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Hull Separation Optimization of Catamaran Unmanned Surface Vehicle Powered with Hydrogen Fuel Cell

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***Abstract*—**This paper presents an optimization of the hull separation, i.e. transverse clearance. The main objective is to identify the feasible speed ranges and find the optimum transverse clearance considering the minimum wave-making resistance. The dimensions and the weight of hardware systems installed in the catamaran structured fuel cell powered USV (Unmanned Surface Vehicle) were considered as constraints. As the CAE (Computer Aided Engineering) platform *FRIENDSHIP-Framework* was used. The hull surface modeling, DoE (Design of Experiment), Tangent search optimization, tool integration and the process automation were performed by FRIENDSHIP-Framework. The hydrodynamic result was evaluated by XPAN the potential solver of SHIPFLOW.

***Keywords*—**Full parametric modeling, Hull Separation, Wave-making resistance, Design Of Experiment, Tangent search method

I. INTRODUCTION

WITH the increase on replacement of power source in ships by regulation reinforcements for environments, fuel cell system as a new power source has become essential for both terrestrial and marine applications against the intensity. For the purpose on developing commercial fuel cell powered USV, catamaran has been chosen because of its outstanding performances with respect to speed, rolling, resistance, maneuvering and sea-keeping. Catamaran resistance and propeller efficiency depend on transverse clearance, hull asymmetry, principal dimensions ratios, and hull form. With the ship speed, displacement, and length of a monohull and a catamaran being equal, the latter should have a higher propulsion power, or with speed and capacity being equal, the catamaran needs less power. However, resistance of a catamaran is usually greater than that of her two isolated hulls summed, except for some ranges of Fn (Froude number) and clearance ratio when it is less than the double resistance of a demihull [1]. Ship design is typically governed by numerous constraints that all need to be observed.

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Evaluating a complex constraint might take tangible effort (for instance, simulating the hydrodynamics for an off-design point) but also constraints that entail less computational burden are difficult to oversee if there are many [2]. The user-friendly integration of hull form modeling, simulation and optimization can be performed a CAE system that offers the flexible integration of tools available in the individual design environment. Viscous resistance interference was found to be relatively independent of speed and hull separation and rather is dependent on demihull-length-to beam ratio. It is evident that a significant reduction in resistance could be achieved by finding the optimum position of stagger [3]. For valuating resistance characteristics of catamaran structured fuel cell powered unmanned surface vehicle, wave interference effect due to the interaction of the wave systems produced by each demihull contributing to the total resistance should be minimized by optimization of the hull separation [4]. Transverse clearance should be flexibly generated and changed according to various required power on fuel cell powered USV considering all dimensions of hardware systems, respectively.The aim of the present work is to investigate the wave-making characteristics of a catamaran hull and to optimize the distance of the hull which has parallel middle body to install lithium polymer batteries and motor driver required for the electricity supply to navigation system and for its systematic integration.

II. DESCRIPTION OF HULL

A. Layout of Equipments

The initial hull shape is mainly featured to satisfy the dimension of the internal equipment. Lithium polymer, motor driver and motor are placed in the parallel middle body region of both side hulls. Both demihulls and center hull are manufactured to adjust hull separation that directly affects the wave-making resistance due to the interference effect. Fuelcell powered USV is installed in the center body. Wiring is possible to connect all systems through the aluminum pipes. (See Fig.1)

B. Hull dimension

Under the consideration of the weight and size of all mechanical and electrical systems, the principal dimensions were developed as shown in Table I.

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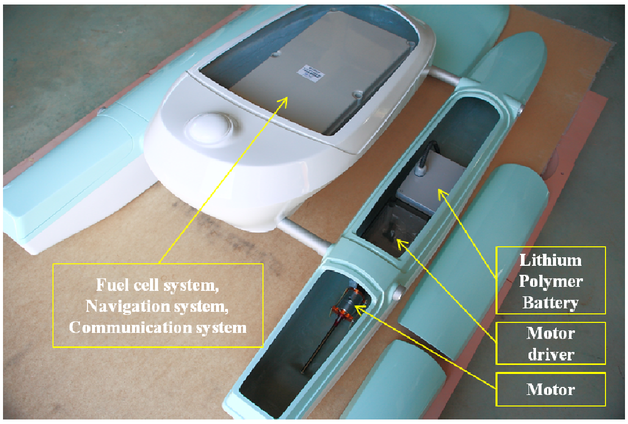

Fig. 1 Layout of equipments

TABLE I
PRINCIPAL PARTICULARS OF FUEL CELL POWERED USV (DEMIHULL)

