Selection of Commercial Waterjets: New Performance Coefficients Point the Way

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ABSTRACT

The successful selection of a waterjet requires a system-wide analysis of that jet's performance across the vessel's entire speed range. A complete physics-based approach is necessary to avoid performance problems and to define a truly successful system. Novel performance coefficients have recently been presented by the author that eliminate the limitations and short-comings associated with traditional "thrust-resistance" plotting techniques.

This paper describes this new parametric model of waterjet performance based on "universal waterjet coefficients". A recent project conducted by the author will also be presented to demonstrate how potential problems are averted and systems optimized through the use of this new calculation methodology.

INTRODUCTION

As it relates to propulsion equipment, for most *designers* there is little to *design*. Certainly, propeller styles may be chosen and a proper pitch selected, but with rare exception we do not design and build engines, gear boxes or propulsors – rather we select available product models and we assemble systems.

For engines and gear boxes, we just need to make sure that the power output, RPMs and power transmission meet our requirements. When the piece of equipment is the propulsor, however, we need to take care that the equilibrium performance relationships are maintained.

As the central element of the hull-propulsor-engine equilibrium (Figure 1), a calculation of propulsor performance must include the relationship between speed, RPM, thrust and power (or torque). Derived evaluations, such as efficiency, fuel consumption and cavitation, can then be determined from these initial figures.

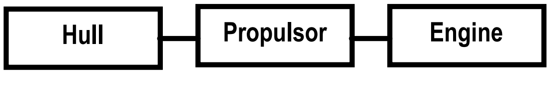

Figure 1. Equilibrium performance schematic

We have the ability to employ non-dimensional relationships to perform such an analysis for a propeller's thrust (hull-propulsor) and torque (propulsor-engine). Non-dimensional coefficients – built around the K_T/K_Q nomenclature – provide for a well-used and successful methodology that has the attractive benefit of a) being based on parameters rather than complete 3D geometry and b) being relatively easy to employ in a comprehensive analysis of vessel performance. It also makes the selection of optimum parameters a numerically simple task.

Predicting waterjet performance, on the other hand, has traditionally employed the graphical mapping of waterjet thrust curves (provided by the manufacturer) onto the vessel's resistance curve, with a check to see that there is adequate thrust to meet the resistance demands.

So what is wrong with this approach? The short-comings are many. The graphical method is inadequate as it isolates RPM from power and does not allow for further computational analysis of derivative performance (e.g., fuel rate, vessel acceleration). This is clearly a deficiency since the review of power-RPM in the context of the engine's power capabilities (i.e., its performance curve) is absolutely critical.

A more compelling weakness is that it does not offer any information about the qualitative nature of this particular jet. This waterjet works, but is this the best waterjet for my application? Is it the most efficient?

TRADITIONAL REPRESENTATIONS

As noted above, designers will typically look to the jet manufacturers for performance data about available commercial models, just as they do for engines and gears. Therefore, we are required to start with the data that is provided by manufacturers. Virtually all commercial waterjet models have data sheets that provide the following information:

1. Nozzle characteristics (diameter, center of effort, transom angle)
2. Impeller characteristics (diameter, variants)
3. Physical characteristics (weight, geometry)
4. Rating (maximum input power and RPM)
5. *Thrust curves* (speed-thrust-power) See Figure 2.
6. *Power-RPM curves* (absorbed shaft power versus RPM) See Figure 3.

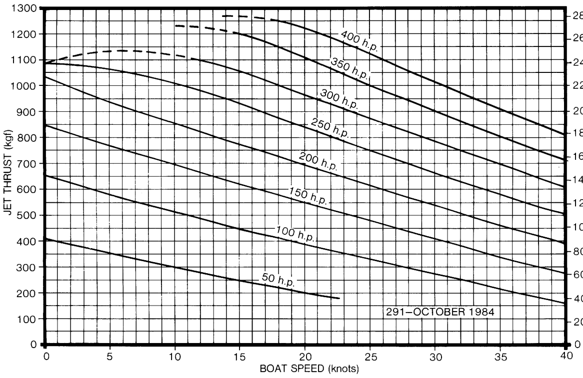

Figure 2. Typical *Thrust curves* (C.W.F.Hamilton & Co.)

