AVOIDING COMMON ERRORS IN HIGH-SPEED CRAFT POWERING PREDICTIONS

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SUMMARY

Overly optimistic resistance, powering and speed predictions for high-speed craft appear to be increasing. Common errors and flaws causing excessive performance speed claims for high-speed craft, especially novel ones, are reviewed. This work will help to avoid *common performance prediction errors* and aid reviewers in identifying them.

1. INTRODUCTION

This paper is not intended to be a comprehensive text for performance prediction for the broad universe of high-speed craft. This is beyond the scope of a paper, or even an entire symposium. Equations are intentionally absent and the references sparse. However, this paper can still be useful in identifying, understanding and avoiding errors in powering predictions. For over twenty years, the author has observed numerous mistakes and errors in high-speed craft predictions. Over fifty errors or mistakes in high-speed craft powering predictions are reviewed. General categories of errors in speed prediction and claims are listed below.

Inappropriate Comparisons
Optimistic Propulsor Predictions
Inconsistent and Unclear Definitions
Low Weight Estimates
Air Lubrication and Lift
Common Powering Prediction Errors
Full Scale, Model Test and Scaling Errors
Designing to an Unrealistic Design Point

MacPherson (1) is a general reference on powering prediction errors.

2. INAPPROPRIATE COMPARISONS

It is common for performance prediction claims to be compared against alternate concepts. The author has often observed alternate concepts presented for comparison whose claimed resistances or powering are excessively high and thus making the concept promoted appear to have an advantage that may not exist. Comparisons are made unfairly with unrepresentative concepts or against bad or false data. A craft concept may also be proposed with a very efficient propulsor and compared against alternate concepts with inefficient propulsors with the performance advantage falsely attributed to the proposed hull form and not the propulsors. Traditional propeller installations can be significantly less efficient at very high speeds than surface piercing propellers or waterjets due to cavitation and appendage drag. Jacobson (2) and Almeter (3) are two of many references providing resistance and powering data as a check. Figure (1) is from Jacobson (2). It plots current transport efficiency limits against non-dimensional Froude Number (based on volume) for several different classes of hull types and provides a sanity check for performance claims.

3. OPTIMISTIC PROPULSOR PREDICTIONS

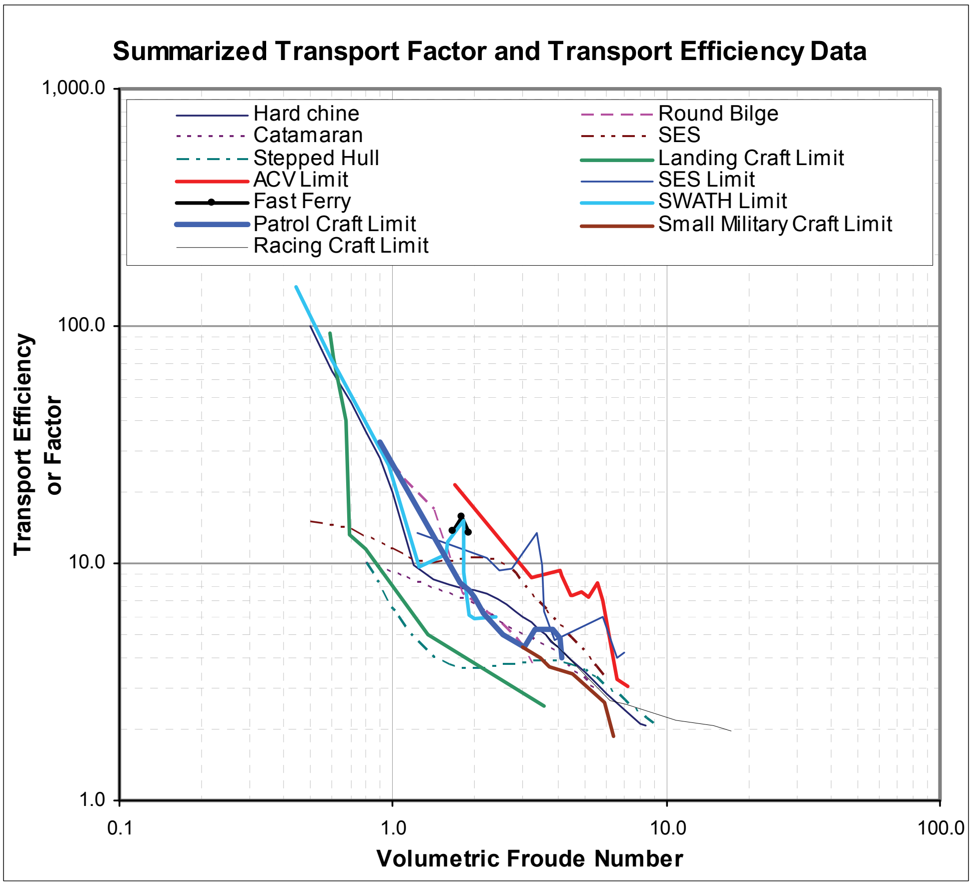
Optimistic propulsor performance prediction, high or low, can result in optimistic performance claims. As an example, low propulsor performance may be predicted for a prototype craft. This allows an unrealistically low resistance to be back calculated from the craft's measured performance. Failure to make speed is often attributed to an "inefficient" propulsor when it is really the fault of a poorly performing hull form. Unrealistically high speeds can also be predicted using unrealistically high propulsor efficiencies. In this case the high "claimed" speed is due to the propulsor and not the hull form. Blount (4) can be used as a guide to propulsor performance for high-speed craft.

