Wake-adapted design and propeller analysis for naval architects

The hydrodynamic design and analysis of marine propellers occurs along a broad spectrum of detail and complexity. Most naval architects use some sort of "system-level" software for propeller analysis, essential for the proper matching of hull, engine, transmission, and propeller, writes Donald MacPherson, VP Technical Director HydroComp, Inc.

Custom and semi-custom propellers – now commonplace for new vessel designs – offer a different set of technical challenges to the naval architect. They differ from stock "off-the-shelf" propellers in two principal ways – they are designed using contemporary foil geometries, and they are optimised and fitted to the individual vessel (or vessel type). To fully take advantage of the benefits that custom or semi-custom propellers make available, or to evaluate them in service, naval architects must look to a different kind of propeller calculation.

Wake fields of velocity

The term "wake" is used in a number of different ways in maritime operation, but for our purpose, we use wake to refer to the measure of local velocity at the stern of a ship. It is how we quantify differences in the environment around the propeller from vessel to vessel.

Consider the following graphic (Figure 1). This is a stylised schematic of a hull showing the creation of its boundary layer and flow vortices at the stern. You will note at point C that the free-stream velocity V gradually reduces and becomes very small at the hull itself. This is the region where the propeller lives, so the propeller will be seeing water that is typically somewhat slower than the ship's velocity. When conducting propeller analyses, we need some measure of this reduction of speed into the propeller, and we use the "wake fraction" coefficient to provide a figure for the overall reduction (reflecting the "speed of advance" at the propeller).

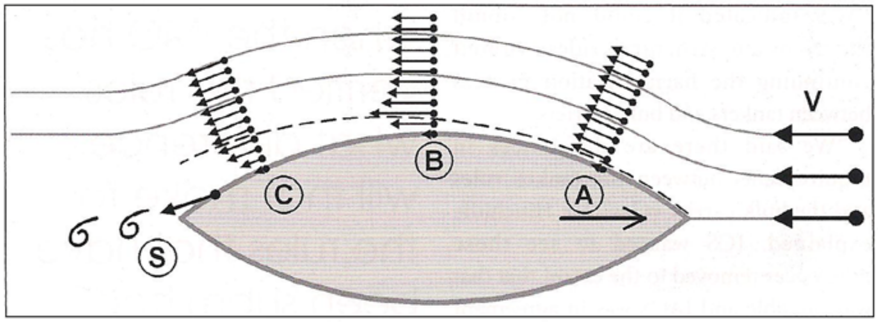


Figure 1: Water flow and boundary layer.

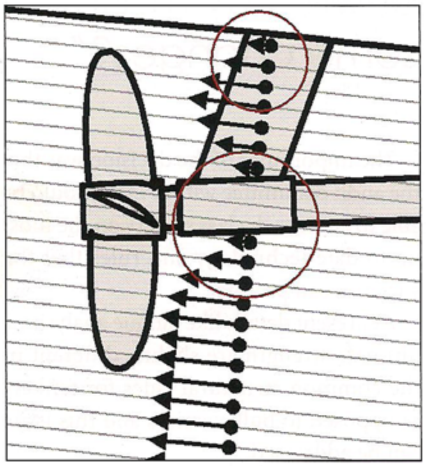


Figure 2: Velocity reduction due to appendages.

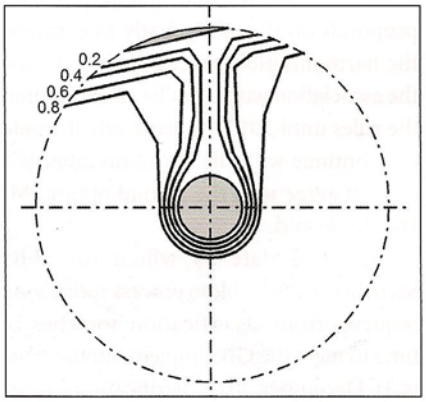


Figure 3: Example axial velocity wake field.

The critical velocities for propeller evaluation are those found in the plane of the propeller disk area. For a given vessel, these velocities can be measured in a model test, or predicted using computational fluid dynamics (CFD) or statistical algorithms. The following graphic (Figure 3) is an example of a wake field plot of axial velocities for a twin-screw vessel with a single strut (P-bracket). The iso-lines on the plot represent velocity as a ratio of the open free-stream velocity. You can easily see the reduction in water velocity nearest the hull's boundary layer, around the propeller hub and shafting, and particularly behind the strut.

Not only are axial velocities considered, but tangential (or rotational) contributions due to upward and transverse flow vectors are also taken into account. These would have a similar plot or be represented by vector arrows on the axial wake field plot.

