The need for (understanding) speed

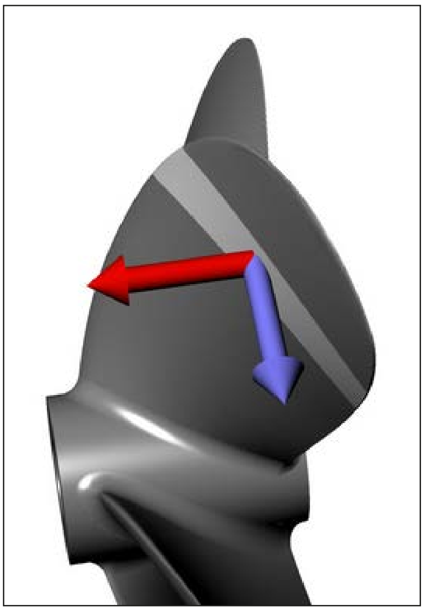
To what level of detail should naval architects be evaluating propeller performance? Donald MacPherson, technical director of HydroComp Inc, puts the case for more active engagement

When it comes to the design of many vessels, naval architects are selling speed… or so one would think. Actually, they are selling speed 'with conditions'. Those conditions are many, but a few of the major objectives and constraints are to deliver speed with:

- High efficiency and minimal fuel consumption
- Emissions within regulated limits
- Acceptable cavitation to avoid erosion
- Noise and vibration within habitable limits
- Consideration of off-design dynamic power demands

Successfully delivering speed for a client is rightly considered by naval architects as a systems engineering task. The big and high value decisions are best achieved by first properly specifying the connected performance of the hull-propulsor-drive system components. While it is common for naval architects to be intimately involved in the selection and integration of engines and transmissions — including their structural interface with the vessel — it is less common that naval architects are involved at the same level of design or engineering for propulsors. For many, the responsibility for successfully delivering the propulsor is off-loaded to a specialist or manufacturer, with little (if any) input over the final design given by the naval architect.

For propeller-driven craft, it is now imperative that naval architects understand in greater detail about the propeller that is being proposed for their vessels. While their job is indeed to evaluate the system, everyone benefits when the naval architect is also involved in the specification and design of the propeller. Not only are client outcomes more successful (making everyone happy), but company risk is lessened, expectations are better shared with manufacturers, and hull form design can be influenced and improved.



Radial definition of blade element slices

So, what does it take for a naval architect to acquire the necessary engineering knowledge on behalf of a client? Let's start to answer that question by reviewing the propeller design process.

Stages of the propeller design process

Propeller design follows an iterative process of refinement, often referred to as a 'design spiral'. During this engineering process, the design matures across multiple evolutionary revisions. A 'solution' is identified at each stage that conforms to an increasing level of detail. The principal stages for propeller design are generally:

1. Identification of principal system characteristics
2. Determine optimum radial distributions of blade shape
3. CAD development of the propeller geometry
4. CFD and FEA analysis for advanced requirements
5. Validation by model testing

Principal system characteristics

Most naval architects are well versed and comfortable with the tasks in Stage 1, where the propeller's performance requirements are established. A tool such as the HydroComp NavCad software is used for this task, for example. A resistance prediction typically establishes the propeller's thrust requirement, and a propulsion system analysis predicts hull-propulsor interaction (such as wake fraction and thrust deduction) and the propeller's corresponding developed thrust.

This stage also is typically where the propeller's principal characteristics and operating rpm are defined. An optimum combination of propeller parameters will be calculated and specified to meet not only the required thrust at speed, but to do so in a way that also meets diameter restrictions, maximum efficiency, thickness requirements (for class rules as needed), engine power constraints, and acceptable cavitation levels. With some software (such as NavCad), an initial assessment of noise and vibration can also be conducted. At this stage, the propeller is described by the following characteristics:

- Configuration (open or ducted) and style (e.g., B Series, Gawn, Kaplan, NACA)
- Blade count, diameter, mean effective pitch, and blade area ratio

Calculations to identify these characteristics are carried out using parametric-empirical methods (also known as [1D] methods). When applied correctly, they can be very capable tools to determine component characteristics for the purposes of system analysis (and to specify final propellers that are of a stock design). They will also provide the framework for continuing to higher-order, more-detailed propeller design or analysis.

