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Parametric Design of Complex Hull Forms

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Abstract

In the present study, we suggest a new method for designing complex ship hull forms with multiple domain B-spline surfaces accounting for their topological arrangement, where all subdomains are fully defined in terms of form parameters, e.g., positional, differential and integral descriptors. For the construction of complex hull forms, free-form elementary models such as forebody, afterbody and bulbs are united by Boolean operation and blending surfaces in compliance with the sectional area curve (*SAC*) of the whole ship. This new design process in this paper is called Sectional Area Curve-Balanced Parametric Design (SAC-BPD).
Keywords: hull form, form parameter, parametric design, surface topology, optimization

1 Introduction

Conventionally, the hull's complicated geometry is modelled in a highly interactive process consuming a considerable amount of time and cumbersome labour to meet all design criteria, e.g., displacement, centre of buoyancy, fairness. Then, on the basis of the numerical flow field analysis, the geometry is changed, often intuitively, by interactive modification. This modelling and modification process is in general dependent on the experience of the naval architect. In an optimization process, the methods are dependent on a defined hull's model with given design variables. So, the different modelling and modification processes produce several designs and, at the end of the modelling and analysis process, a naval architect chooses the most suitable candidates, before model tests are conducted. It is therefore important to develop geometric models for the design methodology of a hull's geometry.

Since the first attempt to generate and vary the ship hull forms mathematically by Taylor(1905) and the advent of Computer Aided Ship Hull Design (CASHD) in the second half of this century, innumerable different computational design methods via curves and surfaces have been developed and reported. Harries(1998) and Kim(2004) give a comprehensive state of the art in CASHD. Generally, CASHD systems can be classified as offset data based systems or form parameter based systems. While the former is primarily concerned with accurately representing a known hull geometry in computer format and modifying it locally to meet design criteria, the latter mainly deals with the ab initio modelling of new hull forms, though possibly derived from a parent. The prevailing modelling systems are generally modelled from offset data and can be modified locally. Today, the majority uses surface or solid modelling techniques. Recently, in the category of form parameter based design of ship hull forms, important developments have taken place to achieve the flexible and accurate representation of practical ship hull forms. Especially, Harries(1998) realized a new design methodology for ship hull surface definition based completely on given form parameters and developed the FRIENDSHIP-Modeller. At that stage he was able to deal with single domain ship hull forms only, such as occur in yacht design, etc. In the meantime the modeller has been further extended (Abt et al 2003) to include the capability of modelling multiple surface domains, e.g., main ship hull form with a bulbous bow, by form parameters. However, in this approach the ship hull surface is not subdivided into several independent topological elements, each consisting of a surface domain and an associated volume.

This paper deals with a new design methodology of ship hull forms with a complex multiple domain surface topology and an associated volume. The practical ship hull geometry with a parallel midbody, bow and stern bulbs contains various types of complex surface topology with regular, irregular and hybrid meshes, particularly in the bow and stern part, and hence a single domain surface representation is not sufficient. To alleviate this problem, we suggest the use of multiple domain surface representation and introduce a new method for representing complex ship hull forms by multiple domain B-spline surfaces accounting for their topological arrangement, where all subdomains are fully defined in terms of form parameters, e.g. potential, differential and integral descriptors, thus contain both individual surface domains ans associated volumes. Figure 1 (a) shows the various surface topologies which can be found in general ship hull forms and figure 1 (b) illustrates a new design concept for complex ship hull forms introduced in this paper.

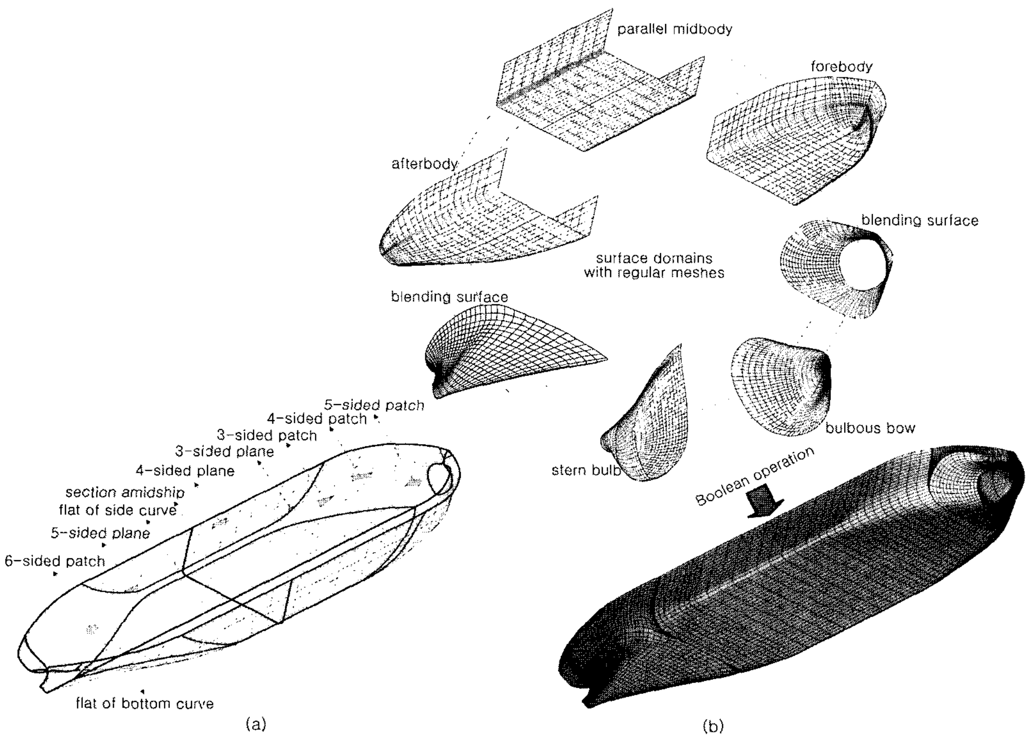


Figure 1: Various surface topologies and design concept for complex ship hull forms introduced in this paper

2 Parametric curve design

Form parameters for the curve constitute the input to the geometrical modelling process that is viewed as an optimization problem in which fairness criteria are employed as measures of merit and additional geometrical information, e.g. interpolating offset points as well as form parameters are treated as design constraints. B-spline curves and surfaces are chosen for all mathematical representations and form the output (Farin 1990), and therefore the B-spline control points are the unknown free variables to be computed. Fairness criteria $J(\mathbf{C})$ (Westgaard 2000) and form parameters can be flexibly selected to best-suit a particular modelling problem. So, the general constrained design optimization model for parametric design of curves can be expressed as: compute the n unknown control points $\mathbf{V} = \{v_{ij}\}_{i=0}^{n-1}, j = 1 \; to \; 2 (or \; 3)$ of the B-spline curve $\mathbf{C}(t)$ by minimizing the object function

