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Investigation of Hydrodynamic Characteristics of High Speed Multihull Vessels including Shallow Water Effect

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Abstract

The objective of this paper is to investigate the hydrodynamic characteristics of high speed catamaran and trimaran ships at different speeds and finite depths using Computational Fluid Dynamics (CFD) techniques. Three dimensional Rankine Source Panel Method with non-linear free-surface boundary condition is used to capture free-surface potential flow around ship hull. Wave pattern, wave resistance, sinkage and trim for varying lateral and longitudinal separation of hull with varying water depths are determined and compared with each other to investigate spacing and depth effects on multihull ship. Computed results show a significant increase in total resistance for water of finite depth compared to deep water. A significant increase in sinkage and trim has also been found in the case of shallow water for both vessels.

Keywords: catamaran; trimaran; wave resistance; Rankine source; lateral spacing; longitudinal spacing

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1. Introduction

Catamaran and trimaran hull forms are very popular because of their lower wave resistance at high speed corresponding to reduction in power and larger deck areas. But there is often a strong interference between the wave systems generated by the hull depending on various lateral and longitudinal positions of hull spacing which causes increased or decreased wave making resistance. Investigation of ship behavior in restricted water depth is needed during sea trials and when ship comes to port or harbor. Shallow water creates restriction in vertical direction resulting in increased velocity and resistance beneath the ship bottom compared to deep water. In order to investigate this phenomenon various experimental and numerical studies have been performed by various researchers.

Resistance components of high speed catamarans were analyzed by Insel and Molland [1] and by Molland et al.[2], the investigation being focused on the effect of the separation distance, length over beam, length over displacement and breadth over draught ratios for a systematic series of high speed displacement catamarans; valuable experimental results were reported in terms of viscous and non viscous resistance components, as well as wake contours. Moraes et al [3] investigated the wave resistance component of high speed catamarans and the effects of shallow water on these wave resistance components using the slender body theory proposed by Michell [4] and a 3D method used by Shipflow software. Results were obtained for different types of twin hulls and attention was given to the effects of catamaran hull spacing. Tarafder and Suzuki [5] investigated the influence of the water depth and the wave interference effects on the first and second order wave making resistance of the catamaran hull using a potential based boundary element

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method. Wang [6] developed a 3D Rankine source panel method for calculating the linear wave-making resistance of a trimaran with Wigley hulls. Non uniform rational B-spline (NURBS) was adopted to represent body surface and to calculate the normal vector and derivative vectors of the NURBS surface. But all of these investigations were mainly carried out only for mathematical and systematic series hull form instead of any existing practical ship's hull forms and they focus mostly on lateral spacing of the outriggers without considering the effect of longitudinal stagger.

This paper focuses on determination of hydrodynamic characteristics of high speed transom stern catamaran and trimaran hull form in different lateral and longitudinal spacing with varying water depth. Wave height, wave making resistace, sinkage and trim at different speeds from deep to shallow water are determined by using 3D Rankine source panel method of Shipflow CFD code with non-linear free-surface boundary conditions. Previously, analytical methods were used which require rigorous computation [1–6]. Moreover, presence of non-linear free surface and application to practical hull form make those methods more complicated.

Nomenclature

F_n	Froude number
R_n	Reynolds number
h	water depth
∇	Laplacian operator
Φ	velocity potential
η	free-surface wave elevation
p	pressure at any point on hull
p_∞	pressure at free-surface

2. Mathematical modeling of the problem

Consider a ship moving with a constant speed U in the direction of the positive x, y axis extends to the starboard side and z- axis upwards where origin is located in the undisturbed free surface at aft perpendicular of the hull form so that the undisturbed incident flow appears to be a streaming flow in the positive-x direction. To determine free-surface shape and the flow far away the hull, panel method solver is used. It is assumed that the fluid is incompressible and inviscid and the flow is irrotational. Consequently, the continuity equation becomes:

$$\vec{\nabla}.\vec{U} = \vec{\nabla}.(\vec{\nabla}\Phi) = \nabla^2\Phi = 0 \tag{1}$$

