Alternative Analysis of Delft Series

This note is a "thank you" for those who have chosen to publish the results of their analysis of this very importants series, and therefore is not intended to be a criticism of the final results of the Delft studies. However it is unlikely that someone would undertake to an independent analysis, which is quite time consuming and tedious at best, unless one believed that there was a better technique that could describe the data more robustly and accurately..

Furthermore, there are probably many individuals who can further improve the study either by providing new data or providing new variables with a stronger basis in theory. Since studies of this sort are essentially open-ended, this can be construed as a solicitation of further input from those who posess theory, data or both. An impediment to this is the overcompetitive nature of this "gentlemen's" sport in which there is less cooperation (which leads to establishment of sound design principles) than in the domain of Naval vessels which could conceivably meet in mortal combat. It is not coincidental that all these papers have been published by a country that has never challenge for the America's Cup but whose facilities have contributed to the efforts of many nations?

This technical note describes an alternative analysis of the Deflt Series, which has been documented in a series of papers [1-6] published by Delft and MIT. This piece is essentially a synthesis of the MIT approach (which relies heavily on the LPP), the Delft (which uses use of more form parameters to correlate with drag) and the approach associated with the MARIN [7-8] which uses estimates form and interference components, and uses an equation based on wavemaking theory to correlate with residual drag.

This note builds on the results of the previous published studies, and incrementally improves it by using a technique developed to analyze other model series, most notably a series of over 35 different SES and hovercraft model series tested at David Taylor and Lockheed in San Diego over a 15 year period. The author of this note was the principle investigator for this two studies of this sort, one an in-house continual study used by a now defunct designer of SES, and another done directly for the US Navy.

Lastly I would like to apologize for using the term for resistance common in the aerospace industry - "drag". Despite his background in Naval Architecture never understood why a 3 syllable latin root word is preferable to a short, descriptive Anglo-Saxon word.

Background

There are two basic criticisms of a regression study that is a tabular polyfit.

1) It is difficult for the users of the formula to assess the differing importance of the various terms, so it takes considerable trial and error to perturb the shape parameters to an optimal combination for the intended operating conditions.

2) There is considerable "bouncing" of the coefficients between small variations of Froude number that is not entirely realistic. This is caused by variable intercorrelation, which results in overfitting the data. Since 9 coefficients are used to describe the residual drag of 39 models, this approach has a ratio degrees of freedom to data of about 25%. I consider this to be overfitting the data, even

if the variables exhibited a high degree of orthogonality, which is not the case, since polynomials of the same variables have strong intercorrelation. The fact that there was considerable changing of the variables between after the addition of the Series III data yet there was little change in the overall results indicates that there is considerable intercorrelation of the data. I make sure that if two variables are highly intercorrelated (a correlation coefficient of 0.8 is a reasonable maximum) they are either redesigned to reduce intercorrelation or combined into a new variable.

Discussion of Paper and Presentation of Alternative Methodologies

(0) The Database

To do a study of this sort, it is imperative to get the same data as in the study, and since the results for the series can be hard to find, that was a trick. But with a few polite letters to Holland, and perusing the MIT library and Prof. Jake Kerwin's personal files, I collected most of the data.

But since the technique used in this study does not require models of a single series, I added as much extra data as I could. This includes the model data for Intrepid and Freedom designed by S&S - Freedom from OTC, Intrepid from the Lockheed tank.

In order to include some geosim data in different tanks and different scales, I also have the full scale Antiope and 1/6 scale Antiope reports, as well as geosims of the first three Delft models tested in Canada. All told I now have about 3K points, and will feel very confident in the equations when I have about 10K, with most of the additions being bigger models and models specifically designed for good performance - like the PACT or Matador series.

Equation (1) - Total Drag

The basic difference in estimating total drag between my analysis is that there is no specific term defining heeled drag. Heeled drag can be explained by changes in the hydrostatic properties of the hull or assymetry resulting in a reduction in the effect aspect ratio of the hull. In other words, if a plausible physical reason for a drag term can not be quantified, it can only be added to the study as a final act of desperation, to be removed when a substite is found. Use of the LPP to estimate L and B as a function of heel has been substited for estimating a drag term dependent on heel angle, although it has been found that heel angle decreased the effective aspect ratio of the hull/keel combination. Of course, this hypothesis should be tested, and continually retested as new data and fitting techniques are added to the analysis.

