The Ten Commandments of Reliable Speed Prediction

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INTRODUCTION

As with all technical development, the techniques used to predict vessel speed have evolved from years of accumulated trial and experience. One of the more successful speed prediction techniques utilizes the *dimensional analysis* of empirical data (from tests or trials). This approach is the principal method used by virtually all small craft speed/power application software.

Every designer and naval architect is likely to be familiar with the more popular dimensional analysis data sets - Savitsky, Holtrop, Series 60, Series 64. Not always, however, have these methods been used successfully. In light of their poor results, some people argue that these methods are inadequate to do real speed prediction. Since it is not possible to fund a model test program for every design - particularly for small craft where budgets are tight - many designers continue to plod along trying to find that successful combination of “fudge factors” which generates reasonable answers.

This paper offers up the *ten commandments of reliable speed prediction*. It will illustrate some of the more common shortcomings found in speed prediction methods and in software using the methods. It will also point out strategies that can be applied to virtually all small craft speed prediction.

COMMANDMENT 1 - USE TECHNIQUES THAT MIRROR PHYSICAL REALITY

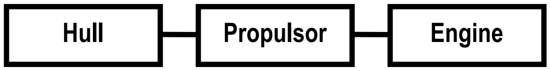
This sounds obvious, doesn’t it? One would think so, but in practice not all techniques reflect a real physical system.

Hull-propulsor-engine equilibrium

The fundamental objective of a speed prediction is to predict the speed of the vessel for a given engine power. To derive engine power from resistance, one traditional prediction path has been to estimate the OPC by some typical value.

The problem with this approach is that the estimated OPC may, or may not, bear any resemblance to actual figures in practice. A single representative OPC (such as the ever popular 0.55) cannot possibly account for the many differences in propulsor performance or in contemporary trends that may effect performance. (Current OPC figures are often in excess of 0.65. This means nearly 15% less engine is really needed!)

Increasing engine powers, higher cavitation levels, more cupped propellers, deeper gear ratios and higher pitches all contribute to changing trends in propulsor performance and OPC. It is therefore necessary to use an equilibrium performance model where the propulsor is the central figure.



In this way, an RPM can be found which satisfies the physical thrust equilibrium requirement between the hull and propeller. *Real* propeller efficiency, OPC and engine power are then derived from this RPM.

Planing hull trim

Take the case of planing hull trim for the next example. Most planing hull resistance methods (e.g., Savitsky, 1964), include vessel trim as one of the initial (independent) variables. In other words, drag is affected by trim, and anything that affects trim affects drag. In the real example below, the bare hull resistance was over 5% in error, simply because an equilibrium trim correction was not applied.

Many computer-based speed prediction programs do not allow for the determination of equilibrium trim. The propeller or waterjet thrust line, appendages, wind, and trim tabs all greatly influence the hull’s trim and drag. An equilibrium trim technique should be employed for all planing hull predictions.

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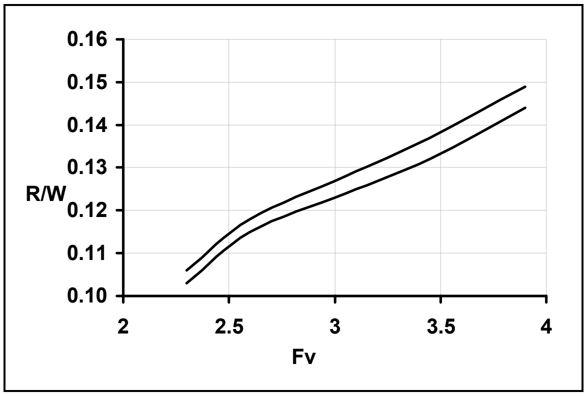

Figure 1 – Drag with and without trim correction

COMMANDMENT 2 - USE CONTEMPORARY TECHNIQUES

Up-to-date techniques represent the current consensus from the various international research institutions. For example, three-dimensional analyses have replaced two-dimensional, with new friction lines and more accurate model-ship scale corrections.

