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IMPLEMENTATION, APPLICATION AND VALIDATION OF THE ZARNICK STRIP THEORY ANALYSIS TECHNIQUE FOR PLANING BOATS

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Abstract. Zarnick developed an approach to calculate the resistance, motions in waves, and resultant pressures of planing craft by stripwise integration of the forces on transverse sections modelled as wedges entering the free surface vertically. A practical software implementation of this technique was developed and compared to model test results for a variety of military, recreational and working craft. Numerous modifications and improvements to the technique were made in the course of this study, most notably to a series of coefficients to represent buoyancy and three-dimensional lift and drag factors, to improve the correlation of the method. The final results of this study show that this method produces better evaluations of resistance for relatively high-speed vessels than previous methods and compares reasonably well with model test results for motions. This method explicitly models variable beam and deadrise, which previous methods cannot address. The basic background of the technique, its implementation and the development and modifications of coefficients is discussed with a history of validation efforts to improve the correlation.

1. INTRODUCTION

Resistance and motions prediction is an ongoing problem in the design of high speed planing craft. Standard analytic methods such as the Savitsky-Brown technique for resistance, and the Hoggard-Jones or Savitsky-Brown equations for motions only account for a very few parameters of the design, generally maximum chine beam, a single characteristic deadrise, weight and longitudinal centre of gravity. Designers know that warping the bottom and varying beam down the length of the vessel can have beneficial or adverse effects, but these effects can only be evaluated during initial design based on comparisons with model tests and model data if comparable data is available.

Motions in waves are often as important as smooth water resistance and even less reliable guidance is available for either prediction or optimisation of craft design for motions. Since motions govern sea loads, inability to reliably predict motions is a structural issue as well.

2. NUMERICAL APPROACHES

A number of investigators have applied three-dimensional panel methods to the problem of planing craft with some success, for example, Jiminez [1] applied panel methods to sailboard resistance prediction and optimisation. However, the free surface location, which is required as an input to the panel equations is a function of the solution of the method, so that the final solution requires iteration on the free surface position. (This is a more significant problem for a relatively heavily loaded powerboat than it might be for a lightly loaded sailboard.) This not only adds to solution time, but in some cases the panelization near the free surface must be modified to avoid numerical difficulties. Panel methods also cannot be used to directly model viscous effects such as boundary layers or spray. Finally, panel methods are extremely computationally intensive and require special skill to panelize the surface appropriately.

2.1 Zarnick Methods

Zarnick [2,3], following the work of Martin [4], developed a mathematical formulation for the instantaneous forces on a planing craft. In Zarnick's method a planing craft is modelled as a series of strips or impacting wedges. At high speeds, the surge perturbation velocity of the water is small relative to the speed of the wedge and can be neglected. The passage of a planing hull with deadrise can therefore be modelled as, from the water fixed system, a wedge entering the water at some vertical velocity (Figure 1). The instantaneous trim and transom draft of the boat predicts the immersed depth, and hence the shape of a stripewise entering wedge at any lengthwise position on the hull. (Figure 2) A characteristic outward normal vector $\vec{n}$ is defined for each strip and submergence (Figure 3). The normal vector is arbitrarily defined at the longitudinal midpoint of the strip and at a height of 2/3 of the submergence above the keel line. The instantaneous deadrise angle is defined as the angle of the normal with respect to the baseplane as seen in the body plan view. The hydrodynamic force on the strip per unit length can then be determined as a sum of the added mass on the impacting wedge and the hydrostatic force.
Since the instantaneous elevation and kinematics of the water surface are readily calculated at any point along the length of the vessel based on trim, heave and wave

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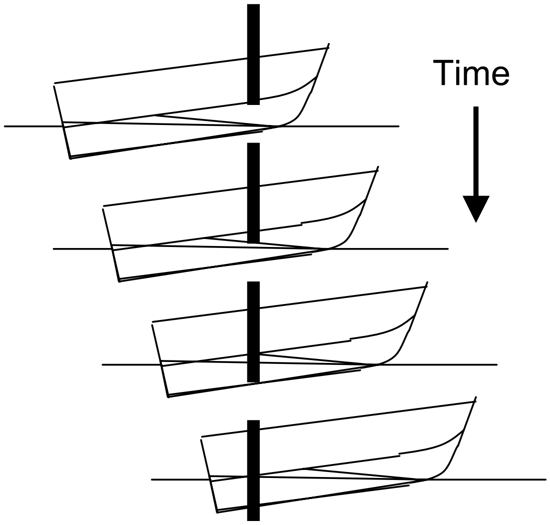

