Journal of
Marine Science and Engineering

MDPI

Article

NURBS-Based Parametric Design for Ship Hull Form

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Abstract: Recently, the NURBS technique has been widely used in the 3D design software for ships. However, in most research, the NURBS technique is only applied to the mathematical representation of hull curves and surfaces, and the parametric deformation of hull surfaces based on geometric feature parameters is less understood. The aims of this paper are to establish the parametric design process of hull surfaces through the classification of geometric feature parameters and the design of feature curves, apply the NURBS technique to the parametric geometric modeling of hull curves and surfaces, and finally achieve the parametric deformation of hull surfaces driven by geometric feature parameters and develop the parametric deformation software. Taking the Series 60 ship as an example, we first analyze the hull geometric features and parameters, then design the longitudinal feature curves and cross-section curves based on the NURBS technique and establish the correlation between them, and finally generate the smooth hull surface by the skinning technique to achieve the parametric geometric deformation of the Series 60 ship. The research in this paper shows that the smoothness of the surfaces generated by the NURBS-based parametric design method is good. Additionally, the extracted feature parameters have a clear geometric meaning and can automatically generate hull forms to meet the design requirements quickly and effectively, which has some practical engineering value.

Keywords: parametric design process; feature parameters; longitudinal feature curves; NURBS technique; cross-section curves; skinning technique

Citation: Zhou, H.; Feng, B.; Liu, Z.; Chang, H.; Cheng, X. NURBS-Based Parametric Design for Ship Hull Form. *J. Mar. Sci. Eng.* **2022**, *10*, 686. https://doi.org/10.3390/jmse10050686

Academic Editors: Michele Viviani, Margareta Lutzhoft and Apsara Abeysiriwardhane

Received: 28 March 2022
Accepted: 15 May 2022
Published: 18 May 2022

1. Introduction

Hull form design is an important part of a ship's overall design, and how to design hull forms with excellent performance quickly and efficiently has been a hot research topic at home and abroad. In recent years, with the rapid development of computer and computational fluid dynamics (CFD), simulation-based design (SBD) hull form optimization has been widely used to develop energy-saving ships. Wu et al. [1], Miao et al. [2], Liu et al. [3], and Nazemian et al. [4] established an integrated CAD/CFD optimization platform to complete the hull form design through simulation-based optimization and obtained ship forms with excellent hydrodynamic performance. The integrated, multidisciplinary hull form optimization platform includes a hull form design module, hydrodynamic performance evaluation module, and optimization module.

As the primary link, the hull form design module plays a crucial role in the whole optimization process and is the basis of subsequent optimization modules. A fast and efficient hull form design method can greatly improve the efficiency and quality of hull form optimization, which is important for research on hull surface expression and modification. At present, hull form design methods are divided into two main categories [5,6].

The first category is based on changing the control point or offset point coordinates to achieve modification of the hull surface, mainly including morphing, hull surface modification based on radial basis function (RBF) interpolation, and free form deformation

(FFD). The morphing method [7] is used to interpolate a number of similar parent ships within the surface by adjusting the morphing coefficients, which in turn generates smooth new ship forms. Feng et al. [8] used the morphing method to optimize the bulbous bow section of a 1300 TEU container ship. This method can ensure the generation of smooth new ship forms under the premise of smooth parent ships and is suitable for local deformation. The disadvantage is that it relies more on the parent ship in order to generate new ship forms that meet the design requirements. Hull surface modification based on RBF interpolation modifies the coordinates of points on the hull surface to generate new ship forms. Shen [9] focused on this modification method in his paper and selected the control points of the NURBS surface of the hull as design variables and modified the hull surface by changing the values of these variables. Chai et al. [10] proposed a new modification method based on hull surface offset points based on Shen's work and successfully applied it to the optimal design of DTMB5415. The advantage of this method is that it is efficient and suitable for modification of local surfaces. The disadvantage is that the selected coordinate points have no specific geometric meaning and more control or offset points need to be selected to achieve modification of the whole ship. FFD is a freeform deformation method based on a mesh that is more flexible and allows one to choose the number of design variables according to the design requirements, and it has been widely used in recent years. Coppedé et al. [11] proposed a combined approach for hull shape modeling and variation, which is based on a combination of the Subdivision Surface technique for hull surface modeling and Free Form Deformation for shape variation. Vernengo et al. [12] focus on the comparison of two different approaches to handle hull shape variations, namely the fully parametric model and a non-parametric method relying on the free form deformation technique. Liu et al. [13] accomplished the local deformation of the bow, waterline, and transom with the free-form deformation (FFD) method. Li et al. [14] also completed the optimization of ship resistance based on the FFD method for geometric modification of the 6600 DWT bulk carrier hull. Although the above surface modification methods based on changing control or offset points can obtain new ship types in most cases, due to the limitation of modification, only the control or offset points can be deformed, and the selected points have no specific geometric meaning and often do not better meet specific design requirements.

The second category is parametric design, in which a set of ship hull form feature parameters (such as principal dimension, bow, and stern parameters) with clear geometric meaning are proposed to control the deformation of the hull surface and generate a series of ship forms that satisfy specific constraints (such as area, centroid of area, curvature and slope of the starting and ending points of the curve, etc.). The advantage of parametric representation of a ship is that each control parameter has a clear geometric meaning and can be defined flexibly, which can play a role in the overall and local deformation of the hull; it can also be better adapted to the variability of ship owners and the complexity of hull forms. Parametric ship design began in the 1970s, when Kuiper [15] expressed the surface of the hull mathematically, which was already different from the traditional method of going through offset points to molded lines to surfaces. By the 1990s, research on the parametric design of hull forms was more intensive. Harries [16,17] proposed a new method and independently designed the F-spline curve and developed the corresponding design module, CAESES, which is based entirely on the given form parameters of ships; this module achieves the goal of feature parameter-driven hull deformation and can be applied to optimize the hydrodynamic performance of the hull form. Based on Harries's method, Kim et al. [18] proposed a parameterized design method for complex ship forms based on Boolean operations. Additionally, many other scholars use NURBS or B-splines to design the hull parametrically. Peng [19] carried out a parametric study of the ball head part based on the secondary development function of CATIA, but the combination of mathematical expressions was used to fit the cross-section curves of the bulb, which has great limitations. Similar to Peng's work, Xu [20] achieved the function of automatic generation of twin skeg by using the mother ship modification method in ship design.

Lu [21] used a single NURBS function to express the hull surface and used it as a basis to investigate the key issues in the design of the ship but did not achieve the parametric deformation of the hull. Different from the research by Peng, Xu, and some other scholars, Birk et al. [22] proposed the automated differentiation method in the form parameter design driven by B-spline curves to ensure that the resulting curves are fair. Zhang [23,24] considered the parameters of bulbous bow and stern, adopted the centroid of the area between section and design waterline as the characteristic parameter, and discussed the maximum curvature points. Zhang [25] applied a new method of a parametric design B-splines curve based on the cubic B-splines to establish a parametric model of a simple high-speed ship. Pérez-Arribas [26–28] presented a practical method for defining a planning hull based on geometric parameters including position, slope, enclosed area, and centroid with B-spline curves and surfaces. Nam et al. [29] used the NURBS technique to design the hull surface according to the given principal dimension of the hull and other parameters. Nam [30] also constructed an intermediate curve represented by NURBS to satisfy the given geometric requirements with respect to the hull characteristic line. Sariöz [31] also studied the parametric representation of ships by the B-spline technique. The above scholars have addressed the issue of dealing with curve fairing in their research. In order to improve the calculation accuracy, Wang et al. [32] introduced the NURBS method to molding the hull surface and obtained the relative ideal results. Xing et al. [33] considered a parametric model for the catamaran's innovative transom stern and finished the local optimization of the stern area and of the propulsive efficiency of a battery-driven, fast catamaran vessel.

There are some other approaches to shape hull modeling and variation based on Reduced Order Models and other mathematical formulations. Demo, N. et al. [34] proposed a self-learning geometrical deformation technique, where different morphing methods are coupled together to propagate surface deformations to volumetric meshes. Villa, D. et al. [35] propose a study to highlight the pro and cons of the application of space reduction techniques, to create a parametric model for both global and local hull shape variations. Villa, D. [36] also proposed a method for the morphing of surface/volume meshes suitable to be used in hydrodynamic shape optimization. Serani et al. [37] presented a multi-objective hull-form optimization method to achieve high-fidelity simulation-based design optimization (SBDO) solutions.

The key work and contributions of this paper are as follows. (1) For complex geometric feature parameters of ships, a classification method is proposed to control hull curves globally and locally, respectively. Longitudinal feature curves and cross-section curves are designed according to this method, and the correlation between them is established. (2) A NURBS-based parametric modeling process for ship hull form is established, and the establishment of a parametric geometric model of a ship is completed with a Series 60 ship as an example. (3) Parametric modeling software for ship models is developed to achieve parametric deformation of hull surfaces driven by feature parameters, and a series of ship models meeting design requirements can be obtained quickly and effectively.

The organizational framework of this paper is as follows. Section 1 introduces the basic materials and methods, such as principles of NURBS, the parametric design process, and the parametric modeling software for modeling of the ship based on the NURBS technique. Section 2 introduces the full parametric modeling process of the Series 60 ship. Section 3 describes an example of Series 60 parametric generation, which further verifies the feasibility of the design method. Section 4 summarizes the work of this paper and suggests future research work.

2. Materials and Methods

Non-uniform rational B-spline curve (NURBS) is a method of designing curves and surfaces that is used for complex problems of surface modeling.

2.1. NURBS Curve

A NURBS curve of the pth degree can be described as a segmented rational polynomial vector function, which is represented as follows:

$$\vec{C}(u) = \frac{\sum_{i=0}^{n} \omega_i \vec{P}_i N_{i,p}(u)}{\sum_{i=0}^{n} \omega_i N_{i,p}(u)} \tag{1}$$

where $\omega_i(0 \leq i \leq n)$ represents the weight factors associated with the control point columns $p_i(0 \leq i \leq n)$ (forming the control polygon), and $N_{i,p}(u)$ is a canonical B-spline basis function of the pth degree defined on the non-periodic non-uniform node vector $\{0, \cdots, 0, u_{p+1}, \cdots, u_n, 1, \cdots, 1\}$. The specific properties of NURBS curves are described in the literature [24].

2.2. NURBS Surface

NURBS curves are defined by a single parameter in one direction, while NURBS surfaces are complex spatial surfaces with bi-directional curvature. NURBS surfaces with way u by v and degree p by q are schematically represented as follows:

$$S(u,v) = \frac{\sum_{i=0}^{n} \sum_{j=0}^{m} \omega_{i,j} P_{i,j} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{n} \sum_{j=0}^{m} \omega_{i,j} N_{i,p}(u) N_{j,q}(v)} \tag{2}$$

where the control vertices $P_{i,j}(0 \leq i \leq n; 0 \leq j \leq m)$ are in a topological complementary rectangular matrix forming a control grid, $\omega_{i,j}$ is the corresponding weight factor, and $N_{i,p}(u)(0 \leq i \leq n)$ and $N_{j,q}(u)(0 \leq j \leq m)$ are B-sample basis functions with degree p and q defined on node vectors $U = \{u_0, \cdots, u_{n+p+1}\}$ and $V = \{v_0, \cdots, v_{m+q+1}\}$, respectively.

2.3. NURBS Representation of Combined Curves

The molded lines of a ship are not single curves, but usually a combination of straight lines, quadratic curves, and free-form curves. Therefore, it is impractical to express complete molded lines directly with a single NURBS curve. How to form smooth molded lines from multiple curves is one of the key issues. Before the advent of NURBS, it was very difficult to achieve combinations of curves. Due to the excellent features and the introduction of weights, NURBS can be well adapted to the problem of splicing different free-form, straight, and quadratic curves in CAD.

Suppose there are $n + 1$ curves, $C_i(0 \leq i \leq n)$, connected at the beginning and end, and they can be connected into a smooth or folded curve according to the basic algorithms of NURBS, such as step-up and interpolation. The basic process is shown in Figure 1.

