Resistance Analysis for a Trimaran

Claire M. De Marco Muscat-Fenech, Andrea M. Grech La Rosa

***Abstract*—**Importance has been given to resistance analysis for various types of vessels; however, explicit guidelines applied to multihull vessels have not been clearly defined. The purpose of this investigation is to highlight the importance of the vessel's layout in terms of three axes positioning, the transverse (separation), the longitudinal (stagger) and the vertical (draught) with respect to resistance analysis. A vessel has the potential to experience less resistance, at a particular range of speeds, for a vast selection of hull positioning. Many potential layouts create opportunities of various design for both the commercial and leisure market.

***Keywords*—**Multihull, Resistance, Trimaran.

NOMENCLATURE

A	Stagger (m)
a_n	Stagger between n^{th} hull and the origin (m)
b	Separation (m)
b_n	Separation between n^{th} hull and the origin (m)
c_b	Block coefficient
c_d	Length to displacement ratio
c_f	Frictional resistance coefficient
c_{fmh}	Frictional resistance coefficient of main hull
c_{fs}	Frictional resistance coefficient of ship
c_m	Sectional area coefficient
c_p	Longitudinal prismatic coefficient
c_r	Residuary resistance coefficient
c_{sr}	Slenderness ratio
c_w	Wavemaking resistance coefficient
c_{wp}	Coefficient of fineness
f	Froude's coefficient
k	Form factor
n	Number of hulls
x-	Coordinate axis
y-	Coordinate axis
z-	Coordinate axis
A_w	Total wetted surface area (m^2)
A_{wn}	Wetted surface area of n^{th} hull (m^2)
A_{wl}	Waterplane area (m^2)
AP	After perpendicular
B	Beam (m)
B_n	Beam of n^{th} hull (m)
B_T	Total beam of multihull (m)
FP	Forward perpendicular
L	Length (m)
L_n	Length of n^{th} hull (m)
L_{pp}	Length between perpendiculars (m)
L_{wl}	Length at water line (m)
L_{oa}	Length overall (m)
R_f	Frictional resistance of model (N)
R_n	Frictional & wave resistance of n^{th}hull(N)
R_T	Total resistance (N)
R_w	Total wave making resistance (N)
R_{ws}	Wave making resistance of ship (N)
ΔR_{wc}	Component due to the side hulls interference (N)
ΔR_{wt}	Mutual interference of central and side hulls (N)
T	Draught (m)
V	Speed (kts)
∇	Volume of displacement (m^3)
Λ	Froude's exponent
δ	Draught ratio
μ	Separation Ratio
σ	Stagger ratio

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I. INTRODUCTION

A multihull is a vessel which is made up of more than one hull. The independent hulls need not be of the same size and geometrical shape nor have the same hydrodynamic performance. The most common arrangements of multihulls are catamarans and trimarans; either having two and three hulls respectively. There are several motives for one to invest in multihull vessels, the primary reasons being: less resistance at high cruising speeds and a larger work plane area. This investigation deals with the effect of varying the position of the hulls such that the performance of the total vessel is optimized. The separation, stagger and draught together with a compound analysis will act as a foundation for trimaran design.

II. THEORY

A vessel consisting of more than one hull is called a multihull. Various configurations exist, some of which need not have identical hulls [1]. The positions of the hulls are very important in order to optimize their performance [2]. Some of the more common forms of multihulls are catamarans and trimarans, having two and three hulls respectively. There are a number of advantages in having a multihull, however the most important is that at high speeds, a significant reduction in resistance is noted compared to a monohull having the same displacement[2].

Depending on the motive for the trimaran's construction, the individual hulls need not be identical or have the same geometry. The hull's geometry is not the only parameter that can be varied; another very important variable is the position of the respective hulls between themselves. By altering the separation and stagger, an optimum position is found, with respect to resistance, whereby the efficiency of the vessel increases. In addition, since a trimaran makes use of three hulls, the total beam of such a vessel would be considerably larger than that of a monohull having the same displacement [2]-[4].The downside to this increase in beam is that expenses, such as harbor fees, would naturally increase since more than one berth is needed to accommodate the vessel.

Fig. 1 BMW's BOR 90 [5]

BMW's BOR 90, better known as the BMW Oracle, is a sailing trimaran that placed first in a number of races, including the 2010 33rd America's Cup. The performance of this vessel is due to the joint effect of a low dead weight due to the CFRP (Carbon Fibre Reinforced Polymer) hulls, optimum positioning of hulls to reduce wave resistance and the large sail area attained as a result of the increased transverse stability [5]. Another renowned vessel is the Earthrace which in 2008, managed to attain the round the world speed record (Fig. 2). The total journey comprised of 23,497 nautical miles covered with biodiesel engines. The actual vessel itself is a trimaran having very dissimilar wave piercing hulls [6].

