Optimization of Trimaran Design Configuration in Calm and Deep Water

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Abstract. The field of sea based modern shipping activities is constantly seeking for its improvements to achieve the economically justified operational patterns. In the same time, the sea transportation activities also need to satisfy currently imposed and, as well as, upcoming in the near future, safety and ecologically friendly footprint characteristics when it comes to the emission of greenhouse gasses and hard particles [1]. Fulfilment of the stated requirements consequently asks for the determination of certain vessels operational parameters such as the total resistance of a vessel which estimation is frequently carried out for predefined calm and deep-water environmental scenario. Current work is dealing with investigation of the total resistance parameter in calm and deep water for the preselected types of the trimaran ship hull configurations. The total resistance is estimated according to [2] recommended procedure through applicability of the robust and reliable method which is capable to address the problem of wave resistance prediction in calm and deep water. The method has origin in ordinary and modified Michell thin – ship wave theory by considering the viscous effects [3]. The differences between the utilized theories are discussed from the qualitative and quantitative point of view of the obtained results in comparison to the open source available theoretical experimental data and from the perspective of common engineering practice. Finally, based on the above description, the performed total resistance studies are used as a base for formulation of the optimization procedure which may be used in the trimaran vessel preliminary designs in the range of the forward speeds commonly expected during the normal operational life of the investigated trimaran vessel.

Keywords. Optimal Trimaran Design, Total Resistance, Calm and Deep water, Viscous effects

1. Introduction

In the ship design process, the integration of computational tools for hydrodynamic performance prediction has steadily progressed in the last decades. Improvement of computational power and evolvement of user-friendly commercial tools have led to a rapidly increasing use of Computational Fluid Dynamics (CFD) for the purpose of optimizing hull designs. The time for setting up and executing CFD simulations is however still limiting the number of parameters and iterations that can be examined within the time frame of early phase design studies. Hence, potential flow computations

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are still highly relevant for examining large design space problems within ship design particularly in the realm of concept studies. Such quick and reliable tools are very suitable for integration into automized optimization and screening processes.

In early phase studies, the relative differences between designs are more important than the absolute values and can for instance serve in narrowing down the relevant parameters for later CFD simulations or model tests.

An example of such a study relates to identifying the most favourable positioning of a trimaran's side hull relative to the centre hull, over the vessel's anticipated operating speeds.

Based on the above, the present work, in the discussion which follows, will demonstrate how to approach to the trimaran (or multihulls) preliminary optimization design problem from a practical point of view. In this respect, the particular attention will be given to the demonstration of the inclusion of the viscous effects so, that the theoretically (numerically) estimated values of the total resistance of the trimaran (or multihulls) will be at the realistic comparable levels to the experimental results and, as well as, the real full scale trimaran results.

2. Calm Water Resistance

Current section will outline the composition of the total resistance R_T used during the analysis of the considered trimaran ship hull configurations while they operate in calm and deep water. As will be shown in the discussion which follows the attention is given to the estimation of the wave making resistance R_W which can be predicted without and with the presence of the viscous effects.

The total resistance R_T in calm water of a high-speed vessel is estimated following [3] and expressed through linear superposition of the subcomponents

$$R_T = R_F(1+k_1) + \Delta R_F + R_W + R_A + R_H \tag{1}$$

where

- R_F = frictional resistance; International Tank Towing Conference (ITTC) 1957 formula,
- $1+k_1$ = hull form factor,
- ΔR_F = friction resistance due to hull roughness,
- R_W = wave-making resistance,
- R_A = still-air resistance,
- R_H = hydrostatic resistance due to flow separation at (dry) transom stern, [5].

In the current work, to simplify the further analysis, only the resistance components due to friction R_F (ITTC 1957) and wave making R_W are taken into account. However, more details related to the estimation of other resistance components stated above can be found for instance in [4, 5].

2.1. Applied Michell Wave Theory

For a generally designed trimaran ship (see Figure 1) which is assumed to advance on a steady straight line course in calm and deep water at constant speed U the wave-making resistance R_W for the main hull and for the two side hulls (each separately) can be expressed as:

$$R_{W_j} = -\frac{4}{\pi}\rho U^2 \nu^2 \int_1^{\infty} \frac{\lambda^2}{\sqrt{\lambda^2-1}} \left|A_j(\lambda)\right|^2 d\lambda$$
$$A_j(\lambda) = -i\nu\lambda \iint_{cp_j} \zeta_j(x,z)\, e^{\nu z\lambda^2 + i\nu x\lambda} dz dx - \int_{-T}^{0} \zeta_j(x_S,z)\, e^{\nu z\lambda^2 + i\nu x_S\lambda} dz \tag{2}$$

where j = 1, 2 and 3 (number of the hull according to Figure 1), where $A_j(\lambda)$ represents the complex wave amplitude of an each hull, ν is defined as $\nu = g/U^2$, index s indicates the transom stern section (if present), g is the acceleration of gravity and i is the imaginary unit.