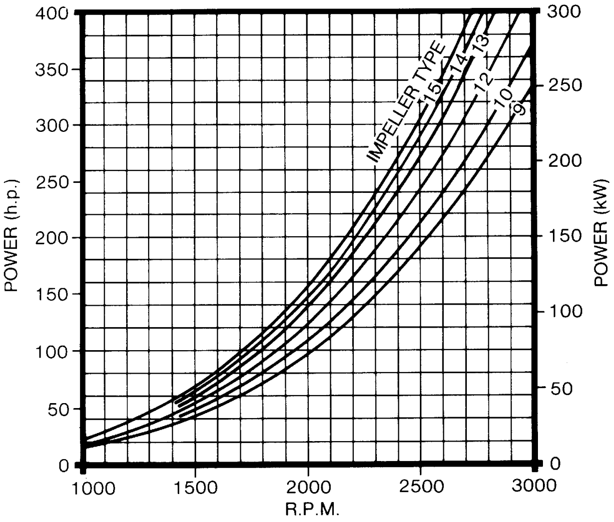

Figure 3. Typical *Power-RPM curves* (C.W.F.Hamilton & Co.)

TYPICAL EXAMPLE

Some months ago, we reviewed a proposed waterjet installation for a boat operating in a speed range somewhat lower than typical (less than 25 knots). Its normalized resistance curve is shown below (Figure 4).

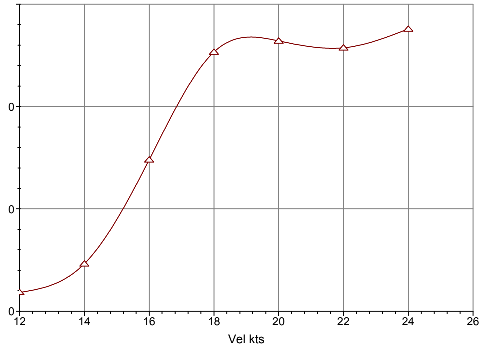

Figure 4. Example case resistance curve

As you can see, there is a large resistance hump at about 19 knots, with a broad flattening of the drag curve up to nearly 24 knots. The design objective was to operate at the high end of the drag "hollow", or at about 22-23 knots with the engines proposed by the operators.

Not only were we asked to help identify the proper waterjet, but to also to recommend an engine/gear set and any obvious hull form improvements. A system analysis was to be prepared for the steady-state performance, as well as vessel acceleration. Our initial analysis showed that the vessel did not meet the performance objectives with the waterjet model and engine under consideration. In fact, the top speed would be limited to 18-19 knots (Figure 5), and the client had already determined that new engines with some 10% more power would be required.

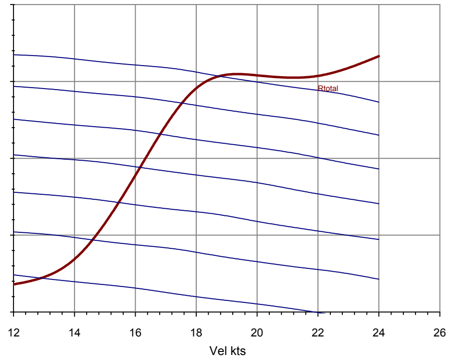

Figure 5. Example case resistance-thrust curves

In this case, it was not sufficient to simply ask the jet manufacturer to select another waterjet model for us. We needed to evaluate changes in hull form and engines, as well as overall performance. And we needed to loop through the design cycle on our own and in "real time".