Fig. 2 Earthrace [6]

A. Frictional Resistance

When a vessel is travelling at low speeds, the frictional resistance makes up the largest percentage of the total resistance. The frictional resistance is highly dependent on the actual surface finish on the vessel's hull. The rougher the surface, the larger the frictional resistance since the flow of fluid around the hull's surface turns turbulent, thus increasing the frictional coefficient [7].

At a range of low speeds, the fictional resistance increases with an increase in speed, however once the vessel has reached its design speed, V, the frictional resistance no longer remains the major contributing factor [8]. Froude had constructed an expression which included all of the above mentioned variables, including the wetted surface area of the hull, A_w.

$$R_f = f\,A_w\,V^{\Lambda} \tag{1}$$

where f is a function of the hull's length. The speed of the vessel, V (in knots) is also incorporated in this equation in such a way that as it increases, the frictional resistance increases proportionately. The velocity is also interdependent on the variable Λ which is used to describe the roughness of the hulls surface. Froude's son [7] has denoted a value for Λ, that being equal to 1.825 which should be sufficient when analyzing the theoretical frictional resistance generated by the hull.

Since multihull vessels have more than one hull, then the frictional resistance may be greater than that of amonohull of equal displacement. The draughts of multihulls are normally smaller however since the load is distributed over a larger area; the multihull normally has a larger wetted surface area. All the factors described above are all directly related to the frictional resistance [8].

The total frictional resistance coefficient for a trimaran having identical outriggers (or side hulls) may therefore be expressed as a function of the wetted surface area of each hull A_{Wn} with respect to the total wetted surface area of all three hulls, A_W [8]:

$$c_f = c_{fmh}\left(\frac{A_{wmh}}{A_w}\right) + c_{fsh}\left(\frac{2A_{wsh}}{A_w}\right) \tag{2}$$

where the subscript mh refers to the main hull, also known as the central hull and the subscript sh refer to the side hull. If the wetted surface area of the three hulls is equivalent, the total friction coefficient is then expressed as:

$$c_f = c_{f1} + c_{f2} + c_{f3} \tag{3}$$

and

$$c_{f1} = c_{f2} = c_{f3} \tag{4}$$

This may be the case when all three hulls are geometrically similar and their displacement is evenly distributed. Three identical hulls are to be considered in this investigation.

B. Residual Resistance

The residual resistance refers to various forms of resistance. Although is comprises many other forms of resistance, the wave making resistance is generally allotted the highest portion of residual resistance. In fact, at high speeds, it may even be larger than the frictional resistance, theoretically creating a very inefficient situation. This leads to discussions on sub and super critical situations which should be analyzed whilst designing a hull in order to maximize its performance for a given power [9].

The wave patterns produced by a vessel travelling in water are dependent on a number of factors including the hull shape, the speed and the trim. The properties of the waves a certain distance away from the vessel may be predicted by means of decay functions which are derived experimentally or theoretically. The decay function for a vessel travelling in deep water may be described using Havelock's theoretical prediction [9].

III. Multihull Vessels

The enhanced design features of a multihull leads to reducing the residual resistance, however the consequence is a new form of resistance: the close positioning of the separate hulls leads to interaction in both the wave patterns and thus the total resistance [8]. From the analysis carried out by [10], the wave resistance is associated with the beam of the hull. Applying this relationship whilst retaining all other variables constant [10]:

$$R_w \; \alpha \; B_n^{\,2} \tag{5}$$

This means that the following lemma may be constructed.

Consider a hull of beam *B* split into two equivalent hulls each having a beam of *B/2*. The wave making resistance for the original hull was R_{wT} however this has now been divided into two equal resistances R_{w1} and R_{w2}.

$$R_w = R_{w1} + R_{w2} \tag{6}$$

This statement is only valid however if the two separate hulls were at the same stagger and draught [10] and that the hulls were separated by an infinite distance, then no interaction of the characteristic divergent and transverse waves would occur between the two hulls.

As mentioned, the interaction of the waves is due to the position of the various hulls with reference to separation, stagger and draught, implying that if the hulls are positioned in such a way that there is no interaction between the hulls, then no interference resistance would be experienced [8]. By investigating the variations in separation, stagger and draught this interference resistance can be reduced, eliminated and even taken advantage of. An interesting point is that although an interference would cause the hull to be inefficient, there are some positions when the interferences produce favourable situations when and the complete vessel would experience less resistance than that addition of the individual hulls acting separately.