Equation. (1) is a linear equation. Thus, the potential Φ can be decomposed in an asymptotic potential ϕ_∞ and a perturbation potential ϕ :

$$\Phi = \phi_\infty + \phi \tag{2}$$

Boundary condition on the impermeable surface of the hull is:

$$(\vec{\nabla}\Phi).\vec{n} = 0 \tag{3}$$

For a generic point P placed at a large distance r from the body, the (asymptotic) boundary condition is:

$$\Phi(P) = \phi_\infty \quad r \rightarrow \infty \tag{4}$$

At the free-surface the kinematic and dynamic boundary conditions have to be imposed. Kinematic free-surface boundary condition implies that the normal velocity at the free- surface is zero:

$$\frac{\partial\Phi}{\partial n} = -\vec{U}.\vec{n_{fs}} = 0 \tag{5}$$

Defining the free-surface as $z = \eta(x, y)$ yields

$$\frac{\partial \Phi}{\partial x}\frac{\partial \eta}{\partial x} + \frac{\partial \Phi}{\partial y}\frac{\partial \eta}{\partial y} - \frac{\partial \Phi}{\partial z} = 0 \tag{6}$$

Dynamic boundary condition requires that the pressure is constant on the free-surface. Applying the Bernoulli's theorem on the undisturbed free-surface far away from the body and at one point on the wavy part of the free-surface yields:

$$g\eta + \frac{1}{2}\Big[\Big(\frac{\partial \Phi}{\partial x}\Big)^2 + \Big(\frac{\partial \Phi}{\partial y}\Big)^2 + \Big(\frac{\partial \Phi}{\partial z}\Big)^2 - U^2\Big] = 0 \tag{7}$$

Finally, it is necessary to impose radiation boundary condition to ensure that no waves upstream of the hull shall be created. Although, the Equation. (1) is linear, the free surface boundary conditions, i.e., Equation (6) and (7) are non-linear with unknown velocity potential Φ and the wave elevation . Moreover, the location of free-surface where these equations are to be applied is initially unknown.

Potential flow methods can be either linear or nonlinear for the free surface. Linear methods apply the boundary conditions on an undisturbed free surface and the nonlinear terms for the unknowns are ignored. For nonlinear methods, the boundary conditions are applied to a free surface with waves using waves generated from the previous solution in the next iteration. Nonlinear methods are considered more accurate than linear method.

Pressure on the hull surface by Bernoulli's equation:

$$p - p_\infty = \frac{1}{2}\rho(U^2 - \nabla\Phi.\nabla\Phi) - \rho g z \tag{8}$$

Hydrodynamic force and wave making resistance:

$$R_w = -\int_S (p - p_\infty) n_x ds \tag{9}$$

$$C_w = \frac{R_w}{0.5\rho S V^2} \tag{10}$$

3. Description of hull

In this paper high speed transom stern R/V ATHENA ship hull has been taken for the investigation. Body plan and perspective view of the hull are shown in Fig. 3. Principal particulars are described in Table 1. Various lateral spacing, s/L of Athena catamaran and longitudinal stagger (a/L) of trimaran side hulls are shown in Fig.2 and Fig.3 respectively

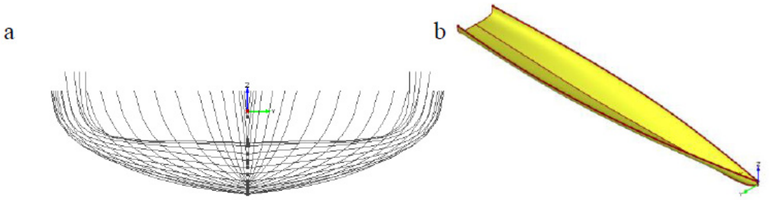

Fig. 1: R/V ATHENA ship hull (a) body plan; (b) perspective view

Table 1: Principal particulars of Athena hull

Length Between Perpendicular	LBP	1 m
Breadth to length ratio	B/L	0.1336
Draft to length ratio	T/L	0.0743
Block coefficient	C_B	0.512
Water plane area coefficient	C_W	0.74

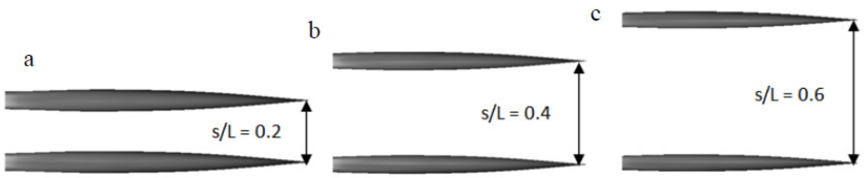

Fig. 2: Three lateral spacing of catamaran (a) s/L = 0.2; (b) s/L = 0.42; (c) s/L = 0.6