Symbol	Quantity	Particulars
L_{pp}	Length	1.487 m
B	Breadth	0.2 m
T	Draft	0.15 m
D	Depth	0.07 m
C_B	Block Coefficient	0.5279
Δ	Displacement	27.5 kg

TABLE II
AFTERBODY HULL FORM

Parameters	Quantity
zTransom	Center Plane Curve
xFOBTail	
zBilgeTail	Bilge Curve

TABLE III
MIDBODY HULL FORM

Parameters	Quantity
xParBeg	Section Shape
xParEnd	
yFOBMax	
Bhalf	
Height	
zBilgeHeight	

TABLE IV
FOREBODY HULL FORM

Parameters	Quantity
CoefficientAtFOBBeak	Section Shape
CoefficientAtDwlForeShoulder	
TangentAtFOBBeak	
TangentAtDwlForeShoulder	
EntranceAngle	Design Waterline
FOBEntranceAngle	Flat Of Bottom

TABLE V
BASIC CURVES DESCRIBING HULL FORM

Curves	Quantity
DWL	DesignWaterLine
FOS	FlatOfSide
CPC	CenterPlaneCurve
Bilge	Bilge Curve
FOB	FlatOfBottom
Deck	Deck Curve
Stem	Stem Curve
TanAtDWL	Tangent Curve at DWL
TanAtDeck	Tangent Curve at Deck
TanAtStem	Tangent Curve at Stem
SAC	Section Area Curve

III. HULL FORM DESIGN BASED ON PARAMETRIC MODELING

A. *Parametric Modification Function*

Parametric modification method is the way to vary hull form by changing generally formulated form parameters. However, the difficulty of deciding hull form variation exists as design parameters change and hull form variation can be different by which design parameters or design range are chosen. Parametric modification function has demerit that design parameters are dependent on designer's know-how. Design parameters and basic curves that affect each section, e.g. afterbody, midbody, forebody, are demonstrated in Table 2,3,4,5.

B. *Full Parametric Design based on basic curves*

As shown in Fig. 2 each basic curves and area curves in the longitudinal direction are generated by using Fspline-curves expressed by form parameters and then 3 dimensional surfaces can be generated by information from basic curves and area curves. Basic curves in the longitudinal direction for generating 3 dimensional hull form consist of form curves expressed by form parameters of Table 2,3,4. and characteristic curves which express longitudinal distribution of 3 dimensional surface characteristic.

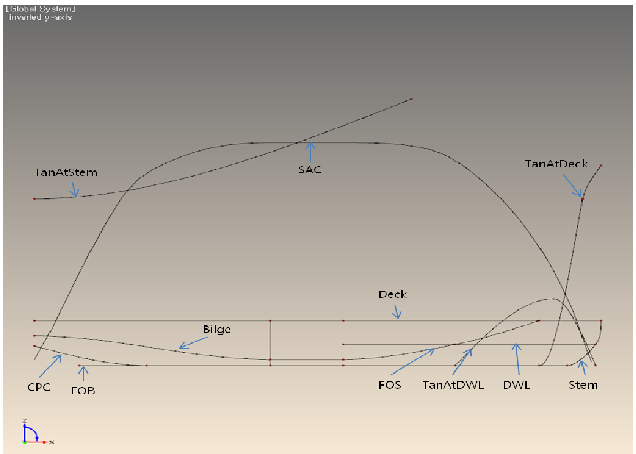

Fig. 2 Full parametric design based on basic curves

IV. DISTANCE OPTIMIZATION OF HULL SEPARATION

The main idea for optimization is simulation-driven design. Computer simulation produced a number of variants and converged to the best design automatically. What design has to do is to set the conditions and to trigger the whole process. As shown in Fig. 3, process flow for hydrodynamic optimization is introduced in section A.

A. Process flow

- Set the values of geometric parameters and define all basic curves.
- Define the hull surfaces based on the all basic curves defined in the previous step.
- Extract offset groups from section information defined by the surfaces.
- Evaluate the hydrostatic values.
- Vary hull form using Lackenby entity. When the change of values of Cp and LCB position were detected, Lackenby entity rearranges section positions to keep the given values maintaining the smoothness of the longitudinal area distribution, i.e. faired SAC.
- Start CFD calculation to obtain the quantitative results of the hydrodynamic characteristics of the varied hull form.
- Start design engine to evaluate the objective values and verify if the design constraints are satisfied. If the process does not meet the termination condition, a new set of values of design variables are produced and given to the geometric parameters at the first stage.

