PARAMETRIC DESIGN OF A SURFACE COMBATANT FOR SIMULATION-DRIVEN DESIGN AND HYDRODYNAMIC OPTIMIZATION

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Abstract- Ship design is an iterative process and generally depends on geometric modeling of ship hull form. Designer has to fulfill several different requirements developed out of regulations and customer's needs. In the hydrodynamic part of the design process, to be able to lead this system to an optimized design, the designer has to understand the behavior of the system within the complete design space. In today's common design processes it is mostly the modeling inside of a computer aided design (CAD) system that drives the process, while design performance is usually checked in the end by simulation. While this can merely be seen as trial and error, simulation-driven design takes a different approach by using simulation upfront to drive the development of the product's shape. For this purpose, the hull form geometry has to be modeled on a functional basis, i.e. the shape has to be defined and generated from a set of meaningful parameters. This paper focuses on parametric modeling of a surface combatant to be able to create variants systematically for further optimization studies. This issue will be addressed based on the CAESES as a unique CAD-CFD integration platform that serves as a workbench for parametric modeling, optimization and data interfaces to external flow simulation codes.

Keywords- Simulation-driven Design, Parametric Modeling, Hull Form Optimization.

I. INTRODUCTION

The ship hull with all its appendages is a rather complex system and a difficult geometry to be modeled. Hydrodynamic characteristic of a ship such as stability, resistance and seakeeping is directly connected with hull geometry. Optimization of the hydrodynamic properties of the hull form plays an important role at the preliminary design stage. In order to be competitive on the market, preliminary design stage has to be performed in a short period and also successfully to create better designs.

The traditional ship design process is often under the control of geometric modeling of the hull form. After this, hydrodynamic performance of the hull is analyzed with various simulation methods, for instance Computational Fluid Dynamics (CFD). If the result is not satisfactory, the iterative steps are repeated until the desired performance is obtained. These hull forms, which revealed by these method, are usually a negotiated solution rather than the optimum, that partially reflects the different performance criteria. This conventional approach is very time-consuming and depends on designer's know-how and experience in both naval architecture and geometric modeling.

In recent years, researchers have worked for application of CAD and CFD methods integrated and simultaneously in order to speed up the preliminary design and analysis stage and make it more efficient. Harries [1] has brought a new approach to geometric modeling of the hull form, thus create a new methodology for effective integration of CAD and CFD. This approach is based on modeling the curves and surfaces that create the hull geometry depending on several form parameters. In this way, any change applied to the parameters will be reflected to whole geometry while keeping the topology unchanged. As a result of this and similar developments in modeling the geometry, a new concept has emerged: Simulation-driven Design, SDD. The conventional approach can only serve to sample the design space and to select the best option from the choice of samples. Driven systematic variation however can be used to scan the complete design space and yields actual trend indications for all considered and varied design variables. Finally, by utilizing formal optimization algorithms, and this is the most consequent implementation of simulation-driven design, the simulation is really used to produce shapes, rather than just evaluating them [2].

In this paper, it will be focused on fully parametric design procedure of a frigate type surface combatant that will be used in further multi-objective optimization studies. CAESES (formerly called Friendship-Framework), a unique CAD-CFD integration platform, will be used to create a fully parametric model from a set of parameters. At first, the upper and lower bounds for main dimensions of the frigate will be defined after a preliminary design study and then a fully parametric model of the parent hull will be created according to global and local parameters. This parent hull will be used in further systematic variation and optimization studies.

