Froude for Thought

GETTING SEMI-PLANING HULL RESISTANCE RIGHT

The semi-planing or semi-displacement hull is the *bête noir* of hull design. Get it right and higher speeds and efficiency are available; M/Y *Silver* (above) is a great example. Differences of 30% are quite possible with all that means at plus and minus values. Trend to the plus percentage and you guzzle fuel as if buying it today at 1960s' prices, go the other way and cost and environmental impact reduce radically. Demonstrable increased hull efficiencies are part of, for example, RINA's green star notation. Here Dr Robert Ranzenbach of Donald L. Blount & Associates, Inc. explains the process of optimisation using the results of public domain tank-testing results and offers design guidance for those taking the semi-displacement or -planing route.

Historically, most megayacht designs have tended towards displacement or planing yachts. Appropriate hull forms and their attendant resistance characteristics for these operating regimes are fairly well understood by naval architects. As the desirable size and speed have increased, many more megayachts are being constructed so that they now operate between displacement and planing regimes, sometimes referred to as semi-displacement or semi-planing depending upon their specific speed and length characteristics.

Recent examples of semi-displacement yachts include *Predator* (below) and *Silver*, 73m LOA yachts with published maximum speeds of 28kt and 27kt respectively. Recent examples of semi-planing yachts include *Lazy Me*, 41m LOA with a published maximum speed of 29kt, and *Pure One* (opposite), 46m LOA with a published maximum speed of 32kt.

The resistance characteristics of yachts operating in these intermediate regimes are not as well understood as displacement or planing yachts and optimising performance of semi-displacement and semi-planing yachts will require enhancements to the design and analysis approach to ensure the same level of confidence. Recently, Company President Donald L. Blount and naval architect James McGrath published a study describing low drag/dynamically stable hull forms based upon analysis of available public domain tow tank data.

Hydrodynamic resistance of the bare hull of a yacht consists of the sum of two components: frictional and wave making.

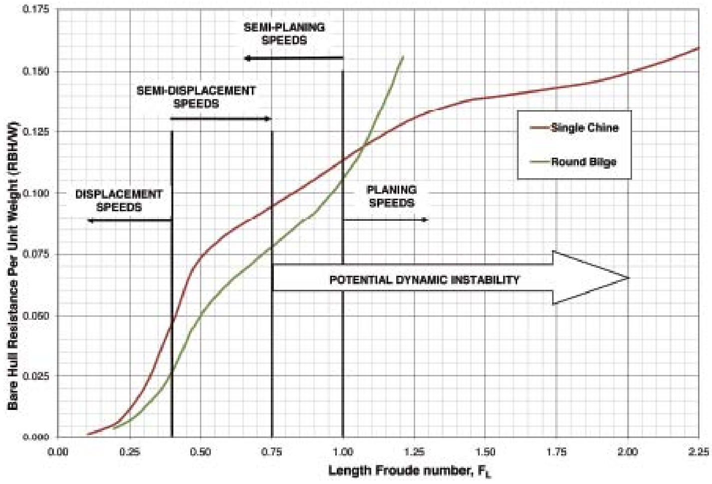
The information provided in that Royal Institute of Naval Architects (RINA) technical paper is valuable because it outlines the significant opportunities to reduce hydrodynamic resistance by carefully selecting hull forms applicable to each specific operating regime and offers specific design guidance. Differences of greater than 30% between the resistances of various hull forms are observed in this intermediate regime and naval architects can ill afford to be on the wrong side of the resistance curve given the present focus on fuel efficiency to reduce operating costs and impact upon the environment.

This experiment-based analytic approach is particularly useful in the early design stage and is an important alternative method to the many computational predictions methods that are available to predict resistance for displacement and planing yachts which are not necessarily appropriate for this intermediate operating regime. A summary of the technical approach, identification of key parameters influencing resistance, and design guidance for yachts operating in the semi-displacement/semi-planing regime is provided here.

Background

Before describing some of the lessons learned from this analysis of public domain tow tank data, a little technical background needs to be given.