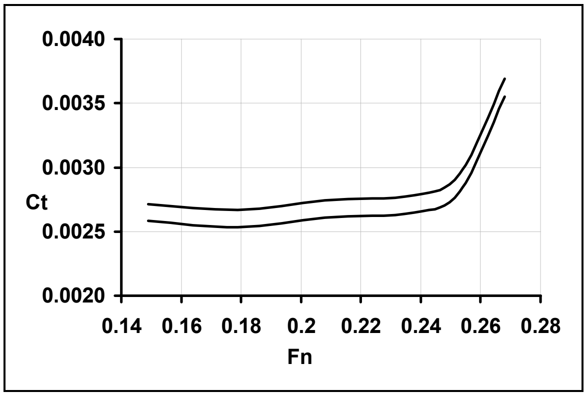

Figure 2 – Effect on C_R prediction of wrong C_F and C_A

Improperly using a new friction line or correlation allowance, however, can lead to less reliable results. Too often, incompatible routines are incorrectly mixed with each other. In an attempt to use contemporary methods, C_R predictions based on the older ATTC friction line (Schoenherr, 1932) are routinely married to the newer ITTC friction line (ITTC, 1957). Add to this the use of the ATTC-based traditional C_A of 0.0004 and significantly incorrect predictions can result.

The proper approach is to numerically recreate the original model-scale results using the known model length and friction line. Then full-scale results - free from incompatibility - can be built with the designer's preference to use traditional values or to fully exploit contemporary practices. Remember to watch out for pre-set routines that mix old data with new.

COMMANDMENT 3 - USE THE RIGHT KIND OF ALGORITHM

All of the methods described here are based on some statistical manipulation of model test and trial data. Hull *parameters* (e.g., C_B, C_P, L/B) are used as the input side of the statistical analysis. How the test data is grouped and the parameters analyzed will determine what role the method should and should not play in a reliable speed prediction.

Systematic series vs. random data

To keep the accuracy of a parametric analysis as high as possible, collections of test data are often grouped into a *series*. In a typical small craft series - such as the YP series (Compton, 1986) - a parent hull is created that has certain design features, such as sectional area curve, turn of bilge, transom immersion or entrance angle. A matrix of models is then built that vary the principal shape parameters (e.g., L/B, B/T, C_P) in a systematic fashion to determine the effect of each parameter on resistance.

The weakness of a systematic series is apparent when the design is of a form that is different from the series. For example, it would be inappropriate to use the semi-displacement YP series for a heavy tug.

Random data methods, on the other hand, are based on many different hull forms and test results. The various components of resistance (e.g., wave-making, transom immersion, bulb effects, viscous components) are broken down into as many pieces as possible and each numerically evaluated independent of the others. While not always able to discretely evaluate the effect of a single parameter on resistance like a series can, these methods frequently offer better prediction of the *magnitude* of resistance.

Design or analysis

The choice of a prediction method often depends on the purpose of the task. In a design or feasibility study, the objective might be to determine suitable overall parameters. A sea trial forensic analysis might require a more detailed review of the entire system performance.

Design methods sacrifice precision for the sake of fewer parameters and well-behaved "average" results. Almost all systematic series fall into this category, along with a few random data methods. Choose a design method for early-stage design studies.

Analysis routines are built with sufficiently detailed components to allow for a finely-tuned analysis of performance. If a hull closely matches a series parent, then a series-based method can also be used for an analysis. Select an analysis method for later-stage design using mature data, or for the evaluation of a trial or model test.

COMMANDMENT 4 - USE A METHOD THAT CONTAINS A SUITABLE DATA SET

Perhaps the most significant contributor to poor prediction reliability is the inappropriate selection of the basic prediction formula. In a setting where only a few methods are available and designers apply these methods to a broad range of hull types, it is easy to see how errors can occur.

Hull type

The selected prediction method should be built from hulls that share the same basic character as the vessel under review. You cannot rely on results from a method derived from a fundamentally different hull type. Referring to body plans and profiles of the included hull forms is the first step to filtering out unsuitable algorithms.

Some designers use the well-known Taylor data (Taylor, 1943) for virtually every vessel under consideration. It should be easy to see how using a plumb bow, cruiser stern, 1940's hull form could lead to trouble predicting drag for new hull types.