4. INCONSISTENT AND UNDEFINED DEFINITIONS

Inconsistent and undefined definitions can result in unrealistic craft performance expectations even when all parties involved are reputable and competent. As an example, a proposal may claim 50 knots for their concept. Many in the US Navy would automatically assume the speed corresponds to Full Load condition at an engine rating that can be run all the time with hundred degree Fahrenheit inlet air and the like. The proposal may be making claims on entirely different conditions; such as near Lightship and intermittent power at a much lower air inlet temperature. This disconnect, often unintentional, can result in an unrealistic proposal that does not meet customer expectations.

A common area of confusion is engine ratings. Terms like Maximum Continuous Rating are not universally understood and agreed upon. Maximum Continuous may not mean maximum continuous as many believe it. Maximum Continuous Rating may only be available for a small percentage of the engine's duty cycle without premature wear. Simply, the engine cannot be run at this rating for extended periods despite the descriptive title of the rating. Machinery ratings are not consistent between manufacturers. Ambient and assumed installation conditions for engine ratings can vary greatly. These conditions include air temperature, water temperature, and inlet and outlet losses – all of which impacts engine performance.

It is critical to define terms. All parties must fully understand the definitions as used and not make assumptions. This may require what sounds like ignorant questions from all directions, but they are critical. Machinery power ratings and the impact of temperature must be clearly understood. The duty cycle or operational profile has to be understood by all parties.



Transport Factor - defined as shown in the equation below:

$$TF = \frac{\Delta * V}{326 * P_B}$$

where:

Δ = Vessel design displacement (in pounds mass)
V = Vessel design speed (in knots)
P_B = Total installed propulsive and lift (brake) horsepower

Figure 1: Transport Factor

5. LOW WEIGHT ESTIMATES

Many high-speed hull forms are very sensitive to weight. A small increase in weight may result in a disproportionate increase in resistance. This results in greater fuel loads, increased power to obtain speed, and potentially a non-convergent design. In summary, weight is bad and a design killer for many high-speed craft concepts. Some concepts, not all, are extremely sensitive to craft weight. An error in the longitudinal center of gravity estimate can also adversely impact the performance prediction.

The author has reviewed numerous high-speed craft concepts based on unrealistically low weights resulting in unrealistic high-speed claims. The performance prediction may be correct for the assumed displacement, but if the displacement is incorrect, accordingly the prediction will be wrong. Almeter (5) and Jacobson (6) are useful references for predicting or checking weight of many high performance craft. Figure (2) is taken from Almeter (5). It plots lightship density (lightship displacement divided by total volume) against total volume for several classes of hull forms and ship types. Figure (3) is the same as figure (2) with the exception that the propulsion weights have been deducted from the lightship weight. Figures (2) and (3) are useful as a sanity check.