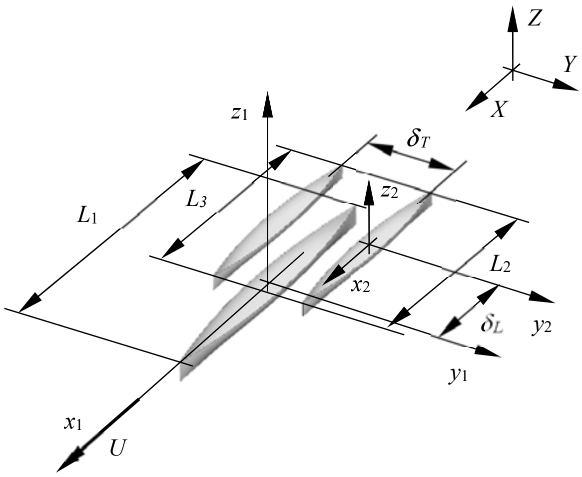


Figure 1. Coordinate systems and main parameters. XYZ – Earth-fixed coordinate system, $x_iy_iz_i$ – body-fixed coordinate system, U – mean forward speed, δ_T – transverse distance, δ_L – longitudinal distance, L_i – body length (ship hull), (i = 1, 2 and 3). Note: The body-fixed coordinate system is not shown on the side hull number 3.

The hydrodynamic interaction effects between the main hull and the side hulls are accounted for by the interference wave resistance function $R_{Wm\Leftrightarrow n}$ which is given by:

$$R_{W_{m\Leftrightarrow n}} = -\frac{8}{\pi}\rho U^2 \nu^2 \int_1^{\infty} \frac{\lambda^2 d\lambda}{\sqrt{\lambda^2-1}} \cos\left(\nu\delta_T\lambda\sqrt{\lambda^2-1}\right)$$
$$\left\{\mathrm{Re}\left[A_m(\lambda)\overline{A_n(\lambda)}\right]\cos(\nu\lambda\delta_L) - \mathrm{Im}\left[A_m(\lambda)\overline{A_n(\lambda)}\right]\sin(\nu\lambda\delta_L)\right\} \tag{3}$$

where the wave amplitude (complex) functions $A_m(\lambda)$ and $A_n(\lambda)$ are expressed by (2, see $A_j(\lambda)$). Re means the real part, Im means the imaginary part and the bar over the wave amplitude functions designates the complex conjugate value. The sub-indexes m and n

are in the same time having values, according to Figure 1, $m = 1$ and $n = 2$, $m = 1$ and $n = 3$, and $m = 2$ and $n = 3$. Here, each outlined combination stands alone, i.e. independently of each other and the total wave-making resistance R_W is finally linearly superimposed and expressed as:

$$R_W = R_{W1} + R_{W2} + R_{W3} + R_{W1\Leftrightarrow 2} + R_{W1\Leftrightarrow 3} + R_{W2\Leftrightarrow 3} \tag{4}$$

(for general multihull case see [6]).

2.2. Wave Making Theories with the viscous effects

As can be recognized the above outlined expressions are providing estimation of the wave-making resistance R_W for a general trimaran according to Michell wave theory based on the potential fluid flow theory (for more details see [5, 6 and 7].

With the inclusion of the viscous effects the above expressions (2 and 3) can be modified according to [8] for each hull separately (see Figure 1) as:

$$R_{W_j} = -\frac{4}{\pi}\rho U^2 \nu^2 \int_1^\infty \frac{\lambda^2}{\sqrt{\lambda^2-1}} \left[\frac{\alpha}{\pi} \int_0^\infty \frac{\lambda^5 q^5}{(q-1)^2 + \alpha^2 \lambda^{10} q^6} \left| A_j(\lambda q) \right|^2 dq \right] d\lambda$$
$$A_j(\lambda q) = -i\nu\lambda q \iint_{cp_j} \zeta_j(x,z) e^{\nu z\lambda^2 q + i\nu x\lambda q} dz dx - \int_{-T}^{0} \zeta_j(x_S,z) e^{\nu z\lambda^2 q + i\nu x_S \lambda q} dz \tag{5}$$

while the interference wave resistance $R_{Wm\Leftrightarrow n}$ between the main hull and two side hulls is given with:

$$R_{W_{m\Leftrightarrow n}} = -\frac{8}{\pi}\rho U^2 \nu^2 \int_1^\infty \frac{\lambda^2 d\lambda}{\sqrt{\lambda^2-1}} \left\{ \frac{\alpha}{\pi} \int_0^\infty \frac{\lambda^5 q^5}{(q-1)^2 + \alpha^2 \lambda^{10} q^6} \cos\left(\nu\delta_T \lambda q \sqrt{\lambda^2-1}\right) \right.$$
$$\left. \left\{ \mathrm{Re}\left[A_m(\lambda q) \overline{A_n(\lambda q)} \right] \cos(\nu\lambda\delta_L) - \mathrm{Im}\left[A_m(\lambda q) \overline{A_n(\lambda q)} \right] \sin(\nu\lambda\delta_L) \right\} dq \right\} \tag{6}$$

Another way which shows how the presence of the viscous effects can be considered is according to [9] and it is outlined as follows for each hull separately (see Figure 1) as:

$$R_{W_j} = -\frac{4}{\pi}\rho U^2 \nu^2 \int_1^\infty \frac{\lambda^2}{\sqrt{\lambda^2-1}} \left[\frac{\beta}{\pi} \int_0^\infty \frac{\lambda^3 q^4}{(q-1)^2 + \beta^2 \lambda^6 q^4} \left| A_j(\lambda q) \right|^2 dq \right] d\lambda$$
$$A_j(\lambda q) = -i\nu\lambda q \iint_{cp_j} \zeta_j(x,z) e^{\nu z\lambda^2 q + i\nu x\lambda q} dz dx - \int_{-T}^{0} \zeta_j(x_S,z) e^{\nu z\lambda^2 q + i\nu x_S \lambda q} dz \tag{7}$$

and for the hydrodynamic interaction resistance $R_{Wm\Leftrightarrow n}$ between the main and the side hulls

$$R_{W_{m\Leftrightarrow n}} = -\frac{8}{\pi}\rho U^2 \nu^2 \int_1^\infty \frac{\lambda^2 d\lambda}{\sqrt{\lambda^2-1}} \left\{ \frac{\beta}{\pi} \int_0^\infty \frac{\lambda^3 q^4}{(q-1)^2 + \beta^2 \lambda^6 q^4} \cos\left(\nu\delta_T \lambda q \sqrt{\lambda^2-1}\right) \right.$$
$$\left. \left\{ \mathrm{Re}\left[A_m(\lambda q) \overline{A_n(\lambda q)} \right] \cos(\nu\lambda\delta_L) - \mathrm{Im}\left[A_m(\lambda q) \overline{A_n(\lambda q)} \right] \sin(\nu\lambda\delta_L) \right\} dq \right\} \tag{8}$$

Like above, $A_j(\lambda q)$ is the complex wave amplitude function, λ and q are the integration variable, while $\zeta_j(x,z)$ is the cross sectional offset for $j = 1$, 2 and 3 (number of the hull according to Figure 1). The parameters $\alpha = t/Fn^5$ and $\beta = t_1/Fn^3$ are the nondimensional viscosity factors according to [8] and [9], respectively, and they are both depended on the mean ship forward speed U. Here, the non-dimensional factors, t and t_1, independent of the ship mean forward speed U, are expressed as $t = 2(\mu/g)\sigma g^{-0.5}L^{-2.5}$ and $t_1 = 4v_t g^{-0.5}L^{-1.5}$. Further, μ is the dynamic viscosity, g is the acceleration of gravity, σ is the thickness of the viscous layer, L is the ship length on the waterline and v_t is the (turbulent) eddy kinematic viscosity (more details can be found in [8] and [9]). All values of the stated parameters and in the previously outlined expressions are given in the basic SI units. The integer values of the sub-indexes j, k and l have the same values as stated in the previous sub sections.

In the limits $\alpha, \beta \rightarrow 0$ it can be shown that the viscosity models expressed by (5 – 8) retrieve the ordinary Michell wave resistance model (without the viscosity corrections) given by the expressions (2 and 3). Finally, in close connections to the above expressions outlined in the previous subsections it should be noted that the details concerning their numerical estimation can be found in [3].

3. Numerical Studies

Current subsection will present estimations of the wave making and total resistance in calm and deep water according to the previous discussion. For this purpose, the distinctively different trimaran examples are accounted for, namely the Wigley trimaran and the commercial cargo carrier trimaran. As will be shown further, the last trimaran design is further used for the optimization investigations concerning finding of the optimal transverse and longitudinal distance between the main and the side hulls which will in turn provide the optimum total resistance of the studied trimaran design.