Hydrodynamic resistance of the bare hull of a yacht consists of the sum of two components: frictional and wave making. Frictional resistance characteristics are dependent upon waterline



length, speed, and wetted surface area of the hull. Wave-making characteristics are related to two non-dimensional similarity parameters, one called Froude Number that is a function of speed (V) and waterline length (L) and another parameter related to the pressure forces acting upon the hull bottom. When Froude number is calculated based upon length, it is called the Length Froude number, FL=V(gL)1/2, where g is the acceleration of gravity.

Non-dimensional similarity parameters such as Froude number are useful to compare physical phenomena at different yacht sizes and speeds because when a non-dimensional similarity parameter is identical the related physical phenomenon is also identical. Using this relationship, naval architects are able to obtain resistance characteristics when performing model-scale tests in towing tanks. If model-scale and full-scale Froude numbers are matched (by properly adjusting the model-scale speed), then the tow tank results can be extrapolated to the full-scale yacht because the wave-making phenomena are identical.

It is important to note that the relative contribution of frictional and wave-making resistance to the total bare hull resistance changes as yacht speed varies. The relative contribution of frictional resistance tends to reduce slightly as speed increases whereas the wave making contribution tends to grow slowly at first until "hull speed" is reached and then grows quickly until one reaches "hump speed". Hump speed is the point associated with maximum growth rate of total resistance. As speed continues to increase, the relative contribution of wave making begins to fall. Hull speed is generally accepted to occur around a FL of about 0.4. Hump speed generally occurs around a FL of 0.5. Yachts should generally not be designed to operate at a cruise or maximum speed equivalent to this FL.

Displacement yachts operate at relatively low speeds and the pressures acting upon the hull are largely the result of hydrostatic pressure associated with the buoyancy force. Beyond displacement speeds, the influence of dynamic pressure associated with the high yacht speed acting upon the hull bottom grows and at planing speeds largely dominates hydrostatic pressure. For semi-displacement and semi-planing yachts, both hydrostatic and hydrodynamic forces must be considered. It is this complicated pressure balance that makes prediction of wave-making resistance so challenging over this intermediate operating regime.

To put things into perspective, consider the FL associated with the maximum speed of the yachts mentioned earlier: *Predator* and *Silver* where FL is equal to approximately 0.6 and *Lazy Me* (right) and *Pure One* where FL is equal to approximately 0.9. This is in comparison to a planing yacht such as *Fortuna*, a 41.5m LOA yacht with speed in excess of 65kt and a FL of approximately 1.9.

Analysis and Results

Publically available results from towing tank tests of the following systematic series were collected and analysed to identify the key influences on resistance over a FL range between 0.4 and 1.0:
NPL (round bilge published in 1969 and 1976)
DTMB Series 62 (single chine published in 1963), 63 (round bilge published in 1963), and 64 (round bilge published in 1965)
NTUA (double chine published in 1999 and 2001)
USCG (single chine published in 2006)
Delft Series (single chine published in 1982 similar to DTMB Series 62)

Figure 1 shows a plot of bare hull resistance per unit weight (RBH/W) versus FL. The resistance curves shown here are for specific yachts but are reflective of the general trends. It can be observed for yachts operating below a FL of 0.4 (displacement) that round bilge yachts offer less resistance when compared to single chine yachts. This trend continues until approximately FL equal to 1.0 which is generally considered the early stages of planing. It should be noted that the boundary definition between what may be called semi-displacement and semi-planing is not generally agreed.