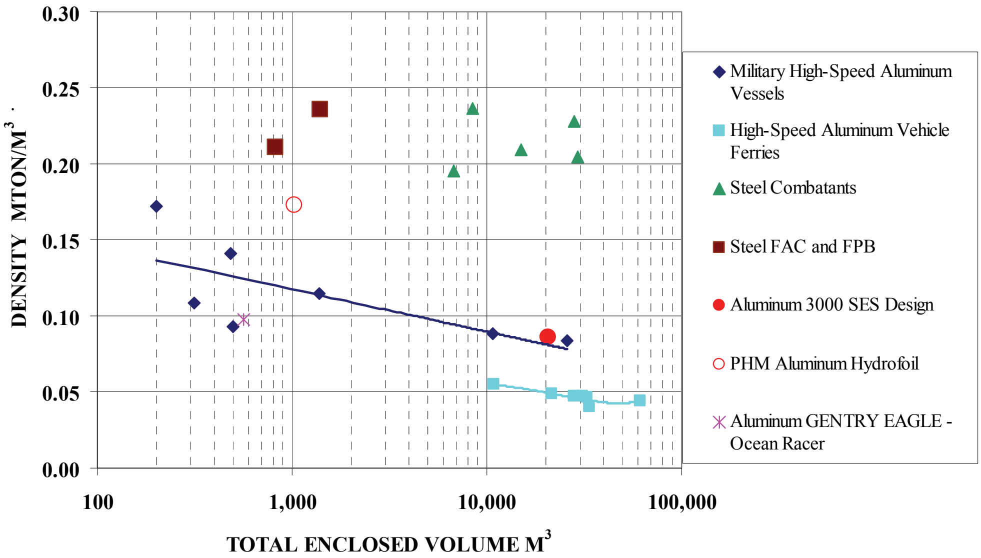


Figure 2: Lightship Density vs. Volume for Different Craft Types

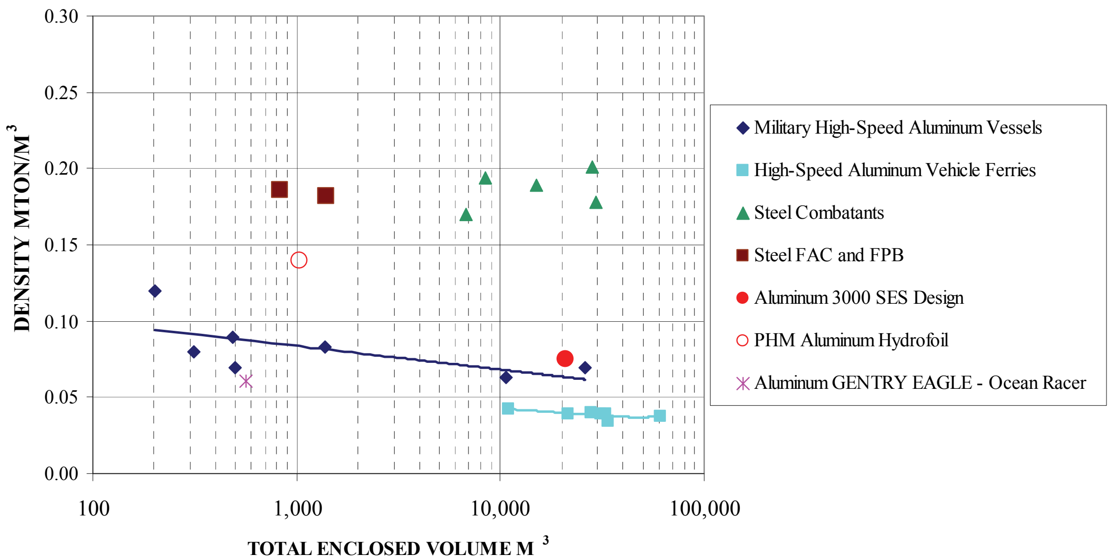


Figure 3: Lightship minus Propulsion Weight Density vs. Volume for Different Craft Types

6. AIR LUBRICATION AND LIFT

Many high performance craft claim significant benefits from aerodynamic lift and air lubrication. A proper discussion is certainly beyond the scope of this paper, but a few critical points will be made. Aerodynamic lift is real and used by hydroplanes, wing in ground (WIG) craft, and seaplanes. These three types of craft have two things in common; they are very fast and extremely lightly loaded by marine standards. Many concepts currently proposed are a fraction of the speed of the aerodynamic lift craft mentioned and dramatically heavier loaded. The Soviets extensively investigated claims that air significantly reduced the drag of inverted planing hulls and concluded it did not, Pavlenko (7). Promoters of aerodynamic lift for all but very high-speed and lightly loaded craft need to substantiate their claims.

Aerodynamic lubrication is a concept that has existed for over a hundred years as demonstrated by a cursory review of United States patents. It is critical for anyone claiming this benefit to substantiate it. Aerodynamic lubrication is not the same as air pockets or cavities found in stepped hulls, air cushion vehicles and the like.