This interference resistance can be calculated, such that [11]:

$$R_w = 3R_{whull} + \Delta R_{wc} + \Delta R_{wt} \tag{7}$$

$$R_w = 3R_{whull} + R_{interfernce} \tag{8}$$

where ΔR_{wc} and ΔR_{wt} can be grouped as the interference resistance due to the "catamaran and trimaran effect".

The transverse distance or the separation between a pair of hulls can affect the interference, such that as the separation increases, the effect of the interference on each hull decreases.

The axis along the length of the hull, the stagger, is mostly mentioned when dealing with trimarans or other multihulls having an odd number of hulls. The research carried out by Yeung [10] has also showed that a stagger in one direction (either fore or aft) influences the interference and hence resistance by the same amount.

When the identical hulls of a multihull vessel are in close proximity to each other, irrespective of stagger or separation, the total resistance experienced is not equal to the sum of the total resistance of all three hulls individual resistance since an interference resistance would be acting on the hulls. This interference may have either a positive or negative effect accordingly. This will be shown within this investigation.

In order to show the presence of the interference resistance at a particular velocity, the numerical difference between the total resistance experienced by a multihull configuration and 3 times the total resistance of an individual hull at the same draught was simulated and calculated. This total resistance includes the frictional resistance together with the wave making resistance and interference resistance.

IV. The virtual Model

The trimaran is simulated for the various combinations of the variables of separation *b*, stagger *a* and draught *T*. The simulations were undertaken using the MAXSURF suite of software by FormSys, version 16.04, using the packages of MAXSURF, for hull design and HULLSPEED, for resistance prediction simulations.

From the results simulated, a number of conclusions will be stated. Each of these conclusions may now be thought of throughout the whole design of the complete multihull, in order to create a vessel capable of achieving high performance standards. Naturally, the conclusions drawn out here are specific to multihull vessels having a number of limitations, namely:

- Symmetric about the total beam median
- All hulls must be identical
- All hulls are at the same draught

HULLSPEED's computations consider the hulls at a fixed draught over the complete velocity range for simplicity of the simulations, even when it is a well-known fact that hulls trim when underway especially at high speeds.

In order to carry out the simulations directly relating to high performance multihull vessels, the individual hulls of the concerning multihull must satisfy various criteria. One of the most distinguishing features of a vessel of this caliber is the slenderness ratio. Monohull vessels are usually limited to a value of approximately 5, whereas the individual hulls of a multihull vessel are capable of attaining much larger values such as 16[1] as can be seen in Table I.

TABLE I
HYDROSTATICS FOR AN INDIVIDUAL HULL

Symbol (unit)	Quantity	Value
B (m)	Beam	1.317
L_{oa}(m)	Length overall	23.153
T (m)	Draught amidships	0.463
T_D(m)	Immersed depth	0.463
Δ(t)	Displacement	6.714
∇(m^3)	Volume (displaced)	6.550
A_{wl} (m^2)	Waterplane area	21.671
A_w (m^2)	Wetted surface area	30.088
c_b (/)	Block coefficient	0.487
c_p (/)	Longitudinal prismatic coefficient	0.662
c_{sr} (/)	Slenderness ratio	16.758
c_m (/)	Sectional area coefficient	0.736
c_{wp} (/)	Waterplane area coefficient	0.746
(L/T) (/)	Beam : Draught ratio	2.846
$(L/\nabla^{1/3})$ (/)	Length :Vol$^{1/3}$ratio	11.795

The slenderness ratio, c_{sr} alone is only used to create constraints for the external dimensions of the hull for a given length or beam. This slenderness ratio must also be coupled with other constraints, which together form the ideal hull shape; another very important dimensionless coefficient that must be analyzed is the block coefficient, c_b, the block coefficient of the separate hulls should have a value between 0.4 – 0.6 to ensure that the underwater volume of the hull is as small as possible [1], [11]; the prismatic coefficient, c_p should be in the vicinity of 0.7, however another way of determining sleekness of the hull is by making use of the rendering option, where different light sources could be used to check for convex or concave areas on the hull surface. If not looked into properly, eddy currents may form and thus an inefficient hull or hydraulically rough hull would be created.

MAXSURF makes use of various surface types which intrinsically affect the outcome of the hull being designed. Throughout this analysis the B-Spline surface type was used. The stiffness of the curves joining the various control points together was set to five in the longitudinal direction and three in the transverse direction. These were selected in order to simulate the stiffness of construction material, possibly fibreglass. The designed hull is symmetrical about the '*xz*' plane.