Figure 1. Planing Hull Passage From Sea Fixed Origin

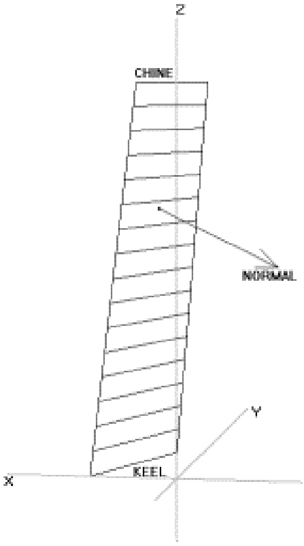

Figure 3. The Stripwise Panel and Its Normal

profile, the Zarnick method can be used for the calculation of resistance and dynamic stability, (i.e. freedom from porpoising) in still water and waves, and motions, velocities, accelerations and forces in waves. The method also gives the longitudinal distribution of forces (for calculation of global loads) directly and can be used with suitable assumptions of the transverse distribution of pressure to estimate pressures. Akers [5] provides details of the calculation of forces and moments, the stripwise integration, the solution of the equations and proposes a process to estimate sealoads.

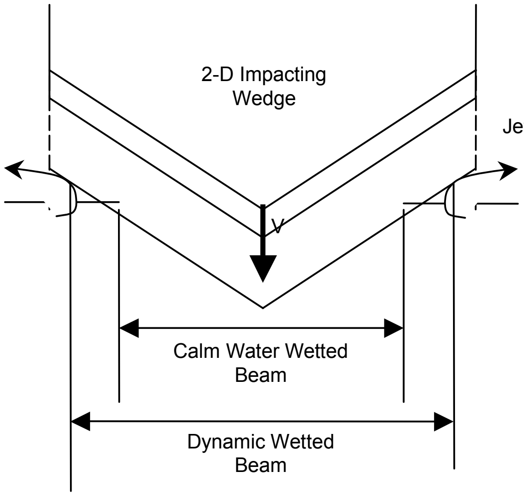

Figure 2. The Entering Wedge Strip

2.2 Hydrostatic Forces

Hydrostatic forces and moments must be included in the analysis, but are difficult to predict. Water rise at the bow of a planing vessel increases hydrostatic lift, flow separation at the stern decreases hydrostatic lift, and both cause an increase in pitching moment. These effects are speed dependent, and there is no single factor that can be used to correct the hydrostatics calculations for flow separation. In his work on rectangular planing surfaces, Shuford [6] suggested that hydrostatic buoyancy should be halved in a dynamic simulation in order to achieve the correct total lift force. Zarnick found that use of an additional factor of one-half for the hydrostatic moment resulted in an accurate trim angle. The algorithm includes a buoyancy force and a buoyancy moment coefficient to correct the vertical force and pitching moment. These coefficients can be set to 0.5 based upon the recommendation of Shuford and Zarnick, or they can be set empirically so that simulation results match tank test results. Determining these coefficients has proven to be an interesting problem, and the recent work with this method has largely involved processes to derive appropriate values of the coefficients.

3. IMPLEMENTATION

Akers [5] has implemented this method in the form of a computer program, POWERSEA, which runs in the Windows 95, 98 or NT environment. The program provides a graphic interface for inputting hull parameters as well as methods for data input from other file types. The hull geometry is ultimately converted of splines representing the keel, chine and deck edge. 201 stripwise stations are derived from this model for subsequent analysis. The program includes both regular waves and irregular seas including Pierson-Moskowitz, JONSWAP, ISSC and Ochi spectral density formulations. The actual wave histories developed from the spectral formulations are synthesized by combining 1024 frequency components. The software is also capable of modelling ship wakes by specifying leading and following packets. Powering options include constant velocity and constant thrust applied at a location and vector as appropriate for the propulsor simulated.

Modelling of appendages such as skegs, struts, rudders and trim tabs are by standardized formulations. An air drag appendage is also included, and can be very important, especially for matching model test data. (Note though that the air drag appendage does not currently include lift, which can be significant for extremely high-speed craft.) The input also includes instructions to report velocities and accelerations at any desired locations. The user also generally has to input an initial condition, and this can be a source of problems, as it is possible to select an unrealistic condition that does not converge to a stable or realistic condition. Finally, the program includes standard Savistky planing and pre-planing analyses operating from the same database.