7. COMMON POWERING PREDICTION ERRORS

Common powering prediction errors include:

Failure to include air drag for superstructure
Unrealistically low air drag coefficients
Neglecting wind speeds
Underestimate or ignore appendage drag
Neglecting momentum drag for air cushion vehicles
Ignoring drag of blisters and pods for propulsors
Underestimating or ignore spray drag
Underestimating wetted surface
Extrapolating beyond legitimate bounds of methods
Over reliance on CFD without calibration
Ignoring interference drag
Transom separation
Ignoring shallow water effects
Neglecting propeller and waterjet cavitation
Neglecting hydrofoil cavitation
Neglecting impact of foil submergence on hydrofoil performance
Underestimating skirt and seal drag
Underestimating cushion air requirements
Inconsistent friction line use
Propeller tunnels
Errors in added sea state drag
Failure to account for sea state impacts on propulsor
Neglecting propulsor lift and height of thrust line
Neglecting impact of shaft angle on propellers
Neglecting trim control devices

7.1 AIR DRAG

Air drag is significant for many high-speed craft and the author has observed air drag coefficients of 0.30 and lower for non-streamlined shapes. Air drag for superstructure is often omitted. In many resistance prediction techniques, systematic series and theoretical, there is no allowance or accounting for air drag. Air drag for hull and superstructure has to be calculated independently and added. As an example, the Soviet BK Series was run behind a shield to eliminate air drag and accordingly the series resistance does not include air drag. References addressing air drag include Walsh (8 and 9). Still air is standard in many calculations and model tests and this can cause an error if the craft has to operate into a wind. As an example, a twenty knot wind speed can almost triple the wind drag of a thirty knot craft. There can be a significant difference between wind speed on craft and free stream wind speed that needs to be addressed.

7.2 APPENDAGE DRAG

Appendage drag includes shafts, skegs, waterjet fences, struts, ride control devices, cooling water pickups and anodes. If the concept requires a large amount of raw water, the momentum drag associated with collecting the water will be significant. This is in addition to the appendage drag. Many high-speed hull forms do not readily accommodate propulsors and main machinery and require blisters, sponsons or pods. As an example, it is not unusual for the side hulls of surface effect ships to have blisters for waterjets. These blisters increase side hull drag and if neglected, the performance will be over estimated. Model tests with an appendaged model do not always properly capture the additional resistance of appendages.

7.3 SPRAY DRAG

Spray drag can be very significant for many hull forms and is often neglected or underestimated. Hydrofoil struts, shafts penetrating the water, and fine bows are a few examples of large spray generators that significantly increase the drag of a design. The spray within tunnels of many craft can be very significant. Modern planing craft designs significantly reduce spray drag through the effective use of spray rails. Spray rails may not be effective for all hull forms.

7.4 WETTED SURFACE

The author has observed several cases of significant underestimation of wetted surface. One source of error is the assumption of water separation off the sides where it does not. An example is assuming that the outboard sides of a surface effect ship are dry when they are wet. Tunnels between hulls or bodies are often claimed to be dry, often due to air lubrication, but quite often are wet.

7.5 ANALYTICAL METHOD

A common error is to use an analytical method that is not relevant to the craft under consideration. This includes resistance, propulsor, wake and thrust deduction analysis. Otherwise legitimate analytical methods are often used beyond the bounds of accuracy. Many analytical methods use equations with higher order terms that can provide false results even slightly beyond their bounds of applicability. It is critical to review applicability and bounds of analytical methods. For example, the longitudinal center of gravity and a constant design waterline are assumed fixed in many methods. This can result in significant error if the design does not match the assumed values. Far too often analytical tools are used without the users fully understanding their applicability and limitations. An unethical individual can always find an analytical method to provide the desired answer. Where possible, the author requires the references that the analytical methods are based on be delivered with calculations.

7.6 INTERFERENCE

Interference between bodies is often underestimated or even ignored. This includes interference between displacement bodies, foils, and air cushions. Interference can also adversely impact running trim that can result in an underestimation of resistance at hump speeds if neglected. Molland (10), for example, documents interference between displacement catamaran hulls.

7.7 TRANSOM SEPARATION

Separation of the water from the transom can significantly impact resistance and complicate theoretically based prediction methods and limit their applicability. It is critical to understand how the prediction methods address transom separation and establish a lower limit for its applicability.

7.8 SHALLOW WATER

The impact of shallow water on resistance cannot be ignored for those craft required to operate in shallow water. Shallow water drag may be significant where the Froude Number based on water depth approaches unity (one) and the craft is in relatively shallow water (significant draft to water depth or length to depth ratios). Paradoxically, resistance can actually reduce at Froude numbers not much greater than unity.

