Reliable Speed Prediction: Propulsion Analysis and a Calculation Example

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ABSTRACT

Speed prediction is more than just bare-hull resistance. Speed is a function of drag and thrust. This paper will discuss propulsion relationships — and our ability to predict how power is converted into thrust for a given application. It will illustrate some of the more common shortcomings found in propulsion analysis, and it will provide a summary of features that must be part of reliable speed prediction software. Finally, it will offer a calculation example where resistance and propulsion analysis are combined to demonstrate various data requirements, decisions, and processes.

INTRODUCTION

The first step to a reliable speed prediction is a proper prediction of resistance — but this is only the first step. Speed is a function of both drag and thrust.

Do you want to run at a faster speed? You can reduce drag, or you can increase thrust. Speed, drag and thrust are tightly connected. Of course, the actual measure of drag and thrust themselves are meaningless, except that they are steps to the really important measure of performance for a designer — speed and power. We purchase power to make a desired speed.

This paper will discuss propulsion relationships — and our ability to predict how power is converted into thrust for a given application. It will illustrate some of the more common shortcomings found in propulsion analysis, and it will provide a summary of features that must be part of reliable speed prediction software. Finally, it will offer a calculation example where resistance and propulsion analysis are combined to demonstrate various data requirements, decisions, and processes.

THE PHYSICS BEHIND THE SYSTEM

The goal of a speed prediction is to model a boat’s performance over a range of boat speeds. Principally, we are looking to define the hull-propulsor-engine equilibrium (Figure 1), which will provide the structure for our propulsion analysis.

Thrust-Drag equilibrium

Between the hull and its propulsor (e.g., propeller, waterjet) is an equilibrium of forces. The delivered thrust of the propulsor must exactly match the drag at each analysis speed. Therefore, we need to identify the characteristics that will provide just the right amount of thrust.

For a propeller, this means finding the right RPM. Let’s use your knowledge of boat operation to help you understand this. We all know that there is one unique throttle position for each speed. Propeller RPM is controlled by the throttle position, and the connection between drag and thrust is through a unique RPM.

Finding the right RPM is all about properly modeling propeller performance on the boat. First, it is necessary to know how the propeller performs in...
service. We need a reliable model for a propeller’s thrust and torque. In other words, we must accurately predict thrust and torque for each speed and RPM.

Second, it is necessary to understand that the force equilibrium described above is a match of drag and delivered thrust, not theoretical propeller thrust. Delivered thrust takes into account the effect of the boat on the propeller. This effect is described by two hull-propulsor interaction coefficients known as wake fraction and thrust deduction. (There is a third coefficient – relative-rotative efficiency – but its effect is quite small, so we will ignore it for this discussion.)

Wake fraction helps define the actual speed of the water reaching the propeller as it passes by the hull and underwater gear. Thrust deduction is a measure of the reduction of usable thrust due to the close proximity of the hull’s afterbody immediately ahead of the propeller. Both affect a propeller’s ability to generate useable delivered thrust.

**Engine-propeller power equilibrium**

So how do we get from propeller thrust to engine power? Engine power is simply a function of propeller efficiency and propulsion system mechanical efficiency.

Propeller efficiency is derived from the propeller performance calculations. In simple terms, it is the ratio of thrust-to-power. So, propeller thrust correlates to propeller power via its efficiency.

It is important to remember that the required propeller power for a particular speed is not the brake power generated by the engine. Brake power is somewhat greater, as we have to consider the propulsion system mechanical efficiency by adding shaft and bearing losses (1%-2%) and reduction gear losses (3%-4%).

**Analysis procedure**

A propulsion analysis will give us speed vs power. Before we can begin, however, we will need to know the following:

1. Range of boat speeds to consider.
2. The total in-service drag at these speeds.
3. An appropriate prediction model for wake fraction and thrust deduction.
5. An estimate of the mechanical system losses.

If we have this, then we can run a propulsion analysis by looking at each speed in isolation. The following are the steps to find each unique performance parameter:

1. Drag for a given speed.
2. Wake fraction and thrust deduction for a given speed.
3. Delivered thrust to match the drag.
4. Theoretical propeller thrust for a delivered thrust.
5. Propeller RPM to provide the right theoretical thrust.
6. Propeller efficiency at the propeller RPM.
7. Propeller power via the propeller efficiency.
8. Engine power given the mechanical losses.

**WHEN TRADITIONAL MEANS FICTIONAL**

Open any book on boat design and you’ll see numerous ways to predict speed and power. Many of these were based on observations of boat performance from many years ago, and they no longer apply. They are either based on obsolete technology or are just too simplistic to be useful anymore.

**Simplistic prediction of OPC**

The ratio of all of the accumulated efficiencies in relating drag to engine power is called OPC, the overall propulsive coefficient. Many references suggest using a single value of OPC for all propulsion systems.

The problem with this approach is that the estimated OPC may, or may not, bear any resemblance to the actual performance of your boat. A single representative OPC (such as the ever-popular 0.55) cannot possibly account for the many differences in propeller operation that effect performance.

