A 'tool chain' for hydrodynamic analysis workflow

Hydrodynamic analysis is an evolutionary process that requires inter-related tools to strike the ideal balance between facility and precision, explains HydroComp's Don McPherson

Ship design is largely an 'evolutionary' workflow process, with design updates reflecting knowledge gained during loops around the design spiral. Each discipline (major dimensions, hull form, weights, powering and arrangement, to name just a few) will influence the others. In early stage design, knowledge is formational and about big decisions. Knowledge becomes more specific as the design matures and is constrained by the earlier design decisions.

Hydrodynamic analysis – whether that is for hull form, propulsor, or the integration of the two – follows these same evolutionary design stages. Workflow effectiveness benefits from tools that are appropriately matched to the task at hand. This article describes the rationale and organisation of a 'tool chain' for hydrodynamic analysis, from parametric studies through full CFD. Each stage sets the table for the next, with increasing precision and benchmarking for confident outcomes. This article will touch only on hull form resistance prediction, but the concepts and conclusions are equally valid for propulsor design.

An appreciation of order

To many, 'order' is the neatness of things (my mother would fit into this category). To scientists and engineers, order is a characterisation of complexity. Equation forms can help explain this. A line is of a lower order: Y = AX+B. With every additional exponent component in a polynomial, the order is raised: Y = AX3+BX2+CX+D. Each equation form is a model describing the output for a given input. Most would say that the higher order model better captures the outcome – but this is only true when the data is sufficiently refined. If you do not know the principal input data with certainty, a higher order model provides no more knowledge or usefulness than a simpler model.

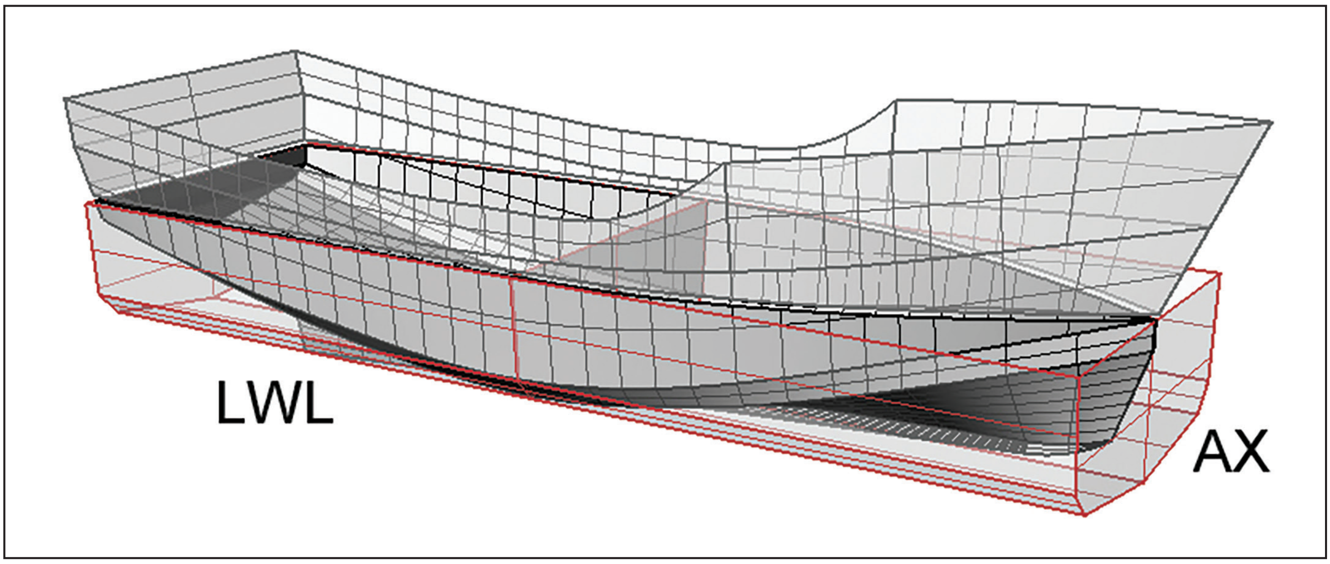
Computational models are numerical predictors of an attribute for the given data, and they are the tools of marine design and optimisation. In the context of hydrodynamic analysis, we have a wide variety of tools to manage our models for prediction of resistance and powering, from quick and simple charts that use just a few parameters, to full RANSE (Reynolds-averaged Navier-Stokes equations) CFD codes that require a complete description of the surfaces that are wetted. So which tool should we use?

