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Propulsor Lift: What's Been Missing in a Complete Performance Analysis

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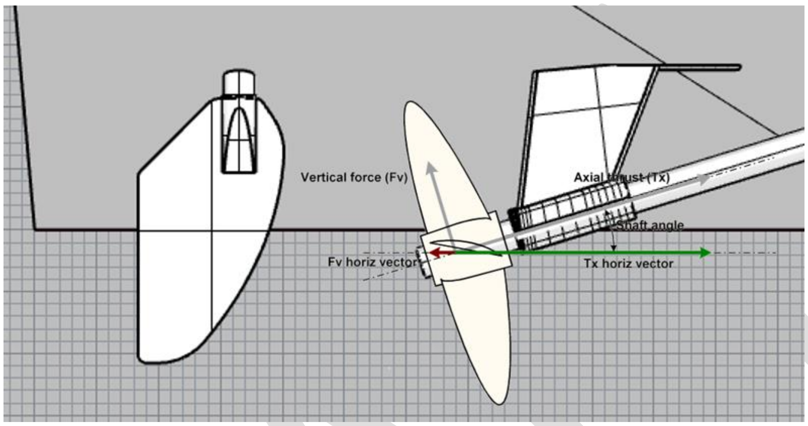

The performance prediction of powerboats, and all craft for that matter, relies on computational models designed to represent the underlying physics. Given that powerboats often reach speeds where dynamic lift forces become significant, the most popular predictive model among naval architects is a sum of forces and moments computation. This paper aims to address an important, yet frequently missing, component for that model: propulsor lift force. Various approaches to determining and employing propeller effect forces to enhance the accuracy of planing hull analysis are described, with a particular focus on improving CFD predictions using propeller effect data obtained from preliminary benchmark analysis.

KEY WORDS: planing; CFD; resistance; prediction; propeller; oblique.

INTRODUCTION

Contemporary prediction methods for planing hull performance analysis, ranging from simple parametric relationships to comprehensive detailed simulations, can be effective design tools. However, not all methods are appropriate for every design scenario. Methods vary in complexity and in how their computational models represent the physics involved. The necessary complexity of the computational model typically depends on the question being posed, the maturity of the design, and the risk tolerance of those conducting the predictions. Regardless of the method, it is essential to consider all relevant and meaningful physical components that affect performance.

Power boats typically reach speeds where dynamic lift forces become significant, unlike slower craft where buoyant forces dominate. The most popular predictive model for power boat performance analysis among naval architects is the sum of forces and moments computation, popularized in parametric form as the "Savitsky method" (Savitsky 1964). This approach aims to capture the significant lift and drag forces of the hull, windage, appendages, and the propulsor's thrust-making forces.

This paper aims to address an important missing component: propulsor lift force. Applied forces, such as those from trim tabs, wedges, or interceptors, can significantly change a boat's trim, and therefore its drag and lift (and the centers of both). Like these stern lift devices, propellers also generate a vertical "in-plane" force when placed in non-axial "oblique" cross flow, as is the case with almost all inboard-style shaft-driven power boats. Without a suitable model for propulsor lift, any performance prediction will be incomplete and potentially misleading.

This is particularly notable when considering the increased use of CFD for power boat analysis, where propeller thrust line forces may or may not be included in the model. There are several propeller effects that can influence CFD planing hull simulations, both for resistance prediction and self-propulsion analysis. While the underlying physics is similar for parametric prediction and CFD simulation, there are some notable differences. Generally, parametric methods define the speed and allow forces and moments to resolve themselves. In contrast, for CFD analysis, particularly for resistance simulations, propeller forces are often not accounted for, and only the horizontal towing force required to maintain the prescribed vessel speed is included. For both CFD resistance and self-propulsion analysis, propeller lift forces in the plane of the propeller are generally neglected.

Examples of propeller effects for both parametric and CFD analyses are demonstrated with a generic power boat. The HydroComp NavCad® software is used for parametric planing hull prediction of resistance with and without propeller force components. It is also used as a preparatory step to predetermine appropriate propeller forces for enhanced CFD analysis using SimericsMP, part of the Orca3D Marine CFD™ system.