The control net was carefully adjusted to ensure that the dimensionless coefficients were constantly being observed in order to ensure that the hull created was within the high speed craft set. Before any fairing took place, the entrance of the hull was amended in order to remove the sharp apex which would have generated errors in the simulations yet to come. By rendering the virtual model of the hull, any incorrect curvatures were instantly highlighted and removed. This was done by fairing the net of control points. Figs. 3 and 4 show the finished rendered model and lines plans of one of the hulls being used for the trimaran, designed for the purpose of this investigation.

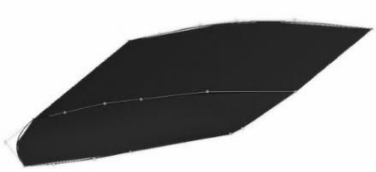
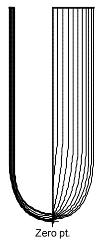
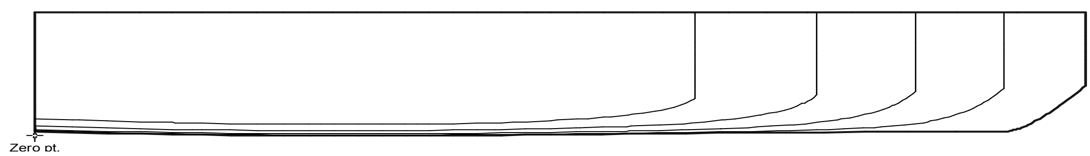


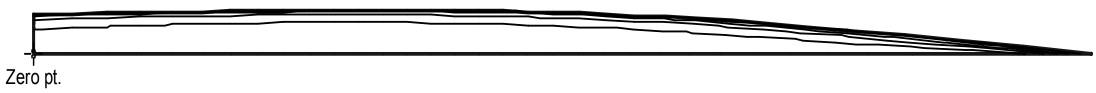
Fig. 3 Rendered image of half of the individual hull of the trimaran



(a)



(b)



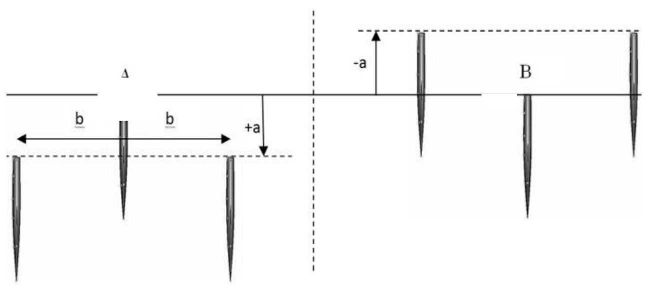
(c)

Fig. 4 Lines plans of an individual hull (a) body plan (b) profile (c) plan

Up to now, only one hull has been defined. Since the study is concerned with the properties of a trimaran consisting of three identical hulls, then the current design was further applied to another two hulls by using the duplicating function in MAXSURF. The hulls were positioned at different separations, staggers and draughts, (however the draughts on each hull were maintained equal for each individual positioning). Keeping the draught constant ensured that the total wetted surface area of each hull is identical.

Hydrostatic data of the individual hull, at the specified draught, designed with the MAXSURF package is given in Table I. The hull was designed to enhance its performance at high speeds. This table clearly shows that all the criteria related to high performance vessels are being satisfied.

The hulls may be shifted in all three axes. The separation, b, the stagger, a and the draught T are in the x- (transverse), y- (longitudinal) and z- (vertical) axis respectively. The first two axes are shown in Fig. 5, together with the convention being used for a positive or negative stagger.



(a) (b)

Fig. 5 Plan view for two staggered trimarans (a) displays a positive stagger and (b) displays a negative stagger

In order to distinguish between one model and another in an organized fashion, ratios were used to define the draught, stagger and separation. These are defined with the following equations:

$$Draught\ Ratio = \delta = \frac{Draught}{Overall\ Length} = \frac{T}{L_{OA}} \tag{9}$$

$$Stagger\ Ratio = \sigma = \frac{Stagger}{Overall\ Length} = \frac{a}{L_{OA}} \tag{10}$$

$$Separation\ Ratio = \mu = \frac{Separation}{Overall\ Length} = \frac{b}{L_{OA}} \tag{11}$$

Based on the values of the hydrostatic data of the individual hull as given in Table I, the draught, stagger band separation ratios considered in this investigation are explained in Table II.

