)/B_{\mathrm{wf}}(z)$.

## 4 Design process

The formation of the hull surface was divided into the following steps:

1) The shape of the maximum section line was determined according to the determined principal dimensions and the type of the maximum section line;

2) The shape of the stem and stern contours was determined according to section 2.2;

3) The shape of the bottom flat end line and the designed waterline was determined according to section 2.1;

4) The shape of the side flat end line was determined according to section 2.4;

5) The coefficients of each draught function in section 3 were determined by the characteristic curves determined in the previous 4 steps;

6) The geometric design objective and geometric constraint information of the waterline under specific draught were obtained by the determined draught function, and the curve approximation model was established according to section 2.2, which was solved by the evolutionary algorithm;

7) Hull surface was generated according to the skin of tribe of waterlines obtained in step 6).

## 5 Design results

Fig. 8 shows the design results and the control points distribution of the designed waterline (7 000 WL) of a 7 000 t bulk carrier. Table 1 lists the values of design objectives (free curve area and centroid position of the waterline), design approximate data and the error between the approximate waterline and the design objective, where $|Error|$ is the relative error between design objective and characteristic parameters of the approximate waterline. Table 2 lists the defined data (control point coordinates and weights) of the approximate waterline, in which rows $x$ and $y$ are the $x$, $y$ coordinates of the control points respectively, and row $\omega$ corresponds to the weights of the control points. According to the relative errors, using the approximation model in this paper for calculation, under the premise of meeting the requirements of engineering accuracy, the design results satisfying the design intention of the designers can be obtained.

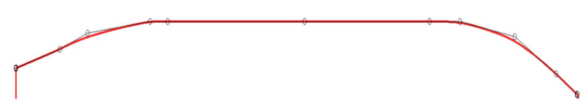


Fig.8 Designed waterline (7 000 WL) design results and control points distribution

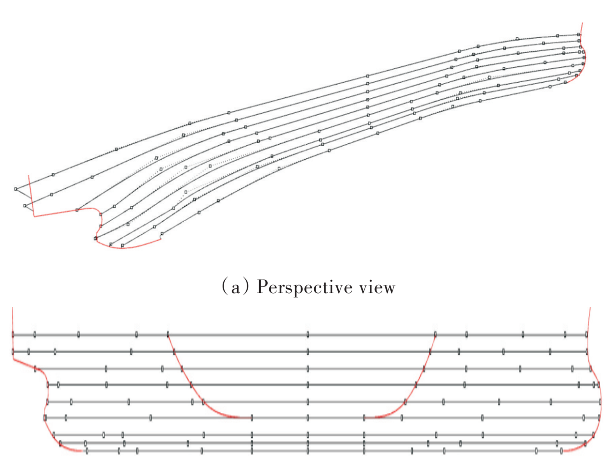
**Table 1 Design objective, approximate design data and errors of the designed waterline (7 000 WL)**

| | Forebody | | | Afterbody | | |
|---|---|---|---|---|---|---|
| | $A_{\mathrm{wf}}$ /m$^2$ | $CG_{xf}$ /m | $CG_{yf}$ /m | $A_{\mathrm{wa}}$ /m$^2$ | $CG_{xa}$ /m | $CG_{ya}$ /m |
| Design objective | 168.123 867 | 33.957 682 | 3.556 745 | 187.357 002 | 37.655 673 | 3.514 651 |
| Approximate design data | 168.123 879 | 33.953 542 | 3.556 738 | 187.361 427 | 37.655 992 | 3.514 643 |
| $\|Error\|$×1 000 | 0.000 1 | 0.121 9 | 0.002 0 | 0.023 6 | 0.008 5 | 0.002 3 |

**Table 2 Control points and weights of the designed waterline (7 000 WL)**

| Forebody | | | Afterbody | | |
|---|---|---|---|---|---|
| $x$ | $y$ | $\omega$ | $x$ | $y$ | $\omega$ |
| 50.764 | 0.405 | 1 | 53.799 | 3.348 | 1 |
| 46.868 | 2.715 | 17.5 | 45.618 | 5.463 | 33.116 |
| 39.153 | 6.894 | 38.466 | 40.420 | 7.300 | 31.292 |
| 28.916 | 8.6 | 18.161 | 28.793 | 8.6 | 29.995 |
| 23.257 | 8.6 | 1 | 25.5 | 8.6 | 1 |
| 0 | 8.6 | 1 | 0 | 8.6 | 1 |

Fig. 9 shows the ship waterline and the distribution of control points according to the proposed method. The approximation design results of the whole hull lines are given in Table 3, and Table 4 gives the