The following parameters in decreasing level of influence on resistance for a particular configuration of hull form over this FL range were identified:

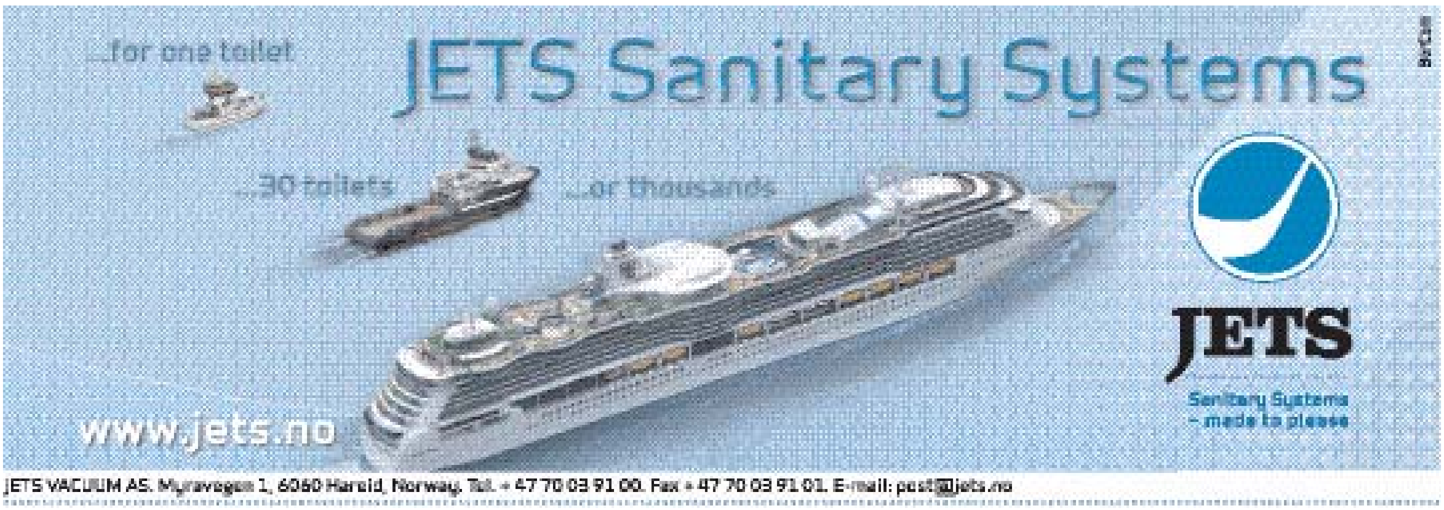
Slenderness Ratio is the dominant factor
Longitudinal centre of buoyancy/length
Length-to-beam ratio

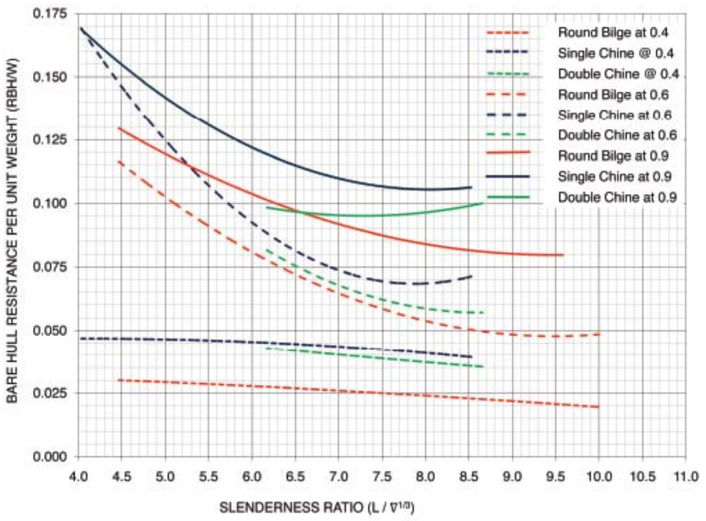
Other parameters such as block and prismatic coefficient commonly identified as key parameters for traditional displacement hull forms.

Only Slenderness Ratio, defined as the length (L) divided by the cube root of the volume of displaced water (∇) equal to $L/\nabla^{1/3}$, will be discussed here. For a more detailed discussion about the other parameters, please consult the original RINA technical paper.