II. FULLY-PARAMETRIC MODELING OF THE HULL FORM

2.1. Geometric Modeling Techniques

Geometric modeling techniques can be classified in many different ways (boundary representation vs. constructive solid geometry, regular vs. irregular

topology etc.), but in this paper a rather simple classification is used [3]:

- *Conventional modeling:* The shape is defined by completely independent objects that do not bear any problem-specific information. Changes are introduced by varying the positions of those objects. A B-spline surface described by a polyhedron of vertex points is a well-known example of a conventional geometric model.
- *Partially parametric modeling:* The shape itself is defined by an existing arbitrary conventional description, while changes applied to the shape are given by means of parameters that are associated with problem-specific properties. A prominent example in the naval field is the swinging of sections, i.e. an existing group of offsets, by a quadratic shift function as described by Lackenby [4].
- *Fully parametric modeling:* The geometry is entirely described by and created from parameters. Parameters are high-level descriptors that reflect the functional characteristics of the product. Variants are simply created by different instances of the parameter set's values. A simple example is a cylinder described by the parameters height and radius.

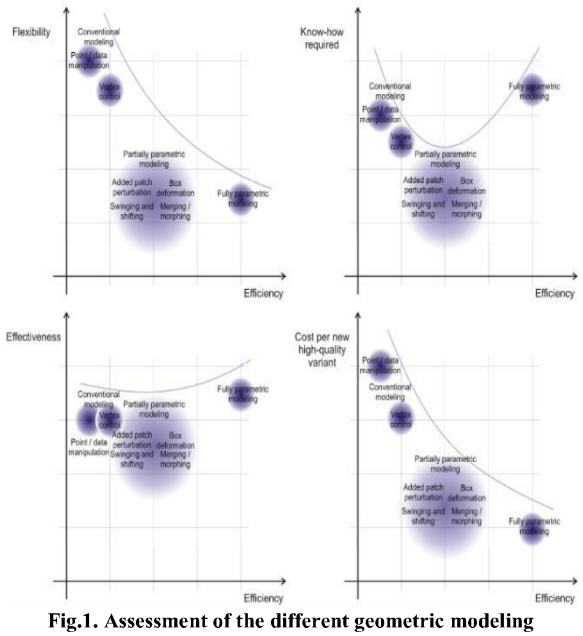


Fig.1. Assessment of the different geometric modeling techniques [3]

In **Fig.1.** various properties of the presented geometric modeling modes are plotted against the efficiency. It can be seen that, out of the three presented modes of modeling, fully parametric modeling is the most efficient and provides the best basis for the creation of reasonable variants. It is also the most effective and economic method. Then again, it is the least flexible (topologically) and requires the most knowhow to set up a model. Conventional modeling is the least efficient and economic method, also requires much know-how, but is the most flexible. Partially parametric modeling takes a kind of in-between role, except that it requires a much smaller amount of know-how than the other two methods.

In the context of optimization a parametric approach has an inherent advantage. While in a non-parametric approach the number of free variables – e.g. point data – that govern the problem rapidly becomes prohibitively high and the fine tuning of the variables to achieve a desirable result often gets very demanding, a parametric approach contents with just a few, but carefully selected form parameters to generate desirable shapes still leaving enough freedom for shape modification. Disadvantage of partially parametric transformation is limited solution space, because only a local area of the geometry is modified while the rest stay pretty much the same.

2.2. Fully Parametric Modeling and CAESES

In parametric modeling the design problem is formulated partly or even fully in terms of parameters. Parameters are the descriptors of the product to be developed and the product is represented at a much higher level then by point data alone as still done very often.

CAESES is a CAE package for the design of functional surfaces. It offers a wide range of CAD functionality for conventional NURBS-modeling, partially parametric modeling with various transformations and fully parametric modeling. Different variation and optimization algorithms for the automatic creation of variants are integrated as so-called Design Engines, and an efficient handling of variants and constraints is offered. CFD solvers are coupled to the CAD through various levels of integration; tool- or project specific integration or by a common data interface. Therefore, results of CFD computations can be easily used as measures of merit for optimization procedures, driving the design process [5]. In CAESES, a hull's geometry is generated in terms of form parameters and fairness criteria. The form parameters are high-level and design relevant descriptors of the envisioned shape like e.g. the waterplane area, the longitudinal center of flotation and the angle of entrance of the design waterline. A mathematically closed B-spline description of a ship hull is generated within a geometric optimization process where fairness is viewed as the measure of merit and form parameters are treated as equality constraints. This yields excellent shape quality and high accuracy without any need for manual B-spline vertex control. The approach is thus applicable to both manual and fully-automated optimization [6].