(a) Perspective view

(b) Front view

Fig.9 Waterline design results and control points distribution

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**Table 3 Design objective, approximate design data and errors of the designed hull lines**

| Waterline height /m | | Forebody $A_{wf}$ /m$^2$ | Forebody $CG_{xf}$ /m | Forebody $CG_{yf}$ /m | Afterbody $A_{wa}$ /m$^2$ | Afterbody $CG_{xa}$ /m | Afterbody $CG_{ya}$ /m |
|---|---|---|---|---|---|---|---|
| 0 | Design objective | 143.331 317 | 22.774 | 2.547 | 140.048 9 | 22.071 | 2.656 |
| | Approximate design data | 143.461 342 | 22.773 | 2.550 | 140.052 | 22.093 | 2.650 |
| | $\|Error\|$ /% | 0.091 | 0.004 | 0.113 | 0.002 | 0.1 | 0.19 |
| 0.5 | Design objective | 202.543 392 | 24.669 | 3.139 | 193.181 8 | 23.585 | 3.245 |
| | Approximate design data | 202.514 694 | 24.601 | 3.154 | 193.531 5 | 23.595 | 3.266 |
| | $\|Error\|$ /% | 0.014 | 0.272 | 0.489 | 0.18 | 0.04 | 0.66 |
| 1 | Design objective | 227.761 633 | 25.501 | 3.356 | 209.356 1 | 23.887 | 3.449 |
| | Approximate design data | 227.855 187 | 25.455 | 3.358 | 209.208 4 | 23.890 | 3.454 |
| | $\|Error\|$ /% | 0.041 | 0.183 | 0.046 | 0.07 | 0.01 | 0.14 |
| 2 | Design objective | 254.651 539 | 26.553 | 3.554 | 224.014 2 | 24.329 | 3.624 |
| | Approximate design data | 255.067 469 | 26.376 | 3.564 | 225.052 7 | 24.351 | 3.610 |
| | $\|Error\|$ /% | 0.163 | 0.666 | 0.290 | 0.46 | 0.09 | 0.39 |
| 3 | Design objective | 202.169 826 | 31.044 | 3.419 | 158.144 3 | 29.42 | 3.442 |
| | Approximate design data | 203.211 047 | 31.022 | 3.452 | 158.061 7 | 29.417 | 3.443 |
| | $\|Error\|$ /% | 0.515 | 0.071 | 0.960 | 0.05 | 0.01 | 0.02 |
| 4 | Design objective | 193.667 993 | 32.434 | 3.448 | 149.284 2 | 31.001 | 3.478 |
| | Approximate design data | 193.600 563 | 32.245 | 3.452 | 149.322 5 | 30.918 | 3.490 |
| | $\|Error\|$ /% | 0.035 | 0.585 | 0.128 | 0.03 | 0.27 | 0.33 |
| 5 | Design objective | 179.187 594 | 32.550 | 3.540 | 151.078 6 | 32.908 | 3.431 |
| | Approximate design data | 179.175 368 | 32.594 | 3.521 | 150.880 9 | 32.865 | 3.440 |
| | $\|Error\|$ /% | 0.007 | 0.136 | 0.539 | 0.13 | 0.13 | 0.27 |
| 6 | Design objective | 171.418 285 | 33.361 | 3.506 | 172.988 189 | 35.939 | 3.351 |
| | Approximate design data | 171.472 260 | 33.341 | 3.511 | 172.987 932 | 35.928 | 3.355 |
| | $\|Error\|$ /% | 0.031 | 0.062 | 0.149 | 0.00 | 0.03 | 0.12 |

**Table 4 Control points and weights of the waterline**

| Waterline height /m | | | Control points and weights | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0 | Forebody | $x$ | 46.175 | 41.575 | 24.842 | 18.917 | 10.2 | 0 |
| | | $y$ | 0.265 | 0.950 | 5.099 | 6.6 | 6.6 | 6.6 |
| | | $\omega$ | 1 | 16.244 2 | 42.998 8 | 4.152 6 | 1 | 1 |
| | Afterbody | $x$ | 40.311 | 34.476 | 31.086 | 19.353 | 10.2 | 0 |
| | | $y$ | 1.006 | 2.752 | 3.765 | 6.6 | 6.6 | 6.6 |
| | | $\omega$ | 1 | 47.842 3 | 21.01 03 | 5.564 | 1 | 1 |
| 0.5 | Forebody | $x$ | 50.524 | 45.355 | 27.806 | 21.868 | 10.2 | 0 |
| | | $y$ | 0.321 | 1.301 | 6.349 | 7.923 | 7.923 | 7.923 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 45.119 | 40.596 | 33.483 | 21.924 | 10.2 | 0 |
| | | $y$ | 0.505 | 1.932 | 5.056 | 7.923 | 7.923 | 7.923 |
| | | $\omega$ | 1 | 23.176 7 | 33.852 4 | 7.392 7 | 1 | 1 |
| 1 | Forebody | $x$ | 51.906 | 49.449 | 32.952 | 24.832 | 10.2 | 0 |
| | | $y$ | 0.321 | 0.864 | 5.629 | 8.332 | 8.332 | 8.332 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 46.348 | 37.270 | 33.755 | 19.019 | 10.2 | 0 |
| | | $y$ | 0.495 | 3.399 | 6.309 | 8.332 | 8.332 | 8.332 |
| | | $\omega$ | 1 | 38.100 3 | 26.036 5 | 19.653 2 | 1 | 1 |
| 2 | Forebody | $x$ | 53.017 | 50.209 | 31.775 | 17.057 | 10.2 | 0 |
| | | $y$ | 0.266 | 1.030 | 8.005 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 48 | 47.823 | 44.151 | 28.688 | 10.2 | 0 |
| | | $y$ | 0.4 | 0.455 | 0.953 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 13.538 4 | 31.350 6 | 8.887 | 1 | 1 |