7.9 CAVITATION

Neglecting propulsor cavitation can result in significant over prediction of speed. Not all propeller models include the effects of cavitation. Waterjets sized for the top speed may not have significant cavitation at top speed, but may cavitate significantly at hump speeds and be unable to push the craft past it to its required speed.

Like propellers, hydrofoils can cavitate and it is critical that this be considered in predictions. The cavitation may not be captured in small models in traditional resistance and powering tests. The efficiency of hydrofoils can also significantly decrease as they approach the surface.

7.10 SKIRT DRAG

There are often errors in skirt drags of surface effect ships and air cushion vehicles. The author sympathizes with all who make these predictions who lack relevant data. There is little available in the public domain on skirt drag and it tends to be empirical and individual equations may have very limited ranges of applicability. Rigid seals, often ship like, have been proposed for surface effect ships. They are often assumed to have the same resistance characteristics of traditional flexible seals. This assumption has to be substantiated if claimed. Aerodynamic momentum drag caused by accelerating the air required for a surface effect ship or air cushion vehicle to operate cannot be ignored.

The air flow to cushions of air cushion vehicles, flexible and rigid seals, can have a significant impact on powering prediction. Not only does the air flow require fan power, but can impact resistance. The air flow should always be compared to other air cushion vehicles as a sanity check.

7.11 COMPUTATIONAL FLUID DYNAMICS

Computational fluid dynamics, CFD, is becoming more widely used and can be extremely useful. Prudent users of CFD are not reluctant to state that CFD is best used for comparative analysis, needs validation, or requires calibration with test data. The author has observed several cases where performance claims have been based solely on CFD and were found to be in significant error. The same CFD code run by different individuals under different assumptions can produce dramatically different results. Accuracy, verifications, and other CFD related discussions are addressed in numerous International Towing Tank Conference documents, including the 23rd Conference listed in the references, ITTC (11). The use of CFD alone, does not guarantee accurate predictions.

7.12 FRICTION LINES

There needs to be consistent use of friction lines and methodologies. As an example, if a prediction is made using a technique derived with a three dimensional friction line and then used with a two dimensional friction line the resistance could be significantly under predicted. The choice of friction line impacts the correlation allowance.

7.13 PROPELLER TUNNELS

Propeller tunnels can significantly impact resistance and propulsor performance. Blount (12) is a good general reference on propeller tunnels.

7.14 SEA STATES

Added drag or resistance from seas can significantly increase resistance and powering. Some hull forms, such as air cushion vehicles are more sensitive to seas than others. It is critical that added drag or resistance be addressed in many cases. Craft can have significantly different added drag in different sea spectrums of the same significant wave height. Both wave height and wave length are often significant.

Sea state can have a significant impact on propulsor performance. Cavitation, aeration, and fluctuations in load can impact the craft's ability to make speed. The amount of submergence of a surface piercing propeller can change dramatically in heavy seas resulting in wide fluctuations in loading and performance. There can also be an involuntary speed loss due to the coxswain pulling back on the throttle.

7.15 PROPULSOR LIFT, THRUST LINE AND SHAFT ANGLE

Certain propulsors, such as surface piercing propellers can generate very significant lift. This impacts resistance and the overall "balance" of the craft. As an example, the back of a hydroplane is significantly supported by its surface piercing propeller at high speed. The effect of the thrust line height often has to be considered. A waterjet, for example, generally has a significantly higher thrust line than a submerged propeller. A prediction method based on a propeller thrust can often be corrected for the different thrust line of a waterjet.

The impact of propulsor lift and thrust line can also be addressed by a thrust deduction (positive or negative). Care has to be taken to avoid "double counting" propulsor lift and thrust line with modeling and thrust deductions.

A classic text on the subject is Hadler (13). This work also discusses the impact of shaft angles on propeller performance.

7.16 TRIM CONTROL DEVICES

Trim control devices include wedges, tabs, and interceptors (guillotines). The devices can be fixed or controllable. The impact can either be minor or dramatic depending on the application. Their benefit can vary with displacement, longitudinal center of gravity and speed. Trim control devices can increase resistance in many cases, especially at very high speed. Trim control devices can also eliminate or cause dynamic instabilities.

In some cases (not all), ignoring trim control device impacts can result in significant errors in powering predictions. Most prediction techniques do not include the impact of trim control devices. However, they can often be corrected or modified by superimposing the impact of the lift control device. Savitsky (14) is one of many references on this subject.

