A New VPP Based on Numerical Modeling

Abstract. The paper describes a new velocity prediction program that uses the lifting-line theory for the calculation of keel- and sail forces, a boundary-layer calculation for the hull, and a new regression for the wave-making resistance.

NOMENCLATURE

V_{boat}	boat speed in the direction of δ
VSECTN	factor describes V-form of the fore section
Hs	significant wave height
x-axis	in center plane, parallel to water plane
y-axis	sideways, parallel to water plane
z-axis	vertical, at right angle to water plane
β_{TW}	true wind angle relative to *x*-axis
δ	leeway angle relative to *x*-axis

1 INTRODUCTION

In the past, I published the program UliTank [1] to calculate the hydrodynamic forces on a sailing yachts hull and the program UliSail [2] for the calculation of the sail forces. The logical next step is the combination of both programs to create a velocity prediction program (VPP), named UliSpeed that determines the equilibrium of forces and moments. The detailed description of the methods to calculate the forces is contained in the two references [1&2]. There are significant differences between the new VPP and classical VPPs, like the one published by the ORC [3]. The viscous resistance of the hull is calculated in the classical VPPs from the simple ITTC correlation line, whereas here an integral boundary-layer method is used. The hull is divided into 40 sections and its potential flow field is determined. The velocity at each section is used to calculate the variation of the skin friction coefficient along the hull. The wave-making resistance comes from a new regression analysis that determines the hull-parameters in the heeled attitude with sinkage and trim. The aerodynamic forces are calculated in the classical VPPs from global lift- and drag-coefficients, that are taken as constant for the entire sail. Here, each sail is divided into 30 strips and the lifting-line method is employed to calculate the variation of the effective angle of attack and of the aerodynamic coefficients along the sail. In this way, the effect of different trim-parameters like sheeting angle, twist and camber become visible. It is no surprise that these additional computations significantly increase the runtime on the computer, but the benefits are more detailed and accurate results and an insight into the flow-field. Such an insight is usually only available from CFD-methods that have longer runtimes, without the possibility to directly optimize the trim-parameters.

2 THE ADDITIONAL COMPUTATIONS

2.1 Equilibrium of Forces and Moments

The calculation of the forces as defined in UliTank and UliSail is not sufficient for the prediction of the boat speed. New additional requirements in the VPP are the equilibrium of the:

- Longitudinal driving force and resistance in x-direction that determine the boat speed
- Side forces created by the keel and the sails in y-direction that determine the leeway
- Vertical forces from sails, keel and buoyancy in z-direction that determine the sinkage
- Heeling- and righting moments around the x-axis that determine the heel angle
- Moments created by sails, keel and buoyancy around the y-axis that determine the pitch angle.
- The moments around the z-axis are ignored, because the helmsman will control the yaw angle.

Therefore, five new variables have to be chosen in such a way that the forces and moments are in equilibrium. From UliSail we carry over the 124 unknown induced velocities. With the new variables, this adds up to 129 variables all together. Like in UliSail, Broyden's algorithm [4] is used to solve for the unknown variables. Good starting values are needed to achieve convergence.

2.2 The Influence of a Rough Hull Surface

Sailing yachts usually do not have a polished hull surface like tank models, but are painted with an antifouling. The roughness of the paint has an impact on the viscous resistance of the hull. In the boundary-layer computation, the friction coefficient for the polished hull is a function of the b.l.-thickness. Mills [5] found an equation that correlates the friction coefficient with the sand grain roughness. For the computation, the hull surface is divided into panels and for each panel the higher value of the two predictions is used. Experimentally determined values of the sand grain roughness for the surface of ships hulls were reported by Schultz [6].

2.3 The Added Resistance in Waves

UliTank was developed as a virtual towing tank, therefore there was no need to include the added resistance in waves. For a VPP this added resistance must be estimated to get realistic speed predictions. The latest Delft-method [7] is used to calculate this resistance. The method requires a wave spectrum as input. A modified JONESWAP-spectrum, as proposed by Lewis & Allos [8] is used. The spectrum is fully defined, if the significant wave height and the peak period are specified. Holthuijsen [9] provides growth curves for these two parameters on deep water that depend only on fetch and wind speed. This fetch-limited situation is applicable if the wind blows for very long time. For short times, it is possible to calculate an equivalent fetch [10]. If this equivalent fetch is less than the geographic value, the sea state is duration-limited and the equivalent fetch must be used in the growth curve.