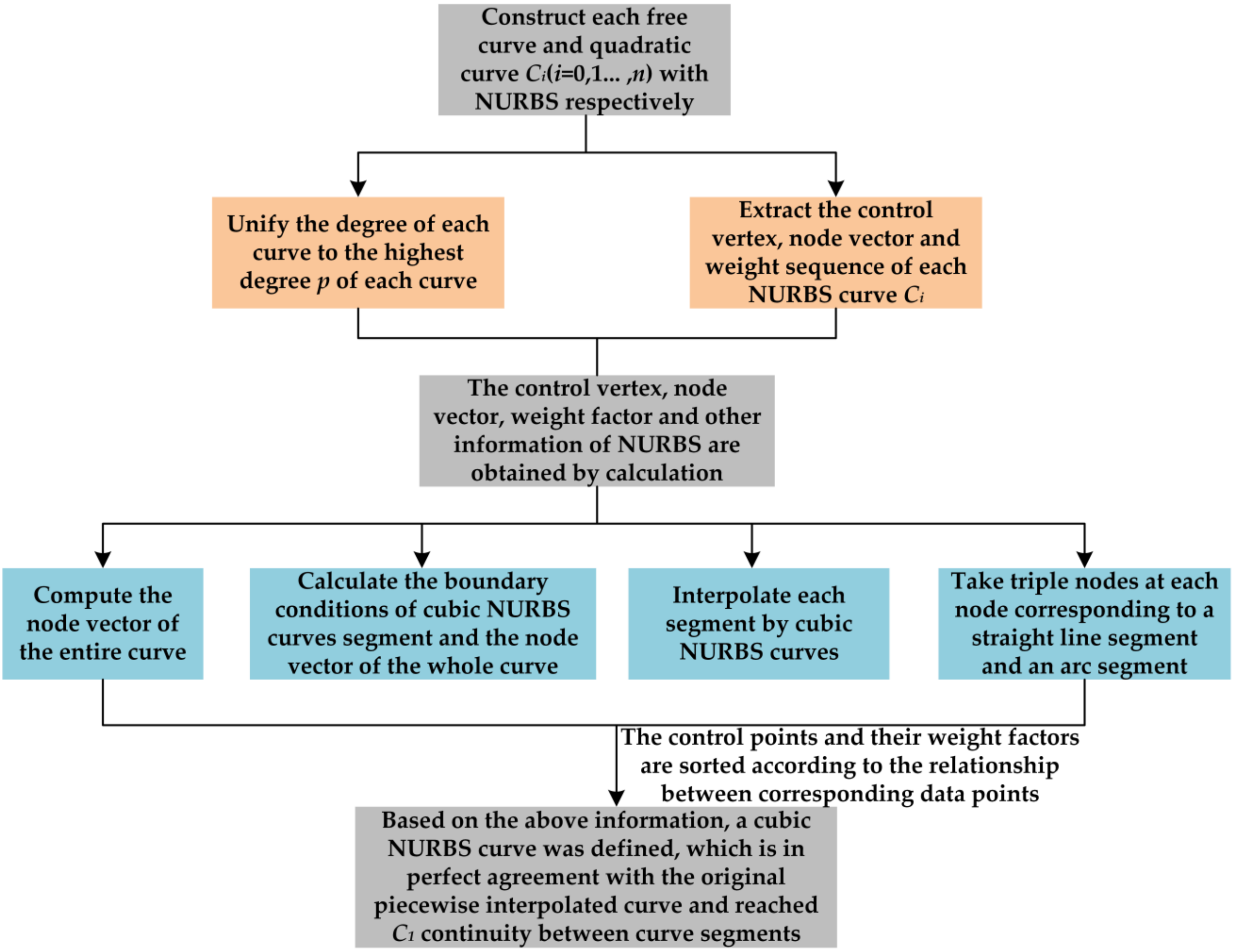

Figure 1. Basic flow of NURBS to express combinatorial curves.

2.4. Parametric Ship Design Process

Based on the idea of geometric parameterization, we can quickly develop smooth hull forms based on the feature parameters and curves and closely link the hull surface with them; thus, transforming the ship design into a reasonable design of the feature parameters and curves. With the feature parameters, longitudinal feature curves are generated based on the NURBS technique, which, in turn, generates a set of cross-section curves and finally obtains the hull surface. The specific steps are as follows.

First, the geometric feature parameters are determined according to the characteristics of the ship by the designer according to specific design requirements, which directly determine the shape of longitudinal feature curves, boundary curves, and cross-section curves of the designed ship, and finally the shape of the hull surface, which is very important in the ship design. Here, the feature parameters are divided into three categories. The first category is the principal particulars, including parameters such as length between perpendiculars, molded depth, and design draft, which are used to express the general shape of the ship. The second category includes local feature parameters that affect the generation of longitudinal feature curves and boundary curves, including coordinates and angles at a fixed position, which only affect the local shape of curves. The third category is the feature parameters required for defining the cross-section curves, which determine the coordinates, slope, curvature, and other geometric characteristics of the starting and ending points of the curve. These parameters can be fixed or changed in the captain's direction. The designer can decide whether the third category of parameters needs to be controlled by the longitudinal feature curves according to the design requirements, i.e., this category determines whether these curves are generated. If additional longitudinal feature curves are required for control, it determines the specific values of the third category parameters at different X positions.

Then, the ship is viewed as a whole, and reasonable and smooth longitudinal feature curves are designed. When designing the longitudinal feature curves, the global shape is first determined based on the first category of parameters, such as dividing the ship into sections (e.g., run, entrance, and parallel middle body sections) according to the features of the ship, then the curves satisfying the second group of parameters are designed for each section. Since the longitudinal feature curves are those necessary to generate the cross-section curves and hull surface, they involve the position integral, integral characteristic, and differential characteristic of the cross-section curves, and their design is directly related to the quality of the hull surface. Therefore, the design of longitudinal feature curves is the key link in the whole parametric design process of the hull form.

Then, sufficient cross-section curves are generated from the longitudinal feature curves. Before generating the set of cross-section curves, their shape needs to be defined, and this process covers the third category of parameters, whose final shape is closely related to the features of the ship characteristics. By defining the appropriate cross-section curve shape for different ship types, the parameterized deformation of the hull surface can be better controlled. Based on the shapes of the established longitudinal feature curves and cross-section curves, a set of cross-section curves is generated along the captain's direction using some rules, as shown in Figure 2.

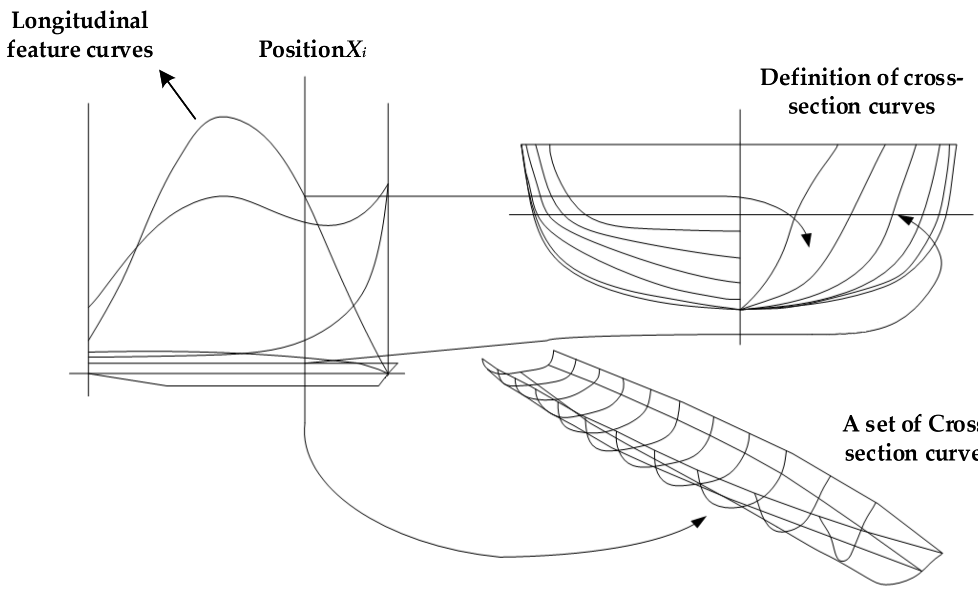

Figure 2. Definition of rules in the parametric ship design process.

The last step is to generate a smooth hull surface based on these cross-section curves by interpolation the design using the skinning technique; then, the feature parameters are associated with the hull surface, which realizes the purpose of driving the hull surface deformation directly with the feature parameters.

The whole flow of the parametric design for the hull form is shown in Figure 3, where the hull surface is expressed in terms of form parameters through which a set of longitudinal feature curves can be obtained, and these curves contain all the shape feature information that each station cross-section curve has; thus linking the hull surface with the feature parameters and curves.

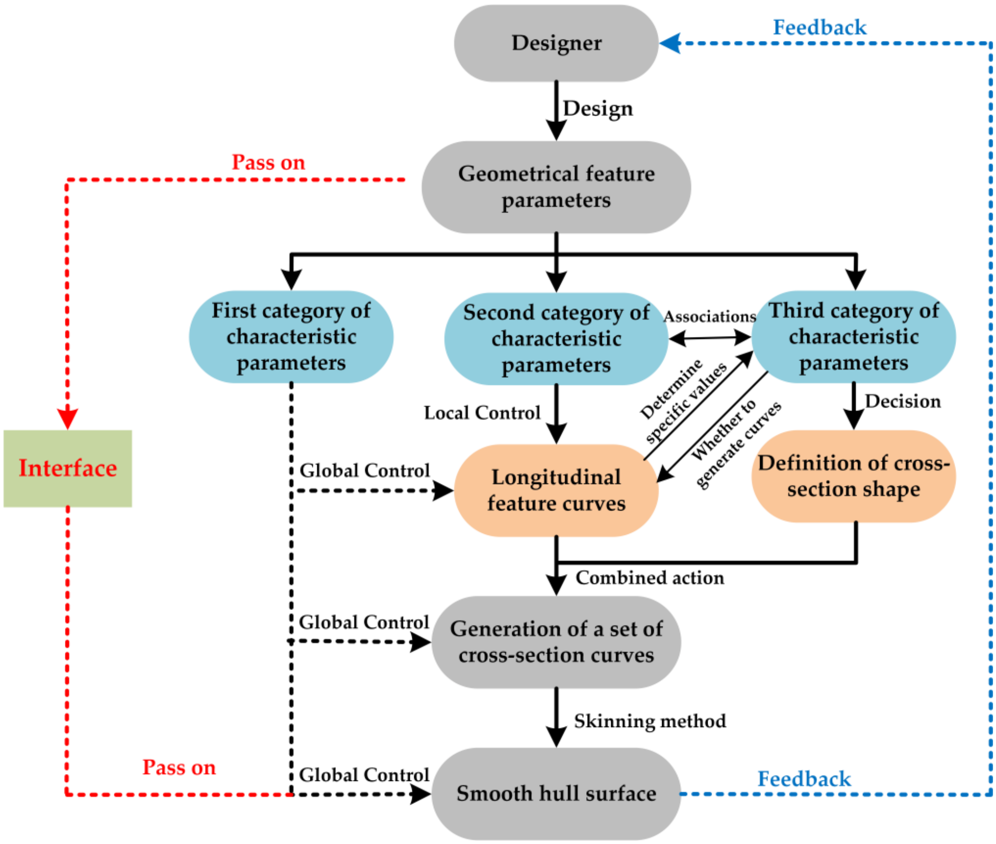

Figure 3. Parametric ship design process.

2.5. Parametric Modeling Software for Ship Models Based on NURBS Technique

Based on the NURBS technique and ship parametric design process, the parametric modeling software for ship models is developed to achieve the parametric deformation of the hull surface driven by feature parameters, which can quickly obtain a series of ship models to meet the design requirements. The software interface is shown in Figure 4.

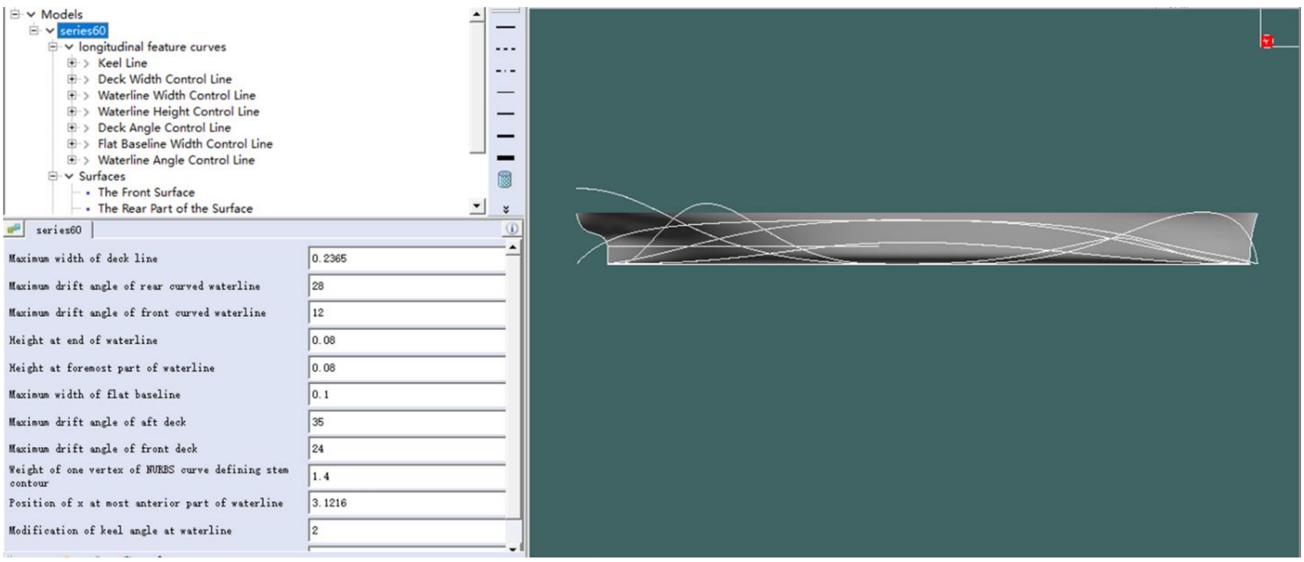

Figure 4. The interface of parametric modeling software for ship models.