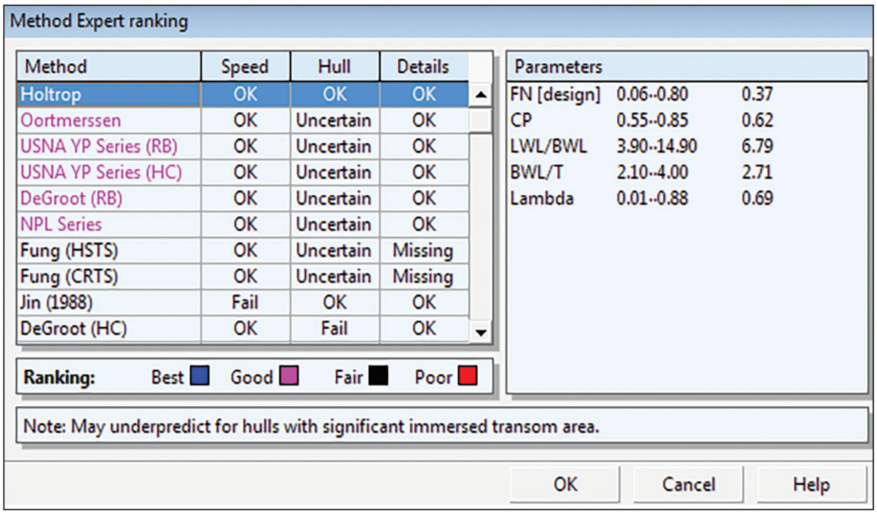
Design is an evolutionary process from lower to higher precision. All naval architects will be familiar with the design spiral, and this offers some insight into the value of having a connected hydrodynamic analysis tool chain from lower to higher order that gives the best 'value' for the 'cost'. In short, we need inter-related tools that hit the 'sweet spot' between facility and precision.

Data and prediction models

When we talk about models we must consider both sides of the coin: data and prediction. Hull form data models for hydrodynamic analysis represent the 'hole in the water'. Prediction models interrogate

Figure 1: Data models of hull form shape





Method Expert ranking

Method	Speed	Hull	Details
Holtrop	OK	OK	OK
Oortmerssen	OK	Uncertain	OK
USNA YP Series (RB)	OK	Uncertain	OK
USNA YP Series (HC)	OK	Uncertain	OK
DeGroot (RB)	OK	Uncertain	OK
NPL Series	OK	Uncertain	OK
Fung (HSTS)	OK	Uncertain	Missing
Fung (CRTS)	OK	Uncertain	Missing
Jin (1988)	Fail	OK	OK
DeGroot (HC)	OK	Fail	OK

Parameters		
FN [design]	0.06‑‑0.80	0.37
CP	0.55‑‑0.85	0.62
LWL/BWL	3.90‑‑14.90	6.79
BWL/T	2.10‑‑4.00	2.71
Lambda	0.01‑‑0.88	0.69

Ranking: Best 🟦 Good 🟪 Fair ⬛ Poor 🟥

Note: May underpredict for hulls with significant immersed transom area.