3.1. Wigley trimaran

To verify and validate the theoretical and numerical procedures associated with the above presented expressions for the estimation of the total resistance R_T in calm and deep water the [6] Wigley trimaran design configuration was selected.

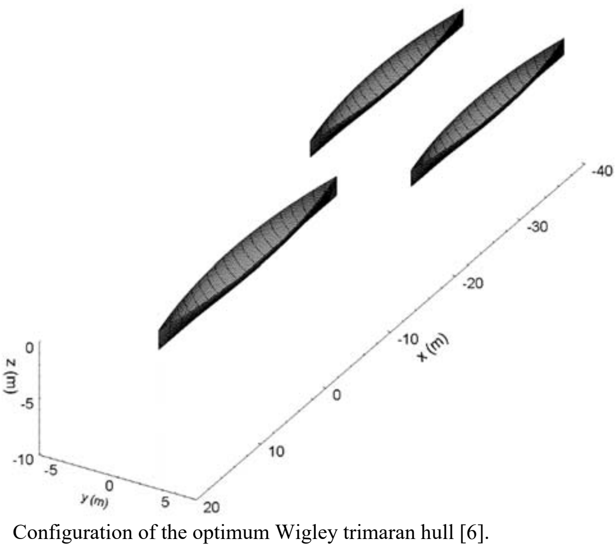


Figure 2. Configuration of the optimum Wigley trimaran hull [6].

The optimum design configuration, shown in Figure 2, according to [6] has been achieved for the design forward speed $U = 12.0$ m/s and the one half transverse $\frac{1}{2}\delta_T = 9.0$ m and longitudinal distance $\delta_L = -29.25$ m with the displaced volume scaling factor $p = 0.2789$.

The results of the wave making resistance R_W and total resistance R_T in this work are compared with the [6] results and the comparison is shown in Figure 3. As can be seen from the figure excellent agreement is achieved for both investigated cases Wigley monohull and trimaran satisfying the constrain of the fixed total displacement volume equal to $\forall = 64.8$ m^3.

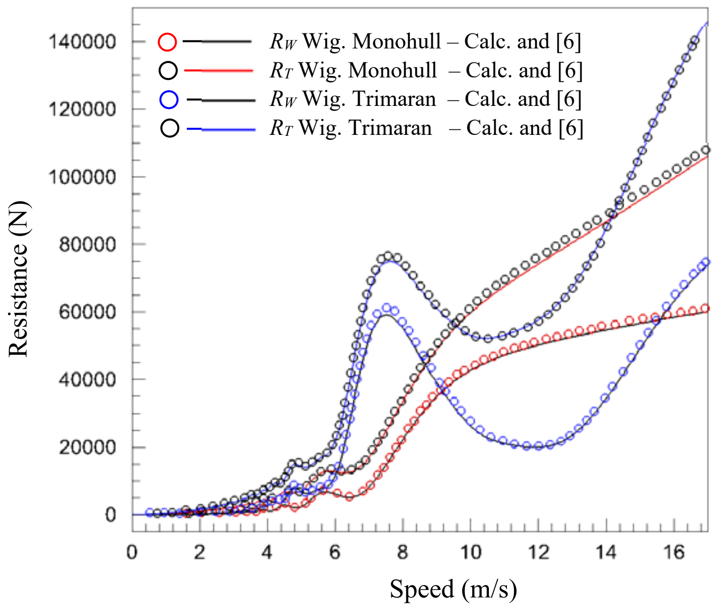


Figure 3. Wave resistance R_W and total resistance R_T (included only the ITTC 1957 friction line, see expression (1)) of the Wigley monohull and Wigley trimaran (shown on Figure 2) having the same total displaced volume $V = 64.8$ m^3. Calculated results are compared with [6] results (full black line and empty red circles – Wigley moohull R_W results, full red line and empty black circles – Wigley monohull R_T results, full black line and empty blue circles – Wigley trimaran R_W results, full blue line and empty black circles – Wigley trimaran R_T results).

The above [6] Wigley trimaran optimal configuration is further studied thru application of the above discussed models which accounts for the presence of the viscous effects. Namely, [8] and [9] viscous models are applied, and the results are presented in Figure 4.

As can be seen from the above figure, the inclusion of the viscosity effects in both wave making resistance viscosity models has the damping behaviour on the wave making and total resistance curves estimated by the application of the ordinary Michell wave theory (for details see subsections 2.1 and 2.2 above). In general, this is normally to be expected from the perspective of the estimation of ship resistance in the real fluid (for details see [8] and [9]). On this way, the well-known overpredictions of the resistance values in the whole Froude number range of interest for a particular ship design due to ordinary Michell theory can be significantly reduced and the theoretical (numerical) predictions can be confined within the commonly expected intervals of the resistance estimations achieved by the experimental work.