3. Parametric Modeling of Series 60 Ship

In this paper, Series 60 is selected as a representative ship model to verify the feasibility of the NURBS-based parametric design method for the hull form. The model is based on the standard Series 60 model of the Iowa Institute of Hydraulic Research (IIHR), which is a typical cargo ship without a bulbous bow that is recognized as a standard ship form by ITTC. The parametric model in this research basically retains the geometric hull form features of the standard Series 60 model, and the principal dimensions of the original parametric ship model are consistent with the standard model (Table 1).

Table 1. Principal dimensions of the standard Series 60 model.

Explanation	Name	Value
Length between perpendiculars	L_{pp}	3.048 m
Beam overall	B_{OA}	0.406 m
Design draft	T_0	0.163 m
Length on waterline	L_{wl}	3.099 m
Depth	D	0.2365 m

3.1. Extraction of Feature Parameters

To create a parametric model of the Series 60, the designer first needs to analyze its features and then design a number of geometrically significant feature parameters based on the experience and classify them. The classification of the feature parameters and the name and meaning of each one are provided in Table 2. The parameters controlling the deformation of the Series 60 ship include length, width, height, angle, and weight factors. These feature parameters can be used as variables to control the deformation of the ship, or as constraints to assist in the geometric design.

The first category of feature parameters covers the global control of the Series 60 ship form, including L_{pp}, T_0, B_{OA} (or B_{d1}), and D, which roughly specify the length between perpendiculars, draft, and molded width and depth, respectively, but cannot control local details.

The first role of the second category of feature parameters is to define the position (x, y, and z directions) and slope control curves of the hull boundary curves (such as deck line, keel line, flat-bottomed line, etc.), which define the basic geometric features of the hull surface; the other role is to influence the local shape of the longitudinal feature curves. According to the features of the Series 60 ship, the boundary curves are divided into deck line, waterline, flat-bottomed line, and keel line, as shown by the blue solid lines in Figure 5. The red points in the figure are the constraint points at specific locations on the boundary curves, which can constrain the dimensions of the ship model in the length, width, and height directions as a whole. These parameters can show the hull geometry well and can be used as design variables to control the deformation of the hull during modeling, or as boundary or control curves for parameter constraints to assist the design. The meanings of the shapes shown in Figure 5 are provided in Table 2.

In the length direction, L_{d0} and L_{d1} are the x-coordinates of the front end of the deck line and the point at the maximum breadth amidships, respectively, and the x-coordinate of the rear end point is always 0; L_{c0} and L_{c2} are the x-coordinates of the front and rear end of the waterline, respectively. Finally, L_0, L_1, and L_2 are the x-coordinates of the front end point, the point at the maximum width, and the rear end point of the flat-bottomed line, respectively. In the width direction, the first and last ends of the deck line, waterline, and flat-bottomed line intersect with the mid-longitudinal section, so the y-coordinate of each one is 0. The waterline and deck line have equal width, represented by B_{d1} amidships; parameter B_1 is the maximum breadth of the flat-bottomed line amidships. Similarly, in the height direction, since the flat-bottomed line is located on the baseline, its z-coordinate is 0, which is a fixed value; the heights of the head and tail ends of the waterline are expressed by H_{c0} and H_{c2}, respectively, while the height of the deck line is expressed by H_d.

Table 2. Feature parameter codes and meanings.

Category		Explanation
First category of feature parameters	L_{pp}	Length between perpendiculars
	T_0	Design draft
	B_{d1}	Maximum width of deck line, same as B_{OA}
	H_d	Height of deck line, same as D
Second category of feature parameters	L_{d0}	Position of most forward x of deck line
	L_{d1}	Position of x at maximum width of deck line
	L_{c2}	Position of x at end of waterline
	L_{c0}	Position of x at most anterior part of waterline
	L_0	Ordinate at which keel line at front of ship intersects baseline
	L_1	x position at maximum width of flat-bottomed line
	L_2	Ordinate of point where keel line at rear of ship intersects baseline
	B_1	Maximum width of flat baseline
	H_{c2}	Height at end of waterline
	H_{c0}	Height at foremost part of waterline
	β_d	Angle at transom of deck line in plan view
	γ_d	Angle at foremost point of deck line in plan view
	δ_b	Maximum drift angle of aft deck
	δ_f	Maximum drift angle of front deck
	α_b	Maximum drift angle of rear curved waterline
	α_f	Maximum drift angle of front curved waterline
	θ_c	Modification of keel angle at waterline
	θ_d	angle of keel at the deck
	W_k	Weight of one vertex of NURBS curve defining stem contour, influencing stem's sharpness
Third category of feature parameters	W_1	Weight factor of point P_1 in cross-section line, influencing lower section's sharpness
	W_2	Weight factor of point P_3 in cross-section line, influencing upper section's sharpness
	W_3	Weight factor of point P_4 in cross-section line, influencing upper section's sharpness
	α	Tangential angle of waterline on cross-section curve
	δ	Tangential angle of deck on cross-section curve
	deck_y	Deck width on cross-section curve
	waterl_y	Width of waterline on cross-section curve
	fob_y	Width of flat-bottomed line on cross-section curve
	deck_z	Deck height on cross-section curve
	waterl_z	Height of waterline on cross-section curve
	keel_z	Height of keel line on cross-section curve

In addition to the three parameters of length, width, and height, there are also control parameters of angle and weight factors. The angle is introduced in three views: section, profile, and plan view. Here, the angle between the tangent line of the cross-section curves at the deck and the waterline and the z-axis is controlled by the longitudinal feature curves. The curves are designed as the front and rear parts, and their maximum values in the front and rear parts of the hull are taken as the feature parameters (the specific values are designed when generating the longitudinal feature curves), which are denoted as α_b, α_f, and δ_b, δ_f (the same geometric meanings as α and δ in Figure 6, where they are indicated as the maximum values). Figure 5c shows the keel line diagram of the bow of the hull in the profile view (xz plane), where θ_c and θ_d are the angles between the tangent lines (dashed lines) of the keel line at P_c and P_d, respectively, and the z-axis. Figure 5b shows the main boundary curve diagram in the xy plane, where β_d and γ_d represent the angles between tangent lines at points of the head and tail ends of the deck line and the x-axis, respectively, and are mainly used to change the shape of the deck line. The tangential angle at points of the head and tail ends of the flat-bottomed line in the figure are always 0 with respect to the x-axis, while the shape of the waterline is jointly determined by several parameters, and the tangential angle is not taken as a parameter here. The weighting factor of point P_k in Figure 5c is denoted as W_k.

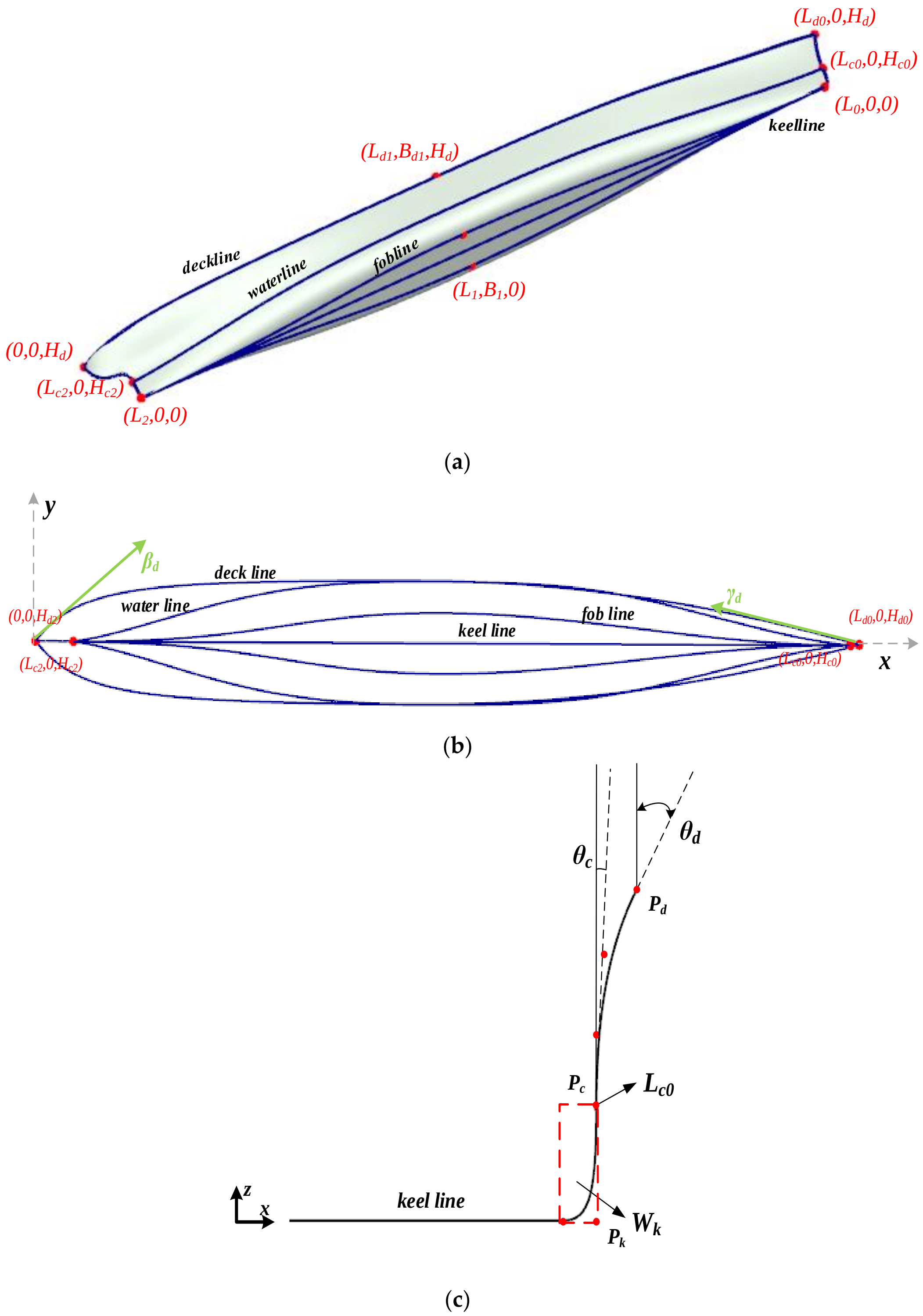

Figure 5. Geometric meanings of the second category of feature parameters. (**a**): parameters of the point positions of the ship; (**b**): parameters in the *xy* plane. (**c**): parameters in the *xz* plane.

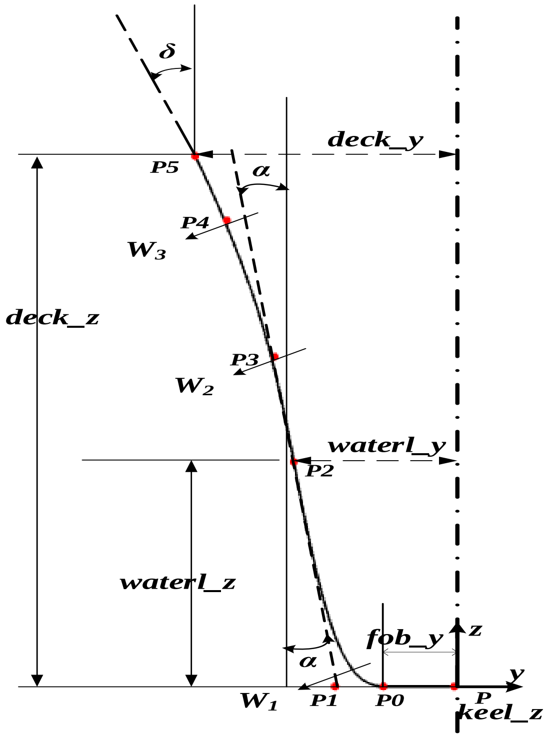

Figure 6. Geometric significance of the third category of characteristic parameters.

The parameters in the third category are used to control the shape of the cross-section curves. Figure 6 shows a schematic diagram of the cross-section curve at a certain point of the hull (the modeling principle of this curve is described in later sections, and only the meaning of the feature parameters is introduced here). α is the angle between the tangent line (dashed line) and the z-axis at point P_2 of this cross-section curve and δ is the angle between the tangent line and the z-axis at point P_5 of the curve. *deck_y* and *deck_z* are the width and height of the deck on this cross-section curve, i.e., the y- and z-coordinates at point P_5; similarly, *waterl_y* and *waterl_z* are the width and height corresponding to the waterline, i.e., the y- and z-coordinates at point P_2; *fob_y* is the width of the flat-bottomed line and *keel_z* is the height of the keel line. Weighting factor w can control the shape of the curves and is introduced in the cross-section curve building section. The weight factors of points P_1, P_3, and P_4 in Figure 6 are denoted as W_1, W_2, and W_3, respectively.

