A Universal Parametric Model for Waterjet Performance

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ABSTRACT

The successful selection of a waterjet for a high-speed marine vehicle requires a system-wide analysis of that jet's performance across the vessel's entire range of speeds. Selecting a waterjet based on a single top-speed design point often results in poor vessel behavior, notably in acceleration, heavy seas or at the planing "hump-speed" regime.

Current waterjet selection practices typically involve graphically plotting the "speed-thrust-power" relationships and matching them to vessel resistance. The analysis of equilibrium engine RPM is notably absent from this process, yet it is vital. Only by extending the "speed-thrust-power" analysis to include the proper selection of impeller, engine RPM and transmission can one define a truly successful system.

The author proposes a new parametric model of waterjet performance based on a set of "universal waterjet coefficients". These coefficients describe both the "speed-thrust-power" relationships and the equally important "power-RPM" relationships. The performance of any commercial waterjet can be defined and predicted with these coefficients, providing the critical part of an off-design system analysis, including equilibrium RPM, thrust, torque, and power.

INTRODUCTION

A practical numerical model of propulsor performance is critical to the system analysis of a vessel's speed and power. 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). Derivative evaluations, such as efficiency, fuel consumption and cavitation, can then be determined from these initial figures.

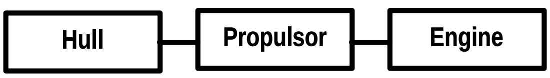

Figure 1. Equilibrium performance schematic

Numerical models for propellers are built around the K_T/K_Q nomenclature. These non-dimensional coefficients provide the necessary relationships to find thrust and power from speed and RPM given a particular set of propeller parameters. It is a well-used successful methodology that has the attractive attributes of being based on parameters rather than complete 3D geometry and being relatively easy to employ in a comprehensive analysis of vessel performance. It also makes the selection of optimum parameters easily achieved.

Predicting waterjet performance, on the other hand, has traditionally been limited to either graphical mapping of resistance curves onto thrust curves or an intricate "first-principles" approach requiring detailed geometric definition of the waterjet. There are numerous outstanding references that describe these techniques, one of the most comprehensive being from Allison [Allison, 1993].

For most practical purposes, however, both methods have short-comings. 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). This is clearly a deficiency, since the review of power-RPM in the context of the engine's capabilities (i.e., its performance curve), is absolutely critical. The "first-principles" approach does allow for a complete analysis, but it is needlessly intricate.

The reality of our world is that naval architects involved in vessel design and analysis do not design waterjets - they select and evaluate different commercial models offered by manufacturers. A naval architect is no more likely to design a custom waterjet than they are to design a custom diesel engine or reduction gear.

The challenge to find a reasonable solution has been placed at the feet of those of us who need 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 new parametric model is proposed that meets all of these criteria.

TRADITIONAL REPRESENTATIONS

As noted above, designers will typically look to the waterjet manufacturers for 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.

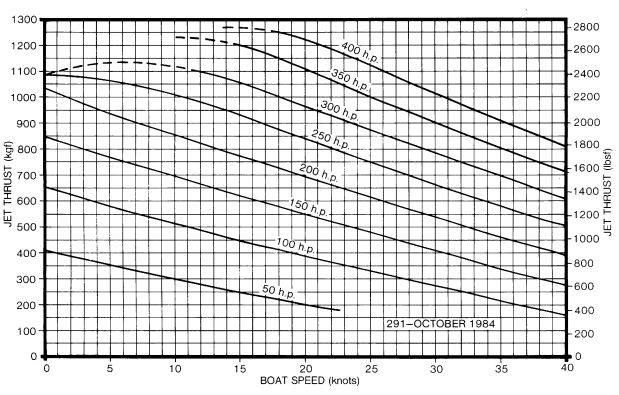

Figure 2. Typical *Thrust curves* (C.W.F.Hamilton & Co.)

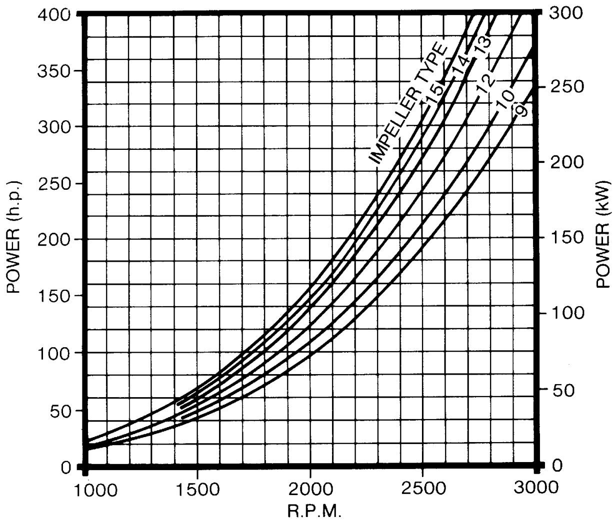

Figure 3. Typical *Power-RPM curves* (C.W.F.Hamilton & Co.)