When the wave spectrum is defined, it is possible to calculate the dissipation rate of the turbulent kinetic energy. This value is needed for the determination of the turbulence level of the flow around the hull [11]. It is an input parameter for the calculation of the boundary-layer.

2.4 Propeller Drag

The ORC-definition of "PIPA" [3] is used to calculate the drag of the propeller.

3 OPTIMIZATION

As in UliSail, it is possible to optimize the four trim parameters, which are the sheeting angle of the boom (*X1*), the twist of the main sail (*X2*), and camber (*X3*) and twist (*X4*) of the jib. The software IFFCO (Implicit Filtering For Constrained Optimization) [12] is again used for this task. The user must supply starting values for the four trim parameters. The search area is limited to a box, defined by the initial starting values *X1, X2, X4* ± 0.2rad and *X3* ± 0.05. This is done to avoid fruitless searches in irrelevant areas. The figure of merit that is optimized, is the boat speed multiplied by a penalty function. The penalty function is copied from UliSail. Its value depends on the smoothness of the induced velocity distribution. This guarantees a solution with realistic induced velocities, without spikes or large gradients in the distribution along the sail. The induced velocities show only at the clew of the headsail a sudden change and at the top of the mainsail, when the mast diameter is almost as large as the sail chord.

The result of the iteration depends on the initial values for the trim parameters at the start. The user will notice that there are multiple local optima, each with a good combination of the trim parameters. The difference in boat speed will often be in the order of 1%. It is therefore necessary to start several runs with different initial starting parameters to find the global optimum.

A good and smooth distribution of the induced velocities is required for the success of Broyden's algorithm. If such a distribution is encountered during optimization, the program will save these values and use them as a starting point for the next iteration. It is therefore possible, that a combination of trim parameters will not produce a converged solution at the start of the program, but later on, after many iterations, when the algorithm has learned a successful distribution of induced velocities, the same trim parameters might lead to a converged and meaningful result.

For larger apparent wind angles, the flow at the jib will be close to separation or even fully separated. The lift coefficient increases with increasing angle of attack until the maximum lift is reached. After that, separation will start and the lift coefficient will decrease. If the algorithm tries to achieve a smooth lift distribution near the maximum, it can happen, that for the same desired lift on one panel the effective angle of attack is below its value at the maximum and on a neighboring panel it is above. In such a case, the distribution of the induced velocities will be either wavy with spikes, or the iteration will not converge. It is therefore necessary, that for the larger apparent wind angles the starting values of the trim parameters are on the right side of the lift curve and close to the desired optimum. A start with larger sheeting angles is recommended.

4 RESULTS

A good test case is the Dehler 33, because one boat of this design was converted into a sailing dynamometer and the test results have been published [13]. In the first step a polar diagram will be created and the result will be compared to the ORC-values. In the next chapter results from UliSpeed will be compared to measurements on the water.

4.1 Polar Diagram

The input variables to the VPP are the complete geometric definitions, the wind speed, and the true wind angle. The output is the boat speed and the leeway for the optimal trim. In a polar diagram, the length of the arrow is a measure of boat speed. The tip of the arrow describes a curve for varying true wind angles. The VMG (velocity made good) is the component in wind direction:

$$VMG = V_{boat} \cdot \cos\left(\beta_{TW} + \delta\right)$$

A series of computer runs with different β_{TW} delivers the points to draw a polar curve like in figure 1. β_{TW} at the maximum VMG is the best course for beating to windward. For the comparison with the ORC-method the certificate of the yacht "Boreas" (AUT 122) was chosen from the ORC database. This Dehler 33-competition has a low displacement and it got its certificate renewed in 2023. UliSpeed was run with the same weights and dimensions as listed in the certificate. The way the ORC draws its polar diagrams is unfortunately not correct. It is necessary to include the leeway, when the direction of the movement of the boat is drawn in the diagram, but the ORC neglects δ in all its speed triangles. I completed therefore the ORC-data with the δ-values from UliSpeed to draw a correct polar diagram.