3.2. Generation of Longitudinal Feature Curves

Among the feature parameters described above, some have a specific value that does not change with the change in X_i position in the captain's direction, including parameters in the first and second categories such as L_{d0}, B_{d1}, H_d, etc. Some parameters do not have a fixed value and take different values at different x positions in the captain's direction, including parameters in the third category, such as the α and δ angles of cross-section curves, and the width and height of boundary curves, such as flat-bottomed line and deck line. These parameters should be established in the longitudinal direction corresponding to the smooth NURBS curves to control their values with the X_i position change in the captain's direction; usually these kinds of curves are called longitudinal feature curves. Based on the third category of feature parameters given in Table 2, theoretically, 11 longitudinal feature curves need to be designed to control the variation in these parameters. Among them, the weight factor can be varied or fixed relative to the ship's captain; it is taken as fixed here, so only 8 longitudinal feature curves need to be designed to control the generation of the cross-section curves. The purpose of this research was to design a ship independently according to the designer's needs while ensuring the overall features of the Series 60 ship.

Since the parametric hull form is closely related to the feature parameters and curves, the design of feature curves is crucial.

Figure 7 shows a schematic diagram of the designed longitudinal feature curves. As can be seen from the figure, for the deck width and waterline width control lines, their values are designed to be equal in the middle region of the Series 60 hull, and together with the flat-bottomed line width control line, they reach maximum values B_{d1} and B_1 at L_{d1} and L_1, respectively. As they continue to extend toward the head and tail ends, their values decrease, and eventually both the deck and waterline width drop to 0 at the bow L_0 and stern L_2, and similarly the flat-bottomed line width control line drops to 0 at the first area L_0 and the last area L_2. The height of the deck is controlled by the deck height control line. The waterline height control line is divided into two parts that control the change in waterline height values; a boundary curve, the keel line height control line, is designed to control the change in keel line height, and the specific shape is shown in Figure 7. For the angle control line, the values of angles α and δ are set to 0 amidships, where angle δ increases continuously toward the stern until it reaches the maximum value δ_b at the stern end, with a trend of increasing and then decreasing in the direction of the bow, reaching the maximum value δ_f at X_i = 2.9 m. The angle increases and then decreases in both directions of bow and stern, and reaches the maximum values α_b, α_f at X_i = 0.6 and 2.52 m. The distribution and variation in these longitudinal feature curves are illustrated in Figure 7.

Figure 7 shows a schematic diagram of longitudinal feature curves in the xz plane. Due to the large magnitude of various angular values, they are reduced by 100 times to be displayed in the xz plane; meanwhile, the control lines in the width direction are in the yz plane, and for display convenience, are rotated 90° around the x-axis so that they are in the xz plane and displayed together with the other control lines. These longitudinal feature curves are created based on the NURBS technique, and each curve is selected with a suitable number of points for control. To better illustrate the curve creation process, the flat-bottomed line width control line is taken as an example.

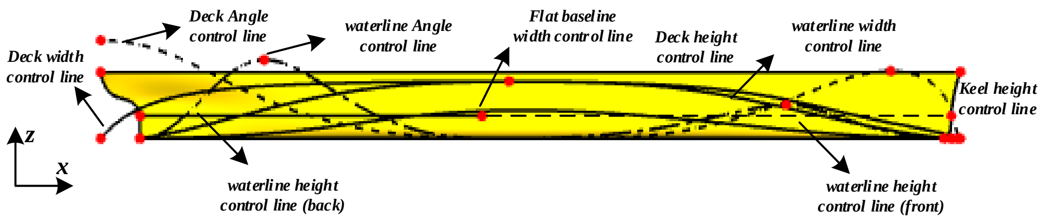

Figure 7. Schematic diagram of longitudinal feature curve of Series 60 vessel. Solid, dashed, and dash-dot black lines are individual longitudinal feature curves, and red points are the corresponding end points or maximum points of feature curves.

Figure 8 shows a schematic diagram of the flat-bottomed line width control feature curve, which consists of two-part back and front curves; both are cubic NURBS curves with four control points and the weight factors of the middle control points are 1.4 and 1.2, calculated by Equation (3), and finally the two curves are connected smoothly by the NURBS expression combination curve technique.

$$\vec{C}_3(u) = \frac{\sum_{i=0}^{3} \omega_i \vec{P}_i N_{i,3}(u)}{\sum_{i=0}^{3} \omega_i N_{i,3}(u)} = \frac{\vec{P}_0 N_{0,3}(u) + 1.4 \cdot \vec{P}_1 N_{1,3}(u) + 1.2 \cdot \vec{P}_2 N_{2,3}(u) + \vec{P}_3 N_{3,3}(u)}{N_{0,3}(u) + 1.4 \cdot N_{1,3}(u) + 1.2 \cdot N_{2,3}(u) + N_{3,3}(u)} \quad (3)$$

In the same way, other feature curves can be designed, which is not described here. The longitudinal feature curves determine the specific values of various parameters in different cross-sections, which in turn determine the specific shapes of the cross-section curves and play a crucial role in the generation and deformation of the hull surface.

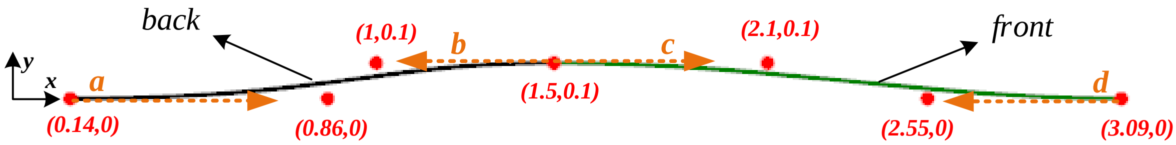

Figure 8. Schematic diagram of the width control feature curve of the flat-bottomed line.

3.3. Definition of Cross-Section Shape

After the longitudinal feature curves are created, the next step is to create the typical shape of the cross-section curve needed for the parametric ship model. Based on the third category of feature parameters obtained in the previous analysis, the cross-section curve is divided into three parts: between the deck line and the waterline (upper curve), between the waterline and the flat-bottomed line (middle curve), and from the flat-bottomed line to the keel line (lower curve). At different x-positions, although its shape varies, the cross-section curve at each stop intersects the boundary curves (deck line, water line, flat-bottomed line, keel line), i.e., the starting and ending positions of the three parts of the curve are uniquely determined for the cross-section curve at the determined x-position. Therefore, the first step is to determine the intersection points of the corresponding cross-section curves with boundary curves on the different X-planes, X_i, i = 1, q, of the captain's range, and then determine the coordinate information of each control point.

Cross-section curves are also NURBS curves in nature, and they differ from longitudinal feature curves in that they require special definitions. The cross-section curves of the hull can be convex, concave, or straight, and they have different shapes at different positions in the direction of the length and depth of the ship. For example, part of the cross-section curve in the parallel middle body of a bulk carrier is straight, while in the bulbous bow part, it is convex outward. At the invisible bulbous bow, part of the cross-section line is concave inward. Similarly, the shape of the cross-section curves in the z-direction of the parallel middle body part of the bulk carrier not only is straight, but the curve in the bilge keel part is outwardly convex. Clearly, different types of ships have different shapes of cross-section curves, and we need to control the curves to be convex, concave, or straight according to the design requirements.

According to the features of the Series 60, the hull form of the whole ship from the stern to the bow has similar features. Here, a typical shape of cross-section curve is chosen to express the hull surface, which has a general shape as follows: the first part of the curve is concave, the second part is convex, and the third part is straight. Therefore, a set of q cross-section curves is defined according to this feature. In order to ensure smooth connection of each section of the curve, the cross-section part above and below the waterline is controlled by the third NURBS curve with four control points and the second NURBS curve with three control points, respectively. The third part of the straight-line section is controlled by the primary NURBS curve with two control points. The general form of the NURBS curve of the pth degree with n + 1 control points is shown as follows:

$$\vec{C}(u) = \frac{\omega_0 \vec{P}_0 N_{0,p}(u) + \omega_1 \vec{P}_1 N_{1,p}(u) + \ldots + \omega_n \vec{P}_n N_{n,p}(u)}{\omega_0 N_{0,p}(u) + \omega_1 N_{1,p}(u) + \ldots + \omega_n N_{n,p}(u)} \tag{4}$$

(1) Definition of the lower curve

This part of the curve is a primary NURBS curve with two control points, with the following equation:

$$\vec{C}_1(u) = \frac{\omega_0 \vec{P}_0 N_{0,p}(u) + \omega_1 \vec{P}_1 N_{1,p}(u)}{\omega_0 N_{0,p}(u) + \omega_1 N_{1,p}(u)}, \ Where\ \omega_0 = \omega_1 = 1 \tag{5}$$

The starting point, $V_0(YV_0,ZV_0)$, and ending point, $V_2(YV_2,ZV_2)$, of this primary (second-order) NURBS curve are the intersection of the cross-section curve with the keel line and the waterline, respectively, as shown in Figure 9.

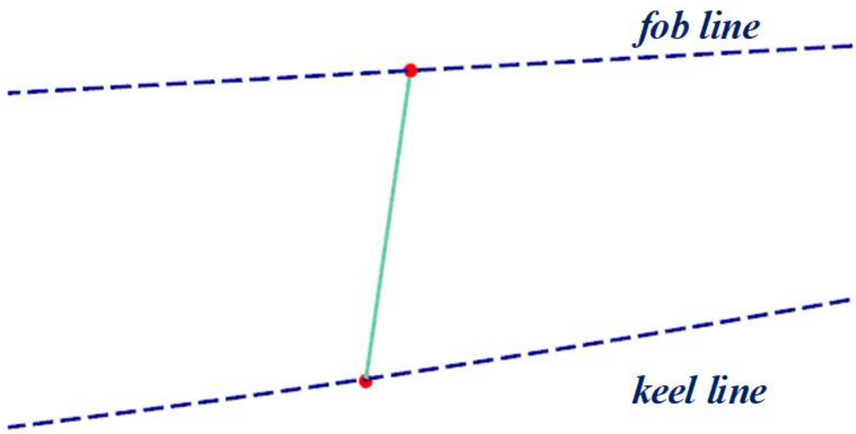

Figure 9. Definition of stations: straight curves.

(2) Definition of the middle curve

Next, the establishment of the second part of the curve is introduced. This part of the curve is controlled by a quadratic NURBS curve with three control points, and the formula is as follows:

$$\vec{C}(u) = \frac{\sum_{i=0}^{2} \omega_i \vec{P}_i N_{i,2}(u)}{\sum_{i=0}^{2} \omega_i N_{i,2}(u)}, \ Where\ \omega_0 = \omega_2 = 1; \omega_1 = W_1 \quad (6)$$

The starting point, $P_0(YP_0,ZP_0)$, and ending point, $P_2(YP_2,ZP_2)$, of the curve are the intersection points of the cross-section curve with the flat-bottomed line and waterline, respectively. For a certain cross-section, the positions of P_0 and P_2 are uniquely determined, so the degree of concavity and convexity of the curve can only be controlled by the intermediate point P_1. Figure 10a shows the relative positional relationship between the second part of the curve and the waterline and flat-bottomed line in space; Figure 10b shows the shape of the curve on the X-plane. Among them, points P_0 and P_1 are both on the base plane, and the z-coordinates ZP_0 and ZP_1 are both 0. Since P_0 and P_2 are the intersections of the curves, YP_0, YP_2, and ZP_2 are also determined. Then, we determine the y coordinate of P_1 to determine the shape of the curve. The coordinates of point P_1 are determined by the following relation:

$$P_1 = (X_i, YP_2 - (ZP_2 - ZP_0) \cdot tg\alpha, 0), ZP_0 = 0 \quad (7)$$

Among them, α represents the angle between the tangent line at the point P_2 of the middle curve and the z-axis, which can be used as a parameter to control the deformation of the curve; angle β between the curve at point P_0 and the y-axis is 0, so the Z-coordinate of P_1 is always 0. The middle curve is located in the middle of the three-segment curve, the lower part is connected with the straight line, and the upper part is connected with the cubic NURBS curve, so ensuring the smoothness of the connection is a key issue. Introducing the angle between the end point of the curve and the coordinate axis solves this problem very well. By establishing the relational Formula (7), angles α and β are related to intermediate control point P_1 of the NURBS curve. Additionally, the coordinates of the control points of the connected curves at both ends can be changed by changing the value of the angles, to finally realize the smooth connection of the curves at both ends.