Range of parameters

After hull type, the method's range of data set parameters must be considered. Extrapolating beyond the scope of the data set is risky.

The most critical parameter to maintain is that of speed (typically Froude number). When it is absolutely necessary to extrapolate speed, a speed-dependent algorithm (i.e., that where speed is a variable in a single relationship) will tend to be better behaved.

The obvious way to avoid difficulty is to have many different methods for all of the hull types of interest and to have feedback regarding the parameter ranges while selecting a method. Certainly the most cost-effective means to acquiring a large library of routines is through a commercial software developer. Over 50 different bare-hull drag methods have been identified and reviewed by the author, so suitable methods can be obtained for virtually every type of monohull and catamaran vessel.

COMMANDMENT 5 - ANCHOR THE PREDICTION TO TEST DATA

Predictions based on the described numerical methods should adhere to the extents of the original data or significant error is risked. As noted above, robust commercial software packages have numerous methods so that a suitable method can generally be applied.

Sometimes a designer encounters a vessel that does not neatly fit into one of the available parametric models. In these cases, techniques exist to improve the prediction by "anchoring" the prediction to known performance.

These techniques, often called *aligned prediction* or *model correlation*, compare the calculated numerical results to a model test or sea trial of a similar vessel. The objective is to first test the numerical algorithm against known performance and develop a multiplier which is applied to the prediction of the new design. Non-dimensional relationships, such as Froude number and resistance-displacement ratio, are used for the correlation.

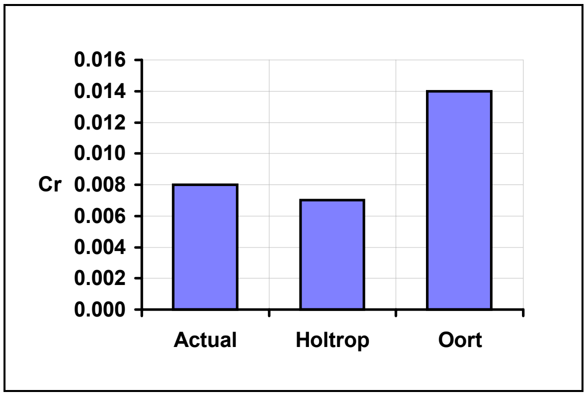

Figure 3a – Supply boat numerical prediction of C_R

This can be a very powerful technique. The initial performance results are first built from the selected method for the vessel's parameters. The results are then refined to reflect the local features of the tested model or ship. Of course, the model and subject hull must be similar in form. It would be inappropriate to correlate a tug to a fast ferry. Likewise, the chosen algorithm should be built from the same basic hull type.

The figures compare the prediction accuracy of a supply boat using the Holtrop method (Holtrop, 1984) with all parameters in range and the Oortmerssen method (Oortmerssen, 1971) with C_P and L/B outside the range. In addition, Oortmerssen did not have any supply boat hulls in the data set, while the Holtrop did.

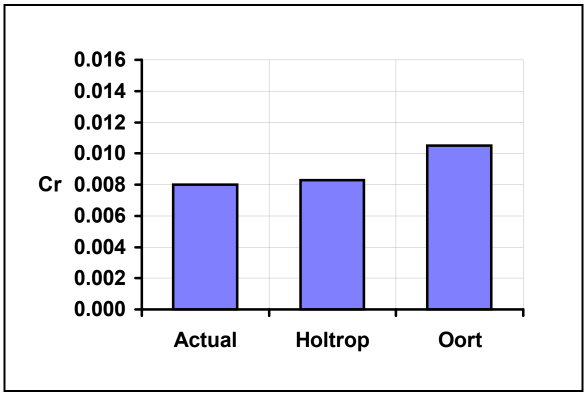

Figure 3b – Aligned prediction of C_R

Both predictions show improvement using aligned prediction. However, selecting an appropriate method (Holtrop) makes the prediction significantly more reliable. This is another reason to acquire a large library of methods.