Equation (2) Frictional Drag

In model test extrapolation, some facilities use a form factor is used to account for the fact that at low Froude number, the drag is higher than that due to friction alone. This form factor can be estimated from a Prohaska plot which estimates the y intercept of the line relating Ct/Cf vs. Fn^4. Holtrop performed a regression relating the form factor to the geometry of the hull. The equation is shown below.

$$k=-0.07+0.487*(B/L)^{1.07}*(T/L)^{0.46}*(L/LR)^{0.121}*(L^3/V)^{0.36}*(1-Cp)^{-0.6}$$

$LR = L * (1 - C_p - 0.06*C_p*LCB) /(4C_p-1)$

Note: LCB is the position of the the center of bouynacy in respect to midships, positive forward.

This equation seems to represent a log-linear regression of the principle components with the form factor, although the constant term would not be present in a pure log-linear regression. Therefore either a non-linear tool was used, or as is more likely, the constant was perturbed by the analyst until the standard error was minimized.

Form factors all also used for the keel and rudder - they are taken from [7], and are on the order of 15%.

Since models of different sizes were used in this study, and two series of geosims were used (Antiope and the larger geosims of the first three Delft models), as well as the near geosims of Intrepid and Freedom tested at different model scales, it seemed likely that the merit of the form factor can be tested, which is important because lumping as much as 35% more model drag to a term that scales along the ITTC curve will considerably reduce full scale predictions.

However, if a database of similar number of runs could be developed for models of a larger scale 9 (say the 1/3 scale America's Cup and 1/4 scale Matador models), the form factor's value could be better estimated, in addition to providing a better ability to separate the different drag components.

Since interference drag (causes by the presence of an appendage inside the boundary layer of the main body) and the stimulator drag all are dependent on dynamic pressure, their intercorrelation is very high. Therefore the friction/form drag, the also included interference drag, described below, and the drag due to turbulence stimulation were lumped together into one term.

Inclusion of more model data of larger scale (hence much larger Reunolds number) and wind tunnel tests of full scale Reynolds number and no wave drag will allow the separate investigation of these effects, but it is likely that the current coefficient for these effects is about as accurate as possible.

Equation (3) - Wetted Surface

It is important to have an accurate parametric predictor for wetted surface, but I believe that equation (3) of the paper gives no meaningful physical insight into the relation of the hull design and the wetted surface.

If we break the product of the canoe body volume and the LWL into its components, we find the equation becomes.

$L_{WL} * (B*T*C_p)^{0.5} * C_m^{0.166} * (a + b * B/T)$

Phusically, there are two ways to look at wetted surface, and possibly they can be combined into a technique that will be accurate. The first is that the wetted area is the midships girth, extruded over the length of the waterline. The greater the prismatic, the closer the value of the total wetted surface to the product of LWL and girth. This would give an expression:

$$Sc = LWL * G * (a + b * C_p^c)$$

Of course, this is a non linear formula, but the equation above suggest that the wetted surface might be proportional to the square root of C_p

However, that still leaves the job of estimating G. We do know three limiting cases:

1) For a triangle (C_m = 0.5) , the minimum girth is the twice hypotenuse of BWL/2 and T.

2) For a C_m of 1.0 (a rectangle), the minimum girth is B+2T.

3) For a B/T = 2.0 and a semicircular section, the C_m = PI/4 and the girth is PI * B/ 2

The third relation convinced me that it is quite reasonable to use linear interpolation on Cm to estimate maximum girth.

A second way to estimate wetted surface is to realise that the wetter surface would be related to the waterplane area by the ratio of the average hull girth to the average hull beam. If we assume the ration of midships girth to waterline beem is close to the relation between avarage girth and average beam, one gets the following equation:

$$Sc = Aw * G / B$$

These two effects can be combined into an equation.

However, if we realize that $A_W = C_W * B *$ LWL and that C_W has a very high linear dependency on cp, it can be seen that these two representations are not as orthogonal as their geometry might suggest.

$$Sc = L_{WL} * G * (a * C_W + b * C_p^{0.5} + c)$$

The constant term c is included to add another degree of freedom to the fit - it should be very close to zero, and if it is, the regression can be modified to eliminate the constant.