In the fully parametric design every parameters can be chosen as design variables in the optimization process. In this research project, however, only the optimum hull separation was considered to be evaluated. Meanwhile all other geometric parameters are fixed during the optimization process. Therefore the hydrostatic characteristic of the demi-hull is maintained, too. Entire process is controlled by FRIENDSHIP-Framework.

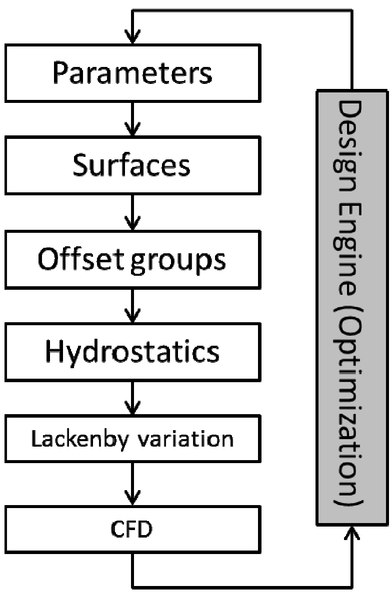

Fig. 3 General process flow

B. CFD calculation

The prime concern of hydrodynamics in this study is wave resistance performance of a catamaran. The non-linear wave-making resistance was assessed by means of the potential module of the famous commercial CFD code SHIPFLOW. The wave-making resistance was determined by pressure integration and transverse wave cut analysis. Since the demi-hull has not complicated shape without bulbous bow and stern bulb, the pressure integration returned the robust result of wave coefficient (Cw). The typical wave system of catamaran is caused from the wave interference between the two demi-hulls and the disturbed wave produces wave pattern resistance downstream after ship's body. The far-field transverse wave cut analysis returns the coefficient of the wave pattern resistance (Cwtwc). In order to combine the two aspects of wave-making resistance, the averaged value of $(2C_w + C_{wtwc})/2$ was introduced. Preventing that the wave-making resistance characteristic is leaning toward Cwtwc, factor 2 was given to Cw value. Since the body is symmetric, one-half of the computational domain was used for numerical treatment. The panels from 1.5 ship length upstream to 3.0 ship length downstream covered the free surface domains. The transverse extension of the free surface was about 1.5 ship length. The number of panels on one-half of the hull and free surface was 2,466.

C. Optimization Approach

Often there exist several feasible Fn areas which are of good advantage to the resistance performance. The feasible speed ranges of catamaran at the fixed distance 0.62 m can be seen in Fig. 4.

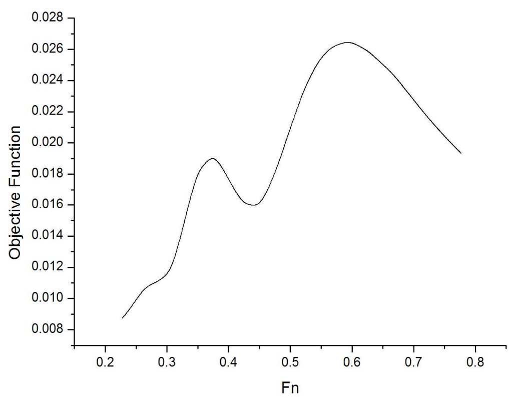

Fig. 4 Nonlinear wave-making resistance characteristics

Feasible Froude number range exists around Fn 0.3 and Fn 0.45 that the favorable interference due to wave superposition in the center wave profile of catamaran can be expected. Wave superposition significantly affects resistance at high speed rather than at medium speed. On the other hand, breaking wave that applies pressure to each hull gradually occurs from Fn 0.3 to Fn 0.37. The upper part in Fig. 5 shows wave pattern at Fn 0.3 and lower part shows it at Fn 0.45, which are obvious that diverging waves are radiating from the bow together with transverse waves.

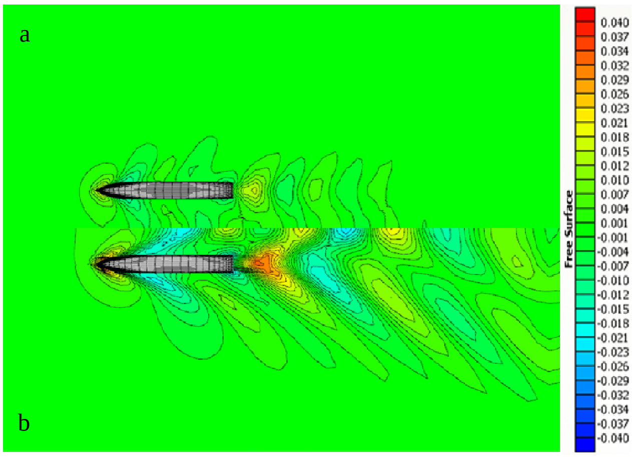

Fig. 5 Wave pattern of feasible Fn ranges at fixed distances : (a) wave pattern at Fn = 0.30 (b) wave pattern at Fn = 0.45