Prior sea trials

A designer should exploit prior sea trials whenever possible as a source of data for aligned predictions. It is first necessary to reduce trial data into individual power and resistance components as described below. These steps have been automated within some contemporary performance prediction software.

a. RPM and vessel speed are used to deduce the thrust and delivered power for the known propeller
b. Thrust is then used to find total system resistance
c. Predictions of non-hull resistance (e.g., wind, appendages) from the trial are deducted to leave bare-hull resistance and non-dimensional drag coefficients

This technique is extremely useful for repowering calculations. It is a very forgiving technique, since any accumulated errors developed in the back-engineering of data are equalized when going forward again through new calculations.

COMMANDMENT 6 - REMEMBER ALL COMPONENTS

One source of prediction error is simply to forget one or more of the important parts of the analysis, such as appendages or added resistance in waves. It is also important to remember that a complete speed prediction is more that just resistance.

Designers occasionally neglect some or all of the “added resistances”, or rely on simple guesses. These added drags contribute significantly to total resistance. Appendages alone can contribute over 25% for fast craft. It is clear that poor estimates of added drag can greatly reduce prediction accuracy.

The various prediction stages can be summarized as follows:

a. Bare-hull drag
b. Appendage drag
c. Wind (static or applied) and wave drag
d. Shallow water drag
e. Propulsive coefficients
f. Equilibrium hull-propulsor-engine analysis

Remember, a speed prediction is not complete without the selection or definition of the engine and propulsor. The objective is to find the speed-to-power relationship, not solely the speed-to-resistance relationship.

COMMANDMENT 7 - USE A PROPER PROPULSOR MODEL

Commandment 1 made note of the need to use a true physical model. This includes a proper numerical model for the propulsor. Even an equilibrium analysis fails without reliable propulsor performance.

Achievable propeller performance

Consider commercial fixed-pitch propellers. Most are derived more-or-less from the Gawn series model (Gawn, 1957). A numerical representation of the performance of this type of propeller (Blount, 1981) can be found in most speed-power software. Some predictions still improperly use B-series propellers (Oosterveld, 1976) as the model for *all* propeller performance.

Yet no one actually builds a propeller with true Gawn geometry. Typical of the differences between commercially available propellers and the standard Gawn are blade outline and thickness, root area section shape, hub diameter and edge thickness.

Fortunately, scale corrections and correlations of thrust and torque (Kt and Kq multipliers) can be effectively applied to account for these differences.

Cavitating performance

Less used, however, are performance corrections for cup and cavitation. As engine power densities have risen over the years, more and more installations are showing very high levels of cavitation.

Modeling the effect of cavitation on performance is one correction to make. The next correction is to determine the effect of cup. After blade area, cup is probably the most frequently used means to control cavitation breakdown on work boats and pleasure craft. Both corrections for cavitation breakdown and cup modification are available to obtain a reliable numerical model of actual propeller performance.

Propeller selection

Getting the right propeller on the hull is a big step to achieving speed. So far, propeller performance has been discussed in analytical terms. These same routines can also be used to select the best propeller parameters.

Mature methods are available to size diameter, pitch and blade area for a given application (MacPherson, 1991). These techniques can use the performance corrections noted above. They offer tremendous flexibility anchored to physical reality, and have eliminated the shortcomings of simple sizing charts, graphs or slide-rules.

COMMANDMENT 8 - MAKE SURE RESULTS CAN BE EVALUATED AND COMPARED TO ESTABLISHED CRITERIA

Results that cannot be placed in their proper context are of little use to anyone. What is the relationship between the engine and propeller? Is the prediction reasonable as compared to other similar hulls? Questions such as these need be answered before a prediction can be deemed complete.

Comparing results to similar vessels

Where possible, it is always useful to compare the prediction results to a similar vessel. Since it is unlikely that the two vessels are identical, non-dimensional coefficients can be used to provide some level of comparison.