The following parameters can be evaluated:

Calm Water	**Seakeeping**
Keel and Chine Offsets	Calm Water Data
CG and Displacement	Calm Force File
Thrust Location and Angle	Wave Spectrum Definition Or Wave Amplitudes and Wave Lengths Or Ship Wake Characteristics
Radius of Gyration	
Thrust Mode (Constant Thrust Or Constant Velocity)	
Speed for setting default	
Buoyancy Coefficients *	
Appendage Characteristics, Location, Centre of Effort	

The result of the analysis is a time history of position (trim and heave), velocity, acceleration at desired locations, and effective horsepower. This is the case for both calm water and wave runs. In the case of calm water, the run is usually started at a speed below those of interest and accelerated to the top speed.

3.1 Hull Form Modelling

The basic theory of Zarnick assumes a simple wedge entering the water. Most modern planing craft have either extended flat chines forming a spray rail for some percentage of the length. Other modern forms, especially those for larger craft such as patrol craft, have double chines with a narrow segment between the two chines at an intermediate angle between the bottom and the side. The analyst has to select a single point to use at each station to model the effective characteristics of the hull form, and this requires some significant thought and perhaps an iterative process of modelling, running and comparison with other methods and data.

For a typical flat chine there are three basic choices, the inner chine, the outer chine, and an average of the two. Since the immersed section changes with draft and trim, two models might be appropriate, one for lower speeds and one for higher speeds to represent appropriate wetted shape of the hull at the intended speed. As a general rule, Ulak [7] found that using the inner chine, thereby modelling the lower portion of the section accurately, was appropriate for accurate pitch and trim above Volume Froude Numbers of about 2.0, whereas modelling the full chine beam produced better powering predictions through the speed range. Double chine or round bilge hull forms also allow a projected chine technique (the intersection of a vertical at the assumed waterline and the continuation of the deadrise near the centreline), and an effective chine technique (the intersection of the hull and the assumed waterline). The chine point can also vary with length. The combined chine technique uses a transition from an outer chine toward the bow. This technique recognizes that the aft sections are generally wetted, especially at low speeds, whereas the forward sections are generally dry.

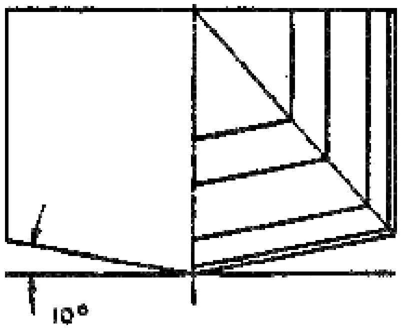

Figure 4. Typical Fridsma Hull

Appendages, especially wedges and flaps that substantially change trim have substantial effects on the results of the analysis. Running the model with and without the appendages is wise to develop a sensitivity analysis of the analysis for these appendages.

4. VALIDATION

4.1 Initial Work

The initial validation of the algorithm and the program was performed on the data of Gerard Fridsma [8, 9]. Fridsma constructed and tested a range of idealized prismatic models (Figure 4) at different speeds and in a range of regular seas as well as calm water at a range of weight and LCG conditions. This study found a significant dependence on the buoyancy coefficients as noted above. Each configuration and wave period/height combination in Fridma's tests was run using the initial coefficients of 0.5 (the "low buoyancy" option") and coefficients intentionally set to accurately reproduce the calm water trim and resistance (the "Fridsma option"). The latter coefficients were typically on the order of 0.7 to 1.0. However the results using the higher buoyancy options generally over predicted the motions. A typical plot of this effect is shown in Figure 5 from Akers [5]. The algorithm was also compared to tests in irregular waves for a limited set of cases, and it was found that pitch and heave response correlated reasonably well. Centre of gravity and bow accelerations were somewhat (30%-34%) under predicted . A method was developed to predict structural loadings on the hull panels, and

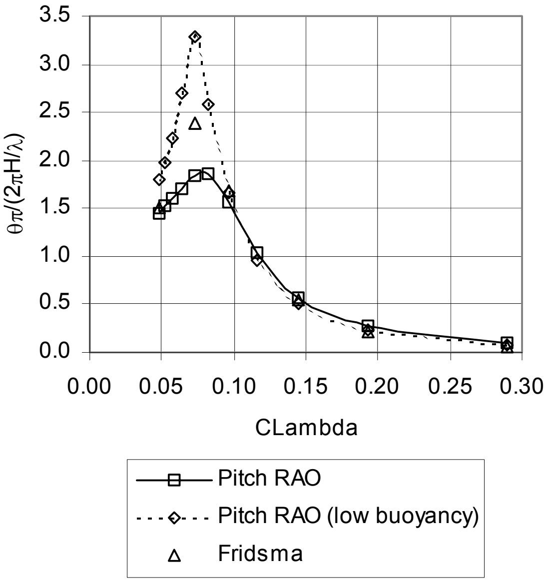

Figure 5. Typical Fridsma Comparison

reasonable values, comparing well to those used by Spencer were determined.