The wake field data is further developed to determine averaged velocities for each radial position (along the propeller blade from root to tip). This data is presented as a radial distribution of velocity, shown below (Figure 4).

Identifying the vessel's specific wake field properties or radial distributions by empirical testing or detail calculation

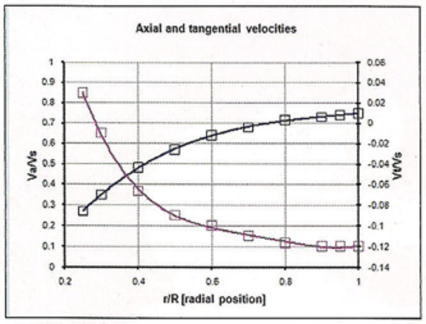


Figure 4: Average axial and tangential velocities.

is not always necessary. Particularly for "semi-custom" designs, representative wake distributions for vessel "types" can be effectively applied to propeller calculations. Representative wake field data can be found in various hydrodynamic technical papers, reports, and texts.

Wake-adapted calculations

Using specialised software, a custom propeller can then be optimally designed to match the unique inflow properties of the vessel (or a semi-custom propeller designed for a vessel "type"). This offers a propeller that is "custom tailored" to fit, or "wake-adapted". Such software is able to consider axial and tangential inflow properties, and ascertain optimised distributions of pitch and camber for prescribed foil characteristics. Of course, the propeller design process would also take into account blade strength, tip and hub loading, and cavitation.

HydroComp PropElements is an example of wake-adapted propeller detail design and analysis software. Unlike general-purpose CFD or more complex codes, PropElements was designed to be readily employed by practicing naval architects, as well as propeller designers and builders. Its analytical core is a unique implementation of a vortex lattice lifting-line calculation, with empirical connections that allow analyses to be viscous and fully-scalable. PropElements calculation modules include Geometry, Performance (Figure 5), Strength, and KT-KQ (curves).

Contemporary propeller geometries – pressure-equalised designs, for example, with variable pitch distribution and camber established for "shockless entry" – are substantially different from series geometries (B-series, AU, Segmental). In system-level propeller sizing and analysis, this is managed using correlation strategies (such as "aligned prediction" to model tests). These propeller geometries can be explicitly evaluated in PropElements, with additional considerations such as skew and nozzles.

Performance versus stock propellers

So how much "green" might be achieved with an optimised wake-adapted propeller? The following example is for the propeller design of a twin-screw vessel using the axial and tangential distributions shown in Figure 4 above. The original propeller was a popular stock model, with a prescribed camber (of flat-faced segmental design) and constant pitch. The newly optimised propeller (with the same basic foil section) was designed with variable camber and pitch to better match the wake, as shown in the plot below (Figure 6).

A comparative summary between the original and an optimised propeller designed by HydroComp PropElements (Table 1) indicates a power reduction and efficiency gain of more than 6%, just by better matching the propeller to a representative wake field.

Other potential design benefits that could be attained with a wake-adapted propeller design tool include unloading the tip (i.e., reducing the pitch into the tip) to mitigate potential noise and vibration problems, and evaluating changes in the outline (chord distribution) or thickness for even better performance.

Detailed analysis of propeller performance

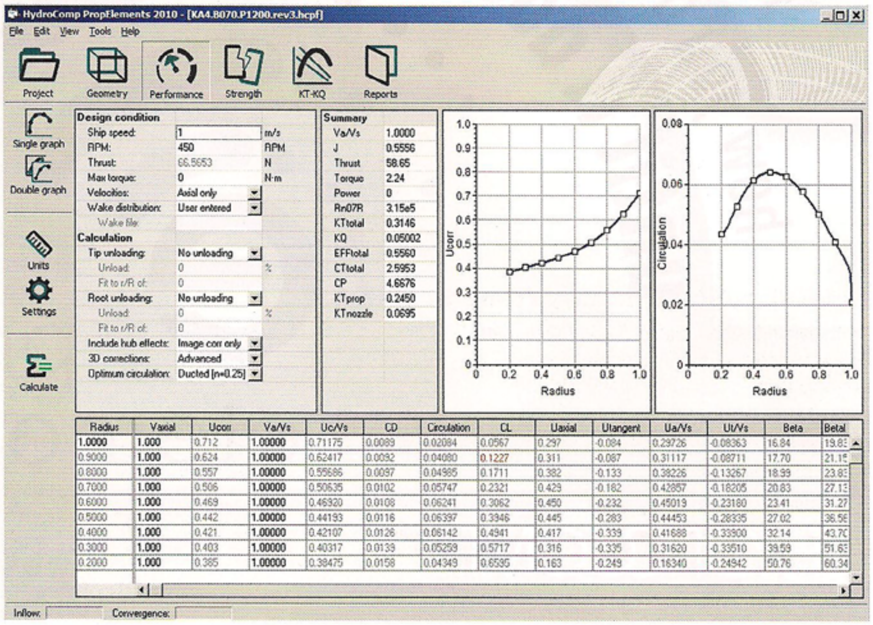
Wake-adapted calculation software such as PropElements can also be applied to analysis, as well as design. The ability to investigate radial values of foil lift and cavitation number, for example, can help identify potential sources of root cavitation or blade impulse excitation. It can help evaluate tip loading (for hydro-acoustics), and also be employed in forensic investigations of blade strength or failure.