NEW WATERJET COEFFICIENTS

As noted in the introduction, designers do not *design* waterjets – the manufacturers do that – but we need to be able to select and evaluate the performance of different waterjets during the design process. Designers need a reasonable solution for a simple, yet reliable, method for predicting waterjet performance. A successful numerical model will have the following characteristics:

1. *Parametric*. It must be based on simply and clearly defined parameters.
2. *Universal*. It must be applicable to all waterjets.
3. *Traditional*. It must utilize traditional definitions and data.
4. *Computationally-friendly*. It must be easily employed in computer codes.

A parametric set of "universal waterjet coefficients" has been proposed that meets all of these criteria [MacPherson, 1999]. Three coefficients were developed to convert the aforementioned commercial waterjet information into non-dimensional representations of the traditional curves.

Speed-Thrust-Power coefficients

The entire *Thrust curve* (Figure 2) can be collapsed into two coefficients, called C_P and C_T (Figure 6a).

$$C_P = \frac{P}{\rho A_n V_S^{\,3}} \qquad C_T = \frac{T}{\rho A_n V_S^{\,2}}$$

where,
P = shaft power
T = thrust
ρ = mass density of water
A_n = nozzle discharge area
V_s = ship velocity

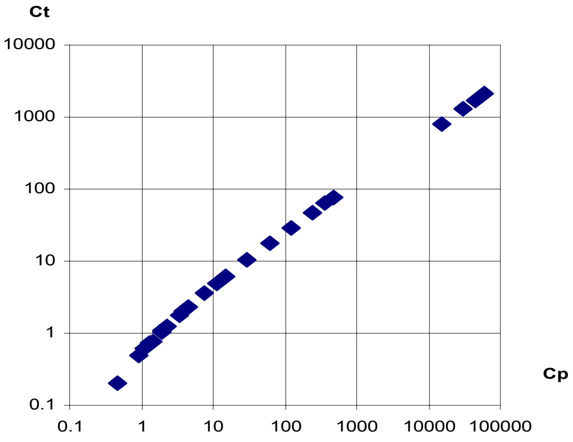

Figure 6a. C_T vs C_P

High values of C_T and C_P reflect the region with high thrust and low speed. This is a waterjet's analogy of the "bollard" region.

(Remember that all terms in the coefficients must be dimensionally compatible. For example, do not forget that power in horsepower units will need to be multiplied by 550 to work with units of pounds and feet.)

Further, these coefficients can be used to determine a "jet efficiency", η_{JET}, which equals C_T/C_P (and also TV_s/P). A plot of η_{JET} vs. C_P is shown below (Figure 6b). Notice the clearly defined efficiency peak.

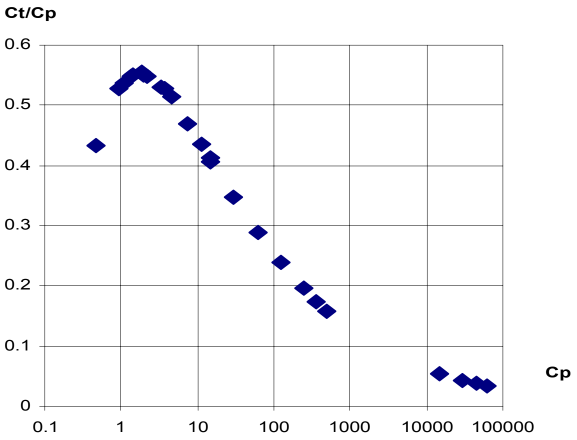

Figure 6b. C_P/C_T (η_{JET}) vs C_T

Power-RPM coefficient

The third waterjet coefficient is K_Q, which is in the same form as K_Q for a conventional propeller. Using power, rather than torque, the formula would be:

$$K_Q = \frac{P}{2\pi\rho n^3 D_i^{\,5}}$$

where,
P = shaft power
ρ = mass density of water
n = shaft speed
D_i = impeller diameter

This coefficient is a function of the selected impeller and is a constant value for each impeller. Data for this coefficient is from the *Power-RPM curve* (Figure 3).