8. FULL SCALE, MODEL TEST AND SCALING ERRORS

Bad data and scaling errors from model basin models and manned models can result in significant prediction errors. International Towing Tank Committee Conference recommended procedures for resistance tests, propulsion tests and waterjet testing are listed in the references. Hubble (15) and Wilson (16) also address model testing of a range of high-speed craft. Common data and scaling errors include:

Ship "methodologies" applied to high-speed craft
Use of outlier data
Unscientific and qualitative testing
Laminar flow – small models
Non-standard scaling methods
Friction scaling (1 + k)
Correlation allowances
Shallow water
Unrealistic wetted surface
Differences between full and model scale sea state

The ITTC procedures listed in the reference section identifies many of the basics of testing and test reporting.

8.1 HIGH-SPEED CRAFT TESTING PROCEDURES

A common problem is the use of standard displacement ship testing methods for high-speed craft where they are not applicable. This is addressed in detail in the references just cited. Standard ship testing methods often result in significant errors in the model data and the scaled predictions. Propulsor ventilation and cavitation can be much more severe on high-speed craft than on more traditional slower vessels. These phenomenons may require propulsor testing in a vacuum facility as discussed in ITTC procedure for propulsion tests or a large diameter model propeller in a cavitation tunnel. Traditional self-propelled models alone may not capture the cavitation impact.

Proper simulation of the fans in air cushion vehicle model testing, especially in added resistance tests, is extremely difficult and critical. The air flow and cushion pressure can fluctuate significantly and this impacts resistance and powering. Scaling of air cushion vehicles has unique challenges and is discussed in Yun (17) and the ITTC seakeeping procedure listed at the end of the references.

8.2 OUTLIER DATA

It is tempting to assume that every piece of data is correct. This is not always true and can result in optimistic predictions often in conflict with other data and observations. The data as the whole must be reviewed and the question asked, "How do I know it is right?" In testing, it is always prudent to know what the data should be before it is taken - partially to aid in identifing errors in the data.

8.3 UNSCIENTIFIC AND QUALITATIVE TESTING

High-speed craft testing, model or full size, needs to be accurate and quantifiable if it is used as a basis for predictions or claims. Unfortunately, often it is not much more than anecdotal observations. Basics include:

Displacement and center of gravity of the craft
Description of hull form with dimensions
Propulsor descriptions with dimensions
Propulsion plant and transmission description
Calibrated instruments
Recording and retention of data
Power or resistance measurements
Air flow and / or fan measurements
Definition of environment (sea states, currents, winds, water depth, etc.)
Reciprocal runs
Repeatability of data, especially of suspect points
RPM measurements
Scaling methodology defined

8.4 LAMINAR FLOW

Many high-speed craft models are small and prone to laminar flow that can result in underestimating the craft's resistance. Even planing models, where the flow may appear violent, can be laminar. Various approaches exist to induce turbulence.

8.5 NON-STANDARD SCALING METHODS

The methods used to scale the data have to be reviewed. The author has observed model test data scaled using unconventional scaling methods (even by high-speed craft standards) that resulted in unrealistical high-speed claims. There is controversy and debate surrounding the viscous form factor (1+k) used in three-dimensional viscous resistance formulations. A wide range of values have been proposed for essentially the same hull. There is controversy on the methods used to measure it. A high value will result in lower predicted resistance at full size, especially where the scale ratios are large. The viscous form factor (1+k) can actually be less than one, Almeter (18). Anything beyond this mention of this subject is beyond the scope of this paper.

The author has observed several instances where a manned model is run at high-speed, say fifty knots, and is claimed to have low resistance and that the manned model running at fifty knots proves that a ship of ten times its length will also have low resistance at fifty knots. This is contrary to scaling laws. Claims like this should make reviewers suspicious.

8.6 CORRELATION ALLOWANCE

The correlation allowance is dependent on the friction line used, viscous form factor, hull form and type, test procedures and even the model basin. All must be considered when determining / selecting the correlation allowance. If one of these variables changes the correlation allowance may also have to change. Correlation allowances are also often used in empirical and analytical based predictions.

8.7 SHALLOW WATER

Shallow water effects must be addressed. This is normally done by testing in sufficient water depth to avoid significant shallow water effects. Depending on the speed, shallow water can increase or decrease resistance. If the desire is to quantify shallow water effects, then the model has to be tested in shallow water.