Calculation of KT-KQ curves can be applied to system level calculations in replacement of direct propeller series predictions. For example, KT-KQ curves from PropElements can be exported in a form that can be used with HydroComp's NavCad speed-power software for propulsion analysis. The following plot (Figure 7) shows the results of a validation study for PropElements, which clearly demonstrates the quantitative accuracy of these calculations.

Summary

As custom-tailored suits offer greater comfort and better fit, a wake-adapted propeller can provide a variety of performance benefits over stock propellers.

Figure 5: HydroComp PropElements wake-adapted propeller design (Performance page).



Design condition

Ship speed: 1 m/s
RPM: 450 RPM
Thrust: 66.5653 N
Max torque: 0 N·m
Velocities: Axial only
Wake distribution: User entered
Wake file:

Calculation

Tip unloading: No unloading
Unload: 0 %
Fit to r/R of: 0
Root unloading: No unloading
Unload: 0 %
Fit to r/R of: 0
Include hub effects: Image corr only
3D corrections: Advanced
Optimum circulation: Ducted [n=0.25]

Summary	
Va/Vs	1.0000
J	0.5556
Thrust	58.65
Torque	2.24
Power	0
Rn07R	3.15e5
KTtotal	0.3146
KQ	0.05002
EFFtotal	0.5560
CTtotal	2.5953
CP	4.6676
KTprop	0.2450
KTnozzle	0.0695

Radius	Vaxial	Ucorr	Va/Vs	Uc/Vs	CD	Circulation	CL	Uaxial	Utangent	Ua/Vs	Ut/Vs	Beta	Betal
1.0000	1.000	0.712	1.00000	0.71175	0.0089	0.02084	0.0567	0.297	-0.084	0.29726	-0.08363	16.84	19.8
0.9000	1.000	0.624	1.00000	0.62417	0.0092	0.04080	0.1227	0.311	-0.087	0.31117	-0.08711	17.70	21.1
0.8000	1.000	0.557	1.00000	0.55686	0.0097	0.04985	0.1711	0.382	-0.133	0.38226	-0.13267	18.99	23.8
0.7000	1.000	0.506	1.00000	0.50635	0.0102	0.05747	0.2321	0.429	-0.182	0.42857	-0.18205	20.83	27.1
0.6000	1.000	0.469	1.00000	0.46920	0.0108	0.06241	0.3062	0.450	-0.232	0.45019	-0.23180	23.41	31.27
0.5000	1.000	0.442	1.00000	0.44193	0.0116	0.06397	0.3946	0.445	-0.283	0.44453	-0.28335	27.02	36.5
0.4000	1.000	0.421	1.00000	0.42107	0.0126	0.06142	0.4941	0.417	-0.339	0.41688	-0.33900	32.14	43.7
0.3000	1.000	0.403	1.00000	0.40317	0.0139	0.05259	0.5717	0.316	-0.335	0.31620	-0.33510	39.59	51.6
0.2000	1.000	0.385	1.00000	0.38475	0.0158	0.04349	0.6595	0.163	-0.249	0.16340	-0.24942	50.76	60.34

Improvements in efficiency of 5% or more are common, with reduction in noise and vibration a typical side benefit.

It is to be expected that engine power densities will grow; fuel costs will increase; and emission reduction become more urgent. With more propeller builders now capable of manufacturing propellers made to order – many fully CNC milled – custom and semi-custom propellers of wake-adapted design should be considered for new construction and repowers.

The widespread installation of these propellers also suggests that naval architects need the ability to analyse their performance in greater detail that has typically been available. Whether for confirmation of propeller designs for newbuild projects or the post-delivery evaluation of trial performance, wake-adapted propeller design and analysis tools will be a commonplace fixture in the naval architect's toolbox.