Radial distributions of blade shape

The next level of calculation detail — and the deepest level of propeller design probably needed by most naval architects — is conducted using a 'wake-adapted' propeller design tool (HydroComp PropElements is a good example of such a tool). This simply means that it allows the user to define the velocities (i.e., the wake field) into the propeller with a greater level of precision. This is often referred to as a [2D] calculation, as it increases the order of detail from just the principal parameters and allows for radial refinement of propeller blade shape into 'element' slices.

In the 'parametric' [1D] calculation in Stage 1, for example, the velocities are described by speed and wake fraction. In Stage 2, these are further refined within the propeller's radial coordinate system. For the purposes of the [2D] order of calculation, the full wake field is typically simplified into 'circumferentially-average' velocities versus radial position.

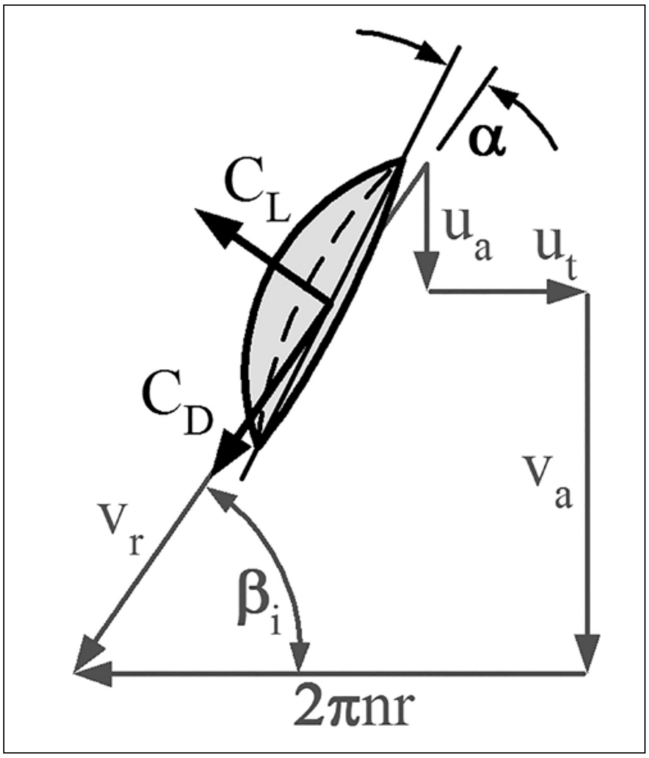
The [2D] analysis also predicts velocities that are 'induced' by the propeller rotation, both axial and rotational (tangential). These induced velocities are organised with the wake field velocities into a set of vectors that describe how the blade section foil shape 'flies' through the water. Note that proper [2D] propeller calculations must also consider additional flow corrections for blade thickness, curvature, and compression. It is at this angle of attack and inflow velocity that the lift and drag of the foil can be predicted, the body forces at each radial position determined, and the thrust and torque integrated for the entire propeller.

The calculation methodologies of this stage can also computationally determine optimised distributions of pitch and camber (mean line) to meet a thrust or power requirement. Cavitation checks are available on each radial section in more detail than the [1D] 'whole-propeller' review of cavitation percentage, for example, which can aid in the selection of specific chord length. A strength calculation based on enhanced beam theory offers additional blade thickness refinement. The design can be modified in the [2D] setting in a way that it cannot for a [1D] calculation, such as to 'unload' the blade toward the tip or hub (typically for hydroacoustic or vibration purposes). Finally, the optimised propeller is then evaluated for thrust, efficiency, power, cavitation, and additional performance metrics.

If the performance of the propeller at the conclusion of this stage is sufficiently different from the results from the earlier Stage 1, a full KT-KQ curve can be developed and the system calculations can be repeated for improved speed predictions.

Companion to CFD or FEA

Many naval architectural firms actively promote the use of CFD for their projects. It may be fair to say that at this point in time all naval architects have considered it!