For example, contemporary OPC figures are often more than 0.65. Even if your drag prediction is spot on, this means that the power prediction is some 15% in error! On the other hand, we periodically see poor waterjet selections, which result in OPC of much less than 0.55 and insufficient engine power.

Increasing engine powers, higher cavitation levels, more cambered and cupped propellers, deeper gear ratios and higher pitches all contribute to changing trends in propulsor performance and OPC. It is therefore necessary to avoid using a simplistic estimate of OPC.

**Obsolete propeller prediction models**

Consider commercial fixed-pitch propellers, such as the popular DynaJet or DynaQuad propellers from Michigan Wheel, as well the commercial models of many other manufacturers. Most are derived from the Gawn series model (ogival, flat-faced). Unfortunately, many propeller prediction tools still improperly use B-
Solving dynamic problems may affect all speeds series propellers (Troost) as the model for all propeller performance.

These tools also do not account for the effect of cup and cavitation, which is something we absolutely must consider these days. 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 [MacPherson 1997]. After blade area, cup is probably the most frequently used means to control cavitation breakdown on work boats and pleasure craft. Corrections for both cavitation breakdown and cup modification are available to obtain a reliable model of actual propeller performance.

HOW PROPELLER SIZING DECISIONS AFFECT PERFORMANCE

We must not assume that we will necessarily have an optimum propeller delivering optimum efficiency across all speeds. There are many ways in which valid propeller sizing decisions mean we have a less than optimum propeller. Remember, we are looking to predict what will be, not what might be.

Potential propeller efficiency

Potential propeller efficiency is directly related to a propeller’s pitch. Within the context of a good propeller sizing, potential efficiency can be increased with a higher pitch. Consider the following plot of propeller curves (Figure 2). For a moderate change in P/D ratio from 0.8 to 1.0, the peak potential propeller efficiency increases by some 6%.

![Figure 2. Propeller curves](image)

![Figure 3. Engine-propeller power-RPM curves](image)

**Figure 3. Engine-propeller power-RPM curves**

**PROPULSION ANALYSIS FOR WATERJETS**

Techniques are available to predict thrust, power and efficiency for waterjets [MacPherson 1999, MacPherson 2000, MacPherson 2002]. However, it is probably more important for waterjets than for propellers that a proper “sizing” be conducted, as the implications of sizing an inappropriate waterjet are far-reaching.
Unlike propeller curves (as illustrated in Figure 2), waterjet efficiency is hidden in published performance data – you are only presented with thrust and power. This is enough, however, to select a waterjet model, and many designers do not even consider efficiency.

Waterjet peak efficiencies are commonly 0.60 or more – very comparable to propellers. Also like propellers, waterjets are designed to reach their peak efficiency over relatively narrow range of boat speeds, but this range of peak efficiency is rarely published. For example, in one project we were asked to evaluate, the selected waterjet was reaching its peak efficiencies above 35 knots, even though the boat speed was only 24 knots [MacPherson 2002]. At these lower operating speeds, the efficiency was less than 0.45. Without a proper waterjet propulsion analysis, we could have significantly missed our speed-power prediction.

**Prediction of waterjet efficiency**

If you are considering a waterjet-driven boat, you will need to be able to predict waterjet efficiency.

**SPEED PREDICTION EXAMPLE**

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**PROPULSION ANALYSIS REQUIREMENTS**

The following is a list of features and calculation techniques that must be part of any thorough and proper propulsion analysis. Use this list to help insure that your speed predictions are as reliable as possible.

- **Prediction of wake fraction and thrust deduction**
  Use suitable prediction methods for these coefficients that are appropriate to the characteristics of your boat. You do not want to use one formula for all boats. You need to match your boat to the collection of available methods.

- **Prediction of basic propeller performance**
  The propeller charts or software that you use must be of the correct propeller type. Many publications and software still rely exclusively on B-series propeller performance, which is not correct for the Gawn-style models that make up most of the small commercial propellers in service.

- **Prediction of propeller cavitation and cup**
  As installed engine power continues to climb, we see more instances where boats are operating with very high levels of cavitation. We also see increased reliance on cupping as a means to control thrust breakdown. Your analysis must include the ability to model these characteristics.

- **A thrust-drag solution for RPM at each speed**
  Efficiency will change at each speed, as the RPM changes to suit the required propeller thrust. One efficiency value cannot represent all speeds – each speed must be evaluated independently.
General vessel parameters

A full and complete description of your hull is necessary for a reliable analysis. Four pages within this Vessel group are used to enter information about your hull. The information is parametric – meaning that the geometry is described by individual numerical values (such as length, beam or displacement) rather than by the three-dimensional geometry.

Since we might be seeing operation across speed regimes, we must describe the boat as fully as possible. The definition of the boat should include all of the characteristics that might contribute to a boat’s drag across its entire speed range, such as LCB, transom immersion, deadrise, and shaft angle.