TABLE II
DRAUGHT, STAGGER AND SEPARATION RATIOS

Draught ratio: δ	Stagger ratio: σ	Separation ratio: μ
0.02	0.0	0.125
0.03	±0.5	0.250
0.04	±1.0	0.375
	±1.5	0.500
	±2.0	0.625
		0.750
		0.875
		1.000
		1.125
		1.250
		1.375
		1.500

The most appropriate resistance theorem that can be applied to such vessels is the slender body theorem. This model works on the basis of Michell's [12] thin ship theorem to calculate the resistance component relating to wave resistance. This complex theory focuses on analyzing a line of sources rather than a planer distribution. The principle behind the slender body theorem is that it calculates the energy in the free surface wave pattern once the slender body has passed through it. This arises since the body is doing work on the fluid to disrupt it and thus a wave is formed. By altering the geometry of the vessel and thus optimizing its shape, less energy may be dissipated into the fluid to create a wave.

V. Results

A. Variation in Separation

Fig. 6 displays the resistance versus speed graphs for several hull configurations, each retaining a constant draught and stagger ratio of 0.02 and 0 respectively. The separation on the other hand is being increased with the respective ratio in increments of 0.125 in order to characterize the effect of the separation alone.

The system used to distinguish between one hull configuration and the other in Fig. 6 and similar graphs is by means of the number assigned to each curve corresponding to the appropriate ratio, this one in particular being the stagger ratio, σ. The optimum view to analyze how the interference resistance is changing with an increment in separation is to plot an interference resistance versus speed graph, as shown in Fig. 7.

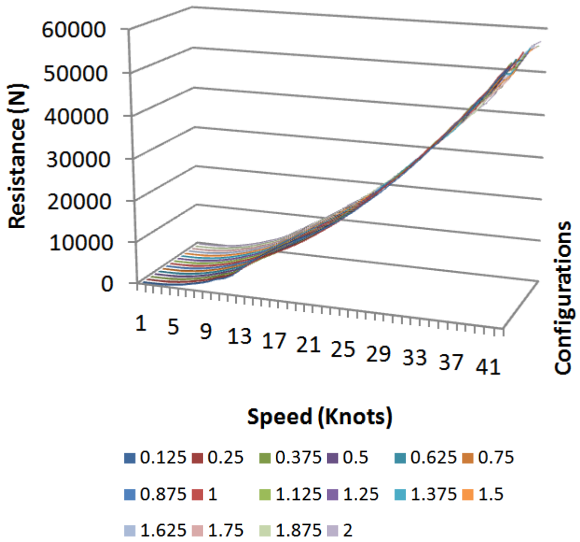


Fig. 6 Resistance against speed plot for hull configurations having a constant stagger and draught ratios of 0 and 0.02 respectively

Fig. 7 shows a variation to the conventional theory. When the separation ratio was excessively small such as 0.125 corresponding to an actual 2.89m, a favorable configuration was observed whereby the total resistance experienced by the hulls was the least achieved in the whole simulation procedure at high velocities.

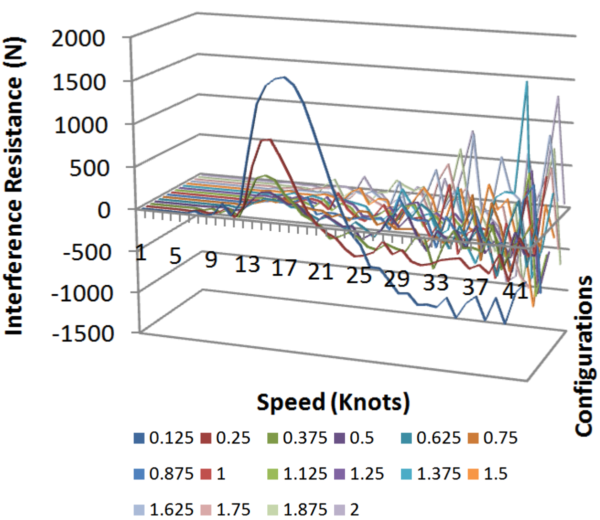


Fig. 7 Interference resistance against speed for hull configurations having a constant stagger and draught ratios of 0 and 0.02 respectively

Although the hull configuration having least separation resulted in least interference resistance at high velocities, its performance at low velocities is highly unsatisfactory. This can be seen from the large value of interference resistance together with a very steep gradient in the graph present in Fig. 7 corresponding to the plot of separation ratio of 0.125.