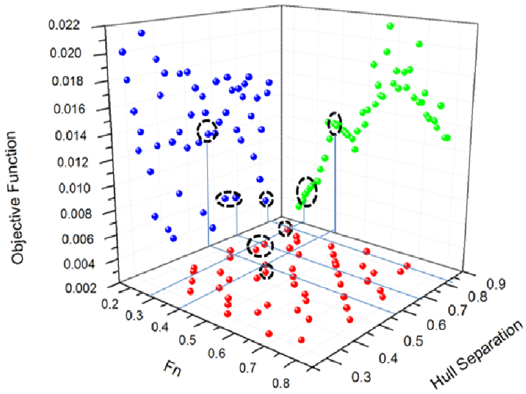

Fig. 7 Feasible distance and Fn at middle speed range

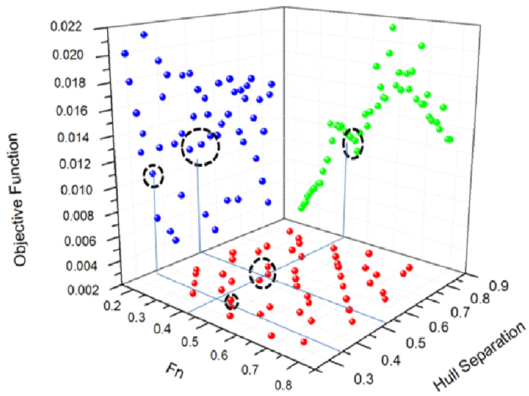

Fig. 6 Feasible distance and Fn at high speed range

Sobol which is deterministic algorithm that imitates the behavior of random sequences known as quasi-random shows the tendency or the relationship between objective function and hull separation, Froude number and hull separation, objective function and Froude number. Hull separation which is parameter is limited from 0.3 to 0.8. In Fig. 6, when hull separation is 0.598m, 0.548m, 0.504m and 0.37m, objective function is 0.0121, 0.0115, 0.0113, 0.0102 and Froude number is 0.40, 0.42, 0.43, 0.45, respectively. The tendency by Sobol shows that if the speed increases from Fn 0.40 to 0.45 hull separation becomes narrower to reach to minimum wave-making resistance. Optimization with constraint that hull separation is limited to vary from 0.6m to 0.3m is performed by Tsearch method. In the start of the optimization at middle speed range, hull separation value at Fn 0.40 which had minimum wave-making resistance at high speed ranges is selected to be a constraint for optimizing hull separation at middle speed ranges. In Fig. 7, when hull separation is 0.824m, 0.691m, 0.643m and 0.598m, objective function is 0.0042, 0.0055, 0.0058, 0.0121 and Froude number is 0.25, 0.27, 0.29, 0.40, respectively.

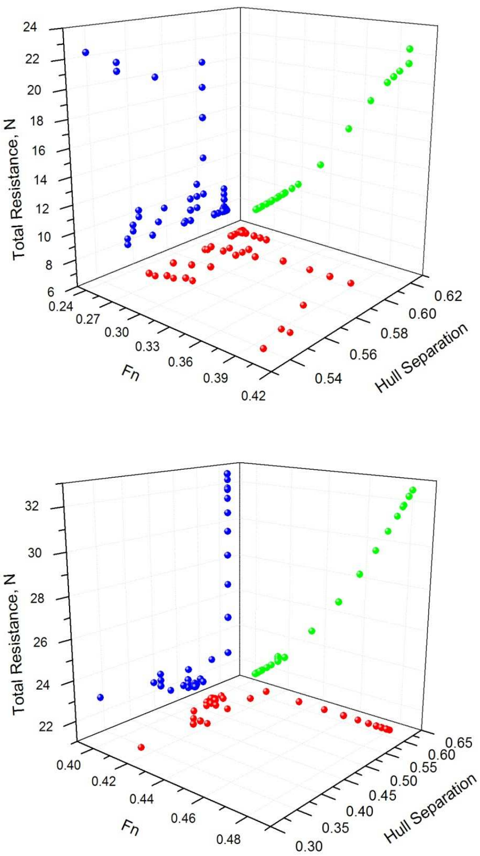

Fig. 8 Optimized speeds and distances at middle speed (upper graph), at high speed (lower graph)

The tendency by Sobol shows that if the speed decreases from Fn 0.40 to 0.25 hull separation becomes wider to reach to minimum wave-making resistance because the favorable interference does not have a strong effect on wave-making resistance at middle speed range.