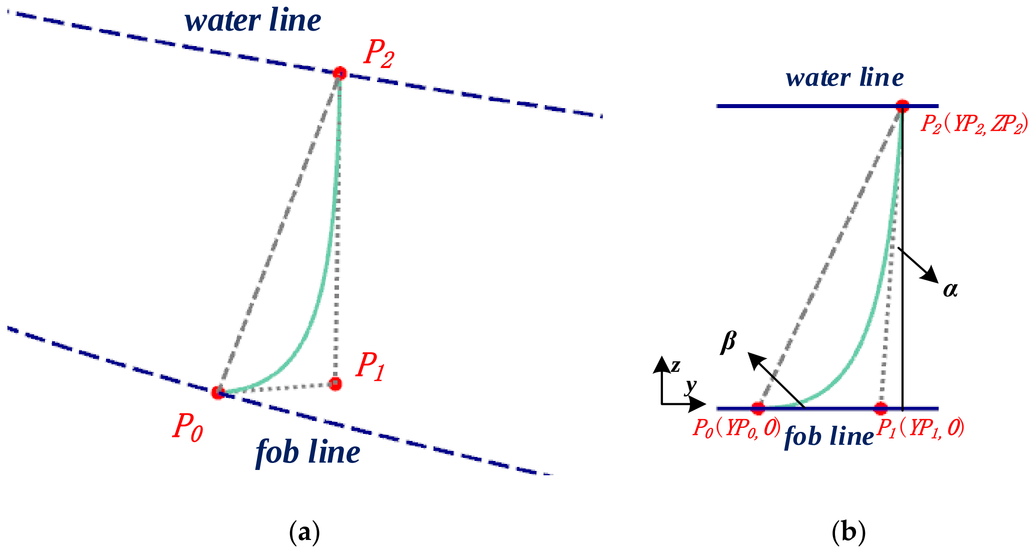

Figure 10. Schematic diagram of middle curve. (**a**): spatial position relationship; (**b**): shape of curve on the X-plane.

In addition, weight factor w of the intermediate point P_1 can also control the shape of the curve. Figure 11 shows the shape change in the curve when weight factor w changes from 1.1 to 1.5. This indicates that the smaller the weight factor, the smaller the degree of convexity of the curve, and the larger the weight factor, the greater the degree of convexity. Therefore, by introducing weight factor w of P_1, a richer curve shape can be obtained. Here, the weight factor of P_1 is denoted as parameter W_1.

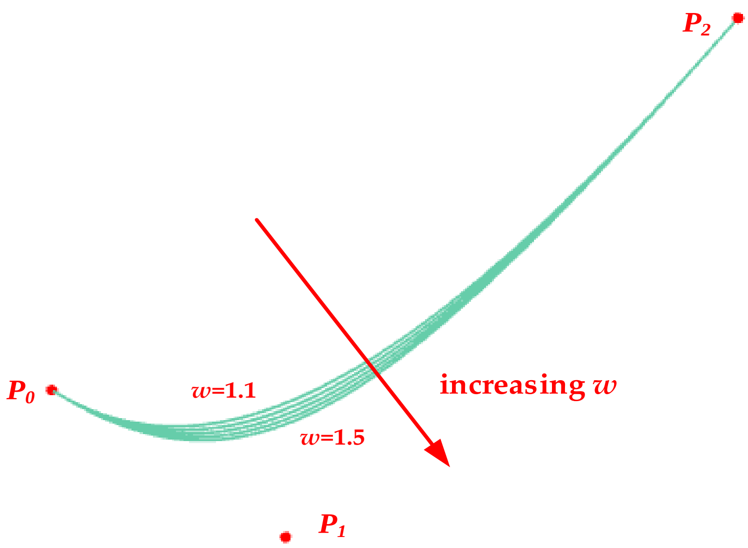

Figure 11. Changing curve shape by changing weighting factor.

(3) Definition of the upper curve

The last part is the curve between the waterline and the deck line. The lower end of this part of the curve is at the point $P_2(YP_2,ZP_2)$, which is connected to the quadratic NURBS curve, and the angle between the tangent line at the connection (the position of point P_2) and the z-axis is α (the same angle α as the middle curve). The upper end point is $P_5(YP_5,ZP_5)$, which intersects with the deck line, and the included angle between the intersection and the z-axis is the side edge of the deck, and is recorded as δ. The left side of Figure 12 shows the spatial position relationship of each curve, and the right side shows the shape of the curve on the X plane.

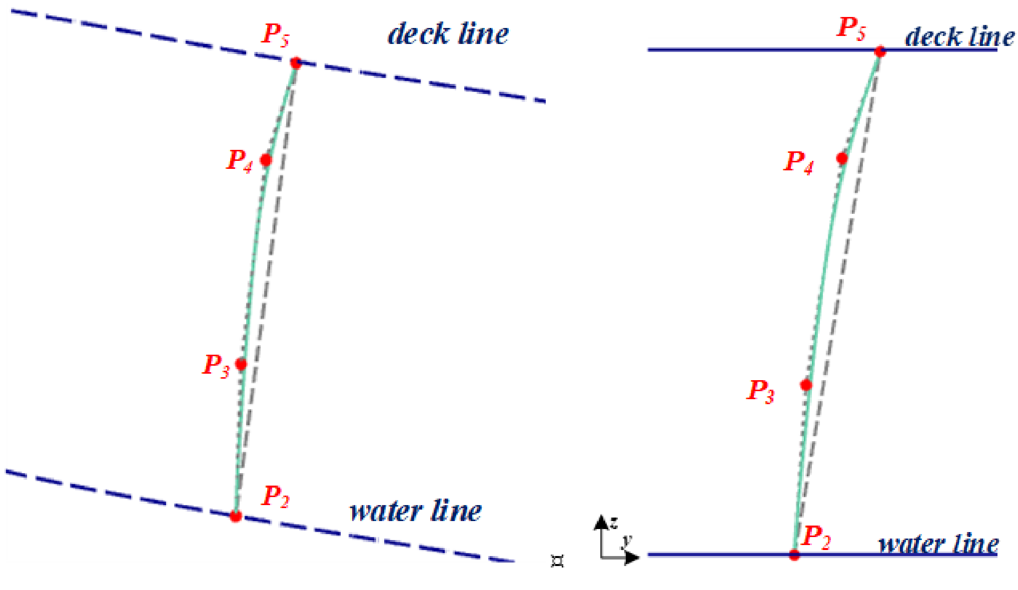

Figure 12. Schematic of the upper curve. (**a**): spatial position relationship; (**b**): shape of the curve on the X-plane.

With the above analysis, the geometric problem is transformed into an attempt to find a NURBS curve starting from point P_2 with starting angle α to angle δ reaching P_5. Figure 13 shows a graphical representation of this geometric problem. This part of the curve can be controlled by a cubic NURBS curve with four control points, with the following equation:

$$\vec{C}(u) = \frac{\sum_{i=0}^{3} \omega_i \vec{P}_i N_{i,3}(u)}{\sum_{i=0}^{3} \omega_i N_{i,3}(u)}, \ Where\ \omega_0 = \omega_3 = 1; \omega_1 = W_2; \omega_2 = W_3 \tag{8}$$

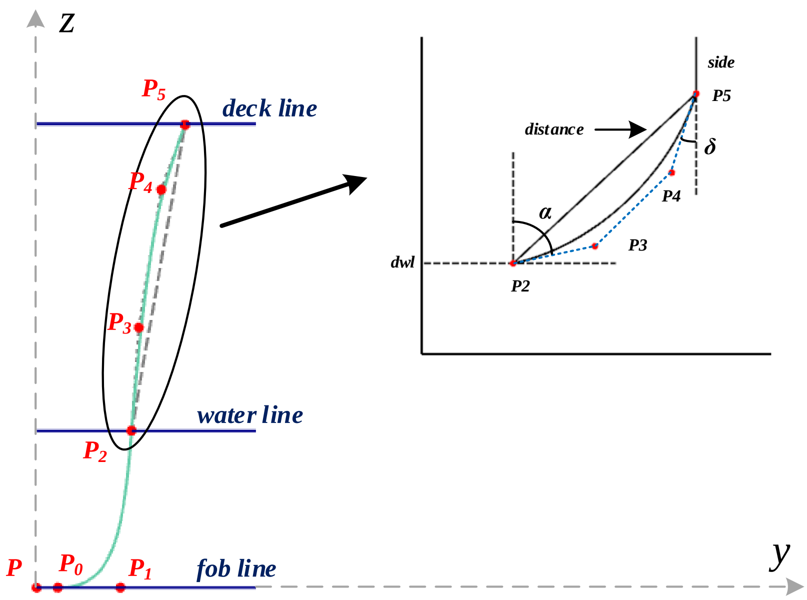

Figure 13. Schematic diagram of the cross-section curve.

Among them, the coordinate information of intermediate control points $P_3(YP_3,ZP_3)$ and $P_4(YP_4,ZP_4)$ are unknown, and starting point P_2 and ending point P_5 are the intersection points of the cross-section curve with the waterline and deck line, respectively; their coordinates are known as the coordinate constraints of the starting and ending points of this curve. The second constraint is the tangential angle of the starting and ending points of the curve: $c'(0) = tg(\alpha)$, $c'(1) = tg(\delta)$. The third constraint is that distance u_1 from P_3 to P_2, distance u_2 from P_2 to P_5, and the distance from P_2 to P_5 satisfy the following relationship equation:

$$\begin{aligned} u_1 &= Dist(P_2, P_3) = Dist(P_2, P_5)/3 \\ u_2 &= Dist(P_4, P_5) = Dist(P_2, P_5)/4.5 \end{aligned} \tag{9}$$

Using the above information, the coordinates of P_3 and P_4 can be found:

$$\begin{bmatrix} YP_3 \\ ZP_3 \\ YP_4 \\ ZP_4 \end{bmatrix} = \begin{bmatrix} YP_2 + u_1 \cdot \sin(\alpha) \\ ZP_2 + u_1 \cdot \cos(\alpha) \\ YP_5 - u_2 \cdot \sin(\delta) \\ ZP_5 - u_2 \cdot \cos(\delta) \end{bmatrix} \tag{10}$$

The weight factors of control points P_3 and P_4, denoted as parameters W_2 and W_3, respectively, can also influence the shape of the curves. The cross-section curves established by this method can meet the design requirements and achieve a smooth connection between curves.

Three NURBS curves are defined by the curves in the previous section, and finally these three curves are connected into one NURBS curve by the NURBS expression composition curve technique, forming a typical cross-section curve. It can better express the hull form features of the Series 60 ship and control its specific form at different positions X_i by longitudinal feature curves, and finally a set of q cross-section curves with different shapes can be obtained (gray curve in Figure 14). The position X_i = 2.8 m is selected as an example, and Figure 14 (right) shows a schematic diagram of the cross-section curves at this position.

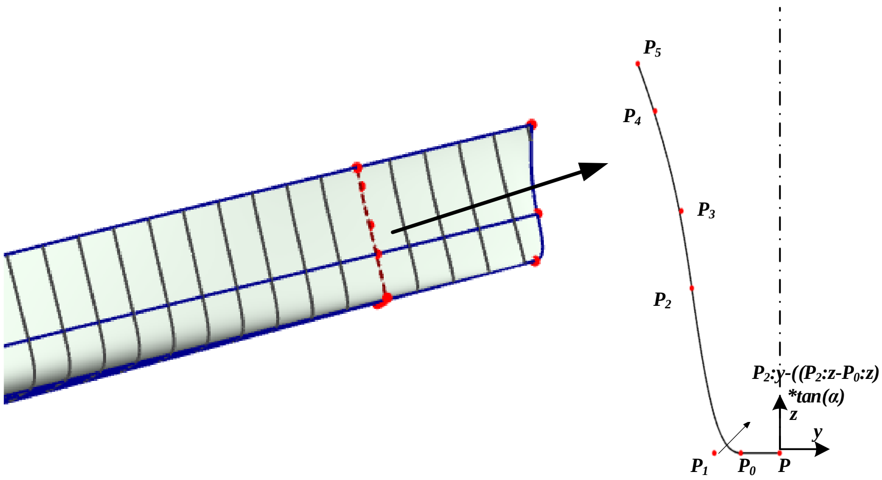

Figure 14. Schematic diagram of the curve cross-section at position X_i = 2.8 m.

In the above cross-section example, the coordinates of each control point (P,P_0, ... ,P_5) are arbitrary, while in the actual hull modeling process, the shape of the cross-section curve at each station is determined, i.e., the coordinates of each control point are also determined, so there should be several specific curves to control the variation in the information of these parameters. From the previous parametric design methods, it is known that the information of form parameters of the cross-section curves is determined by the longitudinal feature curves, i.e., the longitudinal feature curves contain all the information of form parameters of the cross-section curve at each station; thus, linking the ship form with the feature parameters and feature curves.

Still using X_i = 2.8 m position as an example, Figure 14 shows the process of associating the longitudinal feature curves with the form control parameters of the cross-section curve at this position. First, a line perpendicular to the x-axis is created in the xz plane at X_i = 2.8 m. This line intersects with each longitudinal feature curve (width, angle, height control lines, etc.) at a point. The Z-coordinates of these intersection points are transmitted as parameter information to the corresponding control points on the cross-section curve, which in turn causes the information of the control points to change, and finally makes the shape of the cross-section curve change according to the requirements of the longitudinal feature curves. If such an association is established, the cross-section curves can be arranged in a regular and orderly manner along the captain's direction by changing the longitudinal feature curves.