CASE STUDY MODEL

A case study model was developed that is representative of a 12.7 m (41.6 ft) LOA offshore planing craft. Key parameters are:

- 10.9 m (35.9 ft) static LWL; 3.5 m (11.4 ft) chine beam; 0.6 m (2.0 ft) draft; 17 deg deadrise
- 30 kt design cruise speed; 40 kts top speed
- twin-screw shaft-driven propeller; 12 degree shaft angle

Figure 1. Case study vessel profile rendering

To reduce CFD computation time for the study, the appendages were stripped from the geometric model. The prediction condition for the parametric and CFD calculations therefore does not include any appendage drag. The propeller position and shaft line vector are as shown. Windage drag was included for the hull. Bare-hull drag includes prediction of whisker-spray drag.

PLANING HULL FORCES AND MOMENTS

The seminal paper by Daniel Savitsky (1964) is considered the preeminent reference on parametric planing hull performance prediction. The "Savitsky method" that we all know and use, of course, is named for Dan Savitsky. It is interesting to note that his is the first reference cited in the other important companion paper by Jacques Hadler (1966), and (based on limited research by the authors) the term "Savitsky method" was first used in a discussion of Hadler's paper.

Foundational Models

The collection of forces (and corresponding moments about the CG) are illustrated in the figures below. These models represent the principal "wetted" forces relating to the hull. They were not intended to be a complete definition of all potential important forces, such as from windage drag, stern lift devices, or even a towed body. We have seen several evolutionary force component additions to the models, such as trim tabs and whisker spray drag, for example.

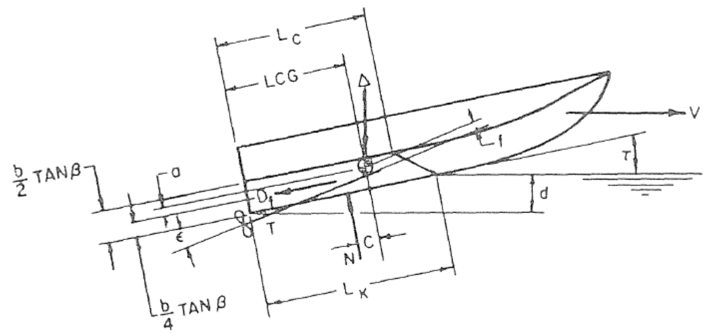

Figure 2. Savitsky forces and moments model

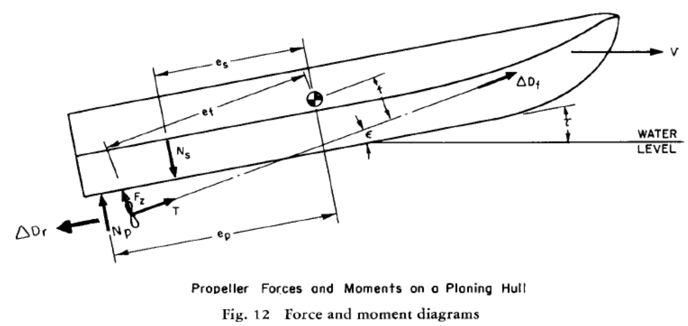

Figure 3. Hadler forces and moments model

That said, there is one notable difference between the Savitsky and Hadler models – the propeller lift force. Savitsky never mentioned the lift force (Fig. 2), but it is included in the Hadler framework (Fig. 3 as FZ). It is fair to say that spreadsheets, papers, and discussions regarding parametric planing hull resistance prediction largely conform to Savitsky's model, with its omission of propeller lift force.

Propeller Lift Force

Hadler describes in some detail the propeller forces that affect a planing hull, including both thrust-line force (T) and normal force (FZ). He further offers a basic approach for the calculation of what he termed the "vertical force" (i.e., the reaction force perpendicular to the thrust-line force in the upward direction). This approach is a circumferential integration of the variation in thrust and torque as a propeller blade rotates, leading to the reaction force. (The implementation of this integration calculation in NavCad is described in a later section.)

However, while the determination of the equilibrium propeller thrust-line force can be easily resolved by matching its horizontal resultant to the vessel's total predicted resistance, the corresponding lift force is a function of the propeller's RPM and its characteristics (e.g., blade count, pitch, style). Of course, it is rare that a propeller's design parameters are available while conducting a resistance prediction, so it is not reasonable to expect that a formal integration calculation to solve for a propeller lift force will be included at this stage.

To address this, HydroComp undertook an in-house R&D study to estimate a vertical force given a thrust-line horizontal resultant force that is calculated from the horizontal resistance. A suitable source for propeller tests in oblique inclined shaft angles was identified (Peck 1973; Peck 1974). In fact, the data was presented as measured vertical lift (L) and horizontal resultant thrust force (T) vectors (Fig. 4).