UNIVERSAL WATERJET COEFFICIENTS

A set of "universal waterjet coefficients" were needed to convert the aforementioned commercial waterjet information into non-dimensional representations of the two sets of curves. Three coefficients were developed that met all four of the original criteria - parametric, universal, traditional and computationally-friendly.

Speed-Thrust-Power coefficients

The entire *Thrust curve* can be collapsed into two coefficients, called C_T and C_P (Figure 4a).

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

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

High values of C_T and C_P reflect the region with high thrust and low speed. This is the 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 4b).

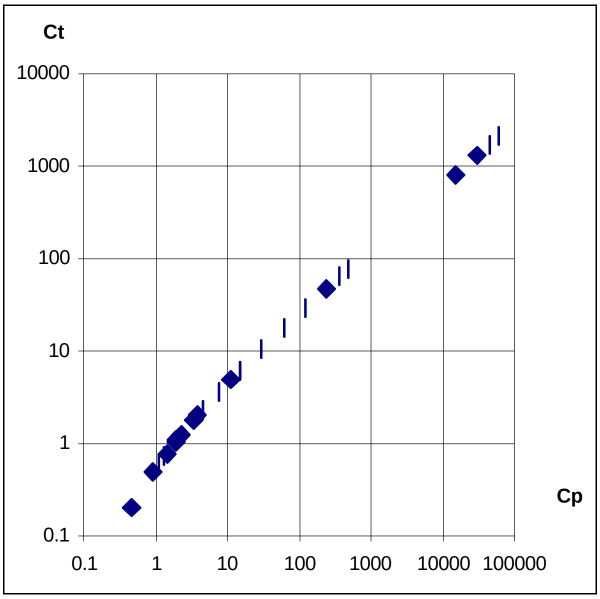

Figure 4a. C_T vs C_P

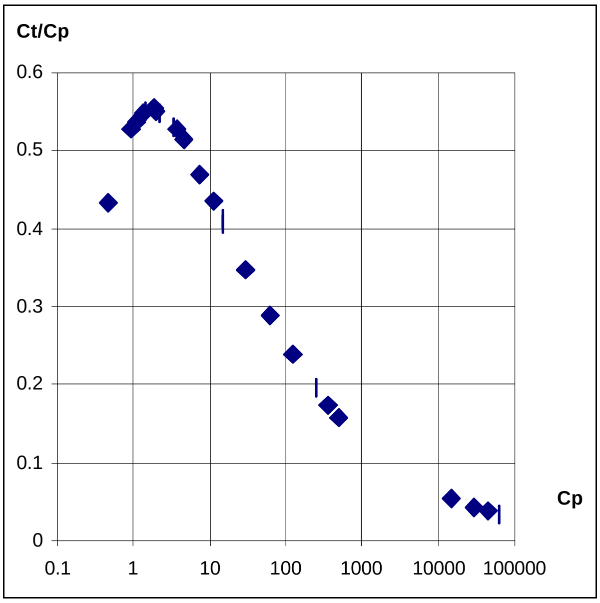

Figure 4b. C_T vs C_P/C_T (η_{JET})

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. Data for this coefficient is taken from the *Power-RPM curve*.

Example

Calculation of the coefficients is illustrated using the 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* (Figure 5) as the dotted lines.

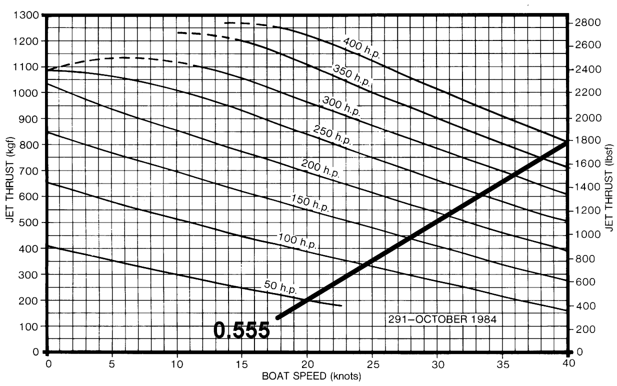

Figure 5. Cavitation region and maximum efficiency line

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 6).

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 regime that is of greatest interest.

IMPLEMENTATION AS CONVENTIONAL PROPELLER 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 coefficients can be manipulated so that they produce 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.
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).

CONCLUSION

These coefficients have been successfully employed in commercial performance prediction software for nearly two years [HydroComp, 1997]. They provide a simple and reliable approach to determine waterjet performance for practical applied engineering purposes.

REFERENCES

Allison, J.L., "Marine Waterjet Propulsion", *SNAME Transactions*, 1993.

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

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