According to the correlation process shown in Figure 15, the Series 60 vessel is made to generate a cross-section curve every 0.065 m under the control of the longitudinal feature curve, and each cross-section curve satisfies the constraint of the boundary curve; the final generated cross-section curve is shown in Figure 16. In the figure, the left side is the cross-section curve of the stern, the right side is the cross-section curve of the bow, the dashed brown line is the cross-section curve at position X_i = 2.8 m, and the red points are its various control points.

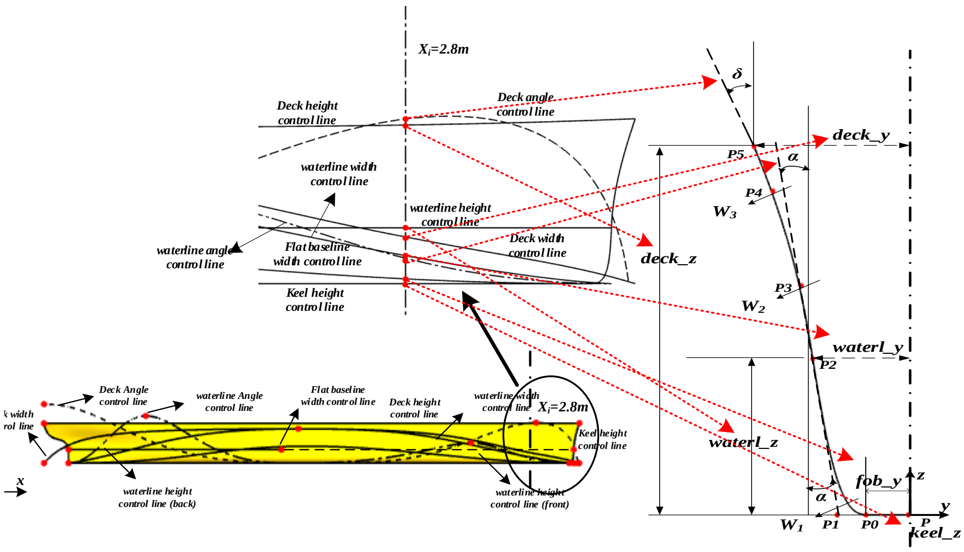

Figure 15. Schematic diagram of the correlation process between the longitudinal feature curve and cross-section curve (X_i = 2.8 m position).

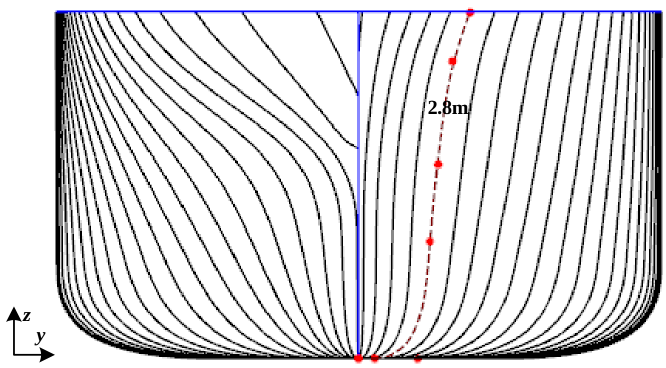

Figure 16. Series 60 cross-section curve diagram.

3.4. Surface Generation

The final step is to generate the hull surface using the skinning technique based on the generated set of q cross-section curves. These q design cross-section curves will form the set of skinning curves used to interpolate the values. The designed cross-sections can be equally or non-equally spaced (more concentrated in important areas). The process of generating B-sample surfaces by the skinning technique is given in [25]. This is not introduced in this paper, but the generation of surfaces by the skinning technique based on NURBS curves is first introduced as an example of surface generation from two surfaces. Suppose that two general expressions of NURBS curves are given:

$$c_1(u) = \sum_{i=0}^{m_1} P_j R_{i,k_1}(u) \tag{11}$$

$$c_1(u') = \sum_{i=0}^{m_2} P_j R_{i,k_2}(u) \tag{12}$$

$C_1(u)$ and $C_2(u)$ are defined on the node vectors U_1 and U_2, respectively, where $R_{i,k}(u) = N_{i,k}(u)\omega_i / \sum_{i=0}^{m} N_{i,k}(u)\omega_i$. To generate a surface between two curves:

$$p(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{l} P_{i,j} R_{i,k;j,l}(u,v) \tag{13}$$

where

$$R_{i,k;j,l}(u,v) = \frac{\omega_{i,j} N_{i,k}(u) N_{j,l}(v)}{\sum_{r=0}^{m} \sum_{s=0}^{l} \omega_{r,s} N_{r,k}(u) N_{r,l}(v)} \tag{14}$$

Here, the v-directional node vector is $V = [0,\ 0,\ 1,\ 1]$. The surface control grid and its vertex weight coefficients must be found:

$$P_{i,j} = P_i + P_j \tag{15}$$

$$\omega_{i,j} = \omega_i \times \omega_j \tag{16}$$

First, the NURBS curves are placed in ascending order using Equations (11) and (12) to make the curves of (11) and (12) into $max(k_1,k_2)$ order NURBS curves, and node insertion techniques are used to make the control polygon vertices of (11) and (12) the same while giving the average node vector.

After the ascending ordering and node insertion, Equations (11) and (12) become k_1 and m_2 vertices with vertex coordinates and weight factors. and ω_i^1 and P_i^2 and ω_i^2, respectively, we have:

$$P_{1j} = P_j^1 + P_1 \tag{17}$$

$$P_{mj} = P_j^2 + P_m \tag{18}$$

$$\overline{P_{1j}P_{i,j}} \times \overline{P_{i,j}P_{mj}} = 0, \ \ i \in [2, m-1] \tag{19}$$

$$\overline{P_{i,j}P_j} \cdot n_j = 0 \tag{20}$$

To construct a NURBS surface with a set of cross-section curves, surface meshing can be performed in segments using the above method, and then the surface is obtained using Equation (13). Figure 17 gives a three-view picture of the Series 60 ship with the superstructure part omitted. The brown part is the deck, the blue part is the hull, and the gray grid lines are the molded lines, including some of the body lines, buttock lines, and waterlines. From the molded lines of the three views, the fully parametric Series 60 model meets the basic smoothness requirements.

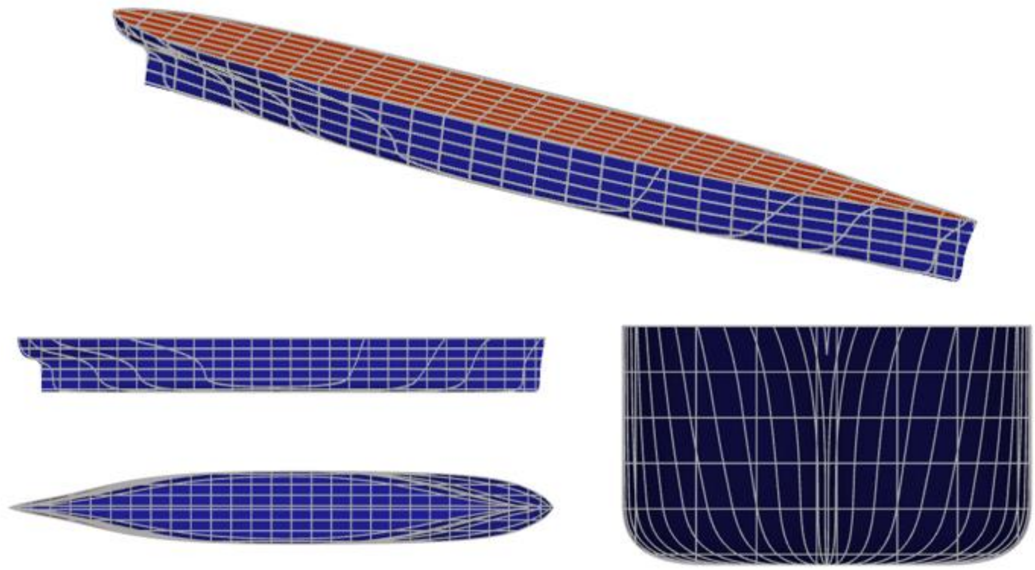

Figure 17. Series 60 parametric model view.

4. Series 60 Parameterized Generation Example

The above section describes the whole process of Series 60 parametric modeling, including the creation of feature parameters, longitudinal feature curves, and cross-section curves, the generation of the hull surface, and finally the deformation of hull surfaces driven by feature parameters. In theory, an infinite number of ship forms can be generated by different combinations of feature parameters. In practical engineering applications, the ideal ship form often needs to be generated under specific constraints. For the Series 60 ship, it is necessary to generate a ship form that meets the design requirements while keeping certain feature parameters unchanged. Therefore, this paper takes the Series 60 ship as an example to realize parameterized generation of a ship under specific constraints.

In the following two examples, some of the feature parameters are selected as constraints for the generation of hull forms, i.e., the values are taken as fixed values; the remaining parameters are taken as design variables, and suitable value boundaries are selected to generate different hull forms by random sampling that satisfy all constraints.

4.1. Example 1

A total of 34 feature parameters were extracted (Table 2), with the first category covering the principal dimensions, keeping the draft and length between perpendiculars constant, and using the molded width and depth as design variables. The third category of parameters must vary along the captain's direction, except for the weight factor, which cannot be used here as a specific design variable. Sixteen parameters, including L_{d0}, L_{d1}, B_{d1}, and β_d, were selected as fixed values to act as constraints in the hull form generation process, and the name and value of each parameter are shown in Table 3. The overall profile of the corresponding hull under this parameter combination is schematically shown in Figure 18.

The remaining 8 parameters, including δ_b, W_k, and δ_f, were used as design variables, and the upper and lower limits of their variation were agreed upon, as shown in Table 4.

The Sobol algorithm [38] was chosen to sample the design variables. This algorithm is based on a Sobol sequence that mimics the behavior of a sequence of random numbers so that the design solution is propagated throughout the variable domain space in a standard form, with the goal of uniform sampling of the design space. The method is mainly used for experimental designs and is able to cover the entire design space.

Table 3. Combination of parameters as constraints.

Name		Value
Length	L_{d0}	3.15 m
	L_{d1}	1.45 m
	L_{c2}	0.12 m
	L_{c0}	3.06 m
	L_0	3 m
	L_1	1.55 m
	L_2	0.12 m
Width	B_{d1}	0.25 m
	B_1	0.06 m
Height	H_d	0.26 m
	H_{c2}	0.08 m
	H_{c0}	0.08 m
Angle	β_d	32°
	γ_d	18°
	θ_c	0°
	θ_d	36°

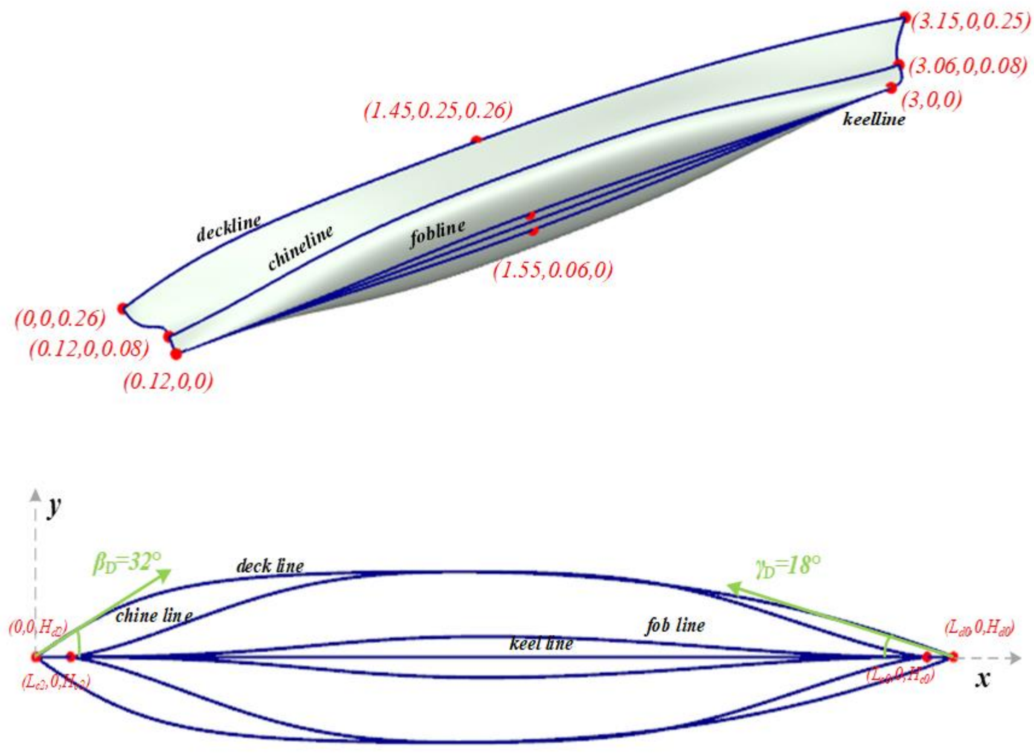

Figure 18. Schematic of the overall profile under constraints.

Table 4. Boundaries of design variables used for sample generation.