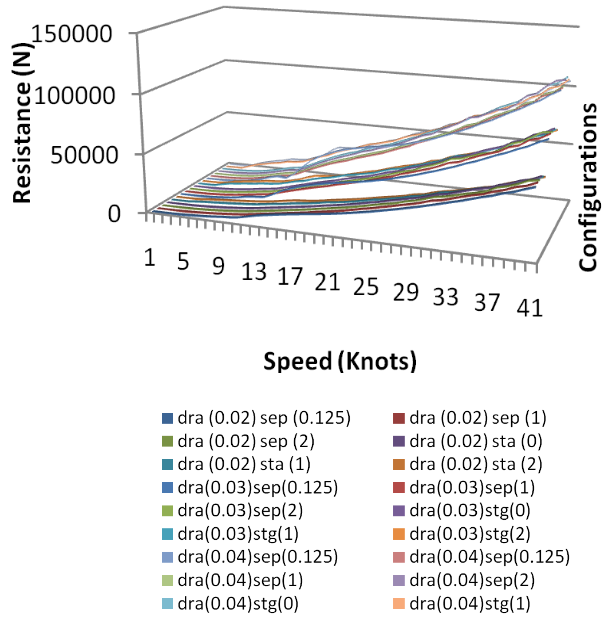


Fig. 8 Resistance against speed plot for trimarans having a variance in stagger, separation and draught ratio

B. Variation in Draught

The resistance vs. speed curves displayed in Fig. 8 show the relationship of draught ratio with speed for a constant stagger and separation ratios of 0 and 1 respectively. As the draught increases, the resistance experienced by the vessel for a given speed also increases. Ideally the draught should be kept as low as possible, for two main reasons:

The first reason is due to the increase in total wetted surface area for each increment of draught. Table III shows the values of the wetted surface area with respect to the draught ratio, δ, for the individual hull alone and it clearly shows that the values for total wetted surface area increase with an increase in draught ratio.

According to Froude's equation, the total wetted surface area is one of the main parameters that determine the frictional resistance.

TABLE III
DIFFERENCE IN TOTAL WETTED SURFACE AREA FOR THE INDIVIDUAL HULLS HAVING DIFFERENT DRAUGHT RATIOS

Draught ratio, δ (/)	0.02	0.03	0.04
Draught, T (m)	0.463	0.695	0.926
Total wetted surface area, A_w (m^2)	30.088	40.793	52.926

The graph presented in Fig. 8 shows the effect of having an increase in draught whilst keeping the stagger ratio constant at a value of 0 and also shows the effects of an increase in draught ratio whist keeping the separation ratio constant at a value of 1. Although the Froude's relation is valid, HULLSPEED calculates the frictional resistance by means of the ITTC 57'correlation law [13]. Therefore the equation may therefore be used such that a general term for the frictional resistance may be calculated. Fig. 9 on the other hand shows a plot of interference resistance against speed for the same plots.

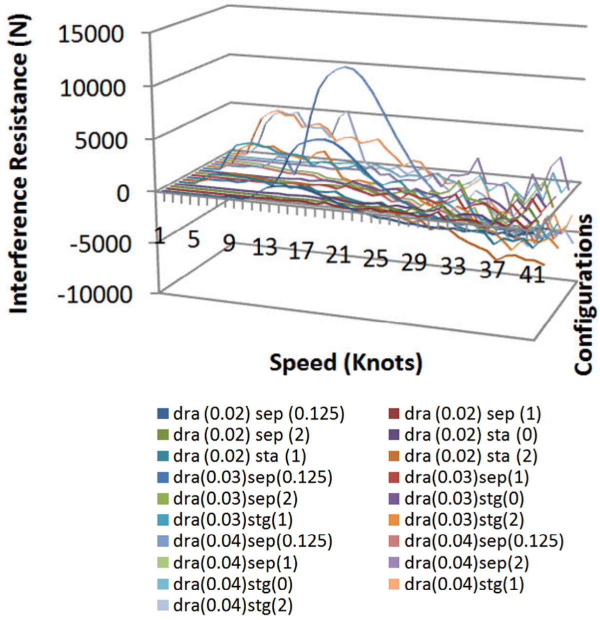


Fig. 9 Interference resistance against speed plot for trimarans having a variance in stagger, separation and draught ratio

Both Figs. 8 and 9 show that an increase in draught ratio will result in an increase in resistance irrespective of the separation and stagger ratios. This observation therefore implies that the draught should be kept as small as possible in order to improve the effectiveness of the vessel.

The second reason as to why the resistance increases with an increase in draught is due to the length to displacement ratio. As the draught increases, the amount of water being displaced increases accordingly. The larger the value of the length to displacement ratio, c_d the less residuary resistance is experienced [9]. This implies that having a large draught will hinder the performance both at low and high speeds. Table IV shows how the length to displacement ratio c_d varies according to the draught for the individual hull of the trimaran.