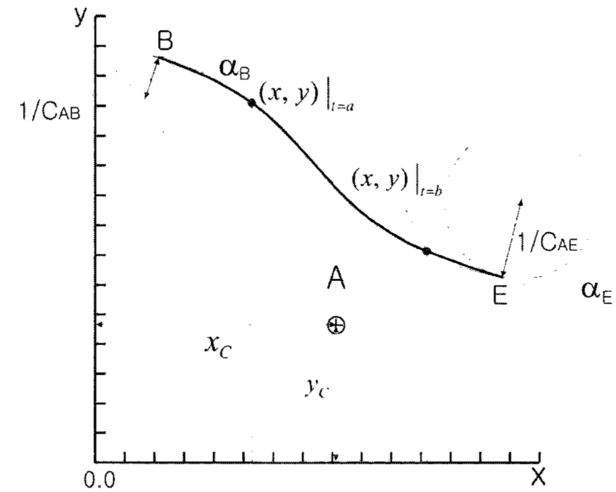


Figure 2: Geometry and form parameters of a single planar curve (Creutz 1977)

Table 1: A set of form parameters for a single planar curve (Harries 1998)

Form parameter	Symbol	Mathematical description
Position at beginning	(x_B, y_B)	$(x, y)\|_{t=0}$
Position at end	(x_E, y_E)	$(x, y)\|_{t=1}$
Tangent angle at beginning	α_B	$y'/x'\|_{t=0}$ or for B-spline curve via. $\mathbf{v}_0\mathbf{v}_1$
Tangent angle at end	α_E	$y'/x'\|_{t=1}$ or for B-spline curve via. $\mathbf{v}_{n-1}\mathbf{v}_n$
Curvature at beginning	C_{AB}	$(x'y'' - x''y')/(x'^2 + y'^2)^{3/2}\|_{t=0}$
Curvature at end	C_{AE}	$(x'y'' - x''y')/(x'^2 + y'^2)^{3/2}\|_{t=1}$
Area between curve and given axis	A	$\frac{1}{2}\left[\int_a^b (yx' - xy')dt + y_b x_b - y_a x_a\right]$
Centroid of area	(x_C, y_C)	$(M_y / A, \; M_x / A)$

$$f = f(\mathbf{V}) = w \cdot J(\mathbf{C}) \tag{1}$$

subject to the equality constraints

$$h_i(\mathbf{V}) = \widetilde{w}_i \cdot (\mathbf{F}_{actual_i} - \mathbf{F}_{given_i}) = 0, \quad i = 1 \ to \ l, \tag{2}$$

The inequality constraints

$$g_i^1(\mathbf{V}) = \breve{w}_i \cdot \|\mathbf{C}(t_i - \mathbf{p}_i)\|^2 \le \varepsilon_i, \ i = 1 \ to \ p, \tag{3}$$

$$g_i^2(\mathbf{V}) = \mathbf{C}_y^+(t_i^+) - \mathbf{C}_y(t) \le 0 \quad if \ \mathbf{C}_x^+(t_i^+) \cap \mathbf{C}_x(t), \quad i = 1 \ to \ m \tag{4}$$

$$g_i^3(\mathbf{V}) = \mathbf{C}_y^-(t_i^-) - \mathbf{C}_y(t) \le 0 \quad if \ \mathbf{C}_x^-(t_i^-) \cap \mathbf{C}_x(t), \quad i = 1 \ to \ m \tag{5}$$

And explicit bounds on unknown control points as design variables

$$v_{ijl} \le v_{ij} \le v_{iju}, \qquad i = 0 \ to \ n-1, \ j = 0 \ to \ 2, \ in \ planar \ curve \\ or \ i = 0 \ to \ n-1, \ j = 0 \ to \ 3, \ in \ spatial \ curve, \tag{6}$$

where $w, \ \widetilde{w}_i, \ \breve{w}_i \ge 0$ are the dimensional weighting factors given to each object function, equality and inequality constraints. High weights of w, $\widetilde{w}_i$ and $\breve{w}_i$ respectively signify increased fairness measure, hard equality constraints and close approximation, and low weights signify reduced influences. $\mathbf{F}_{actual_i}$ and $\mathbf{F}_{given_i}$ are calculated and given form parameters of the curve. They contain positional, differential and integral parameters, e.g., points, tangent vectors and curvatures at beginning and end, the area and its centroid between the curve and chosen axis. Note that the area and its centroid can be defined under the curve locally as well as globally, see figure 2 and table 1. $\mathbf{p}_i$ is one of a set of sequentially organized curve points in the planar or spatial curve. Through the constraint (3) the points on the curve corresponding to each parameter value t_i approximate the points $\mathbf{p}_i$, where the points on the curve at beginning and end belong to the form parameters, thus they are not included in the constraint (3). Constraints (4) and (5) are used in the design of blending curves. $\mathbf{C}^+$ and $\mathbf{C}^-$ are primary curves to be blended. $\mathbf{C}_x^+$ and $\mathbf{C}_x^-$ are x-coordinates of primary curves and $\mathbf{C}_y^+$ and $\mathbf{C}_y^-$ are y-coordinates of primary curves. t_i^+ is a parameter value of the curve $\mathbf{C}^+$ in $\mathbf{C}_x^+(t_i^+) \cap \mathbf{C}_x(t)$ and t_i^- is a parameter value of the curve $\mathbf{C}^-$ in $\mathbf{C}_x^-(t_i^-) \cap \mathbf{C}_x(t)$. These conditions support that the blending curve will act as a bridge between neighboring primary curves to be blend. It is important to note that these constraints are limited to only planar blending curve design. Figure 3 shows the geometry and form parameters of a planar blending curve $\mathbf{C}_3$ between primary curves $\mathbf{C}_1$ and $\mathbf{C}_2$. Here, the enclosed area A_-, which is calculated by Boolean sum, is used as an integral parameter. Constraint (6) is an inequality constraint which represents the lower and upper bounds for the i^{th} unknown control points $\mathbf{v}_{ij}$. Here, j=1 to 2 when the curve is planar and j=1 to 3 when the curve is spatial.

Table 2: Classification of constraints in parametric curve design (Kim 2004)

Design problem	Constraint				
	(2)	(3)	(4)	(5)	(6)
Form parameter curve design	○	×	×	×	○
Constraint curve fitting	△	○	×	×	○
Parametric blending curve design	△	△	○	○	○

From the suitable combination of these constraints (2)-(6), the optimization problems subject to different kinds of constraints make it possible to design different optimal curve shape types. Table 2 shows the typical three types of curve design problems classified by different constraints. Here, "○"means that elements of the constraint are fully available, "△" means that a flexible choice of elements in the constraint is possible, and "×"means that the constraint is not available.