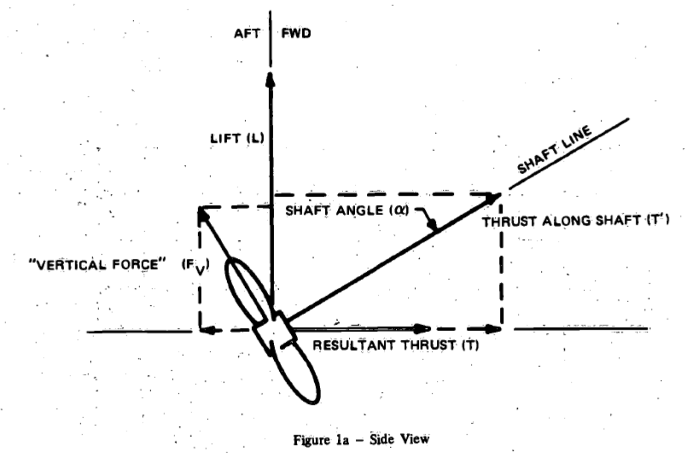

Figure 4. Inclined propeller test force description

A proprietary dimensional analysis model to predict vertical lift force given a horizontal thrust force vector was developed using the published data (an example of which is in Table 1). The predicted vertical lift force can thus be easily applied during a resistance prediction. Consideration of a thrust deduction (which is typically small for planing craft with open shaft-driven propellers) was intentionally omitted in the interest of developing a prediction that would conservatively represent the missing force.

TABLE 4 – PERFORMANCE CHARACTERISTICS OF PROPELLER 4528 AT 7.5 DEGREES SHAFT INCLINATION

INCLINATION ANGLE = 7.500 PITCH RATIO = .800 SIGMA = 14.700

J	KTOUT	10KQOUT	EFFIC	KT/J2	KQ/J3	KL	KBF	BFANG
.6000	.1353	.2257	.5725	.3758	.1045	.0275	.0097	10.0120
.6500	.1135	.1961	.5985	.2686	.0714	.0275	.0117	5.3392
.7000	.0918	.1745	.5859	.1873	.0509	.0250	.0127	1.6834
.7500	.0705	.1482	.5680	.1254	.0351	.0225	.0132	-.5775
.8000	.0503	.1178	.5440	.0786	.0230	.0205	.0136	-1.9393
.8500	.0319	.0964	.4470	.0441	.0157	.0177	.0136	-3.7713

Table 1. Propeller coefficients for 7.5 degrees inclination

It is appropriate to ask if propeller lift force is a significant force contributor, and it is the authors' contention that the omission of this force vector is indeed significant. For example, in the table above (for a relatively modest 7.5 shaft angle inclination with a sub-cavitating four-blade propeller of 1.0 P/D), the vertical lift force is 24% of the horizontal thrust force vector at the J coefficient matching peak efficiency (a typical design point). At a high 15 degrees shaft angle inclination, the proportion grows to nearly 60%. For a practical comparison to trim flaps on a similarly sized hull, an example calculation (Morabito 2013) indicates the flap under consideration produces a lift of 34% total resistance (which is equal to the horizontal thrust force vector). Of course, while design scenarios, propellers, and stern lift devices will vary to suit the specific application, the applied vertical lift of an inclined propeller – and its effect on resistance models – should not be easily dismissed.

Trim Flaps

$$L_{FLAP} = 0.046\, s_F c_F \delta \frac{1}{2}\rho V^2 = 0.046\,(1m)(0.5m)(5°)\frac{1}{2}\left(1025\frac{kg}{m^3}\right)\left(20.6\frac{m}{s}\right)^2 = 25{,}000N\ per\ flap = 50{,}000\ N\ total$$

$$R_{FLAP} = 0.0052\ L_{FLAP}(\tau + \delta) = 0.0052\,(25{,}000N)(6.8° + 5°) = 1500\ N\ per\ flap = 3000\ N\ total$$

Total Resistance

$$R_T = \sum R_i = R_{HULL} + R_{WIND} + R_{APPENDAGE} + R_{FLAP} = 101{,}300N + 6{,}400N + 37{,}400N + 3000\ N = 148{,}100N$$

Figure 5. Sample trim flap calculation result

RESISTANCE PREDICTION

As described in the introduction, the purpose of any prediction model is to evaluate the physics of the problem with the greatest fidelity and cost-effectiveness. Since no prediction method, including tank testing and CFD, can fully simulate all relevant physical properties and attributes, we rely on "appropriate simplification". In service, a boat applies its thrust along its shaft line. However, the modeling of propeller forces has been, and continues to be, an area of simplification that is neither justified nor necessary. Even a small amount of trim or CG change due to differences in propeller force modeling can alter the predicted shape of the wetted area of the planing bottom and, ultimately, the bare-hull drag.