4.2 Wake Impact Studies

Akers, Hoeckley, Peterson and Troesch [10] compared the results of this algorithm to performance of a 25-foot utility boat in calm water and during transition of a wake set up by another boat. This effort was intended to get reliable physical data in a controlled full-scale environment with a reliably reproducible and repeatable wave environment. The time history of the wave generated was measured by videotaping a buoy and the boat was instrumented with accelerometers and a gyro inertial measurement unit.

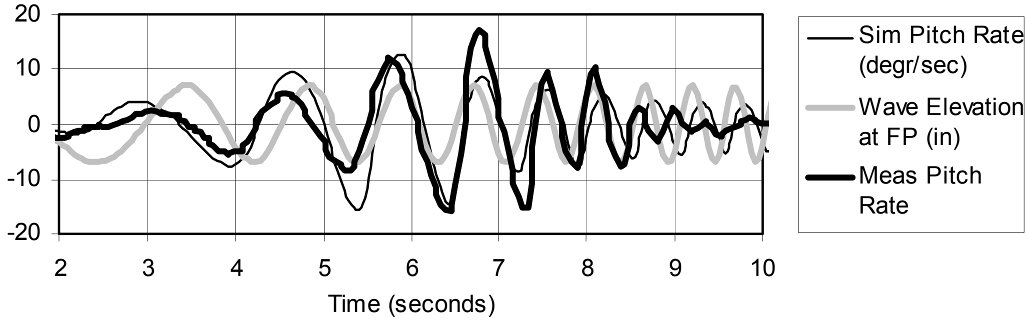

Figure 6. Wake Crossing Comparison

At 22 knots the observed trim of the boat ranged from 2.2 to 4.0 degrees for different runs, and 2.0 to 2.6 degrees at 30 knots. The calm water simulation with the default values of 0.5 resulted in about 6 degrees at 22 knots and 4 degrees at 30. Increasing the buoyancy force and moment coefficients to 0.8 and 1.0 respectively resulted in 4.0 degrees at 22 and 3.5 at 30 knots. These running trim angles are still significantly higher than the observed trim angles, but the Fridsma studies demonstrated that in many cases underestimating the hydrostatic forces gave better dynamic results than by using the exact hydrostatic forces. (Note that overestimating trim in the analysis results is equivalent to requiring a higher angle of attack and a deeper immersion on the hull to maintain equilibrium. Hence the analysis is underestimating vertical forces actually generated for a given kinematic condition of the hull in steady conditions. This may occur because most transient behaviour of a high-speed vessel is the result of hydrodynamic forces, not hydrostatic forces, so more accurate results are obtained if the hydrostatic forces are understated.

The wake set up by the other boat also had to be modelled and since the test boat slowed as it encountered the wake, the exact condition of speed with respect to time as the boat passed through the wake had to be approximated by an analytic function. The speed change was determined from actual measurements and was ramped linearly down from 37 feet per second to 33 feet per second in about ten seconds. The results of a typical experiment at 22 knots are shown in Figure 6.

4.3 Coast Guard Studies

In response to a perceived need to support numerous upcoming procurement initiatives, (which have increased in tempo since 9/11), the U.S. Coast Guard Engineering Logistics Centre, Boat Engineering Branch has been engaged in a series of Survey and Design initiatives to improve the reliability of performance predictions of high speed craft. The branch had previously co-sponsored an initiative relating to Zarnick methods with the U.S. Navy, and based on that and the papers discussed here, tasked Band, Lavis, Associates (BLA) to evaluate a contemporary Zarnick based program. BLA determined that POWERSEA was the only commercially available software for this type of analysis.