Figure 2: HydroComp NavCad's 'Method Expert'

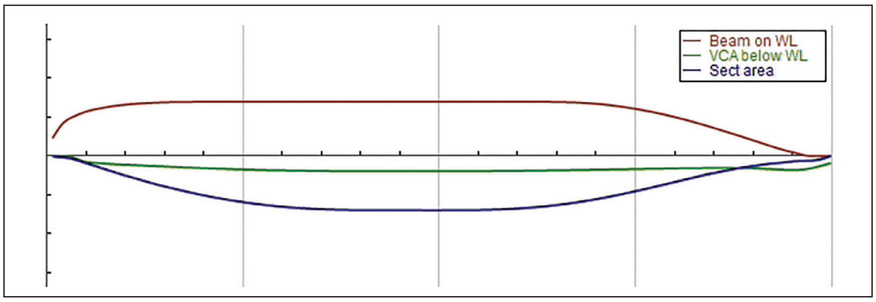


Figure 3: Longitudinal distribution of volume and waterplane characteristics (Duisburg Test Case)

the data and forecast an outcome. Hull form data, such as would be needed for resistance prediction, can be described in a variety of ways. The order of the data can be described in dimensional terms: [1D], [2D], or [3D]. Figure 1 illustrates the order of hull form data:

- Immersed parameter [1D]. These are significant parameters made up of one-dimensional values, such as length/beam ratio (the aspect ratio of the waterplane bounding box) or prismatic coefficient (the ratio of the immersed volume to the red extruded prism of maximum sectional area).
- Immersed volume [2D]. This is typically the longitudinal distribution of shape, such as waterplane cuts, sectional area curve, or the waterplane distribution.
- Immersed surface [3D]. The full 3D envelope is captured via the wetted surface itself.

Prediction models

This is where the strengths and weaknesses of the various hydrodynamic analysis software tools are exposed. They all generally employ one or more of the data models described above, but their capacity to predict performance can be quite different. We will consider a 'tool chain' that connects the workflow from [1D] through [3D] using HydroComp NavCad to illustrate the [1D] and [2D] links in the chain.

Parameter-based empirical prediction [1D]

These methods are largely derived from a statistical regression of historical data. In other words, they use what has already gone before to predict what may come ahead. One might therefore think that they are not very good at projecting or extrapolating beyond their own scope, but this is not always the case. If the method uses a framework that gives a qualitative structure – such as a curve shape that reflects the physics of ship resistance – then methods can extrapolate somewhat beyond their data limits.

Perhaps the most well-known parametric ship resistance method is the Holtrop method. This has wide application for non-planing monohull forms, but it still has its limitations. A comprehensive library of methods, is necessary to ensure that you have a method which satisfies the scope of the parameters and speed range. The Method Expert utility on HydroComp NavCad provides ranking and guidance to the user on the proper selection of a method for a [1D] parametric analysis.

Parametric-empirical methods can also be enhanced using a correlation technique that 'aligns' a prediction to a specific ship. Since many designs are derivative of earlier work, it is immensely valuable to be able to leverage the knowledge invested in model testing and/or sea trials to achieve the highest fidelity prediction for the new design. The 'Aligned Prediction' utility in NavCad provides such a capability.

At the conclusion of these parametric-friendly loops through the design spiral, the naval architect will have answers to those first-order questions of a ship's size, general shape, and powering requirements. They in turn provide the stepping-off point for the next refinement of the design.

Volume-based semi-empirical prediction (2D)

The shape descriptors employed in the parameter-based empirical calculations can now be extended to include a greater refinement of the longitudinal distribution of shape. For example, Figure 3 shows the longitudinal distribution of sectional area, waterplane (beam), and centre of immersed sectional area for a post-Panamax container ship with a bulbous bow. (This is the 'Duisburg Test Case', which is used as a validation benchmark for computational prediction models.)

This hull can be described parametrically as: 7.0 L/B, 3.5 B/T, 6.4 CVOL (fineness), 0.67 CP, 1% aft LCB. Of course, there are an unlimited number of shapes that can fit into that description. The longitudinal distribution gives us a more complete picture of the immersed volume.