A well-known optimization algorithm dealing with constrained design problems is Sequential Quadratic Programming (SQP). The basic idea of SQP is to find a suitable search direction $\mathbf{d}_k$ by solving quadratic subproblems with linear constraints in each iteration k, where the object and constraint functions are continuously differentiable. This subproblem is basically derived by making a second order Taylor approximation in the vicinity of the current approximation of the minimum, and then employs the necessary optimality conditions (Birk et al 2003).

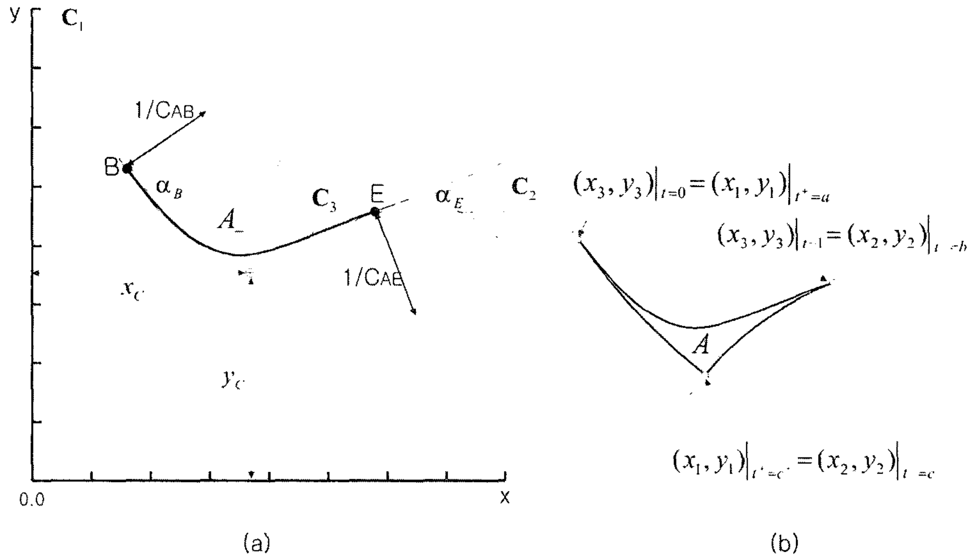


Figure 3: Geometry and from parameters of a planar blending curve

3 Extended parametric curve design

Based on the parametric design of curve with single segment introduced in previous section, complex curves with more primary curves with multiple segments and two (or more) blending curves can be designed parametrically. The optimization scheme is the same as that of the parametric curve design with a single segment. The difference is that the positional and differential parameters of the blending curves are dependent on the primary curves and that the integral parameters have to be computed by Boolean operators. So, an optimization problem of blending curves, which depends on multiple segment primary curves, subject to form parameter constraints can be rewritten as: Compute the unknown control points $\mathbf{V}$ of the B-spline blending curve $\mathbf{C}_i(t)$, $1 \le i \le m$ by minimizing the object function

$$f(\mathbf{V}) = \sum_{i=1}^{m} w_i \cdot J(\mathbf{C}_i) \quad (7)$$

subject to the equality constraints

$$h_i(\mathbf{V}) = \tilde{w}_i \cdot (\mathbf{F}_{actual_i} - \mathbf{F}_{given_i}) = 0, \quad i = 1 \ to \ l,$$

where m is the number of blending curves, and $J(\mathbf{C}_i)$ and w_i are the fairness measure and its weighting factor of the i_{th} segment curve, $\tilde{w}_i$ is the weighting factor which controls the influence of each form parameter constraint. The overall measure of merit like the sum of fairness measures for each blending curve and global form parameters like the total area under multiple segment curves by the *Boolean union* are used. In this paper, the Boolean union means the sum between curves that the overlapped parts of curves are removed and their area under curve is computed only once. Thus the resulting curve by Boolean union is the curve with a summed curve and its not-overlapped area. See Kim(2004) for details. This method is called Sectional Area Curve-Balanced Parametric Design(SAC-BPD). Generally, this method can be applied in the parametric design approach for sectional area curve (*SAC*). For (7), the added integral parameters A_{i-}, M_{iy-}, M_{ix-}, $1 \le i \le m$ generated by blending curves are computed from the Boolean union ($\bigcup$), and thus the global form parameters are calculated as:

$$\begin{aligned}
\nabla_G &= \nabla_R \bigcup \nabla_M \bigcup \nabla_{RB_} \bigcup \nabla_{EB_} \\
x_{C_G} &= \frac{\nabla_R \cdot x_{C_R} \bigcup \nabla_M \cdot x_{C_M} \bigcup \nabla_{RB_} \cdot x_{C_{RB_}} \bigcup \nabla_{EB_} \cdot x_{C_{EB_}}}{\nabla_G} \\
y_{C_G} &= \frac{\nabla_R \cdot y_{C_R} \bigcup \nabla_M \cdot y_{C_M} \bigcup \nabla_{RB_} \cdot y_{C_{RB_}} \bigcup \nabla_{EB_} \cdot y_{C_{EB_}}}{\nabla_G}
\end{aligned} \tag{8}$$

where ∇_i are the areas under the segment curves and are the volumes of *SAC*. The terms R, M, E, RB_ and EB_ are run, midbody, entrance, run blend and entrance blend terms, respectively. For the applicability of this method, figure 4 illustrates a SAC of hull form, featuring a container carrier Ville de Mercure. It consists of the multiple segment primary curves and the blending curves and is divided into seven parts: run, midbody and entrance part of bare hull, bulbous bow, stern bulb, run blend and entrance blend, where the *SAC* of the stern bulb is not considered at this design stage because it belongs to the run part. Here, the *SAC* in run and entrance of the bare hull is defined from the beginning position of the propeller bossing to bottom end position from the aft perpendicular. This is because the curve at a beginning position of the propeller bossing may have a G^1-discontinuity, and the curve in the bow part has little influence on the whole *SAC* but may have an effect on the degeneration of the hull form. Therefore, the *SAC* for the bare hull consists of four segment curves: added run(L_{R1}), main run(L_{R2}), added entrance(L_{E1}) and main entrance(L_{E2}).