	Name	Lower Bound	Upper Bound
1	δ_b	15°	45°
2	δ_f	14°	34°
3	α_b	0°	32°
4	α_f	0°	12°
5	W_k	0.6	2.2
6	W_1	0.8	1.8
7	W_2	0.5	2.1
8	W_3	0.6	2.0

The Sobol algorithm was used to randomly select 9 samples within that range as cases. Figure 19 shows the distribution of the parameters in their respective value ranges; the horizontal coordinates represent the number of schemes, the vertical coordinates are the actual values of each parameter, and the bold points with colors are the exact positions of each scheme in the two-dimensional coordinate system. It can be found that when sampling is performed by the Sobol algorithm, the samples cover the whole design space better, making each scheme representative.

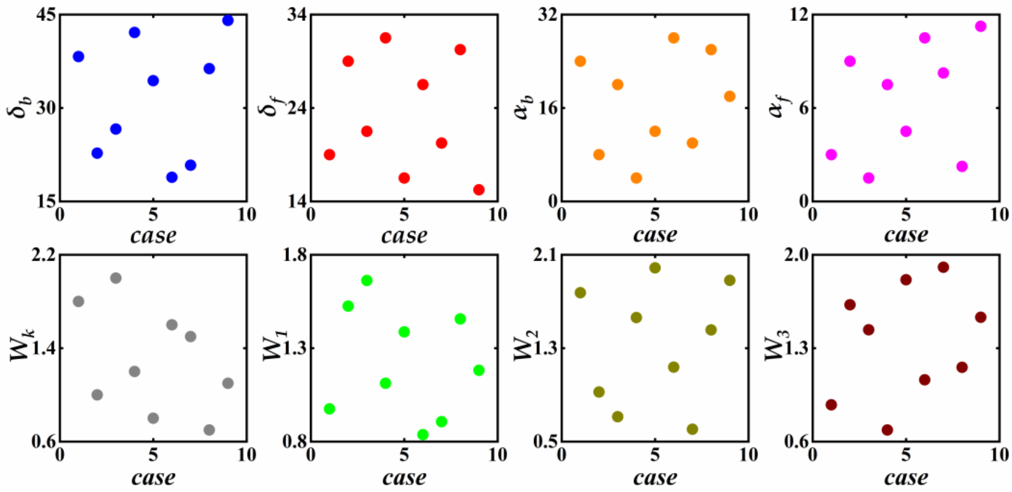

Figure 19. Distribution of design variables in space.

According to the combination of parameters corresponding to each case, the parameterized model is driven to deform automatically to generate the corresponding hull form. Figure 20 shows the cross-section curves of each case; the left side shows the curves of the rear surface of the hull, and the right side shows the front surface. It can be found that the molded line shapes in the diagrams for case 1 to case 9 change to different degrees, which is essentially caused by the changes in tangential angles at the deck line and waterline. The variations in feature parameters δ_f, α_f, and α_b in each case are indicated by the solid green line in Figure 20, and the dashed green line indicates the waterline, which reaches its maximum value at the tail, and δ_b is not shown here. The actual angle values in the figure are consistent with the values of the corresponding feature parameters for each scenario. Due to the change in weight factor control parameters W_k, W_1, W_2, and W_3, the shape of molded lines in the bilge region and middle and upper parts of the hull also changes.

Table 5 shows the quantitative information about the obtained hull shapes, including the block coefficient C_b, the midship section coefficient C_m, the prismatic coefficient C_p, the waterline coefficient C_{wp}, the *volume* and the longitudinal center of buoyancy L_{cb}. It is not difficult to find that the midship section coefficient C_m is positively correlated with the parameter W_1, while the prismatic coefficient C_p does not vary much for the nine cases. The parameters that have a greater impact on the waterline coefficient C_{wp} are δ_b, δ_f, α_b, and α_f, because the modification of these four parameters will lead to a greater change for hull forms at the design waterline, which in turn will lead to a greater change in the waterline surface. Since the principal particulars of the hull are in a constrained state, the *volume* and block coefficient C_b of these nine cases do not vary too much in the range of [0.147 m^3, 0.151 m^3]; the longitudinal center of buoyancy L_{cb} varies in the range of [1.557 m, 1.562 m].

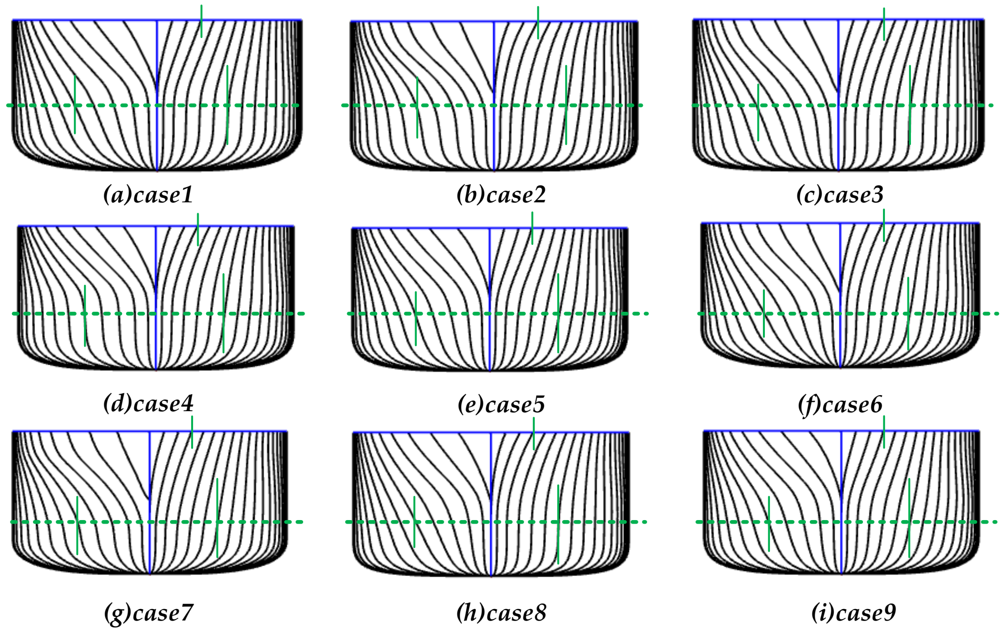

Figure 20. Cross-section view of the hull for each case.

Table 5. The hydrostatic data corresponding to each case.

Case	C_b	C_m	C_p	C_{wp}	$Volume$/m^3	L_{cb}/m
1	0.625	0.961	0.650	0.719	0.155	1.570
2	0.620	0.964	0.643	0.707	0.132	1.578
3	0.623	0.962	0.647	0.733	0.151	1.577
4	0.624	0.966	0.646	0.714	0.126	1.573
5	0.622	0.964	0.646	0.705	0.138	1.574
6	0.621	0.960	0.647	0.702	0.160	1.571
7	0.625	0.964	0.648	0.705	0.134	1.573
8	0.620	0.961	0.646	0.726	0.159	1.572
9	0.618	0.962	0.643	0.677	0.146	1.573

4.2. Example 2

In example 1 there is a constraint on the boundary curves of the hull, while in example 2 the constraint on the bow keel line of the hull is removed and only parameter θ_d is added to constrain the tangential angle of the keel line at the deck, i.e., L_{d0}, L_{c0}, B_{d1}, H_d, etc., are taken as design variables to observe the deformation effect of the keel line of the hull. The values of the other fixed parameters are also changed, as shown in Table 6, and parameters β_d and γ_d, which control the tangential angle of the deck line at the head and tail in the xy plane, are taken as 60° and 36°, respectively, as shown in Figure 21. In addition, δ_b and α_f are also used as constraints to observe the effect of changing the other parameters when the body lines of the hull bow and stern are fixed at one tangential angle. Finally, all the weight factor control parameters are taken as fixed values, and the specific values are given in Table 6.

From Figure 21, it can be seen that after changing the values of parameters β_d and γ_d, the deck line is fuller at the bow and stern, which is a significant change from example 1. The change of ship forms in example 2 will not affect the tangential angle of the deck line at the bow and stern.

Table 7 shows the name and value range of each design variable.

Nine samples were selected for example 1, and the number of samples was increased to 18 to further illustrate the reliability of automatic generation of parametric ship models. The 18 samples were randomly selected in the range with the Sobol algorithm as 18 cases. Figure 22 shows the distribution of parameters in the design space.

Table 6. Combination of parameters as constraints.

Name		Value
Length	L_{d1}	1.5 m
	L_{c2}	0.14 m
	L_1	1.5 m
	L_2	0.14 m
Width	B_1	0.1 m
Height	H_{c2}	0.08 m
	H_{c0}	0.08 m
Angle	β_d	60°
	γ_d	36°
	δ_b	35°
	α_f	6°
	θ_d	0°
Weight	W_k	1.4
	W_1	1
	W_2	1
	W_3	1

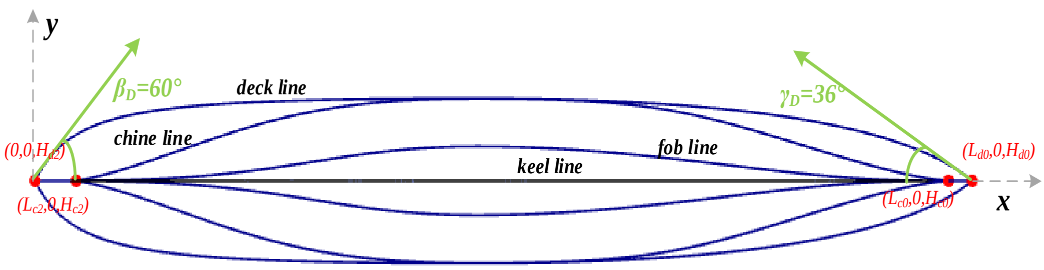

Figure 21. Hull profile under constraint conditions.

Table 7. Boundaries of design variables used for sample generation.

	Name	Lower Bound	Upper Bound
1	δ_f	8°	60°
2	α_b	0°	42°
3	B_{d1}	0.2	0.28
4	H_d	0.22	0.3
5	L_{d0}	3.12	3.18
6	L_{c0}	3.06	3.12
7	L_0	3	3.06
8	θ_c	0°	14°

Table 8 shows the quantitative information about the obtained hull shapes. Unlike example 1, the principal particulars such as L_{d0} and B_{d1} are used as design variables in this example, so they lead to a wide range of variation in *volume* and the longitudinal center of buoyancy, which are [0.124 m^3, 0.164 m^3], [1.569 m, 1.580 m], respectively. In addition, the variation range of the midship section coefficient C_m is reduced after the parameter W_1 is used as a constraint, which is because the parameter W_1 changes the midship section area by controlling the fullness of bilges at the midship section. Since the variation range of parameters δ_f and α_b is slightly increased in example 2, the variation interval of the waterline coefficient C_{wp} is also increased compared to that in example 1, which further verifies the variation relationship between parameters δ_f, α_b, and C_{wp}.

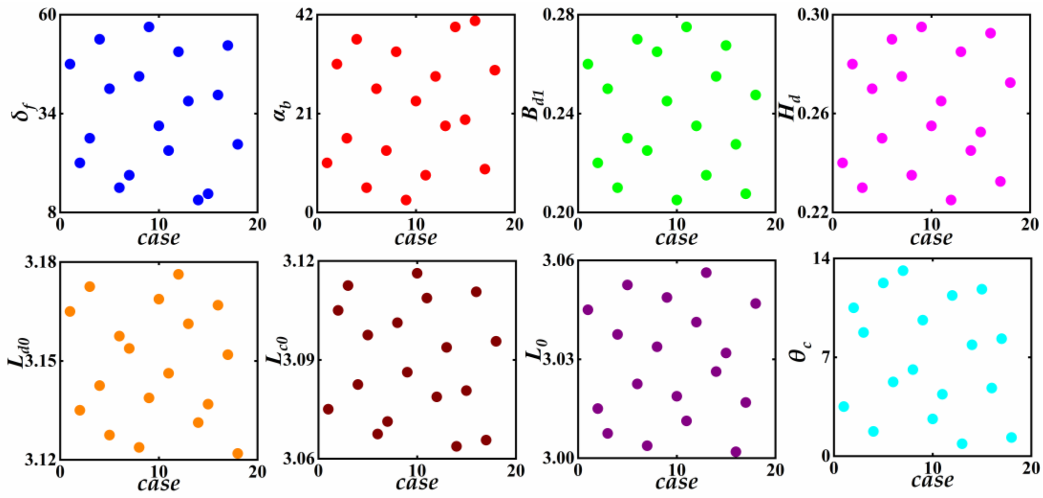

Figure 22. Distribution of design variables in space.

Table 8. The hydrostatic data corresponding to each case.