So, what are the models for applied thrust and propeller forces used in planing hull resistance prediction? Three cases are described below:

1. **Resistance prediction with no propeller effects**: The towing force is typically applied horizontally (even when the vessel trims dynamically) and is positioned through or near the center of gravity. This is similar to prediction models for non-planing craft and is often the physics model for planing hull model tests.

2. **Resistance prediction with shaft line propeller thrust force**: This model is common for planing hull resistance and trim prediction at a given speed. The "general case" approach determines the magnitude of the propulsor shaft line thrust from the sum-of-forces equilibrium, with an offset from the center of gravity (CG) introducing a component in the sum-of-moments equilibrium. The "simple case" puts the shaft line through the CG (with no applied thrust line moment).

3. **Resistance prediction with shaft line propeller thrust and lift forces**: This resistance prediction model most fully represents the physics of the propeller's contribution to the analysis, including the propeller normal forces due to oblique flow.

To illustrate the scope and significance of propeller effects on the prediction of resistance, dynamic trim, and attainable speed, all cases were run with both parametric (HydroComp NavCad), and cases 1 and 3 with CFD (Orca3D Marine CFD) simulations.

Parametric Prediction

With its enhanced planing hull prediction method, NavCad allows for the explicit selection of propulsor thrust type, positioning of the propulsor center-of-effort, and its shaft angle. For each propulsor type (including the horizontal tow and shaft-driven propeller discussed herein, as well as waterjet or surface-piercing propeller), estimates were developed for propulsor stern lift as part of an in-house R&D project. As described above, the estimate for shaft-driven propeller lift effects were developed from model tests of propellers in oblique flow.

For our offshore planing craft example, the cases with a more complete physical model that incorporate propeller effects predict lower resistance, decreased trim, and an increase in attainable speed for a given propeller-delivered thrust. As compared to the simplest case where applied thrust is horizontal and through the CG (Horiz tow), the "Savitsky model" application of thrust line force (TPROP) alone has the greatest effect on predicted resistance at fully planing (post-hump) speeds, while the "Hadler model" component of added propeller lift force (LPROP) shows the greatest influence in the pre-planing and hump-speed regime (Fig. 6).

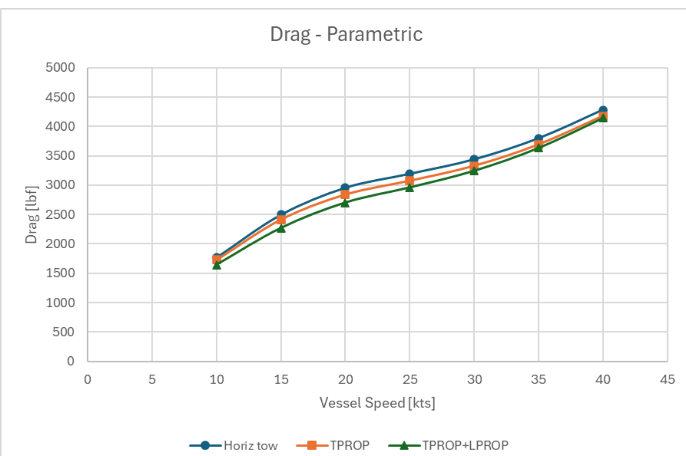

Figure 6. Drag prediction (parametric)

The greatest overall influence of propeller effects is seen in the hump speed region, which is expected as this speed regime is typically where dynamic trim has the greatest influence. Similar to how stern trimming devices are employed to "get over the hump", propulsor lift offers a similar effect. This is evident in the following plot of the trim differential of the two cases with propeller effects from the Horizontal Tow. With case 3, nearly half a degree of lower dynamic trim occurs at the 20-knot hump speed.