Within this system the modeling process is subdivided into three consecutive steps: Parametric design of a suitable set of longitudinal basic curves, parametric modeling of a sufficient set of design sections derived from the basic curves and generation of parametric surfaces under the control of parametric control curves. The flowchart of the parametric surface modeling approach is shown in **Fig.2.**

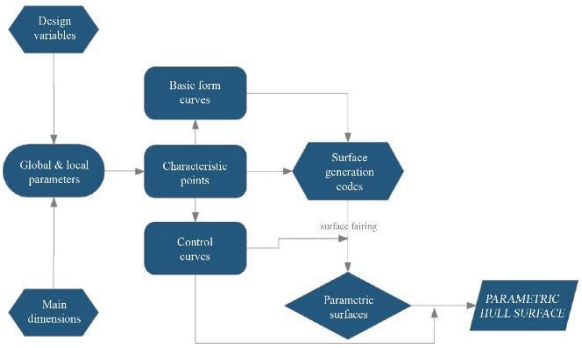


Fig.2. Stages of parametric hull form modeling [7]

As it can be seen from the figure, characteristic points that used to create parametric curves will be connected to the global or local parameters. It is also necessary to connect the parameters to design variables if they are desired to be changed systematically.

2.2.1. General Characteristics of Initial Hull Form

Before the geometric modeling a preliminary design study was realized to define the general characteristics of parent hull. The main dimensions of existing frigates were investigated and the limits of the design space was examined. **Fig.3-6** show some design ratios of existing frigates. As can be seen from the figures, frigates cover a wide design space. To define meaningful upper and lower bounds, the areas that designs are centered around were indicated on graphs.

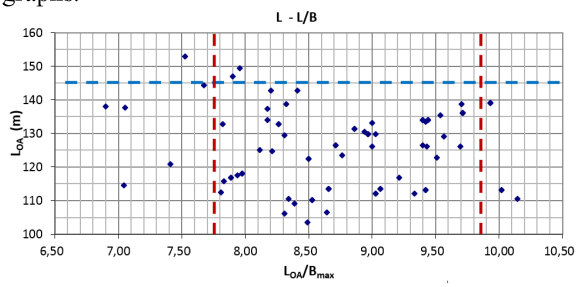


Fig.3. L-L/B range of existing frigates

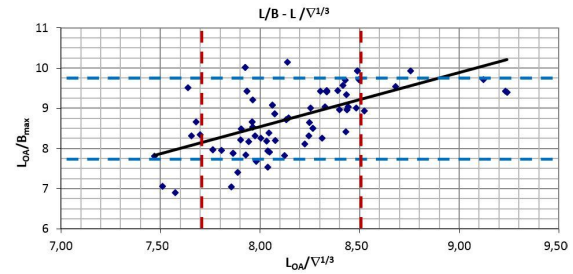


Fig.4. L/B-L/$\nabla^{1/3}$ range of existing frigates

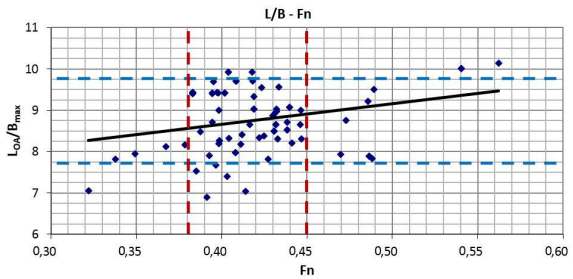


Fig.5. L/B-B range of existing frigates

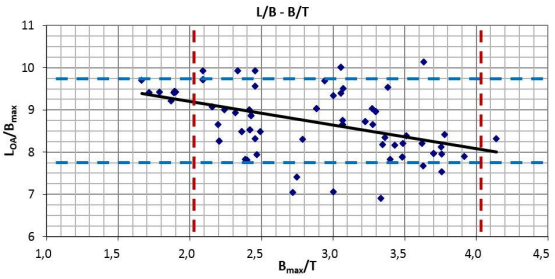


Fig.6. L/B-B/T range of existing frigates

The main dimensions and some non-dimensional coefficients of initial hull form was given in **Table 1.**