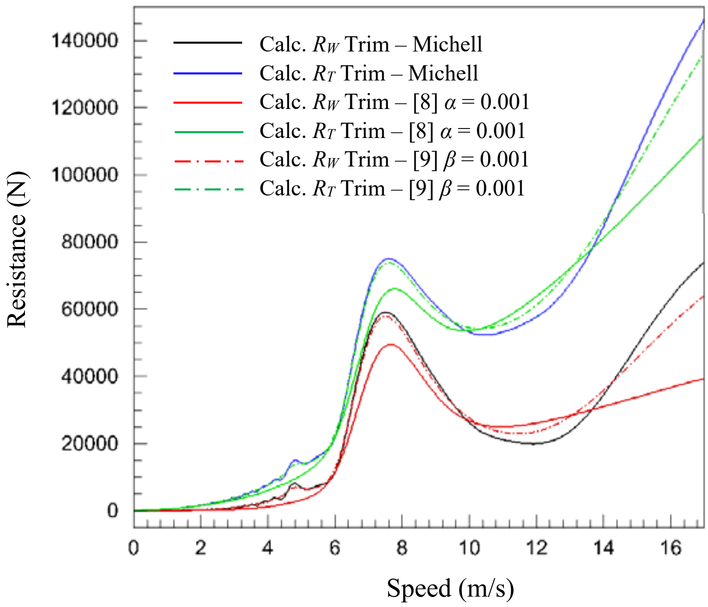
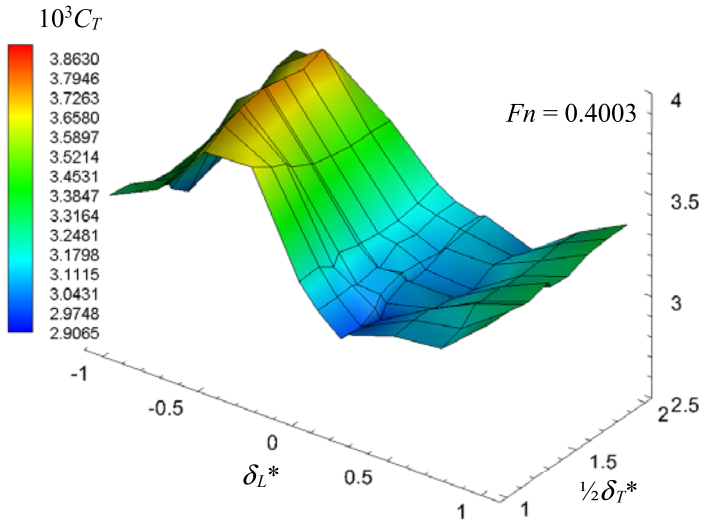


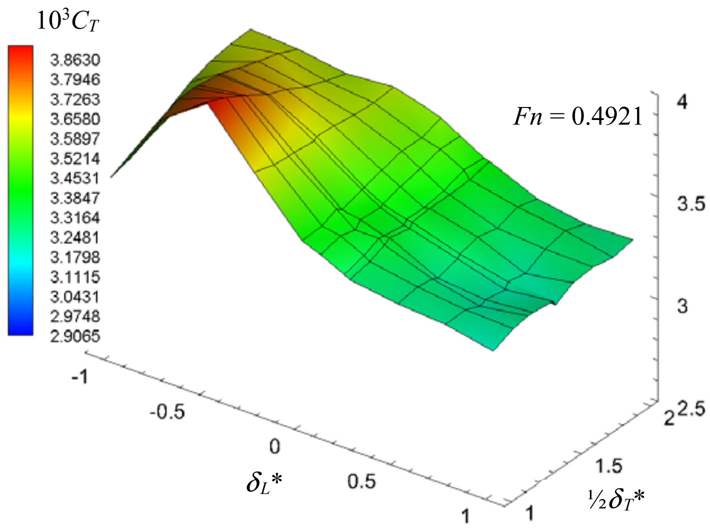
Figure 4. Comparison of the wave resistance R_W and total resistance R_T (included only the ITTC 1957 friction line, see expression (1)) of the Wigley trimaran (shown on Figure 2) according to ordinary Michell wave theory (without any inclusion of the viscous effects) and according to [8] (α = 0.001) and [9] (β = 0.001) wave resistance viscosity models.