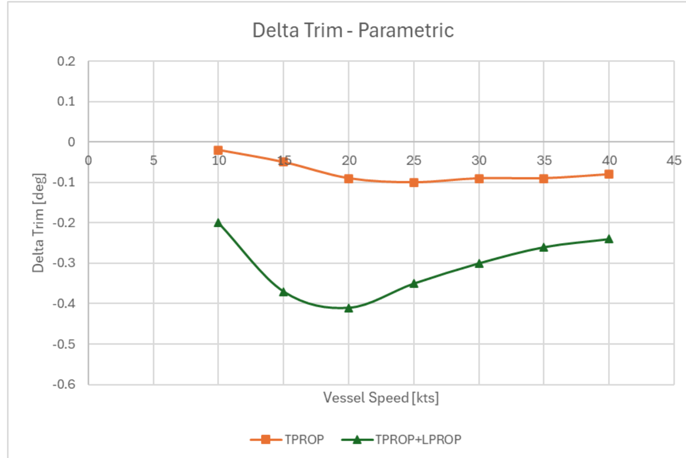

Figure 7. Trim change with propeller effects (parametric)

An important reminder: trim reduction affects not only drag and speed but also dynamic instability (i.e., porpoising). Omitting propeller effects may lead to misleading conclusions about the potential for porpoising. The purpose of a performance simulation is to provide a model for the boat's performance as fully and faithfully as possible (and practical).

CFD Prediction

As mentioned, we continue to see a considerable increase in the effective use of CFD for planing hull analysis. Just as the appropriate application of propeller effects provides a more complete physical model for parametric simulation, the same is true for CFD calculations.

However, there are two challenges in incorporating propeller effects into a CFD resistance prediction. First, while parametric planing hull resistance predictions solve for the necessary thrust line force to achieve force balance (thereby allowing the lift force to be determined), most CFD resistance predictions do not. They establish a given speed and allow for dynamic heave and trim based on the pressures acting on the hull, but they do not inherently incorporate propeller effects into the equilibrium force or moment balance. Second, while it is possible to expand the CFD prediction simulation with supplemental body forces representing the propeller effects, this requires a method to determine these figures prior to initiating the run.

Orca3D Marine CFD software offers an approach to model a Horizontal Tow (case 1) and to include thrust line force and lift propeller effects for a more complete physics model (case 3). The shaft line thrust and lift figures, which are applied in CFD as body forces, are generated for this example using NavCad's planing hull resistance prediction simulation, including the propeller lift force (LPROP) prediction from the dimensional analysis model described above (Fig. 8). While these figures will not establish a precise force balance match (as there is no convergence function to modify the forces), they will closely approximate balanced propeller effect forces for a more complete representation of the physics.

OTHER				
LIFT [lbf]	CGRISE [ft]	LPROP [lbf]	TPROP [lbf]	RBARE/W
21781	-0.03	177	876	0.07222
21186	0.42	295	1467	0.11757
20979	0.90	351	1735	0.13893
20627	1.10	444	2185	0.17495

Figure 8. Prediction of propeller effect forces (NavCad)

The screenshots below show how two propeller effect body forces can be applied in Orca3D Marine CFD. The first image is the CFD configuration entry dialog within Orca3D (Figure 9), and the second image (Fig. 10) shows the same forces adapted into the CFD coordinate system (e.g., from a shaft angle to a 3D dimensional vector). Shaft line thrust is identified as ForceVector1 (with a value from the NavCad TPROP column) and propeller lift as LiftForce1 (from LPROP).

The results of comparative CFD simulation using the default mode without propeller forces (Horiz tow; case 1) and with both forces (TPROP+LPROP; case 3) are shown in the plot below (Figure 11). We observe very similar results to the parametric prediction, with lower drag, decreased dynamic trim, and increased attainable speed over most of the speed range. The bulk of the influence is in the hump-speed range.

Trim change (Fig. 12) is comparable to the parametric predictions. Both simulations – parametric and CFD – illustrate the influence of propeller effects on the predicted speed for a given delivered thrust (as determined by a resistance). This is particularly evident in the hump-speed range, where the speed differential is as much as 5 knots.