This data distribution is used for resistance prediction by the Analytical Distributed Volume Method (ADVM) in the Premium Edition of HydroComp NavCad. It is a [2D] analytical wave-making code that also predicts the viscous properties at scale. It is suitable

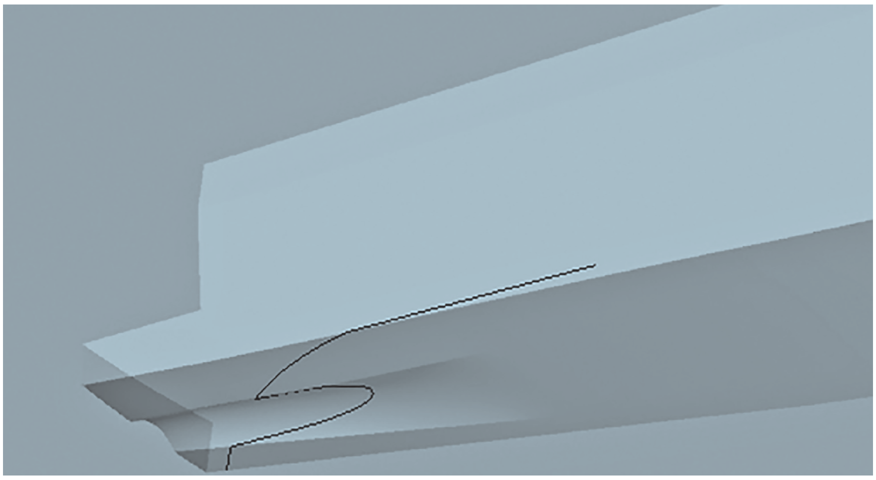


Figure 4: Irregular waterline offsets through a propeller pocket

for monohulls and catamarans, and its prediction of resistance is independent of any statistical underpinning, making it useful as a prediction option for a very broad range of vessel types. The 'semi-empirical' aspect of the method is that certain diverging and transverse wave energy characteristics are constrained based on studies of many different hull types.

The foundation of the NavCad ADVM is an analytical wave-making prediction method similar to slender – and thin – ship codes, such as Michell Integral methods. It differs from these codes, however, in two key ways. First, the ADVM is not limited to thin or slender ships, and allows for successful prediction for wide (high B/T) ships such as the Duisburg Test Case illustrated in Figure 3. That being said, it does tend to somewhat over-predict wave-making for hulls with substantial buttock flow, such as barges and very shallow sailboats.

Second, and more importantly, the method does not use a waterplane cut technique (as is the case for a Michell-based method). Such methods are ill-behaved when they encounter irregular changes in waterplane geometry, such as through tunnel thrusters or propeller pockets. Figure 4 shows how a waterplane cut through a propeller pocket produces a discontinuous flow line. A simplification of the geometry would be required to achieve an outcome with a waterplane cut method. Of course, the local effect of such details is above the order of the [2D] design loop, and will be exposed in the higher-order [3D] CFD link in the tool chain. Instead of waterplane cuts, the NavCad ADVM employs sectional area curve and waterplane distributions which allow for a more well-behaved analysis with no loss of fidelity for the [2D] design and analysis objectives.

The wave energy component of ship resistance can also be communicated via its influence on wave pattern elevations. Figure 5 an example of a wave pattern calculated by this method.

The computational cost of a complete resistance curve and wave pattern plot is just a few minutes on a typical business-grade computer. This [2D] link in the tool chain is a very time and cost-effective option – especially when proceeding to the use of full CFD [3D].

Preparation for (3D) CFD analysis

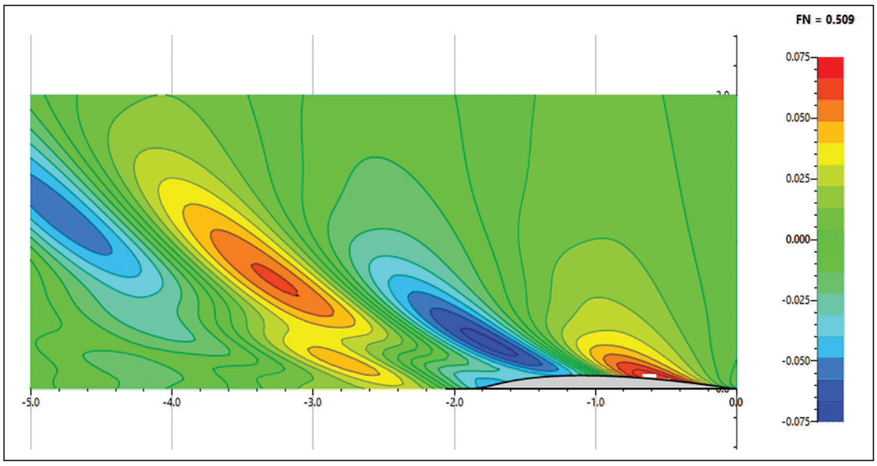
One key to successful [3D] CFD analysis is to first complete the [1D] and [2D] studies for the project at hand. Why? Since [3D] analysis is of the highest order, why should we not go directly to CFD?