3.2. Cargo Carrier Trimaran

The example of the Cargo Carried trimaran has been used for investigation of optimization problem related to locating the optimum transverse and longitudinal distance which will provide optimum lower values of the wave making resistance and total resistance in deep and calm water. The main particulars of the trimaran configuration, with the meaning of the subscripts 1 – main hull and 2 and 3 – the side hulls, are given as follows: $L_{WL_1}/T_1 = 23.89$, $L_{WL_{2,3}}/T_{2,3} = 19.76$, $B_1/T_1 = 2.05$ and $B_{2,3}/T_{2,3} = 1.01$. Here, L_{WL} is the waterline length and B and T are main beam and draft, respectively. The Froude number interval $Fn \in [0.1168, 0.6672]$ shown in Figure 6 is estimated by using the waterline length of the main hull L_{WL_1}. It should be noted that due to breach of the confidentially agreement the authors were not able to provide the offset of the main and side hull(s) nor enclose any kind of the dimensional data related to the main particulars and speeds of the studied cargo carrier trimaran.
In order to investigate the optimal configuration of trimaran design in question the systematic research concerning estimation of the total resistance R_T according to the ordinary Michell wave theory in the sense described above was carried out by considering the text matrix of the longitudinal δ_L and one half transverse distances $\frac{1}{2}\delta_T$ between the main and the side hulls. The following nondimensional intervals of the

mentioned parameters are accounted for δ_L^* x $½\delta_T^* \in [(-1.0, 1.0) \text{ x } (1.0, 2.0)]$ in the interval of preselected Froude numbers Fn as shown in Figure 5. Here, the nondimensional longitudinal distance δ_L^* is defined as ratio of the dimensional longitudinal distance δ_L and absolute value of the minimum dimensional longitudinal distance $|\delta_{Lmin}|$, i.e. $\delta_L^* = \delta_L/|\delta_{Lmin}|$, while the one half nondimensional transverse distance $½\delta_T^*$ is defined as ratio of the one half dimensional transverse distance δ_T and absolute value of the minimum one half dimensional transverse distance $|½\delta_{Tmin}|$, i.e. $\delta_T^* = \delta_T/|\delta_{Tmin}|$. In addition it should be noted that the minus values of the nondimensional longitudinal distance δ_L^* are valid for the situations when the stern part of the side hulls is shifted behind the stern part (transom stern) of the main hull, while, the increasing values of the one half nondimensional transverse distances $½\delta_T^*$ mean that the both side hulls are located more and more away in the transverse direction from the main hull.