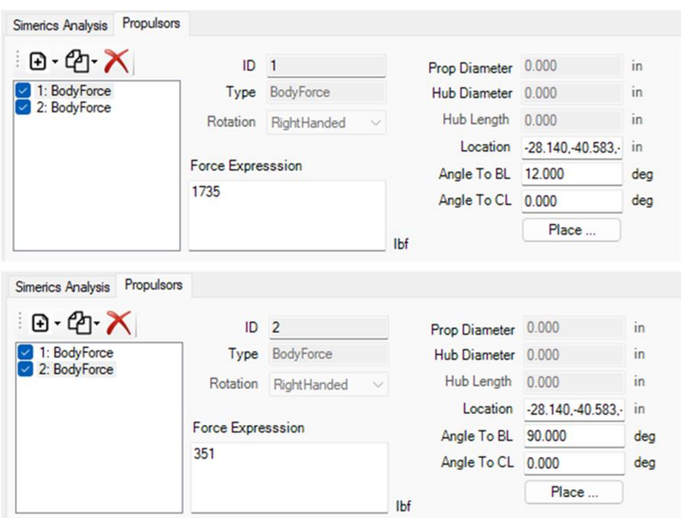

Figure 9. Propeller Force entry dialog

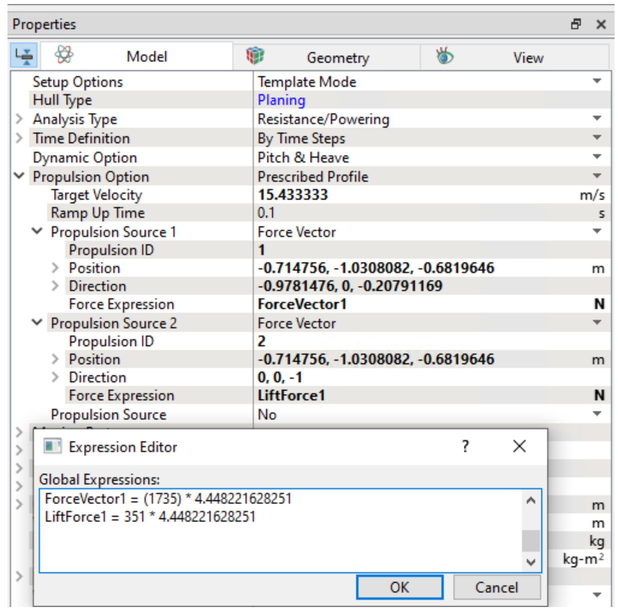

Figure 10. Propeller lift force definition (CFD)

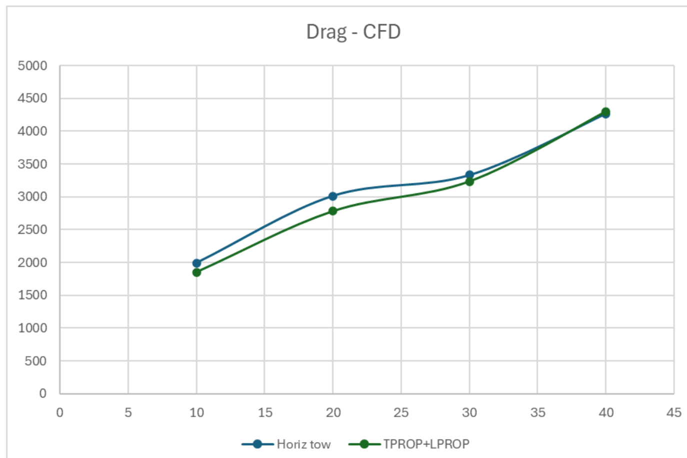

Figure 11. Drag prediction (CFD)

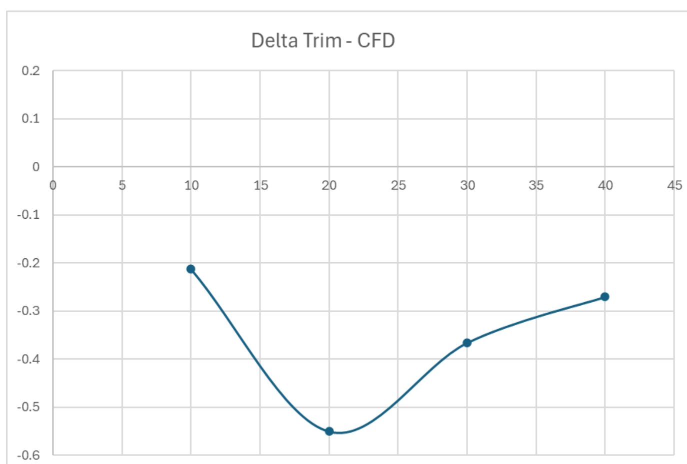

Figure 12. Trim change with propeller effects (CFD)

(The higher-than-expected CFD prediction of drag at the 40 knot speed was a subject of discussion. Given that the trim differentials were comparable between the parametric and CFD simulations, this is attributed to a small over-prediction of spray drag at the flatter running trim.)

Grid convergence and refinement studies were conducted to validate the CFD simulation geometric model and computational settings. The comparative plots shown above were all run with the standard Orca3D Marine CFD planing hull template, as this was deemed most representative of its use in a commercial setting. Additional grid density settings and conservative iteration settings were also investigated. It is important to note that while the addition of propeller effects had a qualitatively significant impact, the quantitative comparisons to the parametric simulation predictions were also noteworthy.