About the author

In its 26th year of operation, HydroComp, Inc. of Durham, New Hampshire, USA provides software and services for the performance analysis and design of marine vehicles to industry, research, academic, and government clients. Donald MacPherson has been HydroComp's Technical Director since its inception. He is the author of numerous technical papers and presentations on applied hydrodynamics, is Instructor of Naval Architecture at the University of New Hampshire, and is a member of SNAME's H8 Propellers panel. HydroComp's web site is www.hydrocompinc.com. *NA*

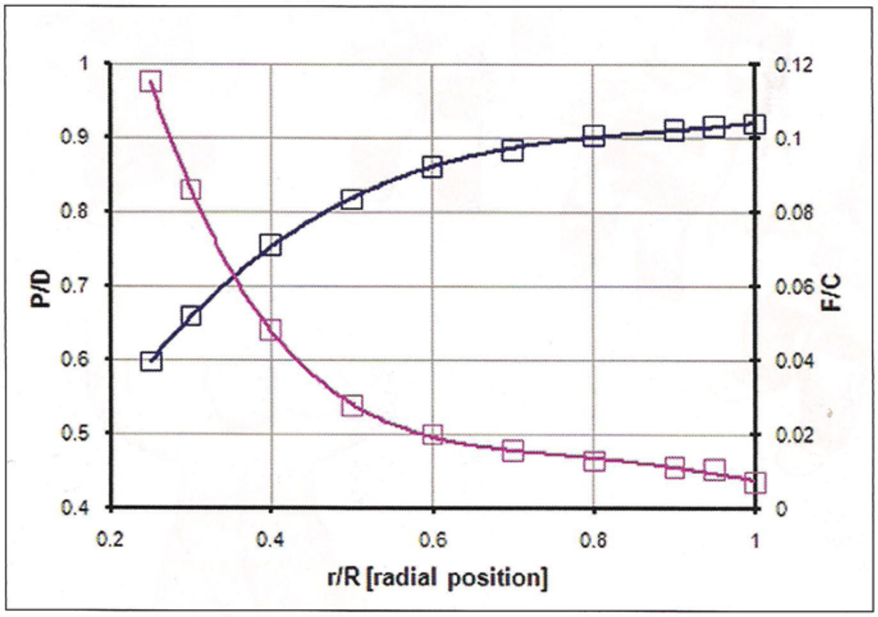


Figure 6: Optimised pitch and camber distributions.

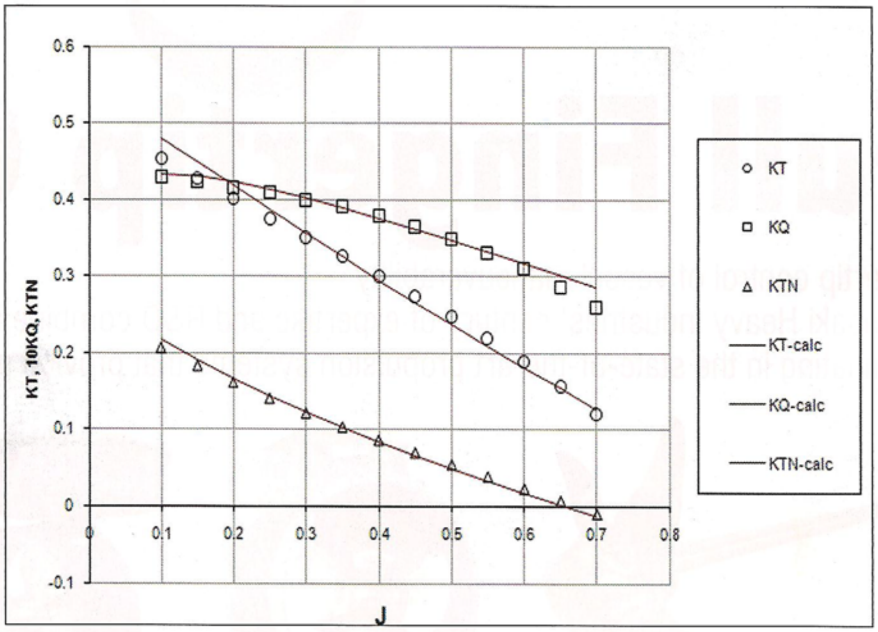


Figure 7: KT-KQ calculation for Ka 4.55 propeller in 19A nozzle.

	Va/Vs [nominal]	J	KT	KQ	CT	CP	EFFY
Original	0.6475	0.6327	0.1247	0.02260	0.3325	0.3876	0.5555
Optimized	0.6475	0.6327	0.1247	0.02217	0.3325	0.3647	0.5904