4.4 Initial Studies

The report, by Ulak [7], compared a range of boats for which the U.S. Coast Guard had model test data with the predictions of a Zarnick method. The specific vessels were chosen to cover a range of speeds and hull shapes

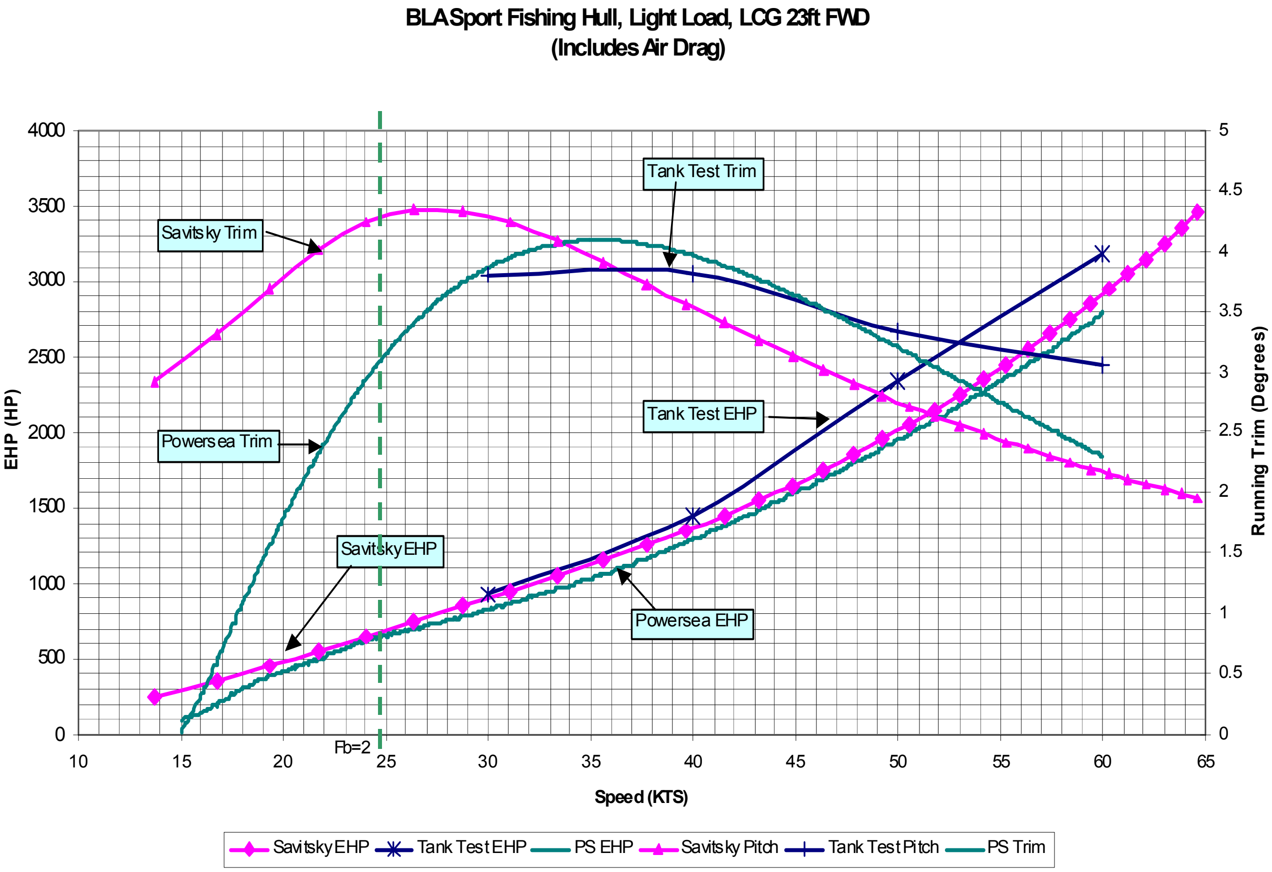

Figure 7. Sport fishing Hull Calm Water Comparison

including types that would not be well represented by the algorithm.

The vessels included in the analysis were:

- 47 MLB, a 47 foot, 28 knot hard chine surf rescue boat with a full length warp to the buttocks, a somewhat rounded stern and a full width wedge at the stern.
- The *Chernesky*, a 46 foot, 26 knot survey boat. This boat has a wide flat chine and a prismatic hull form aft of midships. It initially failed to make speed and was model tested with a prismatic extension and a wedged extension and a variety of loading conditions, so it represented a range of systematic cases, however only calm water data was available for this boat.
- The *Heritage* is a 120 foot, 30 knot patrol boat. It has a double chine.
- The *Island* class patrol boats are 110 feet at 30 knots, and have a "classic semi-displacement" hull form with a deep vee rounded shape forward worked into a nearly flat bottom with hard chines aft. These methods were not expected to model the 110 well, but it was included to confirm the boundaries of the method.
- BLA was also required to select an additional craft for the comparison matrix and chose a high-speed sport fishing boat of their own design. This was a 61 foot, 60 knot single chine boat with considerable rocker and some warp to the bottom running all the way aft.