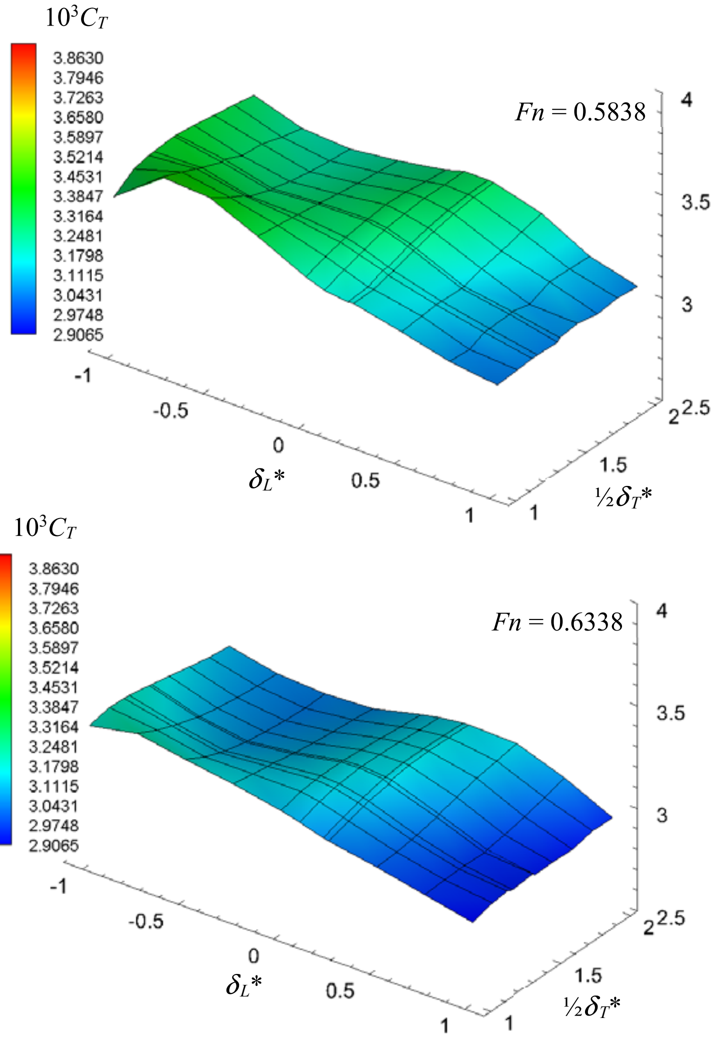


Figure 5. Variation of the nondimensional total resistance $C_T = R_T/(0.5\rho U^2 S_1)$ of the Cargo Carrier trimaran versus nondimensional intervals of the longitudinal and one half transverse distances $\delta_L^* \times ½\delta_T^* \in [(-1.0, 1.0) \times (1.0, 2.0)]$ for preselected four (4) Froude numbers Fn. Here, $\rho = 1000.0$ kg/m^3 is the water density and S_1 is the wetted area of the main trimaran hull at the selected draft T_1 at even keel position.

As can be seen from the results presented in the mentioned figure, in order to achieve the optimised trimaran design in question, it should be noted that it will be beneficial to shift longitudinally the side hulls towards the forward (bow) part of the main hull. This is because for these particular combination(s) of the longitudinal and transverse configuration(s) it has been observed that the nondimensional total resistance C_T (= $R_T/(0.5\rho U^2 S_1)$) for all Froude numbers Fn (not only for those shown here in Figure 5) is significantly lower than it is in the design configurations when the side hulls are put behind the main hull (the stern part of the side hulls is shifted behind the stern part of the main hull).The above statement holds when the side hulls are closer transversally to the main hull.

In addition to the above observations, the presented results in Figure 5 also shows that the peaks of resistance for configurations, when the side hulls are closest transversally to the main hull and in the same time quite far behind of the main hull, are shifting towards the lower values of the longitudinal distance while the transverse distance is kept at the same value. Like it has been mentioned previously, this observation is valid for all Froude numbers *Fn* and not only for those presented in the Figure 5.

The above behaviours of the total resistance C_T are also more clearly illustrated in Figure 6 which shows prediction of the wave making resistance C_W (= $R_W/(0.5\rho U^2 S_1)$) versus the whole interval of the Froude numbers *Fn* has decreasing and therefore beneficial trends for achieving optimal trimaran design when the side hulls are shifted longitudinally towards the forward part of the main hull.

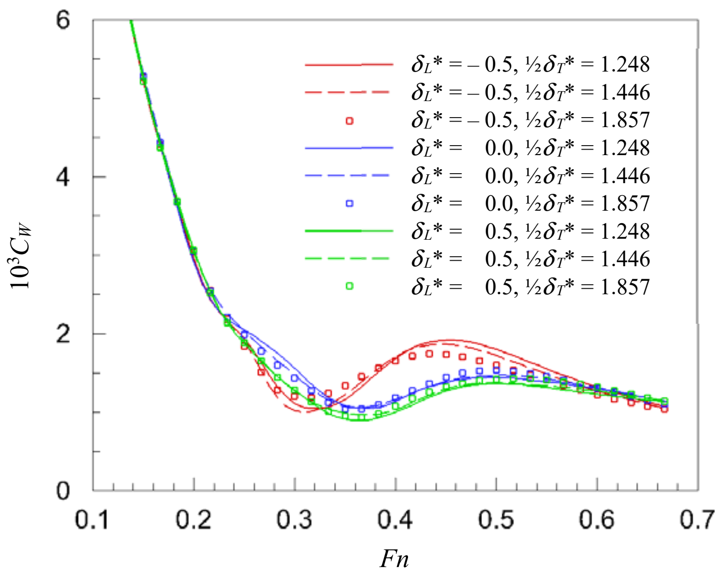


Figure 6. Variation of the nondimensional wave making resistance $C_W = R_W/(0.5\rho U^2 S_1)$ of the Cargo Carrier trimaran versus Froude numbers *Fn* for preselected three (3) nondimensional longitudinal δ_L* and three (3) nondimensional one half transverse distances $\frac{1}{2}\delta_T$*. Here, ρ = 1000.0 kg/m^3 is the water density and S_1 is the wetted area of the main trimaran hull at the selected draft T_1 at even keel position.

However, when it comes to determination of the optimal transverse distances it should be noted that this needs to be carefully done during the preliminary design process since having the trimaran design with the excessive transverse distance between the main and both side hulls can lead quite easily to significant increase of the total resistance C_T in spite of pursuing general rule for beneficial shifting of the side hulls towards the front (bow) part of the main hull (when the nondimensional longitudinal distances δ_L* are greater than zero; i.e. δ_L* > 0.0). This situation is clearly illustrated in the next Figure 7 which shows variation of the wave making resistance C_W versus the whole interval of the nondimensional longitudinal distances δ_L* ∈ [– 1.0, 1.0] at one preselected Froude number *Fn* equal to 0.5838.