Table 1: Main dimensions of the initial hull form

Length overall, L_{OA} (m)	145	L_{WL} / B_{WL}	8.3
Length waterline, L_{WL} (m)	139	L_{WL} / $\nabla^{1/3}$	7.75
Maximum breadth, B_{max} (m)	18.203	LCB/L_{WL}	0.44
Depth, D (m)	11.2		
Waterline breadth, B_{WL} (m)	16.747 (B_{max}*0.92)		

2.2.2. Parametric Modeling of Basic Curves

The main innovation of the software is the use of a new kind curve, called the F-spline (**Fig.7**). F-spline is an optimized curve for smoothness and can be defined with a beginning and an ending point and their tangent angles. Area under the curve and its centroid can be also defined. Harries and Abt [8] has reported that, F-spline curve has been revealed as a result of optimization for Fairness Criteria (Eq. 2) of a B-spline curve consist of m points and the degree of k, expressed as in Eq. 1;

$$Q(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \sum_{i=0}^{m-1} V_i . N_{ik}(t) \qquad (1)$$

$$E_n = \int_{t_B}^{t_E} \left(\left(\frac{d^m x}{dt^n} \right)^2 + \left(\frac{d^m y}{dt^n} \right)^2 \right) dt, \quad n = 1,2,3 \qquad (2)$$

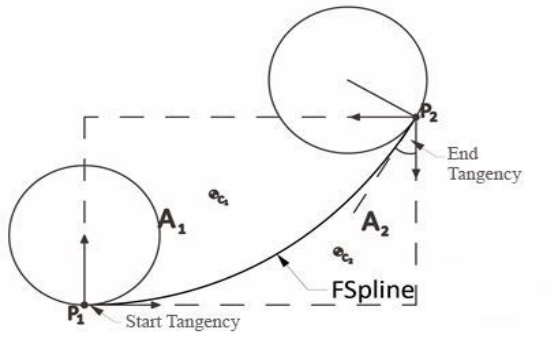
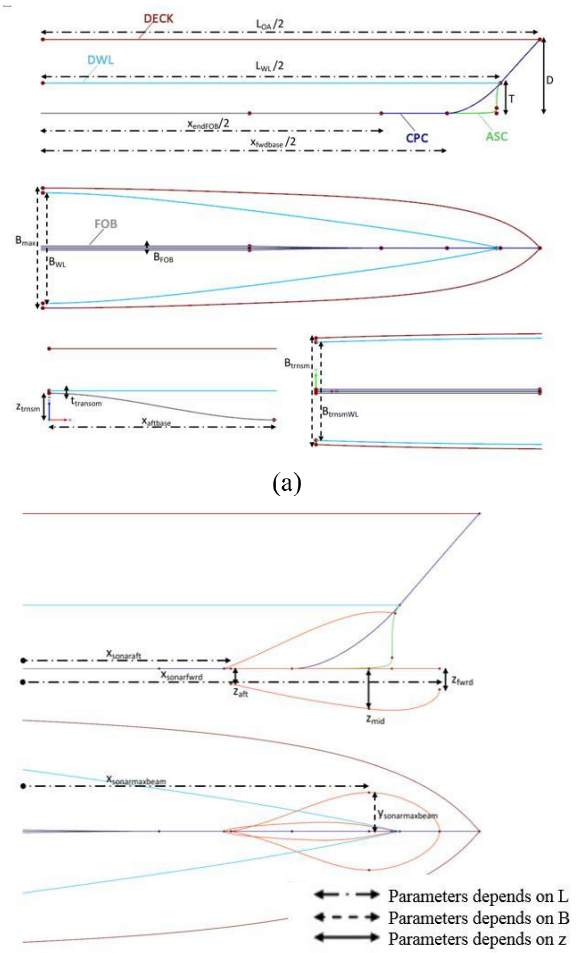