The relation in Table IV demonstrates that an increase in draught results in lower length to displacement ratio, this is one of the determining factors for the hull's performance in the supercritical section of the graph.

C. Variation in Stagger

TABLE IV
CHANGE IN LENGTH TO DISPLACEMENT RATIO WITH INCREASE IN DRAUGHT RATIO

Draught ratio, δ	Draught, T (m)	Waterline Length, L_{WL} (m)	Length to Displacement ratio, c_d
0.02	0.463	22.069	11.795
0.03	0.695	22.354	9.784
0.04	0.926	22.640	8.532

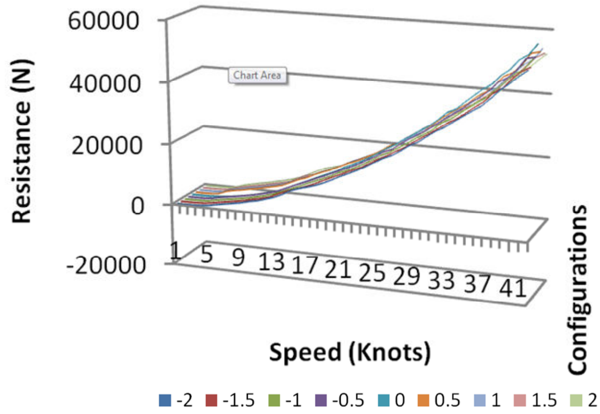


Fig. 10 Resistance against speed for hull configurations having a constant separation and draught ratios of 1 and 0.02 respectively

In the event of having three identical hulls, a positive or negative stagger reduces the amount of resistance acting on the hulls. Fig. 10 displays the resistance verses speed graphs for different hull configurations which have fixed separation and draught ratios of 1 and 0.02 respectively but varying stagger ratio.

As the stagger increases, less interference resistance is acting on the respective hulls. Therefore, the most unfavorable situation is when all three hulls are perfectly collinear, thus having a stagger ratio of 0.

A plot of interference resistance for all layouts related to analyze the effect of stagger in Fig. 10 is displayed in Fig.11. The interference plots shown in Fig. 11 all have similar trends. At low velocities the interference resistance increases, after which the majority of the plots gradually decrease, also moving into the negative resistance zone where superfluous interaction occurs increasing the efficiency of the multihull.

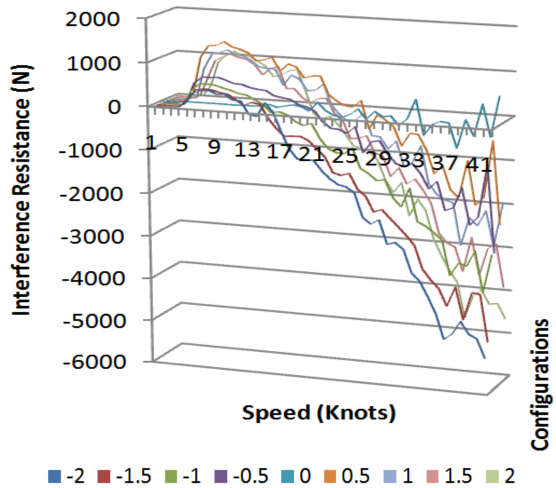


Fig. 11 Interference resistance against velocity plot for hull configurations having a constant separation and draught

Another observation could be that relating to a positive or negative stagger. When the position of a hull is altered by changing its longitudinal positional (i.e. stagger), the same performance is expected. This means that a positive or negative stagger having the same increment will result in an identical solution for the resistance versus speed graph. Fig. 10 displays a sample of some hull configurations which have a constant draught and separation ratio of 0.02 and 1 respectively, but vary their stagger both fore and aft of the central hull using the convention of Fig. 3. The graphs plotted in Fig. 10 also verify that a positive or negative stagger would result in the same performance in terms of resistance analysis. This confirms the theory of Yeung and Wan [10] who identified this characteristic.