The standard template with its NORMAL grid density generated a mesh of approximately 2.0 million cells for the half-body symmetry model. Higher grid densities of 5.4 million cells (FINE) and up to 14 million cells (VERY FINE) were tested at a speed of 30 knots for both cases 1 and 3. Additionally, the number of iterations per time step was increased from the default of 5 to 10 for an intermediate EXTRA FINE density. As shown in Fig. 13, the increased cell count (and iterations for the EXTRA FINE runs) produced a small increase in predicted drag.

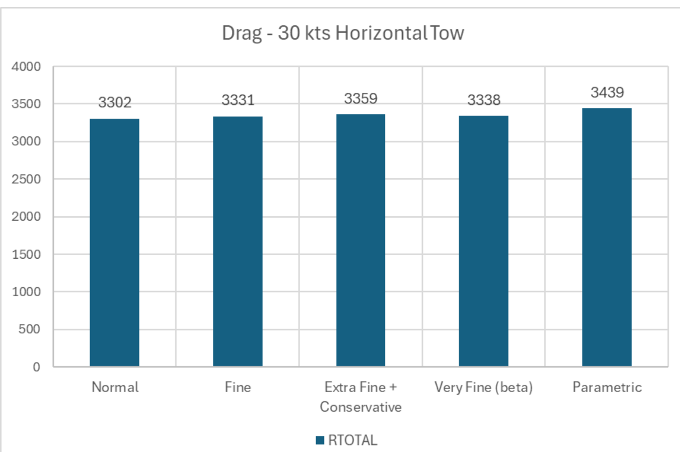

Figure 13. Grid convergence study

Although the grid convergence study indicated that the default NORMAL grid with 2.0 million cells could have been sufficient for this analysis, we chose to use the FINE mesh with 5.4 million cells to ensure that the flow phenomena were adequately resolved for the range of speeds and configurations. The resource expense of the highest grid resolutions was not justified given the very small difference in drag, which was less than 1%. A further review of heave and trim also confirmed that the FINE grid density was sufficient.

The parametric drag prediction was 2.4% higher than the most conservative of the CFD results. The simulation time for the CFD computations with the FINE grid density was approximately seven hours per speed per case on a Windows 10 computer running an Intel i9-11900K processor with 8/16 cores/threads and 64 GB of RAM. In contrast, the parametric predictions were nominally instantaneous.

SELF-PROPULSION ANALYSIS

Incorporating propeller effects into a resistance-only simulation utilizes parametric estimates for the propeller forces developed at a given speed. In a parametric prediction, these forces become an inherent part of the equilibrium force balance. For CFD resistance prediction, the forces are applied as additional influences to approximate a balanced set of forces and moments.

In a CFD self-propulsion analysis, however, force balance is achieved by allowing the model to reach an equilibrium speed for a prescribed propeller force. In other words, while we can improve the predictive model for CFD resistance prediction by incorporating the parametric propeller effect forces, we explicitly incorporate propeller forces for a CFD self-propulsion analysis.

For simplification and resource-effectiveness, the propeller itself is represented by a virtual model – an "actuator disk" (AD). The AD is a momentum source applied in the CFD space as a proxy for a real propeller, and its characteristics are typically defined by open-water propeller data (using KT and KQ coefficients). Unfortunately, standard KT-KQ curves lack an oblique component, so an AD alone omits the important contribution of propeller lift to the system. For a more complete physics model, appropriate propeller performance data is required.

Like parametric analysis that can provide estimated propeller effect data for improved CFD resistance prediction, we can obtain specific propeller performance data in the form of a modified set of KT-KQ curves that include oblique effects. For this, we use the oblique inflow correction feature in NavCad (by modeling and integrating the forces generated from the differing inflow velocities and angles-of-attack seen by a propeller blade as it rotates at an oblique angle), as well as its export of the modified and enhanced KT-KQ data.

For those interested in the calculation methodology for analytical prediction of specific oblique propeller effects, Hadler (1966) describes the foundation and equations to calculate what he termed the "vertical force" (i.e., the reaction force perpendicular to the thrust-line force in the upward direction). This approach is a circumferential integration of the variation in thrust and torque as a propeller blade rotates, leading to the reaction force. The integration technique described by Hadler is very similar to the function developed in NavCad to predict KZP and KT* (defined below) of an oblique flow condition for a specific propeller.