As can be clearly seen from the figure, the wave making resistance C_W has the increasing trend with the increasing one half nondimensional transverse distance ½δ_T*. This means that each hull, i.e. the main hull and both side hulls start to behave like the individual hulls (each hull separately by itself) where the hydrodynamic interaction wave making resistances (and corresponding wave field profiles) went to zero (and therefore they can be neglected). In this kind of scenario, the total resistance is equal to the linear superposition of the total resistance of each individual hull (main hull plus two side hulls) which will be in general always higher that the total resistance of the optimized trimaran design configuration.

In addition to the effects of the longitudinal and transverse distances upon the prediction of the total resistance C_T (and C_W) it should be noted that the same parameter and consequently the optimum hydrodynamic design in calm and deep water is also strongly dependent on the displaced volume scaling factor p as shown by [6], and, as well as, on the geometrical characteristics of the wetted parts of the main hull and the side hulls.

In conclusion to the above discussed observations, it should be kept in mind that the final optimal design configuration of a general trimaran should, beside the above discussed hydrodynamic requirements point of view (valid for calm and deep water), also pursue satisfaction of other trimaran design requirements related to the structural limitations, safe and economically justified operational profile, seakeeping requirements, safe operation in the proximity of the physical barriers (sea bottom, channel side(s)), etc.

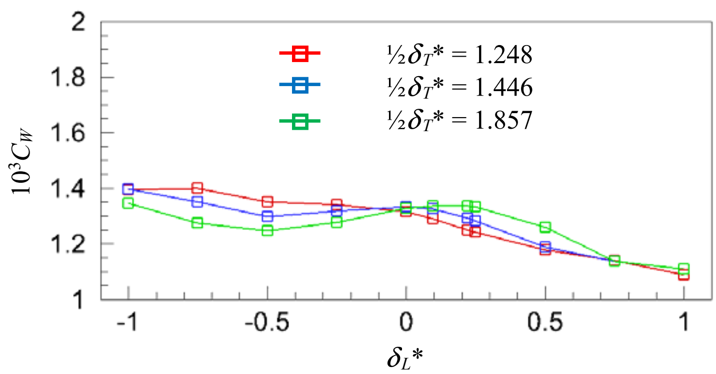


Figure 7. Estimation of nondimensional wave resistance $C_W = R_W/(0.5\rho U^2 S_1)$ of the Cargo Carrier trimaran versus nondimensional longitudinal distances δ_L* in the interval [-1.0, 1.0] at Froude number Fn = 0.5838 for three (3) nondimensional one half transverse distances ½δ_T*. Here, ρ = 1000.0 kg/m^3 is the water density and S_1 is the wetted area of the main trimaran hull at the selected draft T_1 at even keel position.

4. Concluding Remarks

Present study provides insight into the procedure which can be used during the preliminary design of the trimaran (and multihull) type of a high speed vessel in order to achieve her optimal design from the hydrodynamic point of view valid for deep and calm water operating scenarios.

Concerning the above, the attention was given to the development of the theoretical and numerical mathematical models which will be capable to estimate the wave making resistance C_W without and with the inclusion of the viscous effects and consequently the total resistance C_T of the investigated trimaran vessels configurations. The main reason behind the utilization of the wave resistance theories which accounts for the viscous effects laid in the fact that there is a noticeable long term necessity for a realistic theoretical (numerical) predictions of the wave making resistance C_W with better comparability with the experimental results.

The above developed mathematical models are further used in the dedicated test matrix study related to investigation of the optimal trimaran configuration design subject to perpetual change of the longitudinal and transverse distances between the main hull and two side hulls in the preselected interval of the Froude numbers Fn. Based on the behaviour of the results obtained from the carried out investigations it has been observed that from the hydrodynamic optimization (in cam and deep water) point of view of the general trimaran design it will be recommended to consider shifting of the side hulls towards the front part of the main hull. In addition, concerning the determination of optimal transverse distance between the main hull and the side hull should be carried out with all necessary care in order to avoid the trimaran configuration situation where the final configuration will be located quite far away from the pursued optimal configuration due to increase of the total resistance.

Finally, in close relation to the above it should be stressed out that the final optimal trimaran design is also subjected to the hydrodynamic requirements such are the geometrical characteristics of the wetted part of the main hull and the side hull, and, as well as, displaced volume scaling factor p (for further details see [6]). In addition, the successful and optimal trimaran design, as viewed from the general point of view, needs also to satisfy the structural and seakeeping requirements etc. to achieve safe and economically justified operational profile in her operational lifetime.

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