Table 2: Various configuration of trimaran lateral and longitudinal spacing

	Case 1			Case 2			Case 3		
Lateral spacing,s/L		0.2			0.4			0.6	
Longitudinal spacing, a/L	0	0.2	0.3	0	0.2	0.3	0	0.2	0.3

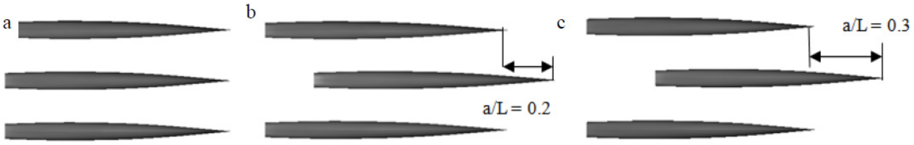

Fig. 3: Case 1 trimaran hull configuration at s/L = 0.2 (a) a/L = 0; (b) a/L = 0.2; (c) a/L = 0.25

4. Results and discussion

In this paper wave making resistance, sinkage and trim of various lateral and longitudinal spacing of catamaran and trimaran hulls at various water depths are investigated which are discussed in this section.

4.1. Mesh generation

The surface of the ship and the water surface are divided into flat, ideally square panels commonly with constant source strength as shown in Fig. 4. This means that the only unknown parameter for each panel is the source strength. An equation corresponding to the boundary condition is applied to one point on each panel, called the collocation point, which gives N points with N equations and N unknown source strengths. From this system of equations, the velocity at every point in the flow is calculated to get the potential flow around the hull.

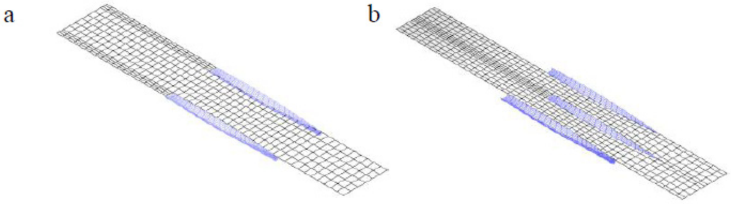

Fig. 4: Flat quadrilateral panel meshes on body and free-surface (a) catamaran; (b) trimaran hulls

4.2. *Wave pattern*

Wave pattern generated by catamaran hull at deep and shallow water is shown in Fig.5. From fig, it is apparent that wave height is increased when it moves deep to shallow water. Wave pattern around trimaran hull is shown in Fig.6. From figs, it is apparent that wave interference is less when there is longitudinal spacing between demihull and side outriggers.

Wave pattern generally consists of transverse and divergent waves in deep water making an angle of according to Kelvin wave pattern. For shallow water case, wave pattern largely depends on depth Froude number. which determines the wave angle on the path of the ship.

Transverse and divergent waves are observed to meet at the location of the highest wave height for both catamaran and trimaran hulls.

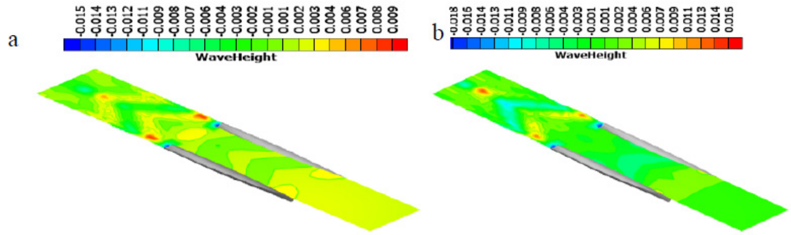

Fig. 5: Wave pattern around catamaran hull at s/L = 0.4 (a) deep water; (b) shallow water