Blade element velocities

The use of CFD for even deeper analytical review is particularly valid where the ship's mission is highly sensitive to noise or vibration (such as military or cruiseships), where it is very heavily loaded and exhibits substantial cavitation, or where the business plan justifies searching for the last bit of efficiency. Finite element analysis (FEA) may also be justified during this stage. The objective of this stage would be additional refinement of not only the radial distribution of parameters (as was investigated with the [2D] calculations), but also for section foil shape details (e.g., camber and nose shape for an objective pressure distribution).

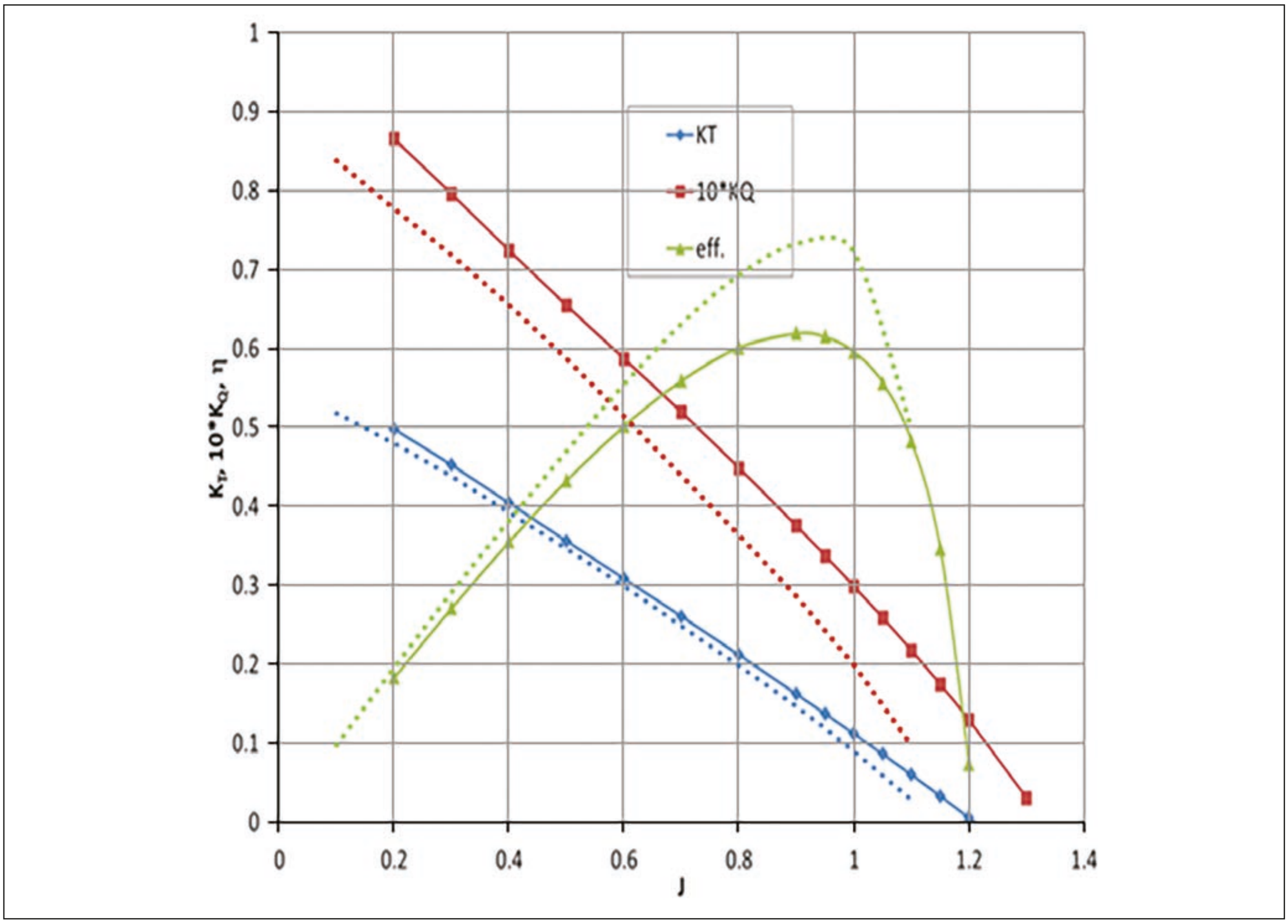
The 'wake-adapted' [2D] analysis is often used to provide the preparatory staging for higher order analysis with FEA or CFD. For example, PropElements can export a polar grid of the 'body forces' and velocities that can be applied as a highly-efficient propeller actuator disk replacement. In fact, employing a [2D] analysis before embarking on CFD can greatly increase its effectiveness by providing a more precise qualitative and quantitative foundation. Conducting CFD studies without a solid [2D] propeller code is like trying to run before learning how to walk — it can be done, but it comes with a lot of pain.