(5) Prediction of Residual Drag

My approach is based on the fact that it is better to regress the tank results directly, and not values derived from manipulating the data, such as splining it to get residual drag at a series of Froude numbers. Therefore, every run of a model became a data point, rather than 14 Fn * 39 models = 546 points.

The Gerritsma study normalizes drag (residual) by the model weight. This makes sure that the least mean squares technique treats all models as equally valid, rather than biasing the coefficients towards fitting the heavier models. This is particularly important when combining runs of different scale, as done in this analysis.

Since I am combining runs of all Froude numbers (and heel and yaw angle), however, it is better to normalize the data by a term which has a high correlation with the dependent variable. This can be done by normalizing the drag by the product of maximum section area (which is proportional to weight) and dynamic pressure, making the independent variable a drag coefficient.

One important conclusion of the Gerritsma approach is that it is essentially impossible to use the same techniques to model the residual drag above and below Fn=0.45.

This is because for low displacement craft, there is a drag hump at about this speed, with drag either leveling off or decreasing with speed, particularly for high B/T boats which begin to be supported by dynamic lift, further reducing wavemaking. However, for higher displacement craft, wavemaking drag continues to increase.

Also there is much less data at these speeds, as the models of series I were not tested in this domain. Since there is much less data, and much less variation in the model parameters (since only series II and II were tested above Fn = 0.45), it is unrealistic to assume that the same theoretical or statistical techniques will work at high and low speed. Furthermore, it is unrealistic to think that heavy displacement craft will ever go that fast as to make data in that domain useful.

Wave making theory that wave drag peaks in the regime of Fn = 0.45, which is the case for not just surface craft, but for surface effect craft as well. Because of this fact, an aside on how these techniques used on this study were developed is in order.

For hovercraft, wavemaking of a constant pressure surface moving over the water is a reasonably well posed boundary value problem that was elegantly solved many years ago by Nick Newman (who was instrumental in designing the IMS LPP such that it could evaluate items that would likely have a high predictive effect on wavemaking). It turns out that the value of wavemaking drag for SES is almost perfectly described by this algorithm. However, the wetted surface is a very complex function of trim, hull shape, speed, sea state, and most importantly, cushion air flow.

This makes SES the antithesis of sail boats, for which the wetted surface (neglecting the effect of deformation of the free surface) and frictional drag is considered well understood, but the wavemaking drag has no theory that fits it. Use of slender body theory (Mitchell Integral) do not fit the data at all, and more elaborate free surface techniques are neither widely available nor gracious in their use of computer time - "Days on Crays" was the how it was put by those who considered themselves lucky to get one hour on a VAX 11/780, a machine with about the power of a desktop computer costing one week of a mid-career engineers pay.

Yet there are several facts from wavemaking drag theory that can be used to help design variables to correlate with drag. I will discuss the low and high spped domains separately.

Low Speed Wavemaking

1) Below Fn = 0.45, wavemaking drag is proportional to V^4. This means that, since two powers of speed are represented by normalizing the dependent variable by dynamic pressure, Fn^2 is an important variable.

2) There is some oscillation in the drag curve, particularly at low Froude number, although not nearly as much as linear theory indicates. However, linear theory indicates that the interference of the diverging and transverse waves are the cause of this oscillation, and that it is proportional to cos(lambda/Fn^2), as well as the square of prismatic coefficient. This term has been taken from Holtrop [7].

3) The effect of B/T is largest around the Fn of 0.3 (shown by the IMS and Gerritsma

studies) but the inclusion of the form factor in friction moves more of the drag to friction/form for high B/T boats, and reduces this effect.

In order to develop a B/T correction as a function of Froude number, a statistical purist (actually a statistical purist would probably never come near this project) would devise a set of Chebechev polynomials - these are polynomials that are mutually ortogonal for a given order and over a given domain. This guarantees that the values of the coefficients will not be effected by intercorrelation, as is often the case with polynomials.