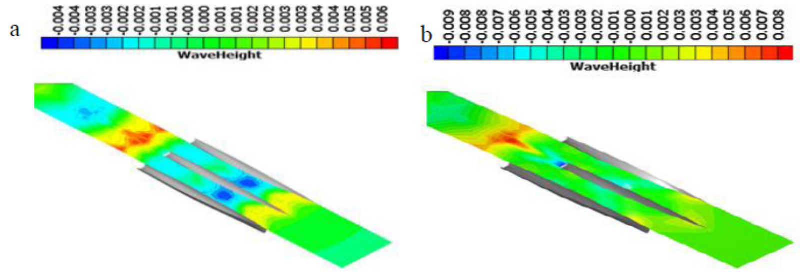

Fig. 6: Wave pattern around trimaran hull (a) no stagger a/L = 0; (b) a/L = 0.3

4.3. *Wave resistance of catamaran hull*

Wave resistance for catamaran hull at various lateral spacing and water depths are shown in Fig.7. Fig.7(a) shows that wave resistance decreases with increase of lateral spacing due to reduction of interference effect. Fig.6 (b-d) shows comparison of wave resistance at deep and shallow water (L/h = 6, L/h =5). It is apparent that for the shallow water case, there is a drastic increase in resistance particularly at Fn. 0.4-0.5. It can be attributed to the fact at this speed range, ship speed approaches to wave speed called critical speed and shallow water effect becomes predominant when more energy is taken from the ship.

4.4. *Wave resistance of trimaran hull*

Wave resistance for trimaran hull at various longitudinal and lateral spacing with shallow water effect are shown in Fig.8. It is apparent that shallow water effect causes drastic increase in wave resistance at critical speed of Fn. 0.5

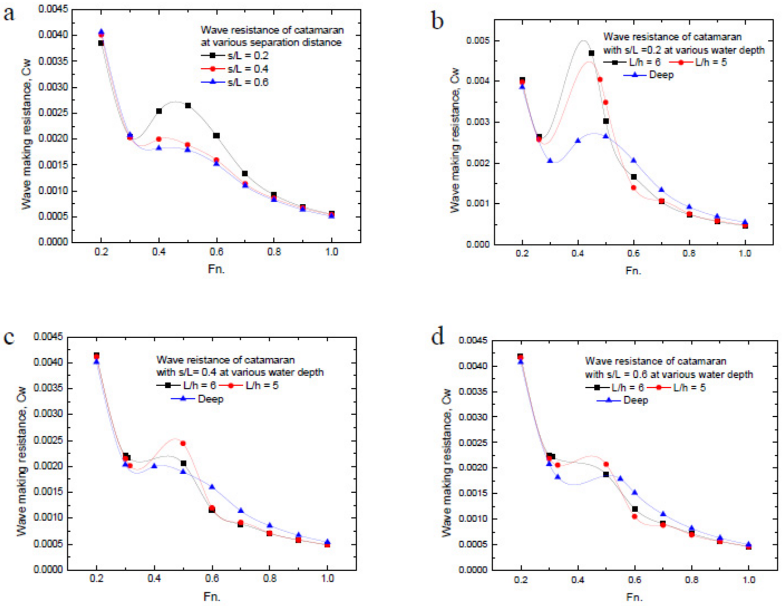

Fig. 7: Wave resistance of catamaran hull (a) various lateral spacing; shallow water effect at (b) s/L = 0.2;(c) s/L = 0.4;(d) s/L = 0.6

and minimum resistance occurs at lateral spacing s/L = 0.6 and longitudinal spacing a/L = 0.3, leads to the conclusion that trimaran interference effect decrease with increase in lateral and longitudinal spacings as shown in Fig.8(c).

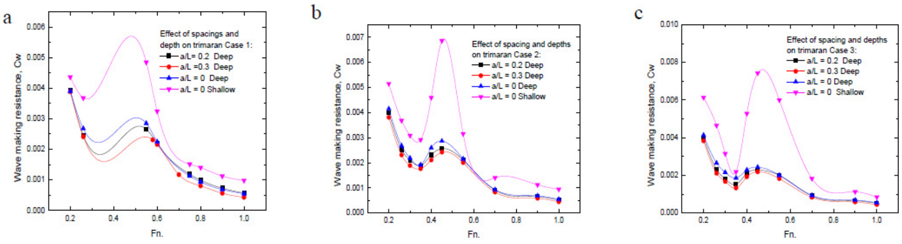

Fig. 8: Wave resistance of trimaran hull at various spacings and water depths (a) Case 1; (b) Case 2;(c) Case 3

4.5. *Sinkage and trim*

Shallow water effect on sinkage and trim of the vessel can be described by squat phenomenon. According to this phenomenon, there is a reduction of pressure under the hull for shallow water for fast moving water. Therefore a combination of vertical sinkage and change of trim occur that cause the ship to dip towards the stern or bow.