Fig.7. F-spline curve

In this work it was aimed to create a fully parametric model for a frigate with different bow types, conventional and with a sonardome. During modeling, positional, differential (tangent values) and integral (area values) parameters were used. These parameters can be divided into two groups: Global parameters that specify main dimensions and ship's general characteristics and local parameters created specifically for a particular curve or surface. For instance, length of the hull is a global parameter while the longitudinal position of maximum width of sonardome is a local parameter.

To model the hull form fully-parametric it was needed longitudinal basic curves to define the outline of the geometry, as shown in **Fig. 8a**. Additional adaptive curve was created to be able to optimize the bow form. This curve was modeled subject to various parameters to allow the formation of different bow types. Similarly some additional parametric curves were created to add a sonar dome to the bow, as shown in **Fig. 8b**. The list of basic curves was also given in Table 2.



(a)

(b)

Fig.8. Curves used in parametric model (a) Basic curves (b) Curves for sonar dome

Table 2: Basic form curves

Name of Parametric Curve	Abbreviation
Central Profile Curve	CPC
Deck Curve	DECK
Design Waterline	DWL
Flat of Bottom	FOB
Adaptive Stem Curve	ASC

2.2.3. Control Curves and Sections

Basic curves are infrastructure for obtaining parametric surfaces. It has to be modeled a sufficient set of design sections especially the locations that the form shape changes dramatically.

In this work, four parametric surface groups was created with use of basic curves and design sections. Sonardome surface was also modeled as completely fitted to bow shape. Basic curves of sonardome and specifically designed Adaptive Stem Curve (ASC) allows to alter bow shape from conventional type to sonardome smoothly with changing a parameter. It is a smooth transition between the surface groups through the ship's length by means of control curves. Control curves (**Fig.9.**) has to be also fair to provide this smooth transition. Therefore, the tangential angles of control curves were controlled by various parameters at the points that the hull form changed. The list of control curves was given in **Table 3**.

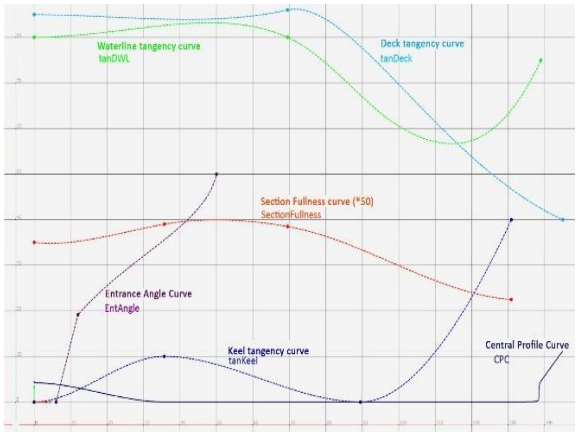


Fig.9. Control curves

Table 3: Basic form curves

Name of Parametric Curve	Abbreviation
Entrance Angle Curve	EntAngle
Tangent Curve at Design Waterline	tanDWL
Tangent Curve at Deck	tanDeck
Tangent Curve at Keel	tanKeel
Sectional Fulness Curve	SectionFullness

Design section curve at any x position imports essential data from basic curves and control curves. An example section curve and its parameters was given in **Fig.10**.