4 Parametric surface design

In this section, we present methods for parametric surface design based on fair-skinning (Harries 1998). According to the type of skin curves, the surface design problem is classified into two methods (Kim 2004):

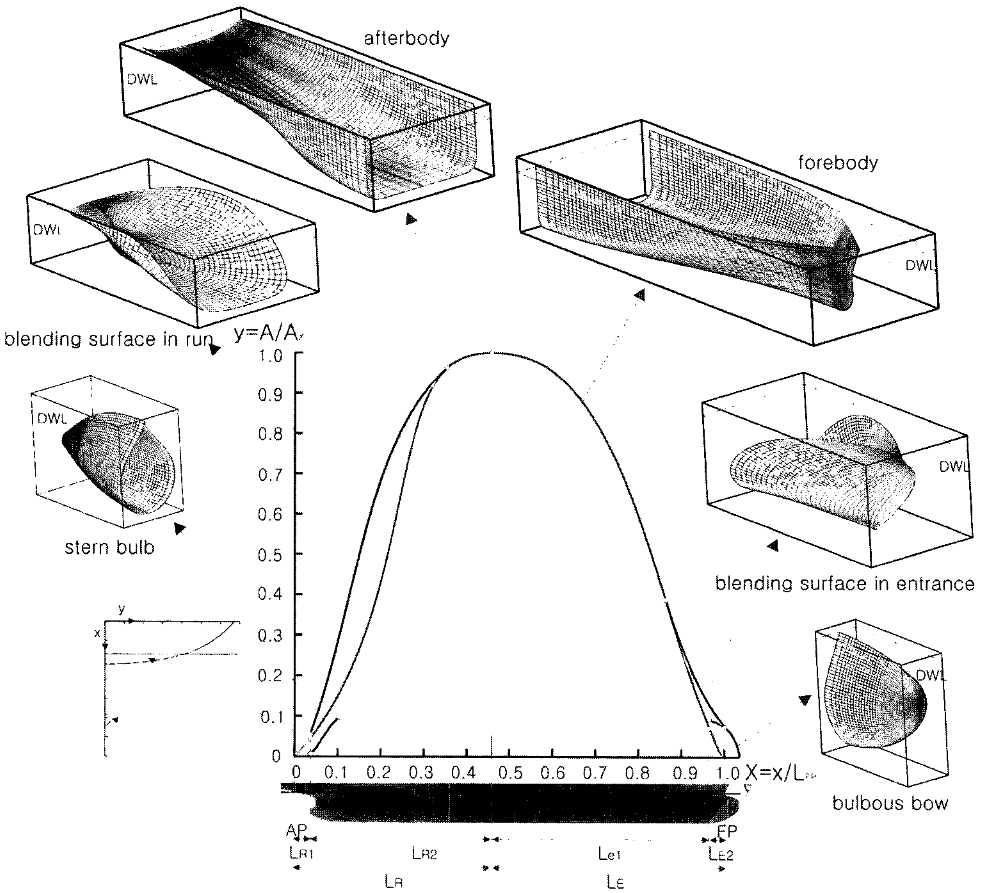


Figure 4: An example of sectional area which comprise the multiple segment primary curves and the blending curves

- ***Direct parametric surface design*** The skinned surface interpolates through an ordered set of planar skin curves (sections) which are positioned along an axis (spine line). The planar skin curves are defined directly in terms of form parameters from which a set of longitudinal basic curves can be laid out. These basic curves contain all information necessary to subsequently create a set of skin curves, and are also defined via curve form parameters.
- ***Indirect parametric surface design*** The skinned surface interpolates through an ordered set of spatial skin curves (blending curves) which are positioned along a spatial spine curve. Because the spatial skin curves can not be defined directly by means of all form parameters, particularly, integral information, they have to be generated by the indirect method, for instance, in blending surface design, the spatial skin curves can be generated by using the curve fitting through the planar guide section curves which can be designed directly in terms of form parameters.

The former method is used in the modeling of bare hull, bulbous bow and stern bulb, and we call this model elementary surface model. Figure 5 presents the primary and secondary basic curves for the design of bare hull form, featuring Ville de Mercure, and figure 6 shows its B-spline surfaces by skinning. The latter method is applied to the blending surface generation, and it is important to consider the topological and geometrical properties of elementary surface models for the blending surface's boundary conditions.