Sinkage and trim for catamaran hull at various lateral spacing and water are shown in Fig.8. It is found that in shallow water, as the speed approaches critical, the vessel firstly rises then sinks significantly through the critical region before rising again at higher speeds. Here maximum sinkage occurs at the stern with lateral spacing 0.4. Sinkage and trim for trimaran hull with no stagger at deep and shallow water are shown in Fig. 9. It is apparent that maximum sinkage and trim angle occurs at critical speed (Fn 0.5) at stern for shallow water case.

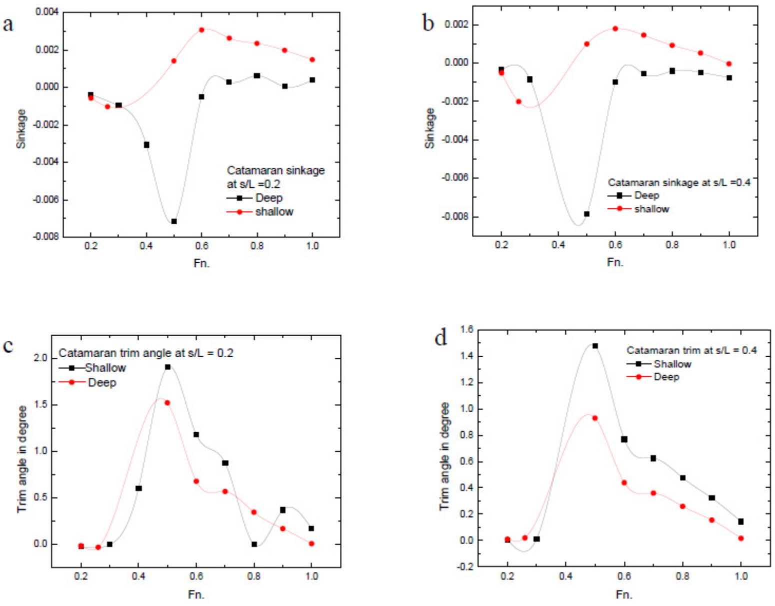

Fig. 9: Sinkage and trim of catamaran hull at various depth (a) sinkages/L = 0.2;(b) sinkages/L = 0.4;(c) trim s/L = 0.2;(d) trim s/L = 0.4

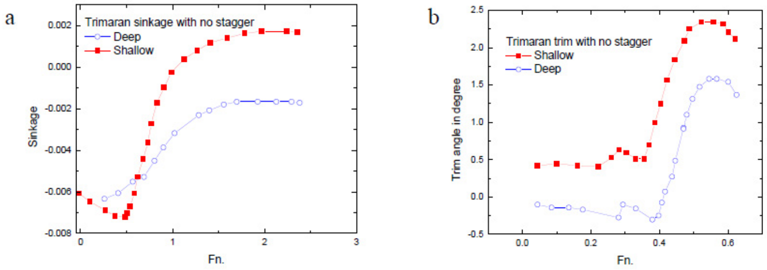

Fig. 10: Trimaran hull with s/L = 0.2 at various depth (a) sinkage; (b) trim

5. Conclusions

This paper investigates various hydrodynamic characteristics of high speed transom stern catamaran and trimaran ship hulls with various lateral and longitudinal spacing and changing water depth. From the above mentioned results and discussions following conclusions can be drawn:

i The 3D Rankine source panel method could be a useful tool for the hydrodynamic analysis of catamaran and trimaran ships at an infinite and finite depth of water.
ii Wave making resistance, sinkage, trim and interference effect can be minimized by optimizing hull separation distance.
iii Computed sinkage and trim effect for shallow water case can play an important role to determine the grounding effect of the ship.
iv As the free-surface wave height only determined from potential flow without considering the viscous effect for simplicity; it may not depicts the real picture of the free-surface flow.
v The computed results depend to a certain extent on the discretization of the body and the free-surface. So, the present technique must be validated with experimental results for such hull shapes.

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