Figure 2 shows a plot of RBH/W versus Slenderness Ratio. The results are plotted for three different types of hull form (round bilge, single chine, and double chine) at three Length Froude numbers, 0.4 (displacement), 0.6 (semi-displacement) and 0.9 (semi-planing). The trend lines for each hull form type are based upon the average of collected data for a variety of yachts.

For semi-displacement yachts, it can be observed that bare hull resistance per unit weight generally decreases relatively significantly as slenderness ratio increases but the trend tends to wane as slenderness ratio increases above 7.5 with a minimum value occurring for round bilge hulls at a slenderness ratio of approximately 9.5. It can also be observed that the round bilge hull form offers the least resistance while the single chine generates the most resistance with double chine in between. This trend is consistent across the range of slenderness ratios shown top of page 202.





Round bilge yachts tend to be more susceptible to this form of instability than single or double chine hulls

For semi-planing yachts, similar trends for single chine and round bilge yachts can be observed but the rate of bare hull-resistance reduction as slenderness ratio increases is lessened. Interestingly, the limited amount of available data for double chine hull suggests that the influence of slenderness ratio is quite muted and at a slenderness ratio of around 6.0 to 6.5, a double-chine hull form may offer the least resistance.

The results show that the bare hull resistance of semi-displacement and semi-planing yachts are strongly dependent upon Slenderness Ratio. For a fixed length, this translates into a strong dependence upon weight unlike for displacement yachts whose FL is less than 0.4. The slenderness ratio dependency is most significant for yachts operating near a FL of 0.6.

Design Guidance

Based upon the analysis of the data described herein and DLBA's design experience, the following design guidance for semi-displacement and semi-planing yachts is provided:
Yachts should have purely round bilge hull forms up to a FL of approximately 0.4
Bulbous bows are an important element to reduce resistance up to a FL of approximately 0.6
Yachts should have round bilge hull forms with longitudinal flow separators/chines/knuckles beginning at the stem above the static waterline, continuing aft to at least amidships below the waterline for FL between 0.4 and 0.9
Double chine hull forms appear to be desirable when operating at a FL greater than approximately 0.8
Single chine hull forms appear most desirable when mostly operating at a FL greater than approximately 1.0

Appendix B of the RINA technical paper provides a table of minimum RBH/W for round bilge, double chine, and single chine hull forms for FL from 0.4 to 1.0 as a function of slenderness ratio. This table provides a benchmark by which naval architects may evaluate the relative bare hull resistance of new hull designs.

Fortunately, many aspects of these design guidance elements do not degrade the seakeeping qualities of the high-performance yachts.

It is important to note that in the quest for low resistance one must not forget to address dynamic instability issues related to speed-induced bow diving, heel and/or uncontrolled course keeping (yaw) changes which are non-oscillatory. These instabilities result when a heavily loaded yacht operates at speeds in excess of approximately 25kt and the velocity of water at the surface of the hull generates low (suction) pressures. Should these dynamic pressures occur asymmetrically, as might happen in a seaway, one side of the yacht may be sucked down (resulting in a heel angle) and remain in that attitude until speed is reduced. The heeled attitude will likely induce a yaw moment resulting in course deviation/bow steering.

Round bilge yachts tend to be more susceptible to this form of instability than single or double chine hulls, although the latter two may also exhibit this characteristic at high speed when overloaded and/or operated with a low trim by the bow. Whenever a round bilge yacht is powered so that it may operate at speeds greater than FL = 0.75 or chine hulls have operational conditions such that the ratio of Longitudinal Centre of Gravity (LCG) divided by the Length (L) approaches 45% Forward of the Transom (FOT) or greater, then it is recommended that model experiments be conducted to evaluate the potential for dynamic instabilities.

Conclusion

Growing numbers of megayacht designs are being constructed as semi-displacement or semi-planing yachts. The analysis of public domain tow tank data has identified the dominant influence of hull form and slenderness ratio over this intermediate operating regime. It is hoped that this information will assist naval architects in the early design stages by providing optimal minimum resistance targets.

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Yacht images courtesy of: Baglietto, Feadship, www.puremarinegroup.com and Justin Ratcliffe

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