Never the less by developing a series that is a 3 term polynomial with B/T, we can model this behavior, and then develop a new term which has the behavior of the 3 term polynomial in one term. The results indicate the B/T corrections is:

$$\text{Correction} = Ax * q * B/T * (a * Fn + b * Fn^2 + c * Fn^3)$$

Coefficients a, b and c are set so that they are equal to 0 at Fn=0 and Fn=0.45, and equal to a maximum of 1.0 at Fn=0.30.

4) The effect of Volumetric is to increase drag mightily at high Froude number. Since this effect is quite different from the effect of B/T and both effects can be studied and modeled in the same run.

$$\text{Correction} = Ax * q * V^{1/3}/L * (Fn - 0.3)^2$$

5) Since Gerritsma's study and common practice indicate that there is an optimum prismatic coefficient which increases with Froude number. Since Gerritsma represents drag as a second order polynomial (with a small dependence of volumeteric coefficient), it is possible to develop and initial estimate for optimal Cp and the penalty function would be proportional to:

$$(C_p - C_{popt})^2$$

Trial and error determined that this penalty is proportional to Fn^4.

6) Wavemaking theory suggests that the minimum drag hull form is one that is symmetric about midships. Viscous effects indicate that the effect of the boundary layer make the optimal LCB somewhat aft of this point, say 2 to 3%. Taking Gerritsma's results on the LCB polynomial and using it to develop an expression for optimal LCB, it is possible to develop a penalty for non-optimal LCB as a function of Froude number.

High Speed Drag

For high speed, Gerritsma uses a fit which includes polynomials of L/B and the ratio of volume to waterplane area. In the latest paper he also uses a coefficient for LCB, which was not possible in the previous studies, since the Delft II did not contain any variation in LCB. Unfortunately the fit only included the linear term, implying that there is no optimal LCB. More reasonable would be to assume that there is no discontinuity in optimal LCB, and use a correction factor similar to the low speed regime. However, since all the Series II have LCB at 2% aft and all the Series III at 4.4% aft (except for one variation forward and one aft), there may be some bias in regard to this variable in the high speed regime.

Alternative Analysis of Delft Series

It is common in planing boat analysis to use a loading factor to represent drag in the planing regime, with the loading factor a non-dimensionalized ration of weight to waterplane area (although if the weight is used this coefficient has the units of density). In my studies, I have often found it more physically intuitive to represent this term by the ratio of the maximum section area to the waterplane area, in essence the ratio of the drag producing to the lift producing areas.

Since it is desirable not to have any disconnect in the prediction formula at Fn=0.45, it is simple to devise a polynomial on speed of the form.

$$A + B * (Fn-0.45) + C * (Fn-0.45)^2$$

The coefficients A, B and C are themselves functions of the following factors. For predictive purposes, the value of A is substituted with the drag at Fn = 0.45 computed with the low speed equations.

Ax / Ax

L / B

Why use B /L rather than L/B, it could be just contrariness or it could be a bias that I prefer coefficient with a positive correlation what they wish to explain.

Drag Change Due to Heel

The LPP can predict L and B, then L and B and be made factors of heel, and that should do it. Any assymetry factors will be adjustments to the induced drag, which can't happen without heel for real boats. However, just to test, it is easy to include a term that includes heel squared (just to make sure, some models have negative heel angle, but would not have a negative drag due to heel) - although that would make port tack kind of fun). I used such a term, and it was negligible, so why waste it.

Induced Drag

The current IMS approach estimates the reduction in effective span of the hull keel by using ratio of midships area to span squared [6], and then correcting this for B/T ratio. The statistics essentially suport this conclusion, except for high B/T models at high heel angle.

For induced drag, adding high B/T models shows that the IMS equations under predicts induced drag for high B/T at high speed and heel. It does not take a big stretch of the imagination to figure that the lift from the keel is sucking down the free surface and increasing wave drag.

What is the appropriate volume, Froude, number, etc. What does theory have to offer - not much. So I simply made a series of variables combining induced drag with B/T, heel and Froude number. The bottom line to this is that for a high B/T boat at moderate Froude number and 20 degrees heel, IMS under predicts induced drag by half.

Summary

The results of this study are in the public domain, with the exception that they can not be resold by a commercial software product without a license, either for resale or internal use. They are available on spreadsheet obtainable by mailing a disk and mailer to

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