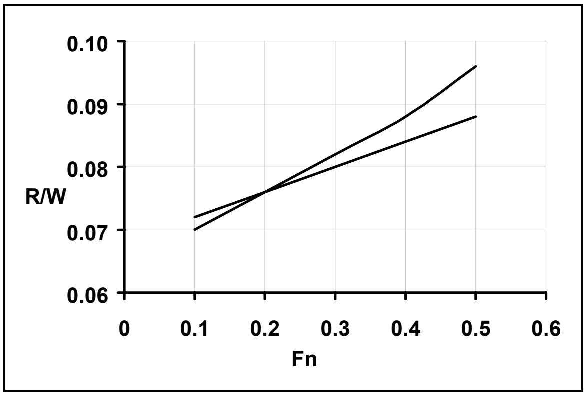

Figure 4 – Example non-dimensional curves

Resistance-displacement ratio vs Froude number is a useful graph to plot. This incorporates drag, length, displacement and speed in one curve. Vessels of similar shape and character should have similar curves. Wildly different curves should raise questions. This does not necessarily invalidate the results, but it does provide some valuable feedback for confirmation.

Reviewing results graphically

Tables of numbers can sometimes overwhelm a designer and hide the real meaning of the analysis. A few well-developed graphs can speak volumes. One very useful graph is a Ps-N graph (engine-propeller power versus RPM).

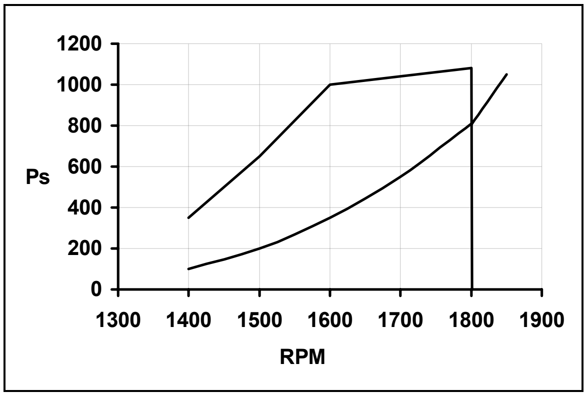

Figure 5 – Example Ps-N graph

In the example above, the vessel has enough engine power to go 20 knots, but the propeller is underpitched causing an RPM limit at only 19 knots. Only a graph can easily communicate this information.

COMMANDMENT 9 - USE VALIDATED METHODS, ALGORITHMS AND TECHNIQUES

A numerical method should not necessarily be accepted on face value - even if it appears to meet the character and parametric ranges of the subject hull. Two levels of validation should be performed, one to insure that the coding was correct and one to develop a sense of trends for a particular hull type.

Validate numerical codes

Numerical speed prediction algorithms can be incorrect for a number of reasons. A few of which are:

a. Publication errors
b. Nomenclature confusion
c. Coding errors

The author suggests checking the routines against model test data, ideally data from the original testing. Original data can be uncovered for most routines (albeit with some difficulty at times). Running the original data through these routines can reveal a lot about the reliability of the codes.

As one might guess, a great deal of time and effort can be spent validating routines, time which could be better spent in design and the actual prediction of speed. Specialists with significant experience can generally provide the needed guidance without the effort of an in-depth personal validation. Some commercial software packages are offered by companies with this experience. The intrinsic experience that accompanies these packages are of great value.

However, just because a company offers a neatly-wrapped commercial software tool is no guarantee that the codes have been validated. The following graphs illustrate the results for two widely-used small craft resistance prediction algorithms from two commercially-available software packages.

The resistance curves were compared to original test data. You can see how the errors from one software package are immediately obvious. The cause of these errors in the first case is surmised to be publication errors (which were corrected in an alternate paper). In the second case, the correct algorithm was obtained through personal contact with the original presenter of the method.

Any validation study of the methods by the developer would have quickly exposed the errors. This should be a clear warning to purchasers of commercial software and in-house developers - do not use codes without validation!