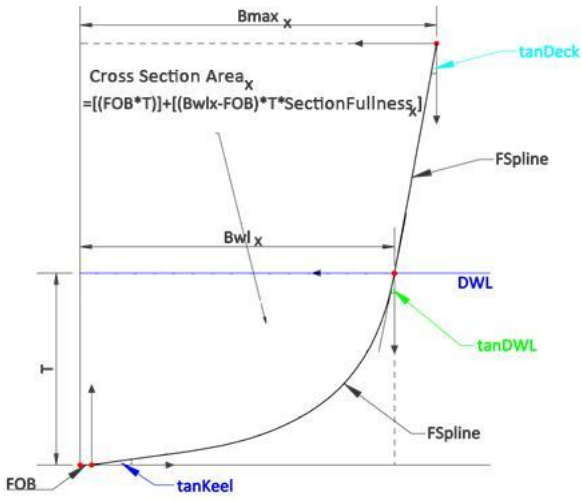


Fig.10. Section curve at any x position

RESULTS AND DISCUSSION

In CAESES there are several types of surface generation methods like commonly used B-Spline and NURBS. Differently, a new parametric and optimized surface type, called as meta-surface, was used to create hull form, shown in **Fig.11**. Thus, the hull surface is completely controlled by parameters and new forms that will be created with the change of parameters will also have a smooth surface as well as the parent hull. The both hulls with/without sonardome are exactly identical except dome geometry.

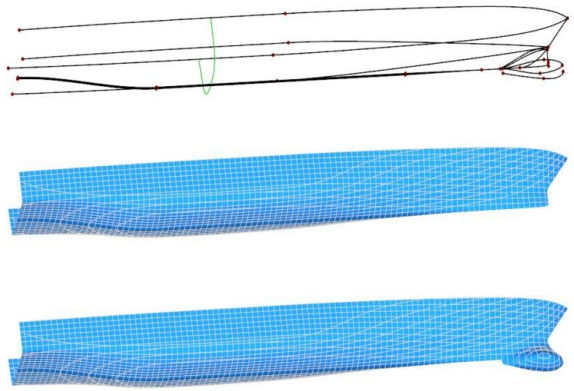


Fig.11. Parametric surface of parent hull form, with and without sonardome

After modeling the parent hull form the geometry was arranged to have desired properties according to preliminary design study by manually changing the parameters used for parametric design. Additional parameters has defined to be able to calculate the form coefficients. Some coefficients and values were arranged to be separately calculated for aft and fore ship to allow further optimization studies.

Also an internal optimization loop was formed to ensure the displacement value kept same even though some parameters would change. This feature will be useful for optimization studies.

Finally a systematic variation study was realized for single length according to design variables defined as a result of preliminary design study. Three parameters was chosen to change systematically and the other parameters were kept constant. Variable and constant parameters was given in **Fig. 12**. As a result of systematic variation process 225 alternative hull forms were generated.

Variable parameters			
L_{WL}/B_{WL}		7.5, 7.7, 7.9, 8.1, 8.3, 8.5, 8.7, 8.9, 9.1	
Ⓜ=L_{WL} / $\nabla^{1/3}$		7.5, 7.75, 8, 8.25, 8.5	
LCB/L_{WL}		0.42, 0.44, 0.46, 0.48, 0.50	
Constant parameters			
L_{WL}	139 m	C_B	0.490
L_{WL}/D	12.4	C_P	0.607
i_E	12°	$C_{WPkiç}$, $C_{WPbaş}$	0.984 , 0.600
B_{max}/B_{WL}	0.92	C_M	0.807
B_T/B_X	0.92	$t_{transom}$	0.4 m

Fig.12. Variable and constant parameters for systematic variation

CONCLUSIONS

In this paper, it was mentioned about the advantages of fully-parametric modeling and compared with other modeling approaches. A frigate hull form was modeled as a case study and finally created lots of variants automatically with similar surface topology. This work takes lead to connection of CFD, seakeeping and stability software to CAESES to collect the multi-objective optimization process under one roof and handle it automatically.

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