Case	C_b	C_m	C_p	C_{wp}	$Volume$/m^3	L_{cb}/m
1	0.625	0.961	0.650	0.719	0.155	1.570
2	0.620	0.964	0.643	0.707	0.132	1.578
3	0.623	0.962	0.647	0.733	0.151	1.577
4	0.624	0.966	0.646	0.714	0.126	1.573
5	0.622	0.964	0.646	0.705	0.138	1.574
6	0.621	0.960	0.647	0.702	0.160	1.571
7	0.625	0.964	0.648	0.705	0.134	1.573
8	0.620	0.961	0.646	0.726	0.159	1.572
9	0.618	0.962	0.643	0.677	0.146	1.573
10	0.622	0.967	0.644	0.717	0.124	1.580
11	0.616	0.959	0.643	0.694	0.164	1.576
12	0.628	0.963	0.652	0.747	0.141	1.571
13	0.622	0.965	0.644	0.697	0.129	1.576
14	0.626	0.961	0.651	0.737	0.152	1.570
15	0.622	0.960	0.648	0.716	0.160	1.572
16	0.618	0.963	0.641	0.706	0.136	1.578
17	0.631	0.967	0.653	0.731	0.125	1.569
18	0.619	0.962	0.644	0.706	0.148	1.574

Similar to example 1, the corresponding ship form is generated by automatic parametric deformation according to the parameter combination, and the ship form of each case has a uniform scaling ratio. Figure 23 shows a schematic diagram of the cross-section curves corresponding to each case; the left side shows the curves of the rear part and the right side shows the front part. The dashed green and red lines indicate the waterline, the solid green line indicates that the angle varies in each case, and the solid red line indicates that the angle is constrained in each case.

In the principal dimensions of the hull, due to the change in parameters B_{d1} and H_d, leading to a change in the ship's molded width and depth, the scale of each case in Figure 23 changes to different degrees; the specific dimensions are indicated by the thick colored dots in Figure 22. In the aft part of the hull, the maximum tangential angle δ_b at the deck at the stern end is kept the same at 35° in each case because the δ_b of the aft profile (left side) is controlled to be constant, while the tangential angle at the waterline varies. Similarly, for the forward hull profile (right side), it can be found that tangential angle α_f at the waterline at X_i = 2.52 m is 6°, while the angle at the deck is different in each case.

The longitudinal boundary curve of the hull is deformed by changing parameters such as θ_c and L_{d0}. In order to better compare the real effect of deformation, the deformation effect when intercepting x = 2.55 m to the foremost part of the hull with the same scaling ratio is shown in Figure 24. It can be found that the tangential angle θ_d of the keel line at the deck is kept at 0°, while the tangential angle θ_c at the waterline changes; in addition, the x coordinates of the deck line, the waterline, and the foremost point of the flat-bottomed line also change, and various hull surface shapes can be obtained by combining them. The specific values of the parameters corresponding to each scheme are shown in the coordinates of the coarse points in Figure 22.

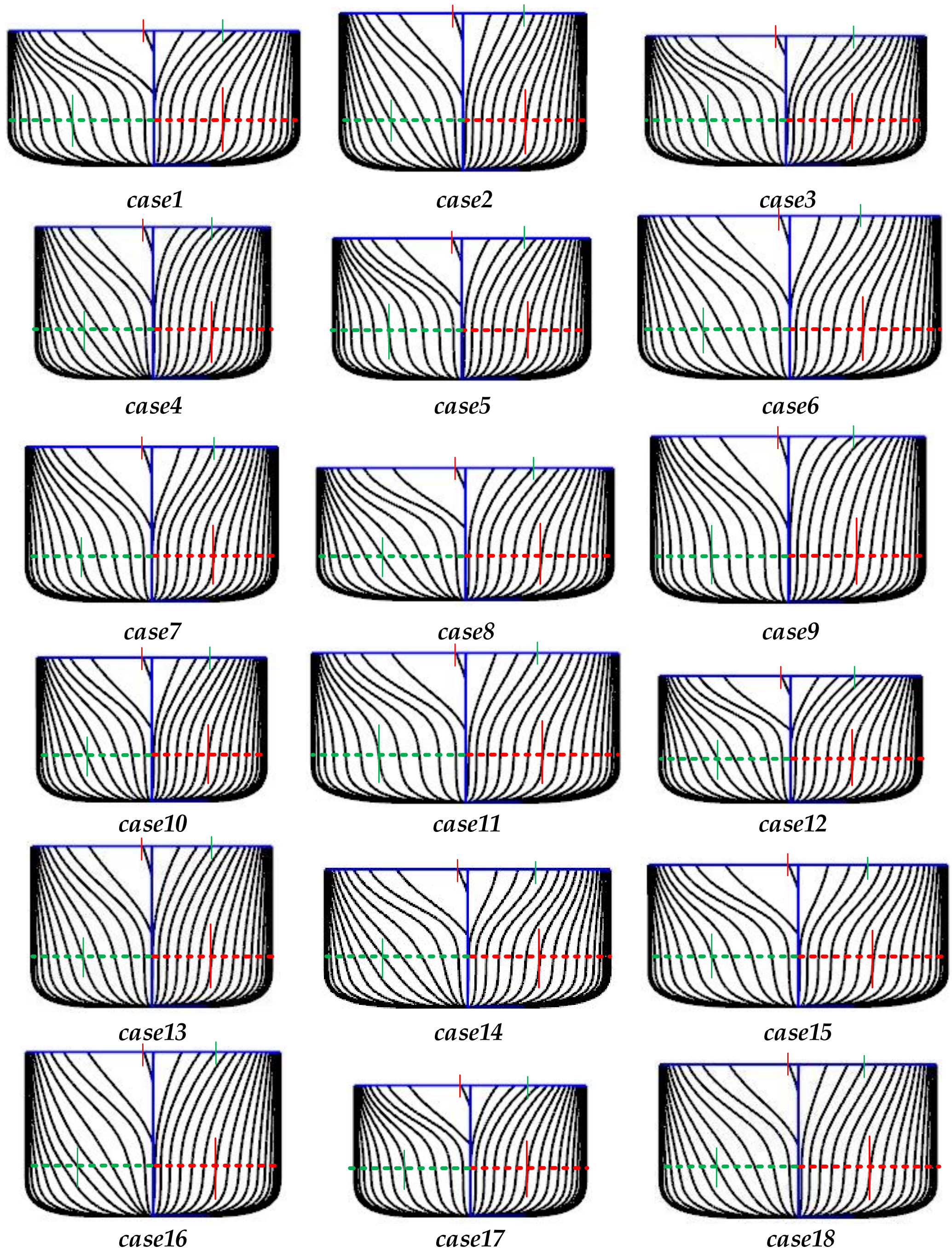

Figure 23. Schematic diagram of hull cross-section lines in each case. The dashed green and red lines indicate the waterline, the solid green line indicates that the angle varies in each case, and the solid red line indicates that the angle is constrained in each case.

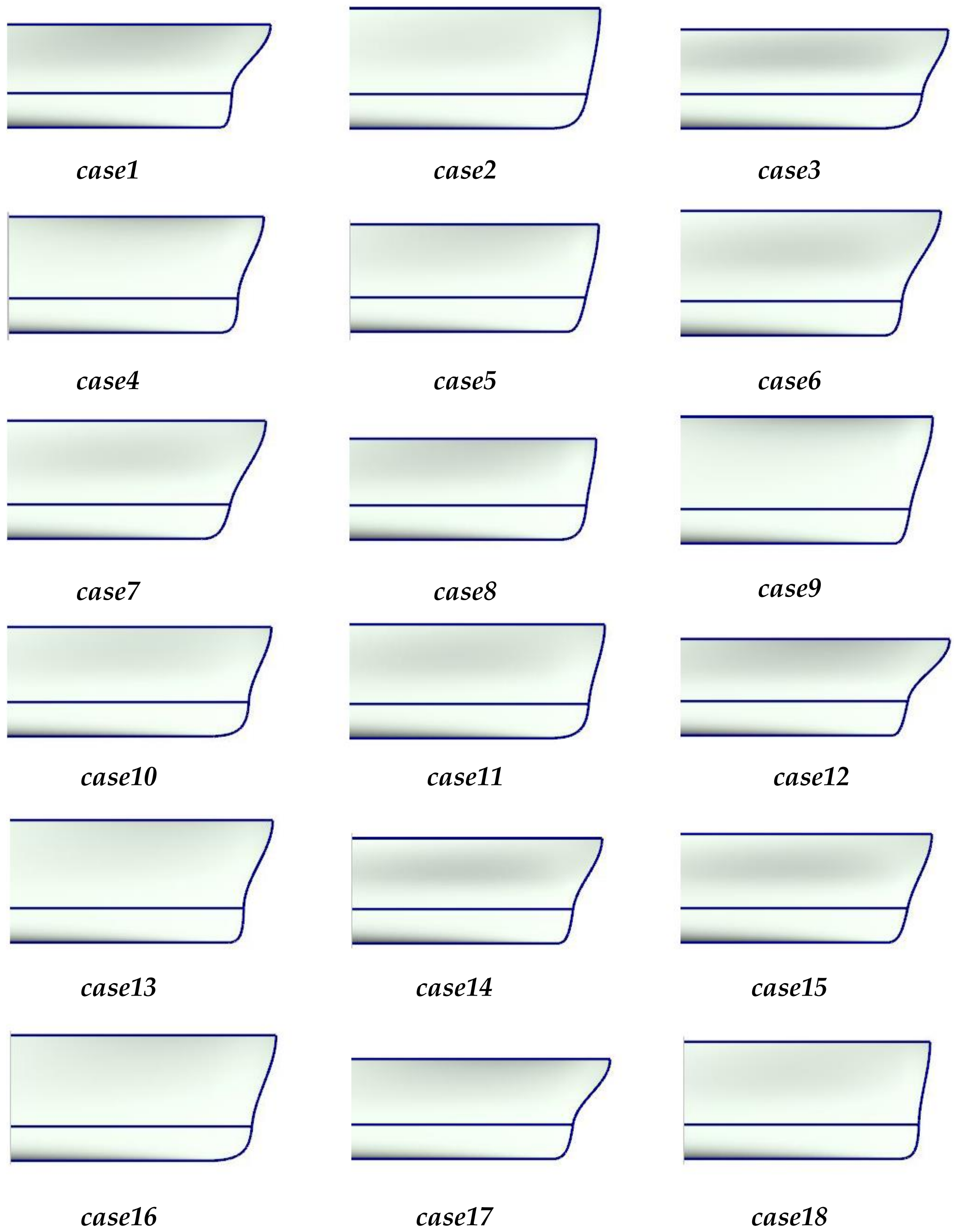

Figure 24. Hull shape in each case.

5. Results and Discussion

The parametric design method is a process of creating longitudinal feature curves by analyzing feature parameters, then controlling the orderly generation of groups of cross-section curves and finally constructing hull surfaces. Establishing feature curves and cross-section features is the key to applying parametric design to hull forms. In this paper, taking the Series 60 ship as an example, we analyzed the hull feature parameters, used NURBS curves and a surface program to create longitudinal feature curves, and then combined the hull form features to create typical cross-section features, realized the association between cross-section and longitudinal feature curves at different x positions of the hull, and used the skinning technique to complete the generation of the hull surface, and finally realized the process of generating a feature parameter-driven hull form. The conclusions are as follows:

(1) The Series 60 parametric model built based on the NURBS technique can automatically generate hull forms that meet design requirements under specific constraints. It is found through design examples that parameters such as the length, width, height, angle, and weight factor of the basic boundary curves and cross-section curves of the hull can be precisely controlled, which has a better deformation effect than other hull deformation methods.
(2) This method realizes the process of feature parameter-driven hull surface deformation, and combined with the algorithm, it can provide designers with many sample ship forms in a short time; thus, reducing the time for manual modeling and modification and greatly improving the efficiency of design and providing certain engineering use value.
(3) The smoothness of the hull surface generated by the parametric design method is good and meets the basic design requirements, so it can be used as the basic model for subsequent performance analysis.

The outlook for future research is as follows:

(1) In this study, only the simpler Series 60 ship form was chosen, but an actual ship form is much more complicated. Therefore, in order to better apply the method to engineering practice, carrying out parametric modeling of complex hulls such as container ships and bulk carriers at a later stage is proposed.
(2) Due to the limitation of NURBS, it is not applicable to all parametric modeling of curves and surfaces. With increased hull surface complexity and stronger design requirements, a new sample curve is needed to support the parametric modeling of complex hulls.
(3) With the use of hydrodynamic analysis software, the hull form is automatically optimized under certain engineering constraints with the indices of resistance, seakeeping performance, and maneuverability as the optimization targets; finally, a hull form with excellent performance is obtained.
(4) Based on sensitivity analysis techniques or combined with expert experience, the technique of automatic extraction of feature parameters will be investigated in depth in future research.

Author Contributions: Conceptualization: H.Z. and B.F.; methodology: H.Z., B.F. and Z.L.; validation: H.Z. and H.C.; formal analysis: H.Z. and Z.L.; data curation: H.Z.; visualization, X.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant numbers 551720105011, 51979211), Key Research and Development Plan of Hubei Province (2021BID008), Research on the Intelligentized Design Technology for Hull Form. Green Intelligent Inland Ship Innovation Programme. High-tech ship research project (2019 [357]).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in this article (Tables and Figures).

Conflicts of Interest: The authors declare no conflict of interest.

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