Example

Calculation of the coefficients is illustrated using one manufacturer's charts and geometric data. Properties are:

Nozzle area (A_n) = 0.0177 m^2
Impeller diameter (D_i) = 0.290 m

For one point from the *Thrust curve* (Figure 2):

Speed (V_s)= 20 kts (10.29 m/s)
Power (P) = 300 hp (223.7 kW)
Thrust (T) = 965 kgf (9460 N)
$C_T = 4.93$
$C_P = 11.33$

For impeller 12 on the *Power-RPM curve* (Figure 3):

Power (P) = 400 hp (298.3 kW)
RPM (n) = 2940 rpm
$K_Q = 0.1918$

Additional considerations

It is important to point out that this is for sub-cavitating performance only. No attempt has been made to account for the loss of thrust when cavitating. The cavitating regime can be seen in the *Thrust curve* (Figures 2 and 7 below) as the dotted lines.

One practical outcome of the use of these coefficients is to easily identify the operational location of maximum jet efficiency. A "maximum efficiency" line can be plotted on the *Thrust curve* (the heavy line in Figure 7).

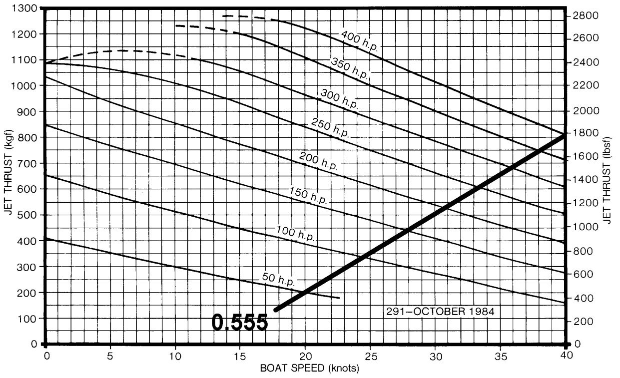

Figure 7. Cavitation region and maximum efficiency line

This will aid in the selection of waterjets by matching maximum efficiency to the resistance curve. In other words, it is possible to choose the waterjet model that has its best performance in the speed regime that is of greatest interest.

IMPLEMENTATION FOR COMPREHENSIVE ANALYSIS

Extensive use has been made of K_T/K_Q formula for conventional propellers. Virtually all performance prediction analysis uses these equations in some form or another. Conveniently, the proposed waterjet coefficients can be manipulated to mimic K_T/K_Q relationships. This makes implementation into existing computer codes a simple and familiar task.

This translation uses the impeller diameter (D_i) as a corollary for the propeller diameter. Therefore, K_Q is exactly the same in both systems - no change is necessary.

To obtain a matching K_T for a given speed and RPM, the process is:

1. Calculate P from K_Q (which is a fixed value).
2. Calculate C_P from P.
3. Find the matching C_T for C_P.
4. Calculate T from C_T.
5. Calculate K_T from T (using D_i as the diameter).

These coefficients have been successfully employed in commercial performance prediction software (NavCad) for over two years [HydroComp, 1997].

USING THE NEW COEFFICIENTS

In the example project described earlier, we were presented with a proposed waterjet for consideration. Our computer analysis (using the new coefficients) showed that although the waterjet was rated for the proper power and RPM, the boat's top speed would be limited to only 18 to 19 knots fro this engine/waterjet combination (Figure 5).

At first glance, it would appear that larger engines are needed to reach the target speed – as was the initial impression of the client. *But is this necessarily true*?

These new coefficients now allow us to calculate propulsor efficiency for waterjets in a way we could not with traditional methods. The analysis, in fact, confirmed a relatively low propulsor efficiency (e.g., 0.43) at 18-19 knots. We also found that the efficiency was increasing with speed – suggesting that this was not a bad waterjet, just the wrong waterjet. It was just designed for peak efficiency at a much higher speed than our range of interest.

Looking at an alternate waterjet model may very well offer a significant increase in propulsor efficiency, which in turn may allow us to reach the target speed without any increase in installed power. (And, of course, a side benefit of reduced fuel consumption will be icing on the cake.)