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**Table 4 (continue)**

| Waterline height /m | | | Control points and weights | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 | Forebody | $x$ | 53.280 | 44.236 | 34.814 | 24.662 | 17.786 | 0 |
| | | $y$ | 0.246 | 3.698 | 6.900 | 8.600 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 47.514 | 43.146 | 32.692 | 21.046 | 19.089 | 0 |
| | | $y$ | 0.015 | 1.794 | 7.669 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 15.116 3 | 37.146 4 | 41.159 9 | 1 | 1 |
| 4 | Forebody | $x$ | 52.954 | 52.061 | 49.354 | 28.506 | 19.652 | 0 |
| | | $y$ | 0.210 | 0.612 | 2.577 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 47.402 | 45.539 | 36.730 | 25.694 | 21.275 | 0 |
| | | $y$ | 0.015 | 0.794 | 6.486 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 44.642 3 | 43.839 9 | 12.647 6 | 1 | 1 |
| 5 | Forebody | $x$ | 51.492 | 48.154 | 38.673 | 28.815 | 21.131 | 0 |
| | | $y$ | 0.212 | 1.974 | 6.287 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 49.714 | 49.708 | 36.819 | 26.510 | 23.008 | 0 |
| | | $y$ | 0.015 | 0.017 | 7.096 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 32.986 3 | 36.840 4 | 14.057 1 | 1 | 1 |
| 6 | Forebody | $x$ | 50.845 | 44.121 | 35.617 | 27.522 | 22.289 | 0 |
| | | $y$ | 0.268 | 4.156 | 7.448 | 8.600 | 8.600 | 8.6 |
| | | $\omega$ | 1 | 29.821 6 | 22.807 4 | 2.495 9 | 1 | 1 |
| | Afterbody | $x$ | 53.752 | 50.878 | 46.074 | 32.243 | 24.366 | 0 |
| | | $y$ | 1.753 | 2.601 | 3.948 | 8.6 | 8.6 | 8.6 |
| | | $\omega$ | 1 | 27.096 6 | 36.207 1 | 8.105 9 | 1 | 1 |

coordinates and the corresponding weights of control points of the whole hull waterline.

Fig. 10 shows the hull surface formed according to the skin of section lines in Fig. 9.

Fig.10 Hull surface

It can be seen from Fig. 10 that the surface obtained by the proposed method is initially fair, and the reason for the slight unfairness is that the values of the shape parameters in the draught function were not coordinated enough. Therefore, in the following research work, how to quickly obtain the coordinated shape parameters or more scientific draught function will be considered.

## 6 Conclusion

By analyzing the shape characteristics of each characteristic curve of the ship, a vertical parameterization self-design method of hull form based on NURBS was proposed. In this method, the NURBS approximation model of lightweight stem and stern contours and waterline was given, and the hull form design was transformed into characteristic parameter design and characteristic curve design with the draught function as the link. This method can use fewer parameters to drive and generate the design hull form. Design examples show that the design method was feasible in the initial design stage. In the follow-up study, it can be considered how to select or improve the evolutionary algorithm in the parameterization design of the ship characteristic curves, so as to improve the design efficiency and stability. The molded line characteristics of each hull form can be summarized to give the regression formula of draught function for ship series, so as to guide the adjustment of the shape of draught function curve.

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# 轻量化NURBS船体曲面自行设计垂向参数化方法

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**摘　要**：[**目的**]当前常规的船体曲面设计局限于现有母型船设计空间，并且不能以足够少的参数驱动生成设计船型。为了解决上述问题，[**方法**]将吃水函数与NURBS方法相结合，提出船舶自行设计垂向参数化方法。以船体水线为基本设计单元，以平底线、设计水线、首尾轮廓线、平边线及最大横剖线为特征约束，以特征参数对应的吃水函数值为设计目标，建立水线逼近模型。可应用进化算法对该逼近模型进行求解，最后通过蒙皮法生成船体曲面。[**结果**]相关特征线的设计实例表明了该方法的实用性和先进性。[**结论**]应用该方法可以通过尽可能少的数据量完成船体曲面设计，且更适用于新船型的自行设计。

**关键词**：NURBS；船体曲面；自行设计；垂向参数化；特征线

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