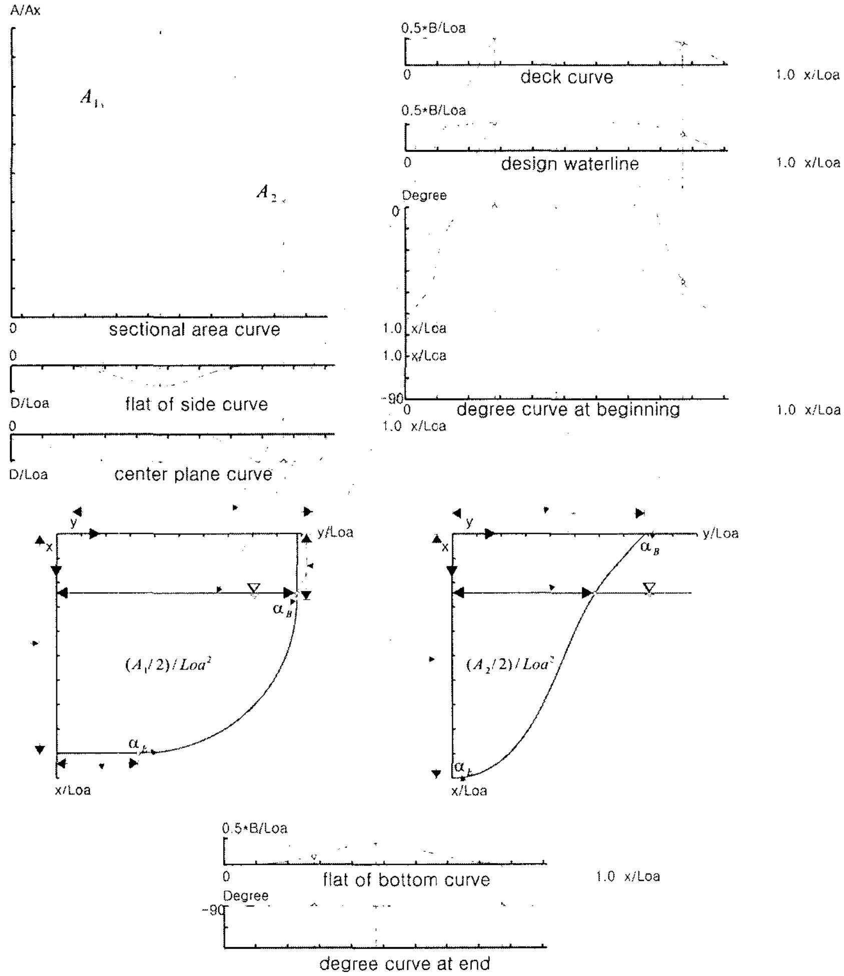


Figure 5: Relationship between basic curves and hull sections

Figure 7 (a) shows the blending zone of the sectional area curve in the bare hull's forebody. Then, the boundary curves on the elementary surface models to be blended have to be declared. The process is as follows: First, generate the boundary curve in the parameter domain of a bulb surface using form parameter design, and define the boundary curve on a bulb surface (figure 7 (b)). Second, generate two guide section curves in the blending domain using the parametric blending design based on the blending waterline curve and sectional area curve, and calculate the intermediate points necessary to design a boundary curve on a bare hull's surface (figure 7 (c)). Third, generate a planar boundary curve through intermediate points on the center plane subject to tangent condition at the ends (figure 7 (d)). Fourth, project a planar boundary curve onto the bare hull's surface, and generate a boundary curve on a bare hull's surface and in the parameter domain (figure 7 (e)). Figure 8 (a) shows the transitional tangent ribbon of boundary curves on the bare hull's and bulb's surfaces (Umlauf 1993). To consider the integral information in the blending surface design, we use guide sections (thick section curve) which are designed by form parameters (figure 8 (b)). Then, the transitional blending curves through these sections are generated by the blending curve fitting (figure 8 (c)). In figure 8 (d) the resulting surface by skinning is illustrated. Figure 8 (e) presents the waterlines, buttocks and sections in a perspective view of the blending surface related to a bare hull and a bulbous bow.

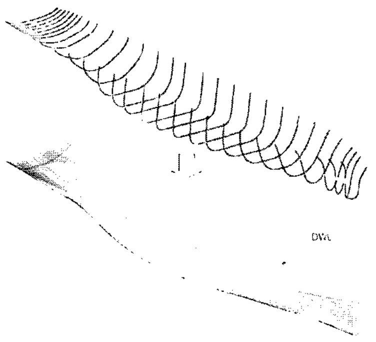


Figure 6: Bare hull surfaces generated by skinning

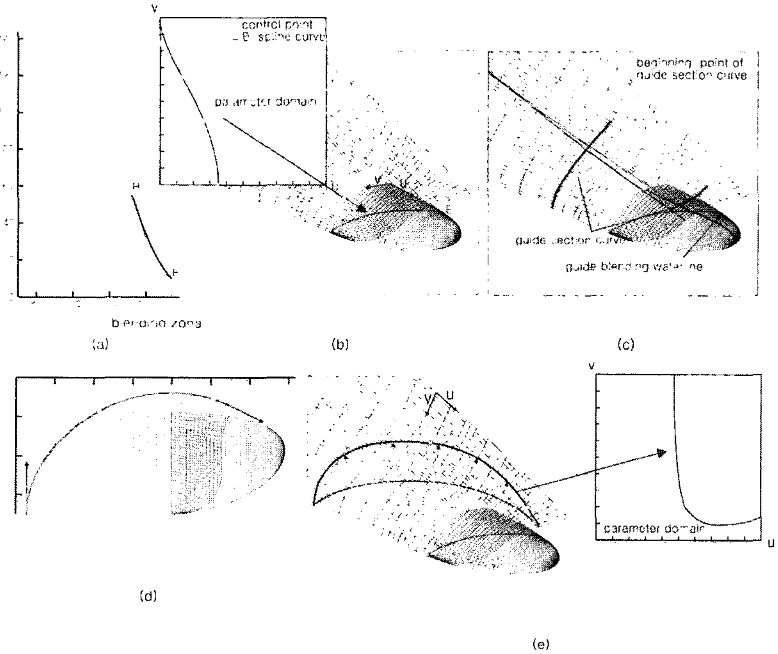


Figure 7: Generation of boundary curves for blending surface design

3 Design approach of complex ship hull form

Our main approach to represent and design ship hull forms with a complex surface topology is based on the construction of multiple domain B-spline surfaces with G^1-continuity and an associated volume, e.g., free-form elementary models and blending surfaces, and divided into the following:

- Basic curve generation for free-form surface domain elements by parametric design and surface generation by skinning
- SAC-BPD of multiple domain hull forms

In the first approach, the complex hull form is divided into free-form elementary models and blending surfaces, all of which are center plane symmetric and can be represented by regular meshes. Figure 1(a) (the upper circle) illustrates the free-form elementary models and blending surfaces with regular meshes which are modeled by parametric design and represented as single domain B-spline surfaces by skinning, respectively.

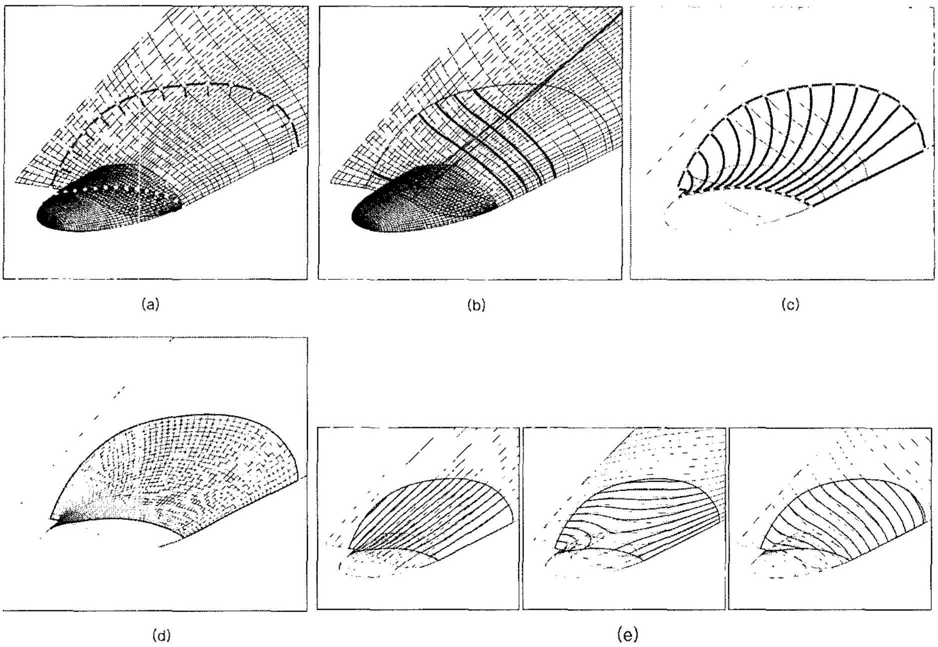


Figure 8: Generation of skin curves by indirect parametric surface design

In the second approach, the free-form elementary models and blending surfaces modeled by parametric design are combined by Boolean operations, considering G^1-continuity at boundary positions, and by SAC-BPD so that the combined hull form satisfies the given whole sectional area curve, see figure 1 (b)(below).