Looking at alternatives

A waterjet model optimized for a lower speed would indeed make it possible to achieve the target speed without an increase in power (Figure 8). The propulsor efficiency of the alternative waterjet was adequate at cruising (e.g., 0.47) and quite good in the target speed range (e.g., 0.54). The target speed is attainable and power and fuel rate at cruising was reduced by some 10%. *Again – with no change in the engine.*

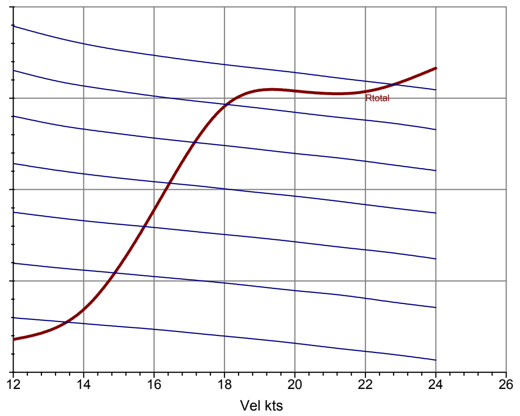

Figure 8. Example resistance-thrust curves with alternative waterjet

Vessel acceleration

The new waterjet performance coefficients simplify the investigation of many different powering scenarios in a computer calculation – including vessel acceleration. The following acceleration analysis and plot (Figure 9) was developed with the same software that was used for the general performance analysis.

The purpose of the acceleration analysis was to investigate the difference in "time-to-speed" for the two waterjet options with the higher horsepower engine. As you can see, the alternate waterjet reduced the time to reach 22 knots from 42 seconds to 33 seconds. To reach 24 knots, the initial waterjet selection would take nearly 100 seconds, while the alternate waterjet only 44.

None of this information would have been available to the designer without a performance calculation methodology such as the one built around these new coefficients.

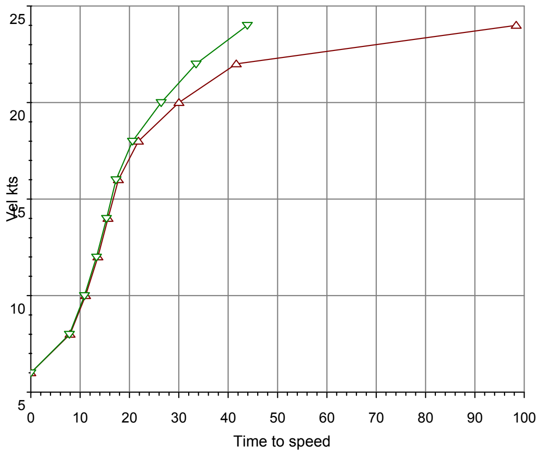

Figure 9. Vessel acceleration comparison

CONCLUSION

This paper would be incomplete without reminding the reader that waterjets are typically optimized by the manufacturers for each applications. In other words, the waterjet that you finally receive will have been "tweaked" to insure that it meets the performance requirements of the installation. (Think of this as fine-tuning the pitch or blade area of a propeller.)

This does not mean, however, that the prediction of waterjet performance should only be placed in the hands of the manufacturers. As the designer, you are uniquely responsible for the entire system. Only you can know all of the interacting and mitigating aspects of the design.

The real engineering example that was presented herein illustrates why designers must have reliable tools to evaluate waterjet performance – and its impact on design. Traditional methods may be useful to insure that a particular waterjet will meet a performance milestone, but they are generally inadequate for any comparative review of which waterjet may be the right choice for the design.

The new "universal waterjet coefficients" offers the designer a technique that can point the way to the right choice. Not only do they allow for an integrated "hull-propulsor-engine" analysis, but they make it possible to evaluate derivative vessel performance, such as efficiency and acceleration.

REFERENCES

C.W.F. Hamilton & Co., various product brochures.

HydroComp, Inc., "Waterjet Data Files for NavCad", HCI Report No. 119, December 1997.

MacPherson, D.M., "A Universal Parametric Model for Waterjet Performance ", *Proceedings* FAST '99, 1999.