The reasons for first conducting the [1D] and [2D] steps in the workflow will depend on the purpose of the [3D] computation. Mature and validated CFD is a complex model for predicting characteristics of fluid flow that allows observation of flow (unlike [1D] and [2D] analyses for the most part), works in a ship's native scale (without extrapolation from model scale), and can be used for design optimisation of local shape (such as the propeller pocket described above).

Some compelling reasons for using lower order analyses prior to [3D] CFD are:

- **For better analysis**. Analysis is all about accurately predicting attributes for prescribed data. It is the user's responsibility to make sure that both the data and prediction models are properly established. However, confidence in outcomes requires a benchmark. The lower order analyses provide these benchmarks, along with increased confidence, improved efficiency, and decreased risk.
- **For design**. Design is the application of analysis to investigate the influence of changes in data on outcome. It is typically an iterative process of 'test-and-move'. Test one condition, gain knowledge, compare to other condition, and move to a new and better condition. Repeat until the study converges to an acceptable definition of what is 'sufficient' or 'optimum'.

Figure 5: Wave pattern elevation calculation (Wigley hull)



Lower order analysis can very quickly and inexpensively conduct design studies suitable to pare down the set of 'all-possible-designs' to a manageable few that will meet the objectives and justify higher order study.

Rapid design space optimisation

The advent of more affordable and accessible CFD offers exciting possibilities for ship design. To insure that overall [3D] computational efficiency and cost-effectiveness is as high as possible, it is necessary to first make use of [1D] and [2D] rapid design space optimisation. With the introduction of the Premium edition, NavCad is able to provide integrated support for design optimisation, and naval architects can make CFD studies more effective by using NavCad Premium to 'set the table' for it.

A preparatory design space study establishes a starting geometry for CFD that is substantially closer to the final outcome, which greatly increases the success of analysed designs and the value of CFD. In addition to quickly narrowing the design space, NavCad Premium can also be used to assign confidence and validate the CFD model. Its predictions are quantitatively very reliable and robust, allowing follow-on CFD prediction values such as resistance or propulsor thrust, to be judged against those generated by NavCad Premium during its design space investigation.

What order of tool is needed?

We have described a tool chain for hydrodynamic analysis workflow by naval architects and designers. It is important, however, to remember that not all three links are necessarily needed for each project or task. It is fair to say that [3D] needs the preparatory steps of [1D] and [2D], and that [2D] builds upon [1D] analysis. That being said, when is a lower-order calculation sufficient? When is value gained by going to a higher order? *NA*