The *Island* class studies were dropped after some initial work that confirmed that there was no reliable way to model a round bilge boat of this type. Initial studies of the other four designs brought out a number of issues relating to the use of the initial version of the software. The modelling issues discussed previously affected the results significantly. The Heritage analysis resulted in good correlation at speeds between 27 knots and 35 knots based on a combined chine technique, but a projected chine worked better at lower and higher speeds.

The sport fishing hull, since it was closest to the ideal assumed by the algorithm, was probably modelled best overall, however, even these predictions were sensitive to the selection of buoyancy coefficients. Typical comparisons are shown in Figure 7 and Figure 8. Though reasonably good, the calm water prediction is not much better than a standard Savistsky analysis. Extensive simulation of the 47 MLB (which was probably had the most complete set of test data) was also somewhat disappointing.

4.5 Improvements

The basic problem is that the Zarnick technique is strictly two-dimensional. This means that each section has

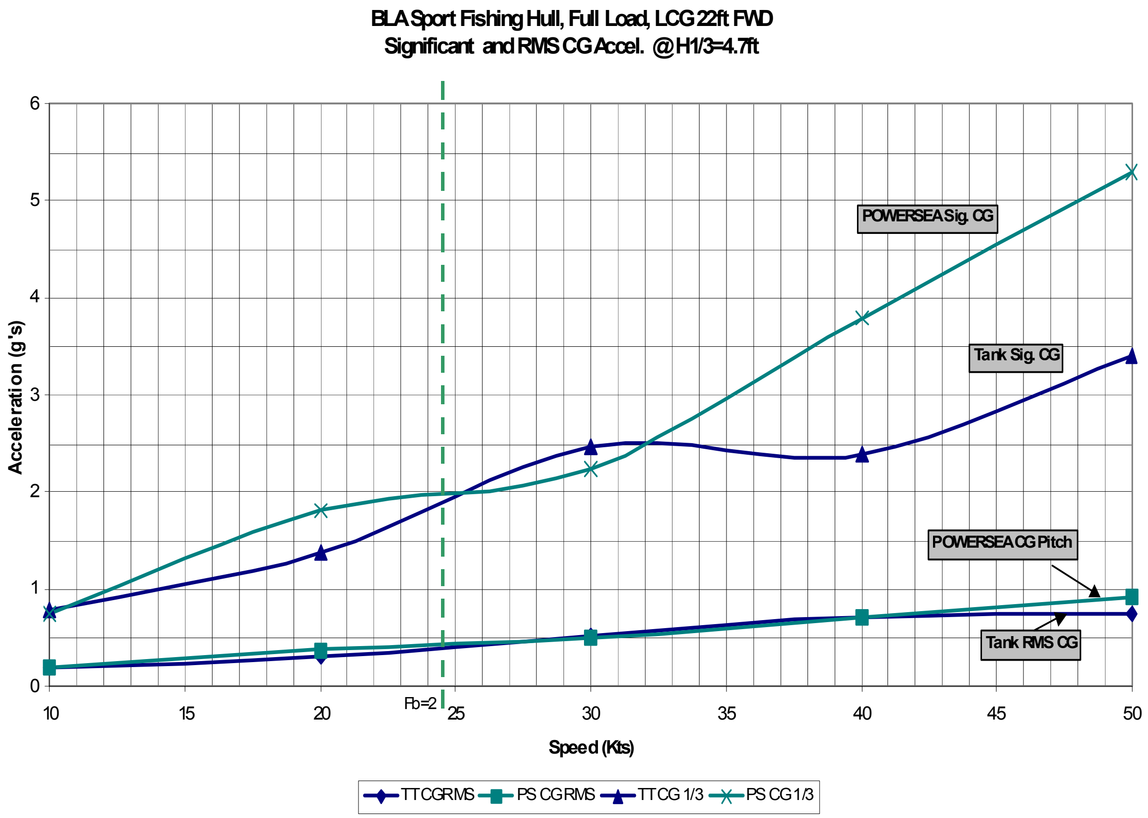

Figure 8. Sport fishing Hull Rough Water Comparison

constant deadrise, i.e. no warp or longitudinal camber. As a result the effective lift produced by the angle of attack of the section due to for and aft curvature is ignored. The method therefore underestimates lift and thus generally requires more trim to achieve equilibrium. In addition, the forces on the sections, are strictly based on added mass in the basic theory because the force is due to the substantial derivative of added mass-like "imaginary" forces. Especially aft, the change of vertical velocity of wedges is zero, hence there are no mass-like forces. The strict interpretation of the algorithm would therefore result in no forces aft, which is clearly incorrect. The standard algorithm thus adds the cross-flow drag coefficient to produce force due to the essentially constant vertical velocity of the wedge as well as the added mass coefficient. However, this is an arbitrary value. As a result of all of these approximations, corrections are required. (In addition to the buoyancy forces and moments.) Though strictly speaking, they are not all buoyancy forces, there is no real point in separating them.