Figure 9 shows the design concept of complex ship hull forms by SAC-BPD proposed in this paper. The design process comprises seven steps:

1. Modeling of a bare hull
2. Modeling of a bulbous bow
3. Modeling of a stern bulb
4. SAC-BPD of the multiple domain hull form with bulbs
5. Blending surface design of a forebody
6. Blending surface design of an afterbody
7. Boolean combination of parametric surface models

Each step is characterized by its input, the process that is completely form parameter oriented and the output to be generated. The output of each process step constitutes the input to the next process step. In the first, second and third steps, the surface models and their *SACs* of bare hull, bulbous bow and stern bulb are generated by direct parametric surface design via following individual design parameters:

- Principal dimensions and form coefficients, e.g., prismatic coefficient C_P,
- Form parameters of primary basic curves,
- Form parameters for secondary basic curves.

Here, we call above parameters *local design parameters* for each elementary model and design parameters of the whole ship to be combined by elementary models *global design parameters*.

Then, based on the *SACs* of elementary models, the sectional area blending curves which join between bare hull and bulbs is generated by the parametric blending design of multiple segment planar curves (the fourth step). This step is the SAC-BPD for the whole ship and can be divided into two cases:

- The case that local design parameters for the sectional area blending curves are given as design conditions to be satisfied.
- The case that global design parameters for the whole ship's *SAC* are given as design conditions to be satisfied.

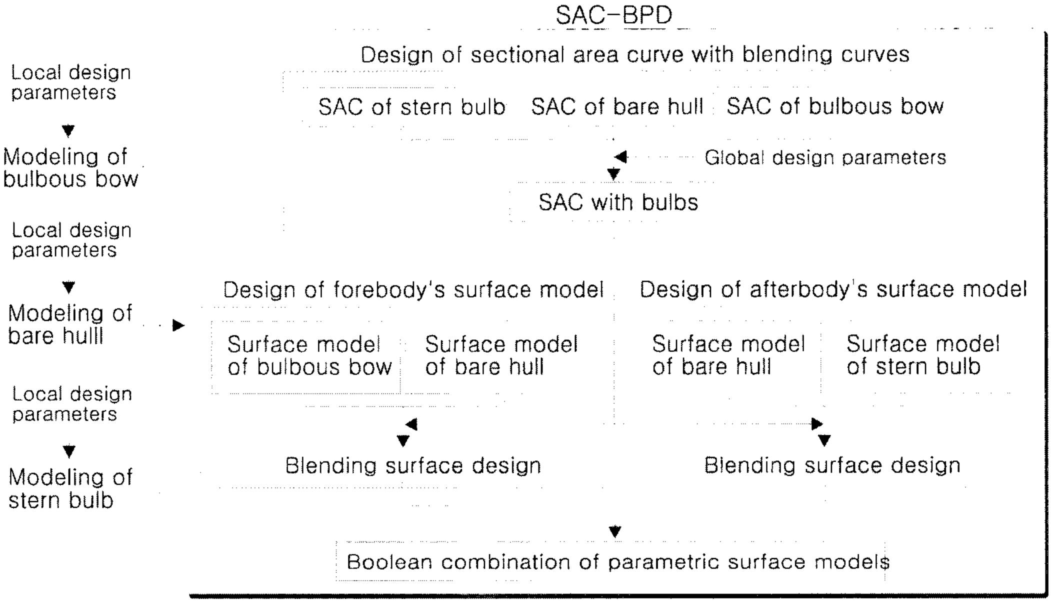


Figure 9: Design concept of ship hull forms with a complex topology

Table 3: Principal dimensions and desired design parameters of the Ville de Mercure

Design parameter	Symbol	Data	Value	Unit
Length between perpendiculars	L_{PP}		153.0	*m*
Breadth	B		27.5	*m*
Depth	D		14.0	*m*
Draft	T		10.6	*m*
Displacement	Δ_{GT}		29621.724	ton
Longitudinal centre of buoyancy	$x_{C_{GT}}$	$x_{C_{GT}} / L_{PP}$	0.4960	
Section area coefficient amidships	$C_{M_{GT}}$		0.9868	
Prismatic coefficient	$C_{P_{GT}}$		0.656	

In the first case, SAC-BPD is performed in order to meet local design parameters for the sectional area blending curves, e.g., volume and center of buoyancy of the blending curve, where global design parameters of the whole ship's *SAC* are determined automatically. As shown in figure 4, the volumes of blending curves occupied in the whole ship's *SAC* are small, thus notice that it is difficult to have the accurate local design parameters of the sectional area blending curves in practice specified by designer. If these specified local parameters are infeasible, the feasible sectional area blending curves can still be designed by SAC-BPD, because the SAC-BPD is based on the optimization technique, where the resulting form parameters do not have to match the given infeasible local parameters, but approximate them within the permissible domain. In the second case, SAC-BPD is performed in order to meet global design parameters for the whole ship's *SAC*, e.g., volume and center of buoyancy of the whole ship's *SAC*, where local design parameters of the sectional area blending curves are determined automatically. Global design parameters are computed from (8) and Boolean union. If infeasible global design parameters are given, *SACs* of elementary surface models as well as the sectional area blending curves must be modified by iteration using the optimization technique. Here, the whole ship hull form can globally or locally be varied according to the flexible selection of elementary surface models. In the fifth and sixth steps, blending surface modeling, based on elementary surface models and a *SAC* of the whole ship with bulbs, is accomplished separately in the forebody and afterbody by indirect parametric surface design. From the fourth step to the sixth step is the core of SAC-BPD in this thesis. In the last step the multiple surface models of the resulting hull form with bulbs are represented by Boolean combination based on topological and geometric considerations.

Table 4: Principal dimensions and desired local design parameters of the elementary surface models of the Ville de Mercure

Design parameter	Symbol	Data	Value	Unit
Bare hull				
Length between perpendiculars	L_{PP}		153.0	m
Breadth	B		27.5	m
Depth	D		14.0	m
Draft	T		10.6	m
Displacement	Δ_{GT}		27544.59	ton
Longitudinal centre of buoyancy	$x_{C_{GT}}$	$x_{C_{GT}} / L_{PP}$	0.5140	
Section area coefficient amidships	$C_{M_{GT}}$		0.9868	
Prismatic coefficient	$C_{P_{GT}}$		0.610	
Bulbous bow				
Protruding length	L_{PR_W}		11.57	m
Maximum breadth	B_{B_W}		4.1255	m
Total height	D_{B_W}		10.4940	m
Height of forwardmost point of the bulb over the base	Z_W		6.5190	m
Displacement	Δ_{B_W}		233.12	ton
Longitudinal centre of buoyancy	x_{C_W}	x_{C_W} / L_{PP}	Initially open	
Maximum section area coefficient	C_{M_W}		0.630	
Prismatic coefficient	C_{P_W}		0.720	
Stern bulb				
Protruding length	L_{PR_S}		10.5712	m
Maximum breadth	B_{B_S}		5.500	m
Total height	D_{B_S}		7.950	m
Height of forwardmost point of the bulb over the base	Z_S		3.7842	m
Radius of propeller bossing	R_S		0.575	m
Displacement	Δ_{B_S}		159.74	ton
Longitudinal centre of buoyancy	x_{C_S}	x_{C_S} / L_{PP}	Initially open	
Maximum section area coefficient	C_{M_S}		0.6501	
Prismatic coefficient	C_{P_S}		0.5181	