Displacement and semi-displacement data page

Data accuracy is essential to a reliable prediction. In some cases, however, you may have to estimate values for certain data items. When needed, it is valuable to employ a collection of parametric estimates for a variety of different vessel types.

Wetted surface estimate

Vessel details

We often place boats into the general categories of displacement, semi-displacement or planing. While they may be useful to help us describe the nature of the design, they are not good hydrodynamic distinctions.

How do you describe a hard-chine boat that is running at low speed? Is it still a planing hull or is it operating in a semi-displacement mode? What about a displacement hull that is over-powered and runs beyond its “hull speed”? As we know, perhaps the most significant contributor to good prediction reliability is the appropriate selection of the prediction method. 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 drawings of the method’s hull forms is the first step to selecting a suitable method.

After principal hull type, the method’s range of data set parameters must be considered. The most critical parameter to watch is speed (typically Froude number), then the hull form parameters. The obvious
way to avoid difficulty is to evaluate many different methods and to select one that offers a good correlation between your boat and the method.

**Resistance prediction method page**

**Added drag from appendages and wind**

The prediction of vessel drag is not complete with just the bare-hull drag. Added appendage and wind drag can be a significant portion of the total drag – especially for planing craft. Appendages alone can contribute over 25% for fast craft. Poor estimates of added drag can greatly reduce prediction accuracy.

**Added drag prediction page**

In addition to summary estimates of appendage and wind drag, you can also define and evaluate the collection of individual appendages as part of the Added drag group.

**Propulsion analysis parameters**

As was described in the introduction of this paper, a speed prediction is not complete without a systematic propulsion analysis. The definition of a suitable prediction method for wake fraction and thrust deduction is the first of the Propulsion tasks.

In the same way that the vessel drag prediction methods were ranked, so too are the methods for the prediction wake fraction and thrust deduction. Do not forget any characteristics that affect the coefficients, such as whether the propellers are in tunnels (pockets).
As described above, the engine can affect propeller sizing decisions — particularly when the design point for the sizing results in reduced pitch. You will need to describe information about the engine and power delivery, as well as the propeller sizing objectives.

The reduction gear is defined by its ratio and gear efficiency. In advanced software, the reduction ratio will be integral to the propeller sizing process.

The definition of propeller performance conforms to the advice noted earlier — that it allows for the correct basic propeller style (Gawn), as well as any needed correction for cup and cavitation. It also provides a means to correlate theoretical performance to what is deliverable.

Thrust (T) and power (P) factors are correlation multipliers that we use to better match real on-the-water performance for the propellers. The factors correct for small differences in performance that we might find with a commercial propeller.

A suitable propeller can be sized prior to a final analysis. The propeller BAR, diameter and pitch — as well as the reduction ratio — are found for the described design conditions.

All data has been entered and intermediate calculations (such as propeller sizing) are completed. The only thing left is to Calculate the full resistance and propulsion results for your vessel.
2. Use contemporary techniques

Follow the current calculation recommendations of the international hydrodynamic societies. For example, be sure to use recommended propeller scale correction and model expansion methodologies.

3. Use the right kind of prediction method

Some prediction methods are strong for design, others for analysis. Learn how the method’s test data was developed into the numerical method.

4. Use a method that contains a suitable data set

Know what hulls were used to develop the methods you wish to use. Consider the speed range and hull parameters.

5. Correlate predictions to real test data

Compare your predictions to boat tests. In fact, we recommend instituting a rigorous sea trial program to analyze boat tests and compare them to predictions [MacPherson 1995, MacPherson 2003].

6. Remember all speed prediction components

Speed prediction is more than just bare-hull resistance. Don’t forget appendage and wind drag, and the propulsion analysis.

7. Use a proper propulsor model

Make sure that the propeller definition uses the correct basic propeller style (e.g., Gawn), as well as any needed correction for cup and cavitation.

8. Test the results against established criteria

Compare your prediction against other predictions using non-dimensional measures, such as transport efficiency. View results graphically across a range of speeds to see that the curve shapes are sensible.

9. Use validated methods, algorithms and techniques

Simply plugging data through an equation is no guarantee of success. Publication and coding errors are all too common – especially with in-house software. Be careful to validate the code, not only with data from the original method hull forms, but with other hulls.

10. Follow a consistent prediction strategy

Remember your objective – to get reliable answers. If you have experience with a particular method that gives you a consistent trend, you are better off than with a method that is perfect sometimes and poor at others. Establish a process and then stick with it.

Summary

This example has illustrated a number of important features that are necessary for a reliable propulsion analysis and speed prediction. Below is a list of “ten commandments of reliable speed prediction” [MacPherson 1996] that will provide a solid basis for anyone conducting speed-power predictions and propulsion analyses:

1. Use representations of real physical systems

Do not use simplistic calculations, such as a single OPC for all boats.

2. Use contemporary techniques

Follow the current calculation recommendations of the international hydrodynamic societies. For example, be sure to use recommended propeller scale correction and model expansion methodologies.

3. Use the right kind of prediction method

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REFERENCES


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