Based on these early results, BLA and Ship Motions Associates worked together to develop an improved version of the software that addressed some minor use issues, but most importantly, had an internal correction coefficient matrix so that the program automatically optimised the "quasi-buoyancy" coefficient based on speed and loading. This later version of the program was used to rerun the 47 MLB data.

Figure 9 shows the results of a typical calm water comparison with the automatically optimised coefficients. Figure 10 shows a comparison of motions in irregular seas. This is clearly an improvement, especially since the point of the program is not so much calm water performance as motions and loads.

4.6 Results

The usefulness of Zarnick's strip theory approach was demonstrated to a limited degree – it works best when the simulation is tuned to match tank test data. In general, with tank test data for verification of simulated results, POWERSEA should outperform the Savitsky planing method for single, hard-chined hulls at speeds corresponding to a beam Froude number of 2.0 or greater.

Each hull examined in the study was unique, so there was no measure of the repeatability and applicability of the hull modelling procedures developed for the multi-chine and round bilge hulls. The recommended approach requires "tuning" the model with calm water resistance data, then using it as a tool for performing critical response and motions/accelerations analysis. "Tuning" involves making changes in the optimised buoyancy coefficients and hull geometry until tank test results are reproduced within an acceptable error margin. This might suggest that the program is of little use, but it is difficult to do motion testing, so the ability to determine