4 Example

Throughout this paper, a container carrier Ville de Mercure (HANSA 1986) has been used as an application example. In this section we present its final modeling results. Principal dimensions and desired global design parameters for modeling the container Ville de Mercure are summarized in table 3, while table 4 presents principal dimensions and local design parameters for its elementary surface models, where longitudinal centers of buoyancy of the bulbous bow and stern bulb are not given initially, but determined by iteration using the optimization technique. This is because it is difficult to define initially and exactly both volumes (or displacements) and longitudinal centers of buoyancy of them in order to design the envisioned shape without degeneration.

Each elementary surface model is generated by the process sequence of individual parametric design. Here, to generate the complex hull form subject to global design parameters, local design parameters of blending surfaces, which join between bare hull and bulbs in the forebody and afterbody, are computed by the SAC-BPD based on an optimization technique, which includes the parametric blending design of multiple segment planar curves and the indirect parametric surface design. Figure 4 shows the surface modeling results and associated volumes of bare hull, bulbous bow and stern bulb by individual parametric design. Table 5 presents the comparison of given and modeled local design parameters of the elementary surface models.

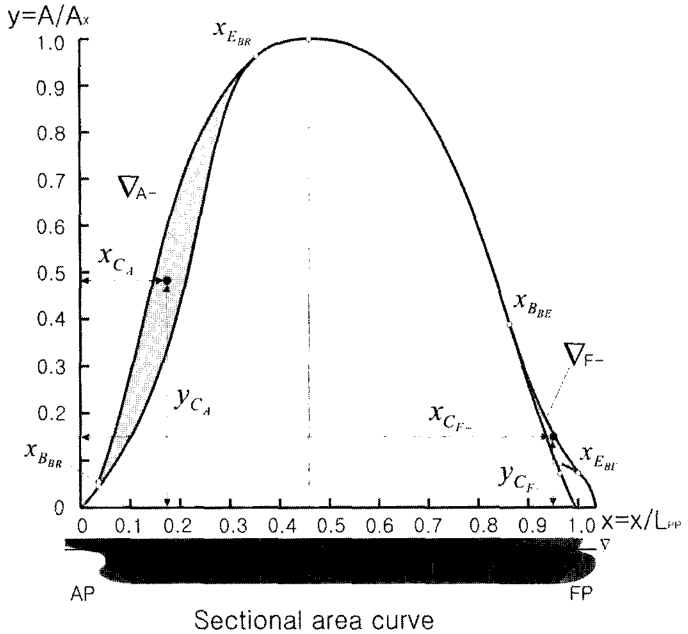
Table 5: Comparison of given and calculated local design parameters of the elementary surface models of the Ville de Mercure

Design requirement	Symbol	Data	Given	Calculated	Error
Bare hull					
Prismatic coefficient	C_{P_G}		0.6100	0.6100	-3.62e-06
Displacement (Ton)	Δ_G		27544.5909	27544.4351	-0.1559
Longitudinal centre of buoyancy	x_{C_G}	x_{C_G} / L_{PP}	0.5140	0.5140	-7.14e-06
Bulbous bow					
Prismatic coefficient	C_{P_W}		0.7200	0.7200	7.86e-06
Displacement (Ton)	Δ_{B_W}		233.1158	233.1184	0.0025
Longitudinal centre of buoyancy	x_{C_W}	x_{C_W} / L_{PP}	initially open	0.9911	
Stern bulb					
Prismatic coefficient	C_{P_S}		0.5180	0.5180	6.70e-07
Displacement (Ton)	Δ_{B_S}		159.7029	159.7031	0.0002
Longitudinal centre of buoyancy	x_{C_S}	x_{C_S} / L_{PP}	initially open	0.0807	

The *SAC*s of these elementary models are combined by Boolean operation in compliance with global design parameters, where B-spline control points of sectional area blending curves between the surface domains are used as unknown design variables in the parametric design process. Figure 4 shows the *SAC* of the whole ship including the *SAC*s of elementary models and blending curves. Local design parameters of blending surfaces can be given as design conditions by the designer. In that case, global design parameters are not specified to avoid conflicts. If infeasible global design parameters are given, there are two methods for the SAC-BPD: The first is the method which remodels the elementary models and blending surfaces so that the given global design parameters are met exactly. The second is the method which designs the blending surfaces so that global design parameters are only approximated. The former is concerned with global variation of an envisioned hull form, the latter deals with the local variation of an envisioned hull form. Our SAC-BPD is performed by the second method to model the container carrier *Ville de Mercure*. Table 6 and figure 10 present principal dimensions and local design parameters of the resulting blending surfaces in the forebody and afterbody which are generated by SAC-BPD. The displacement- and LCB-distribution of resulted elementary models and blending surfaces between perpendiculars are illustrated in figure 11. Table 7 shows the comparison of given and modeled global design parameters of whole ship. Based on the whole *SAC*, elementary models are combined together by the blending surfaces, which are modeled by indirect parametric surface design. The final hull form model for the container carrier Ville de Mercure is displayed in figure 12.

Table 6: Principal dimensions and local design parameters of the resulting blending surfaces of the Ville de Mercure

Design parameter	Symbol	Data	Value	Unit
Afterbody				
Longitudinal beginning position	$x_{B_{BR}}$		5.3288	m
Longitudinal end position	$x_{B_{ER}}$		54.0591	m
Added blending volume	∇_{A-}		1816.86	m^3
Added blending displacement	Δ_{A-}		1864.10	ton
Volume coefficient	$C_{\nabla_{A-}}$	$\nabla_{A-} / \nabla_{GT}$	0.0629	
Longitudinal centre of buoyancy of added blending area	$x_{C_{A-}}$	$x_{C_{A-}} / L_{PP}$	0.1769	
Height coordinate of added blending area's centroid	$y_{C_{A-}}$	$y_{C_{A-}} / L_{PP}$	0.4505	
Forebody				
Longitudinal beginning position	$x_{B_{BE}}$		132.0510	m
Longitudinal end position	$x_{B_{EE}}$		154.5000	m
Added blending volume	∇_{F-}		121.2972	m^3
Added blending displacement	Δ_{F-}		124.4509	ton
Volume coefficient	$C_{\nabla_{F-}}$	$\nabla_{F-} / \nabla_{GT}$	0.0042	
Longitudinal centre of buoyancy of added blending area	$x_{C_{F-}}$	$x_{C_{F-}} / L_{PP}$	0.9451	
Height coordinate of added blending area's centroid	$y_{C_{F-}}$	$x_{C_{F-}} / L_{PP}$	0.1462	