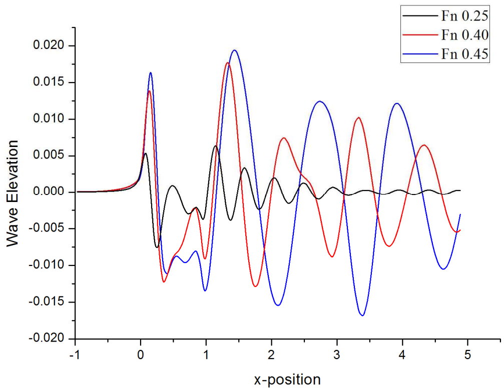

Fig. 9 Wave elevation in the inner wave profile

After DOE, local optimization by Tsearch method results that hull separation converges on 0.62m as Froude number at middle speed range in Fig. 8 converges on minimum number, 0.25, of the constraint and results that hull separation converges on 0.54m as Froude number at high speed range in Fig. 8 converges on minimum number, 0.40, of the constraint. Wave-making resistance considering varying wetted surfaces and frictional resistance from ITTC 57 are calculated to obtain total resistance.

Due to the interference between the bow wave systems, a deep crest and trough are present in Fig. 9. Moreover, the wave crest and trough move downstream as the Froude number increases. Remarkable results can be observed that favorable interference after wave superposition diminishes second crest at Fn 0.40 and that radiating wave at Fn 0.25 tends to decrease from 0.5 position to 1 position where it dominates the wave-making resistance.

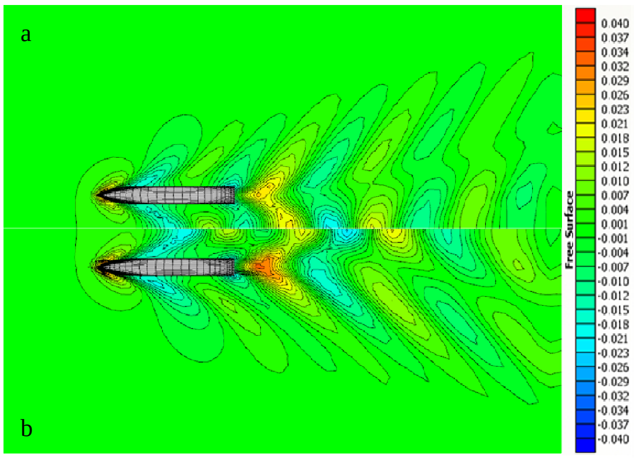

Fig. 10 Wave pattern at optimized high speed ranges : (a) wave pattern at Fn = 0.40 (b) wave pattern at Fn = 0.45

As it can be seen in Fig. 10, 11, the presence of the twin hull has a strong influence on the wave pattern in the inner region, whereas on the outer region the change respect to the monohull is rather small.

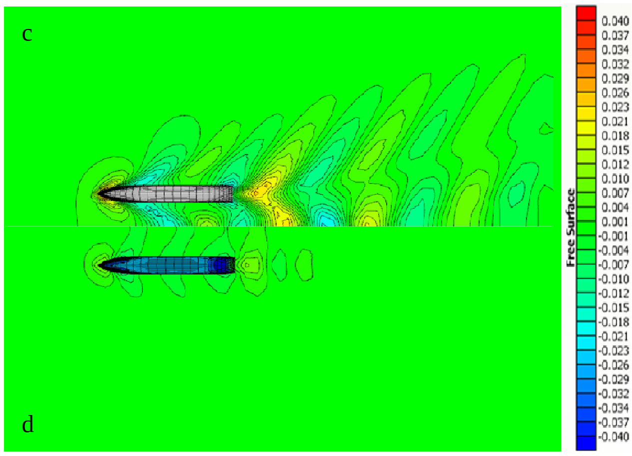

Fig. 11 Wave pattern at optimized middle speed ranges : (c) wave pattern at Fn = 0.40 (d) wave pattern at Fn = 0.25

V. Conclusion

Full parametric modeling of a fuel cell powered unmanned surface vehicle considering all the dimensions of navigation system, motor system, lithium polymer batteries, fuel cell system and communication system have been applied. An analysis of the performances and the interference dependency on the separation distance between the twin hulls has been performed by combining an optimization framework and hydrodynamic analysis tool (SHIPFLOW 4.4**).** With the performances and the interference dependency, the results of optimizing hull separation at middle speed and at high speed have been successfully converged on 0.62m and 0.54m, respectively.

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