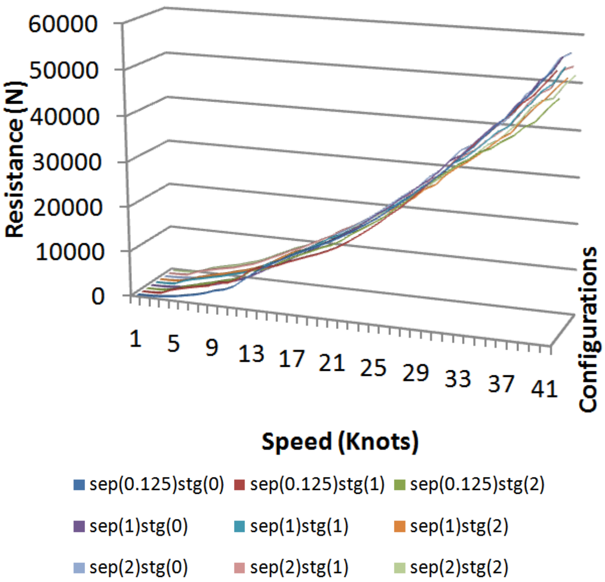


Fig. 12 Resistance against speed for hull configurations having a variable separation and stagger ratios with a fixed draught ratio of 0.02

D. Compound Variations

Compound variations of separation and stagger ratios leads to defining optimal hull configurations. Fig. 12 shows the resistance versus speed plot of nine different hull configurations each having a constant draught ratio of 0.02, whilst varying the separation and stagger ratios accordingly. The corresponding interference resistance graph is exhibited in Fig. 13, highlighting those hull configurations that may be more applicable for certain design requirements. Depending on the purpose of the vessel being designed, the optimal hull configuration may be identified from such a selection of plots.

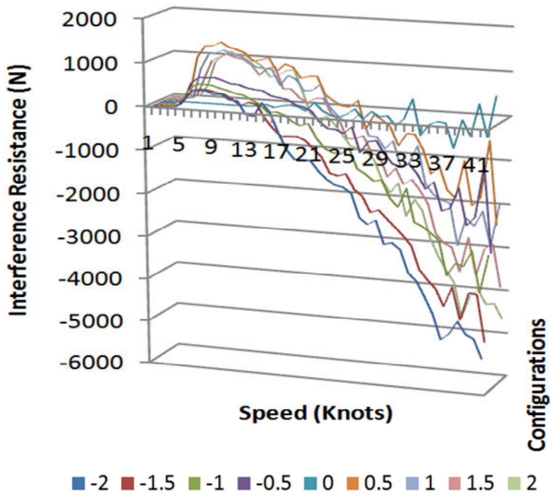


Fig. 13 Interference resistance against speed for hull configurations having a variable separation and stagger ratios with a fixed draught ratio of 0.02

A separation ratio of 0.125 (the actual true separation relating to these hulls is 2.89m) coupled with a stagger of 2 (actual true stagger id of 46.31m) is ideal for specific performance at high velocities. A free surface wave profile of the ideal configuration is shown in Fig. 14 at its optimal design speed.

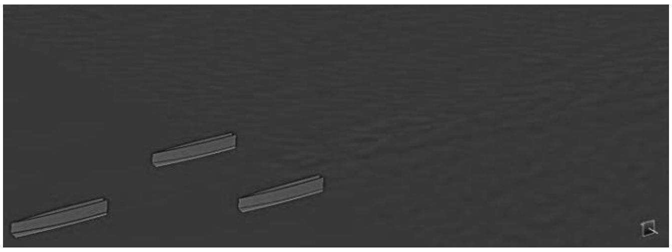


Fig. 14 Optimal hull configuration design for high speeds, travelling at one of its ideal speeds: 40 knots, simulated in HULLSPEED

If the separation ratio was increased further beyond 1, the properties of the vessel improve at low velocities. Here again a stagger ratio of 2 would be ideal since the plots in Fig. 11 clearly show a reduction in resistance irrespective of separation so long as the stagger increases. Unfortunately, other parameters such as stress analysis in the structure joining the hulls may constrain the designer from choosing very large staggers. Further stress computation may be required before discarding hull configurations having such large staggers.

VI. Conclusions

The analysis carried out through numerous simulations resulted in identifying specific findings for trimarans of identical hulls. The relationships derived from these findings should act as a steady platform for more advanced research on multihull vessels. Having said this, clear concise guidelines have been defined such that these guidelines may optimize the hull layout with respect to resistance theory. The guidelines being:

- Variation in Separation: A larger separation will lead to a reduction in resistance for the same speed having identical hulls however some narrow beams prove to have better resistance qualities.
- Variation in Draught: A reduction in draught will lead to a reduction in resistance for the same speed.
- Variation in Stagger: An increase in stagger will lead to a reduction in resistance for the same speed.
- Positive and Negative Stagger: A positive or negative stagger results in the same reduction in resistance.
- Compound Variations: Compound analysis of separation and stagger ratios leads to defining optimal hull configurations.

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