The NavCad oblique propeller performance calculation and corresponding data export has recently been updated for use in CFD analysis. This includes not only the prediction and definition of the vertical propeller lift, but also a reduction in thrust-line force due to oblique effects (Fig. 14). This new set of performance figures can be exported to define the AD characteristics, which includes figures for the oblique-corrected axial thrust and torque coefficients (KT, KQ), the net shaft line thrust coefficient (KT*), and the prediction and definition of the normal lift force (KZP). The fully corrected figures to be used for the AD are KT* and KQ, with KZP used to add a supplemental propeller lift body force (that corresponds to the J coefficient of the computation).

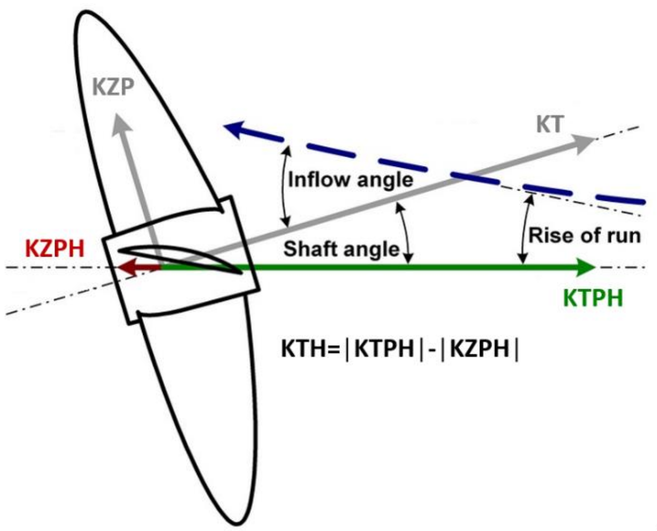

Figure 14. Oblique propeller coefficients

Of course, sizing a suitable propeller is necessary before one can properly define the AD settings. Once again, we can turn to the parametric tool for this task. In the case of NavCad, optimized propeller sizing can be conducted by focusing on the *Vessel-Propeller* relationship of the *Vessel-Propeller-Drive* system simulation. In other words, there is no need to know anything about the prime mover (i.e., engine or motor) or transmission at this stage of the design. The propeller will be sized to meet a design horizontal thrust load as determined by the predicted resistance and hull-propulsor interaction coefficients (e.g., wake fraction, thrust deduction). Only then is it appropriate to export the oblique-corrected set of performance coefficients specific to that thrust-optimized propeller.

Self-propulsion analysis is a more comprehensive physics model than resistance alone, as it introduces hull-propulsor interaction effects, the "drag augment" pressures on the hull of thrust deduction. Incorporating thrust and lift for a propeller that has been properly sized for the application offers a more mature design simulation, further improving the fidelity of the self-propulsion model.

SUMMARY

Engineering "model-based" simulations for design or analysis comprise multiple elements used to represent the physics of the simulated system – namely, a geometric model, an applied force model, and a prediction model. In the context of planing hull performance prediction, well-established parametric methods (e.g., Savitsky, Hadler), CFD-based analyses, and even model testing must contain these elements, despite differing levels of detail in describing the geometry and various analytical methods for representing the physics. Regardless of the tool or analytical methods used, to achieve realistic outcomes that align with a designer's objectives, it is essential that the applied force model fully incorporates all influential and significant attributes.

A case study was conducted to describe and compare the implications of propeller effect lift and shaft-line thrust forces on predictions of planing hull performance. The results of this case study conclusively demonstrate that these forces must be part of the applied force model. The parametric tool used for this review (HydroComp NavCad) includes propeller effect forces by default, whereas CFD simulations typically need to add these effects as body forces. A simple workflow to add these body forces (using NavCad-generated force data) was illustrated using the specific body force utilities available with the Orca3D Marine CFD system.

Some may ask why not just use the higher drag of a simplified planing hull prediction model as a design margin. A design margin should be a single, well-documented supplement. It often is seen that design margins added to resistance are then inappropriately supplemented with a second engine power margin used for the same objectives. A simulation model chosen for its tendency to over-predict resistance or power creates a risky hidden supplemental margin (that may or may not always over-predict) and is not explicitly documented, promoting an inconsistent engineering process. The case study example described herein clearly illustrates a reliable and accessible workflow process to incorporate propeller effects in both parametric and CFD-based simulation, avoiding the unnecessary simplification of the applied force model.

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