8.8 WETTED SURFACE MEASUREMENTS

Wetted surface measurements of high-speed craft are often in error. The wetted surface measurements can be very difficult and often require an experienced eye. The spray and the solid water, including pileup, have to be separated. A low measurement of area will result in a high scaled resistance and conversely a high measurement will result in a low scaled resistance.

8.9 DIFFERENCES BETWEEN MODEL AND FULL SCALE SEA STATES

Despite having the same scaled significant wave height, the model and full scale seas can be different. Added resistance in seas can have a strong dependency on wave length or period, craft speed, and relative heading and not just wave height. The differences, if any, between the model and full size wave spectrums have to be understood. Full scale sea states usually have a significant wind that is generally absent in model sea states.

9. DESIGNING TO AN UNREALISTIC DESIGN POINT

Designing to an unrealistic design point is not an error in itself, but can result in an unsuitable craft. As an example, if the contractual speed requirement is based on calm water in a partial load condition, the propulsors may be optimized for this condition and inadequate for many of the craft's more demanding conditions. This scenario could result in the craft failing to get past hump in a fully loaded condition. Many high-speed craft concepts have significant added drag in waves that can prevent the concept from getting past hump in anything beyond calm water. Hull fouling and degraded engine performance are additional speed killers.

10. POWERING MARGINS

A resistance or powering margin is the difference between the predicted and required performance. The predicted is after all allowances, correlations and corrections are applied. An allowance is an addition or correction to account for roughness, acceleration, sea state, poor engine performance, etc.. The terms margin and allowance are often used interchangeably and this can create the false impression more margin exists than actual. Prediction methods often require calibration or correlation. This is not the same as a margin. If a method is found to underestimate the required power by twenty percent, increasing the calculated power by twenty percent is not a margin, but a correction. The required or desired margin is dependent on the perceived potential error in the overall methodology and the willingness or tolerance of the designer to take risk. Using this logic, there should not be fixed universal margins for powering. Each analysis is unique.

The unnecessary compounding of margins must be avoided. As an example, if there was a ten percent error applied each for resistance prediction method, propulsor modeling, weight estimating, and engine performance, the accumulative error would be almost fifty percent. The use of such large margins would cause almost every successfully built high performance craft unfeasible on paper.

It is critical that the designer understands the accuracy and limitations of the total prediction methodology used. This is generally done by running test cases as illustrated by figure 4 taken from Almeter (5). Figure 4 is a plot of the difference between the SWPE (Ship Wave Patter Evaluator) thin ship computer program and measured or derived resistance for a wide range of high speed displacement hull forms, including multi-hulls, at model and full scale. The average error of this methodology was found to be only one percent (negative) with a standard deviation of eight percent, which is comparatively low for a prediction analysis for complex multi-hull forms that can be made in a few hours. Unless there was an extreme intolerance of error the margin used for this approach would be very low for craft similar to those reflected in this figure.

Errors in predictions can be huge for conventional hull forms. Figure (5) is a plot of predicted resistance using the four relevant methods in NAVCAD, a commonly used commercial software program, for a traditional mono-hull planing craft. There is a disturbingly large spread in the predictions, especially at hump. Obviously, they cannot all be right. Full size operation of the craft has shown that all of the predictions are probably wrong for this craft (not due to errors in NAVCAD). The craft's performance has been found to be much less than predicted by any of the methods shown in figure (5). The craft in question is extremely heavily loaded and probably outside the legitimate bounds of the methods, despite several of the methods documentation indicating otherwise. The craft's top end speed was seven knots less than predicted and its time to accelerate through hump was several times greater than can be expected from the predictions. These are large errors with very significant consequences. The mistake was in the use of prediction methods that were not relevant. Other methods could have been used, analytical and model testing, that would have provided better predictions. This is just one of over fifty potential mistakes discussed in this paper. However, the remedy is not conservatism and the overuse of margins, but to make responsible and knowledgeable predictions.

11. CONCLUSION

Errors of high-speed craft powering predictions are as numerous and diverse as high-speed craft concepts. Over fifty different errors are discussed in this paper and the listing is not complete. Unrealistic performance claims can result in investment of precious resources in dead ends and cause the neglect of promising concepts with legitimate performance claims. It is hoped that this paper will help in avoiding errors in predictions and to aid reviewers in their identification. If a performance claim appears too good to be true, it is deserving of close scrutiny.

There are numerous options for powering predictions of high-speed craft including simple empirical predictions, sophisticated analytical predictions, model testing, manned model and even full size testing. The most accurate prediction method is not always the most expensive.