Tasks appropriate for [1D] analysis

- **Prediction of speed and required engine** power. Parametric methods can typically offer reliable prediction of speed and power for most ships and boats. However, selection of the right empirical-based method is critical, as is proper modeling of propulsors. NavCad's Method Expert, for example, offers this important user guidance. This is further enhanced with alignment to model tests or sea trials of similar vessels.
- **Selection of propeller parameters**. Propeller sizing (also called engine-propeller matching) can use [1D] methods to select the critical propeller and driveline design characteristics – propeller diameter and blade area, blade count, and even reduction gear ratio. Even if the design of the final propeller is to be off-loaded to a supplier, it is the responsibility of the designer to select the proper gear ratio (for shaft RPM) and principal parameters as they relate to the hull-propeller-engine system.
- **Initial design guidance**. The ship design process is not limited to hydrodynamic analysis. Designers are responsible for many other objectives – capacities, stability, structure, and more. At early design stages, naval architects do not need 'optimum' hull characteristics; rather they need guidance on general design 'trends' to reduce resistance and power. Parametric [1D] calculations are perfect to advise designers on how principal characteristics – maximum section area, LCB, transom immersion, bulb area – will influence resistance.
- **Benchmarking for [2D] analysis**. It is always beneficial to run a lower order calculation as a benchmark for the next higher order calculation. The [1D] parametric-empirical predictions can serve as checks of [2D] outcomes to make sure that the [2D] data model is correct.
- **When to proceed to higher-order analysis**. The parametric-empirical [1D] calculations as found in HydroComp NavCad will be sufficient if your objective is the quantitative prediction of speed and power for the purposes of determining maximum ship speed, selecting propulsion components, or investigating operational fuel consumption, for example. It is also suitable for forensic studies of existing performance. Running higher order calculations is justified if a qualitative optimisation of the immersed volume is needed, if the vessel does not well match the data set of a parametric method in the library, or for investigations of local characteristics of flow.

Tasks appropriate for [2D] analysis

- **Prediction of ship resistance**. The ADVM computation in NavCad Premium edition is not built from a regression data set, so its resistance predictions are independent of any particular hull type. This makes it an ideal companion to [1D] calculations as an additional confidence check. Like the [1D] calculation, these can also be enhanced with alignment to existing model tests.
- **Investigation of the influence of distributed shape changes on resistance.** When the principal parameters of a design (L/B, B/T) have been established, a [2D] computation can be used to investigate resistance based on the distribution of the immersed volume. This capability can be used to optimise and design hydrodynamically-significant features such as 'shoulders' in the sectional area curve, immersed transom area, length of entrance or run, or characteristics of bulbous bow geometry, for example.
- **Narrow the design space for [3D] CFD**. While computers are increasing in power and [3D] codes are becoming more efficient, the [3D] CFD computational requirements in time, skill, and resources are still considerable. Anything that reduces the number of iterations to find a [3D] solution makes the analysis more efficient and the entire project more profitable. The [2D] ADVM calculation – particularly if driven as a simulation solver by an optimising code – will 'set the table' for CFD by narrowing the design space for investigation.
- **Benchmarking for [3D] analysis**. As was the case for [1D] benchmarking of [2D] calculations, it is absolutely critical for the success of [3D] resistance predictions to have the knowledge derived from the [2D] link in the tool chain. Differences in outcome can point to potential errors in the [3D] data

model (such as incorrect gridding) or in CFD settings (turbulence models or convergence). While many CFD codes have a proven track record, user mistakes happen. Without the appropriate benchmarks from the lower order [2D] distributed volume calculation, it is often difficult to have sufficient confidence in the results of the [3D] CFD calculations.

- **When to proceed to higher-order analysis**. The distributed-volume [2D] calculations from the Premium edition of NavCad serve as an additional resistance prediction method that allows for a better understanding of the influence of volume changes. It can be used for design optimisation of shape characteristics, or on a broader level for narrowing the design space and making [3D] CFD studies more cost-effective and time-efficient with better outcomes. Full CFD studies are called for if localized optimisation is needed, if flow is to be observed, or as a final validation stage of the design spiral.

Summary

The evolutionary nature of ship design calls for a multi-order 'tool chain' for hydrodynamic analysis.

Workflow from [1D] parametric analysis through [3D] CFD requires computational models and tools that are appropriately matched to the task. An interactive suite of tools that hits the 'sweet spot' between facility and precision is critical for successful and cost-effective hydrodynamic outcomes. Fortunately, such tools are easily accessible and appropriate for any naval architectural office.

About the author

Donald MacPherson is an internationally-recognised specialist in applied hydrodynamics with particular emphasis on the design of propulsors. In addition to being the co-founder VP technical director of HydroComp, he is also an instructor of naval architecture at the University of New Hampshire.