Firgure 10: Geometry of blending sectional area curve

Table 7: Boolean union results of the multiple segment curves in figure 4

Design requirement	Symbol	Data	Given	Calculated	Error
Total prismatic coefficient	$C_{P_{GT}}$		0.6560	0.6560	-7.3974e-06
Displacement (Ton)	Δ_{GT}		29621.72	29621.40	-3.2567e-01
Longitudinal centre of buoyancy	$x_{C_{GT}}$	$x_{C_{GT}} / L_{PP}$	0.4960	0.4960	-3.5167e-06

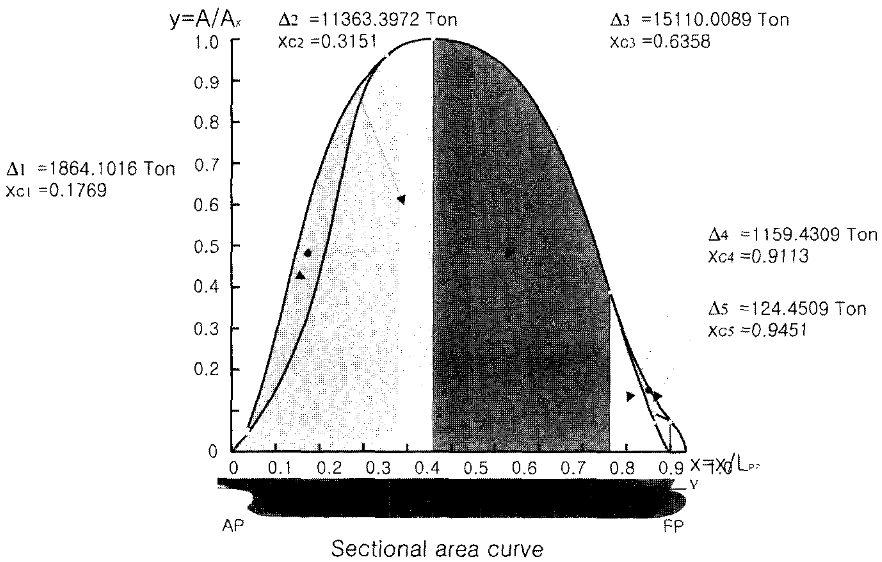


Figure 11: Displacement- and LCB-distribution of elementary models and blending surfaces between perpendiculars of the Ville de Mercure

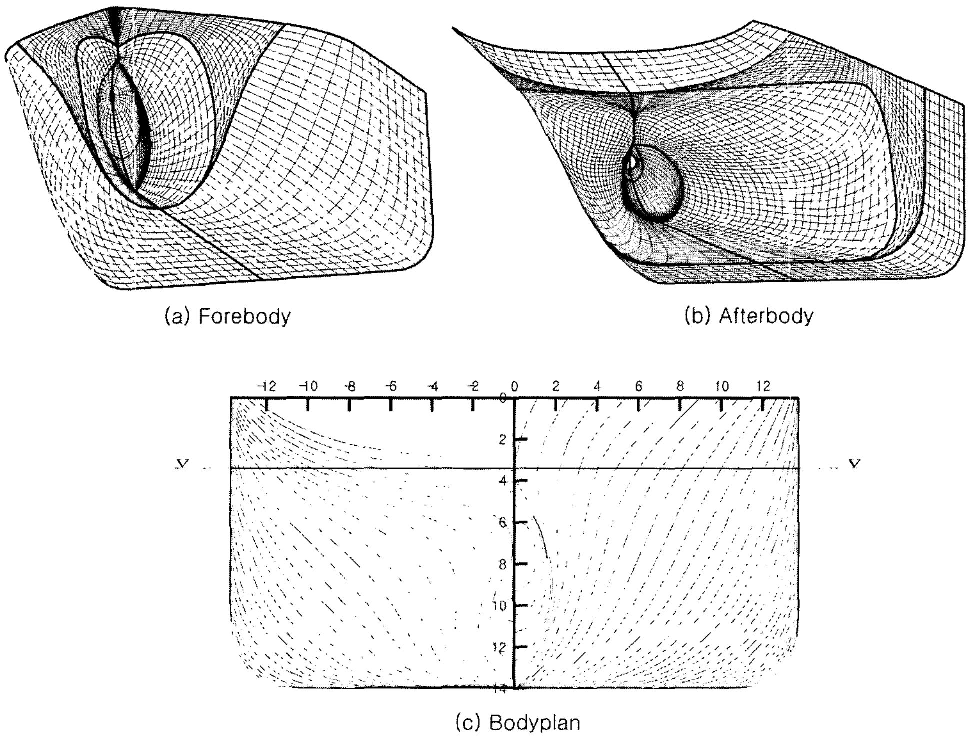


Figure 12: Final hull form model for the Ville de Mercure

4 Conclusion

New methodology for parametric design of ship hull forms with a complex multiple domain surface topology is presented. In this study the hull forms are divided into 4 elementary models - afterbody, forebody, bulbous bow and stern bulb - and two blending surfaces which join between them under the SAC-balanced design requirement. The parallel midbody can automatically be generated in the process of afterbody's and forebody's modeling. Each of the elementary models is fully defined in terms of its individual form parameters and combined by parametric design of blending surfaces via global form parameters and by Boolean operation.

Based on our results and experience the following conclusions can be drawn:

- *Use of different fairness criteria and design constraints* The parametric curve design method based on the viewpoint of optimization can be accomplished by minimizing different fairness measures subject to different design constraints.
- *Use of Boolean operators* In parametric design of multiple segment planar curves with blending curves, Boolean operators are applied to calculate integral form parameters.
- *Parametric design of multiple segment curves* Longitudinal basic curves with straight lines, which can typically be found in hull form design, are constructed by multiple segment curves including blending curves in which they are combined topologically and geometrically by Boolean operation and parametric design.

- *Complex free-form modeling capability* To express the hull form with a complex surface topology, we divide it into four types of elementary models, e.g., afterbody, forebody; bulbs, and two blending surfaces which join them. Each of the boundary surface models are generated by fully form parameter based design and combined by Boolean union.
- *Direct and indirect parametric surface design* Direct and indirect parametric surface design support the design methods to generate the free-form elementary models and blending surfaces satisfying the integral form parameters, e.g., volume(or displacement) and LCB, which are given by *SACs*.

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