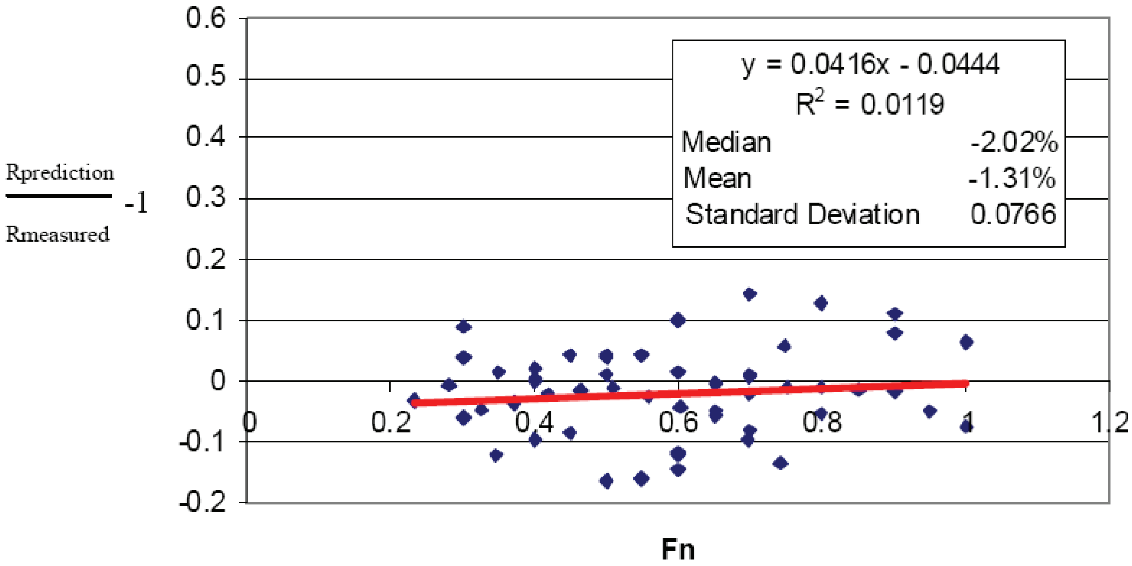


Figure 4: Error of SWPE Computer Program for Several High Speed Displacement Hull Forms

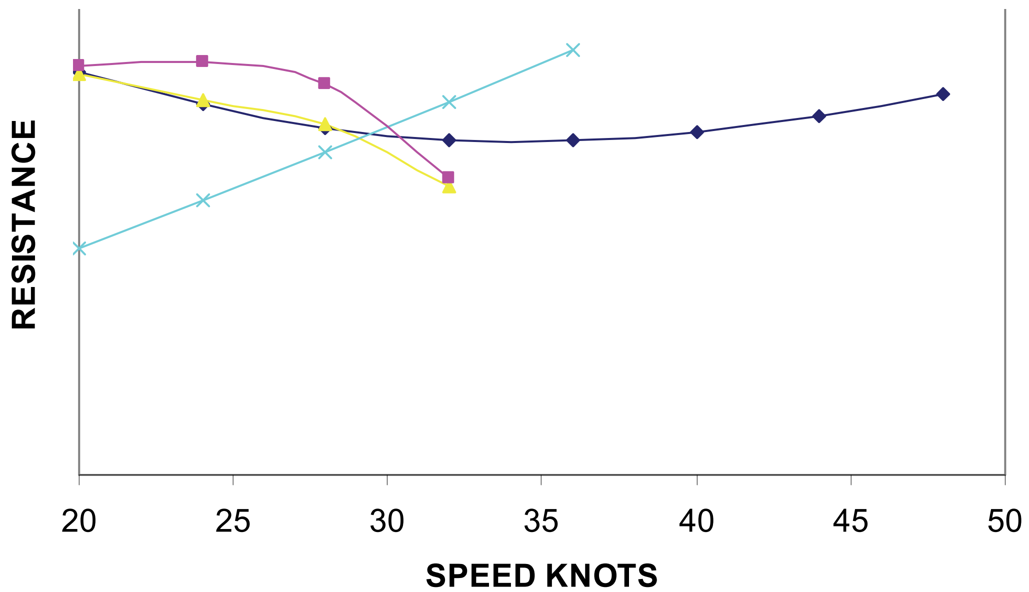


Figure 5: Comparison of Different Resistance Prediction Techniques for a Heavily Loaded Planing Hull

12. ACKNOWLEDGEMENTS

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