A case for greater involvement

Why should a naval architect be involved in propeller design at a more detailed level? Is it not the job of the naval architect to get the system right? And then hand it off to a specialist if needed? Valid questions.

Let's consider a real case that we observed recently regarding CFD modeling of a propeller for an integrated self-propulsion study. The calculation report showed a KT-KQ curve — with no comparison to a baseline or validation model, just the set of curves. Are the curves correct? It is hard to tell. So, supporting calculations were run with HydroComp PropElements to provide a quantitative baseline check on the calculations. Guess what? Big problems: KT was pretty good, but KQ was greatly over-predicted.

What caused the problems? It was the CAD function in the CFD code. It simplified the sections into a polyline-faceted geometry. This geometric treatment was never caught until the [3D] CFD calculations were checked against the [2D] benchmarks and an investigation started to determine why they were so different. After correcting the

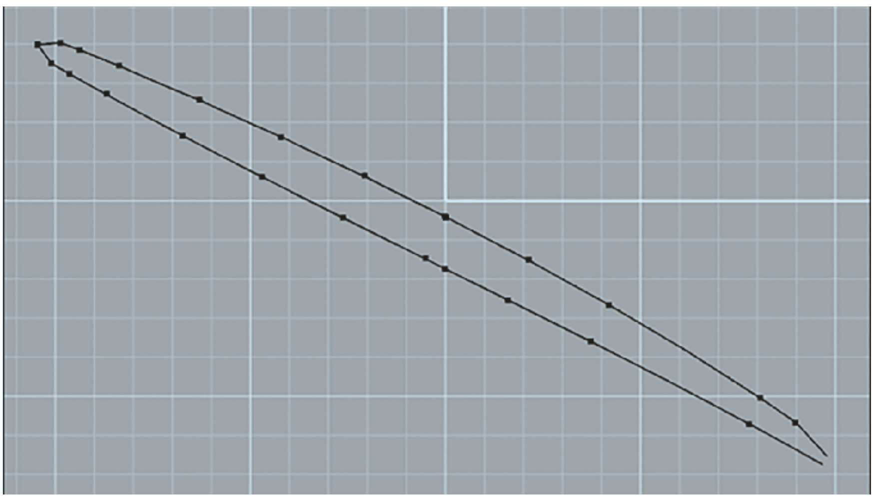


Validation study with (2D) propeller code

nose with geometry that was refined to better capture the curvature, the KQ calculation was much closer to the [2D] benchmark.

Of course, checking higher order codes is not the only reason for naval architects to be actively involved with more detailed propeller calculations. It is precisely because naval architects are the "keepers of the system knowledge" that they need to be a partner in the propeller design process. A propeller design impacts the system.

For example, let's consider a hull form that causes a 'shadowing' of water velocity behind a skeg. This disruption of uniformity in the wake field might cause excessive cavitation, radiated noise, and structural fatigue failure. Contracted propeller specialists or manufacturers typically only have design authority over the propeller, so they are limited to improvements that they can suggest to mitigate inflow problems — such things as increased skew, thicker blades, or reduced diameter (to lengthen the hydraulic transmission of pulses), all of which also have a fuel-efficiency penalty. On the other hand, the naval architect can do those things as well, but can also consider changing the stern lines, altering the shaft angle, looking to a different shaft rpm, and many other measures to improve the propeller component and the system. It is certainly appropriate in many projects to involve a propeller specialist, but it should always be done with knowledgeable interaction from the naval architect. *NA*



Inaccurate polyline simplification of blade shape