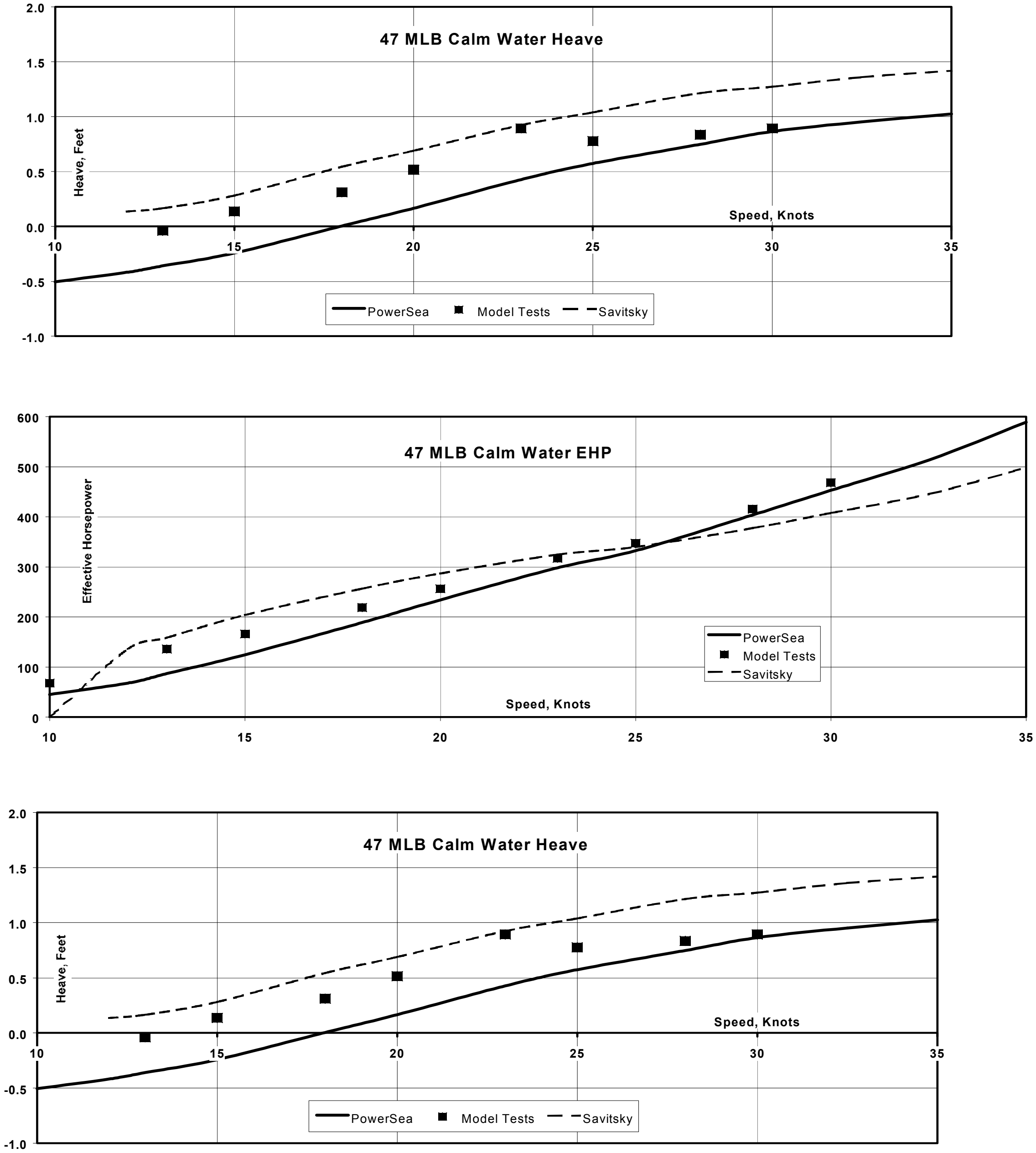

Figure 9. 47 MLB Calm Water Comparison with Optimized Coefficients

good motion responses from calm water information is actually a powerful tool. Even if motion testing is accomplished, the speed of planning boats is such that it is difficult to get a statistically valid record of waves – the run times are too short. Thus running an abbreviated series of tests in waves can allow very good predictions for realistic exposures.

POWERSEA can be used with caution as a design and modification tool, especially for conceptual designs, particularly when calm water trim and EHP data can be developed. Since this data may be available from other sources such as standard series data as well as model tests of the particular design, a wise user could develop useful data at an early stage, provided it is used with caution.

It is also important, though, to remark that though the current algorithm is limited in its usefulness, it is the only methodology currently available for motions of planing hulls in waves.

5. FUTURE EFFORTS

5.1 More Correlation

The most obvious improvement is continued work to develop better and more proven correlation constants. This work is ongoing by the various authors. There are also differences between the forces in calm water and in waves. This is probably because of the differences in three dimensional pressure distribution on the panels themselves and on adjacent panels in waves and calm water. Understanding the detailed physics of this process will improve the correlation.

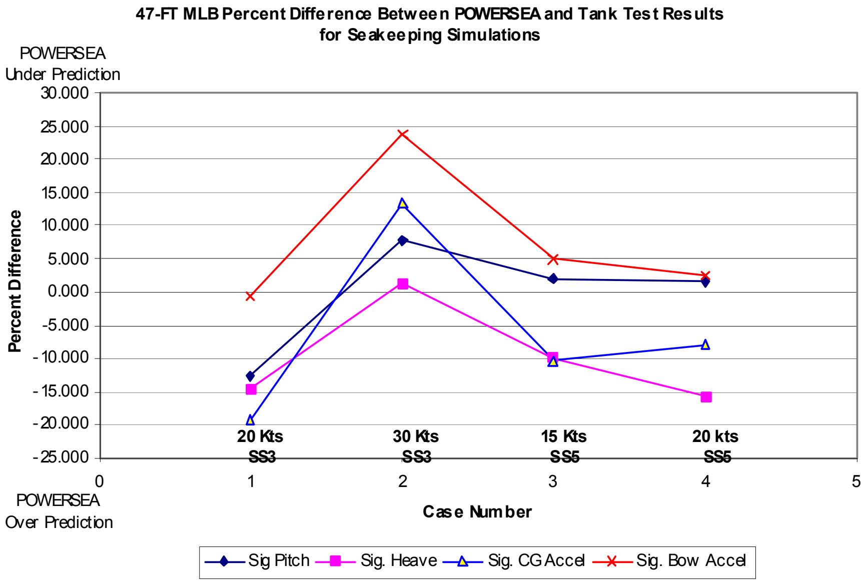

Figure 10. 47 MLB Rough Water Comparison with Optimized Coefficients

5.2 Structural Data

Sectional load calculation tools are not fully implemented in POWERSEA in the current release. While one can save a sectional load data file, this feature is not yet fully implemented for general use. This is a straightforward improvement that can come with time.

5.3 Hydrofoils And Catamarans

Hydrofoils have been used as motion control devices, and to augment lift, thereby decreasing resistance, in a number of different ways. The effect of hydrofoils on lift, drag and motion is available from hydrofoil design sources. The resistance and motion of a planing catamaran in head seas can be simulated by modelling half the craft. However, especially high speed catamarans have relatively close hull spacing, and the hulls may interfere with each other and change their added mass.

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