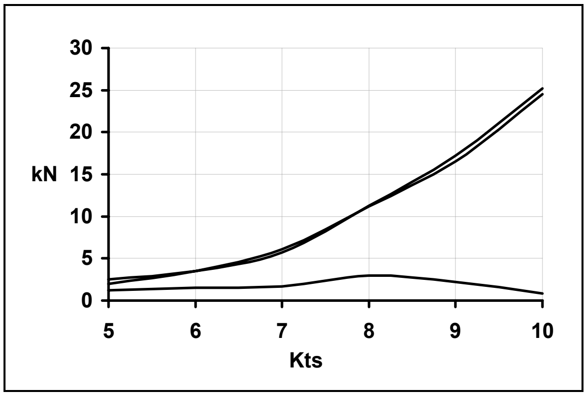

Figure 6a – Work boat resistance validation

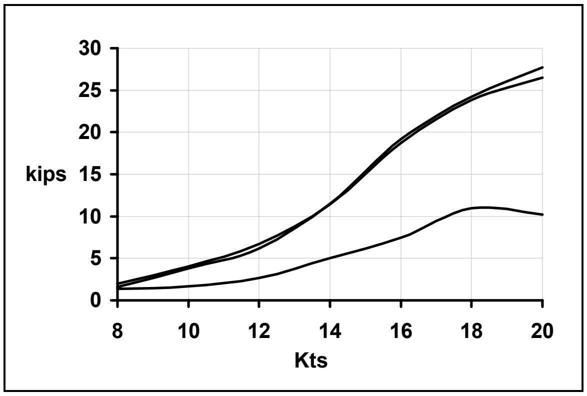

Figure 6b – Patrol boat resistance validation

Compare to representative vessels

Every method has some data smoothing inherent in its statistical development. So in some small way, all algorithms represent a averaging of the data.

Running the methods with particular hulls of interest can identify trends that are germane to the vessel at hand. For example, we know that Holtrop tends to underpredict fast transom stern craft by a small amount. While Holtrop is a very reliable method on its own merit, knowing this tendency can improve prediction precision even more.

Remember the objective is to generate good results – not just to process some data though formula. Learning the trends for the vessels of interest is a very important part of a reliable prediction.

COMMANDMENT 10 - FOLLOW A CONSISTENT PREDICTION STRATEGY

The following strategy is offered to guide the designer in making appropriate prediction decisions. Which method or series is best? What is the sensitivity of exceeding a certain hull parameter?

In general, a few systematic steps can be followed to choose a correct method and apply any corrections. By following the steps shown below and being aware of the nature and makeup of the numerical methods, a designer can be assured of the most reliable prediction results. (This strategy applies to the prediction of both resistance and propulsive coefficients.)

CONCLUSION

Empirically-based routines are the principal speed prediction tool for small craft. Regardless of the type of prediction being considered, these ten commandments of reliable speed prediction can help all marine designers and builders offer the best possible product to their client.

For some, these techniques can be used with in-house developed prediction methods. For others, the most cost-effective implementation of these techniques are through the use of competent, professionally-developed commercial software.

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1. If possible, match the hull lines to a series parent. (This can be found in the original test literature, or in the User’s Guide of some commercial software packages.) If no series suitably matches the hull, use a random data method.

2. Choose a method suitable for the maturity of the data. If the design is young and the evaluation of discrete details are not yet required, select a *design* oriented method, otherwise choose a method more suitable for a comprehensive *analysis* (MacPherson, 1993). Design oriented methods are built with limited parameters to make them better for early-stage design or feasibility studies, and precision is sacrificed for the sake of limiting the required data and to achieved well-behaved *average* results.

3. Check the range of parameters for both hull and speed. Is it necessary to exceed any of these parameters? Do not exceed the method’s numerically significant hull parameters. Other parameters may be exceeded - *but with caution*.

4. *Never* exceed the method’s speed parameters beyond a very small amount. If this is absolutely necessary, a *speed-dependent method* will be better behaved than a step-wise method.

5. If using an aligned prediction, never exceed the speed parameters of the correlating model beyond a very small amount. There is no way to accurately gauge what the curve will be doing beyond its own data set - are the coefficients slowly falling or will they quickly slope up?

6. Check to see if the method has shown any trends (e.g., Holtrop’s tendency to under-predict fast transom stern craft) and make any corrections that are deemed appropriate. (Again, this could be found in literature or in the User’s Guide of some commercial software packages.)

Figure 7 – Prediction strategy