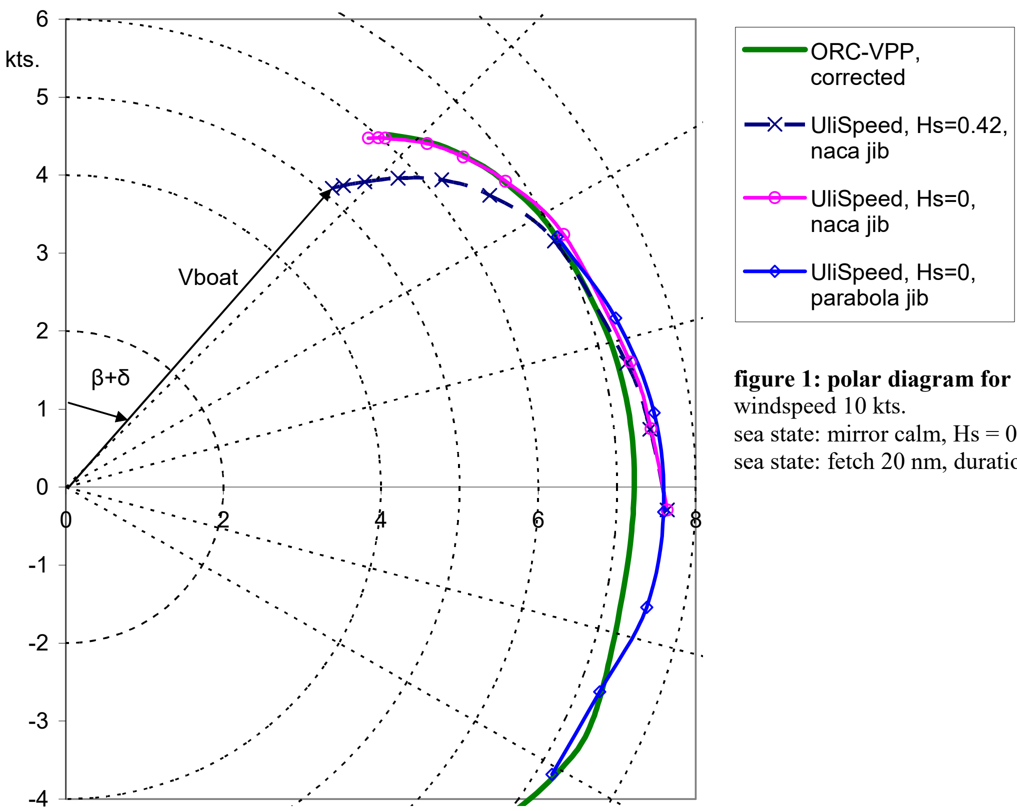

figure 1: polar diagram for Dehler 33
windspeed 10 kts.
sea state: mirror calm, Hs = 0 m
sea state: fetch 20 nm, duration 6 h, Hs = 0.42

The ORC-curve is close to the results from UliSpeed for the case without waves on beating courses. On a reaching course, ORC is too pessimistic. Compared to the speed data initially published by the ORC, the correction through the inclusion of δ reduced the best VMG by 5%.

The results from UliSpeed show, that the added resistance in waves lowers the VMG by 12%, the speed reduction disappears on reaching courses. The best VMG is achieved on mirror calm sea on a course of 38°, whereas at a sea state with waves it is best to steer 43° to the wind.

The best profile for the jib depends on β_{TW}. Below 70° the boat is faster, if the profile follows a NACA-meanline, above, the profile of a parabola, sheeted to the toe rail, is faster.

4.2 Comparison with Measurements

The measurements of full-scale tests with the sailing dynamometer "Dyna" have partly been published [13]. Because of the additional internal frame for the force measurements, the boat was heavier than a normal Dehler 33. The boat speed was very accurately measured with a Laser-Doppler-Velocimeter. Unfortunately, the same standard was not demanded for the measurement of wind speed and direction. An anemometer at the mast top recorded these values. The sails significantly influence the flow field in the vicinity of the boat. Since UliSpeed uses the Biot-Savart-law, it is possible to calculate the difference between the wind speed and direction at the mast top and the true values. Hansen [14] also recognized the need to correct the measured values. He used experiments in the wind tunnel with a model of Dyna to measure the necessary corrections. The corrections, calculated with UliSpeed and the experimental values from Hansen are in good agreement. The wind direction was measured too large by 3.2° to 3.7° and the wind speed was measured too high by 5% to 8%. In addition, Hansen discovered a misalignment of the wind vane by 1.5° between measurements on port- vs. starboard tack. Since the tacking information was not included in the published data, this correction could not be applied.

On two days during the test campaign, an offshore wind blew and the sea was only slightly agitated. A comparison of the measured boat speed and the predictions from UliSpeed is depicted in figure 2. On July 6 the average wind speed was 8.1 kts and the number of crew was three. On July 7 it blew with 12 kts and there were four crew. To avoid zigzag-curves, figure 2 shows the quotient of boat speed divided by wind speed.

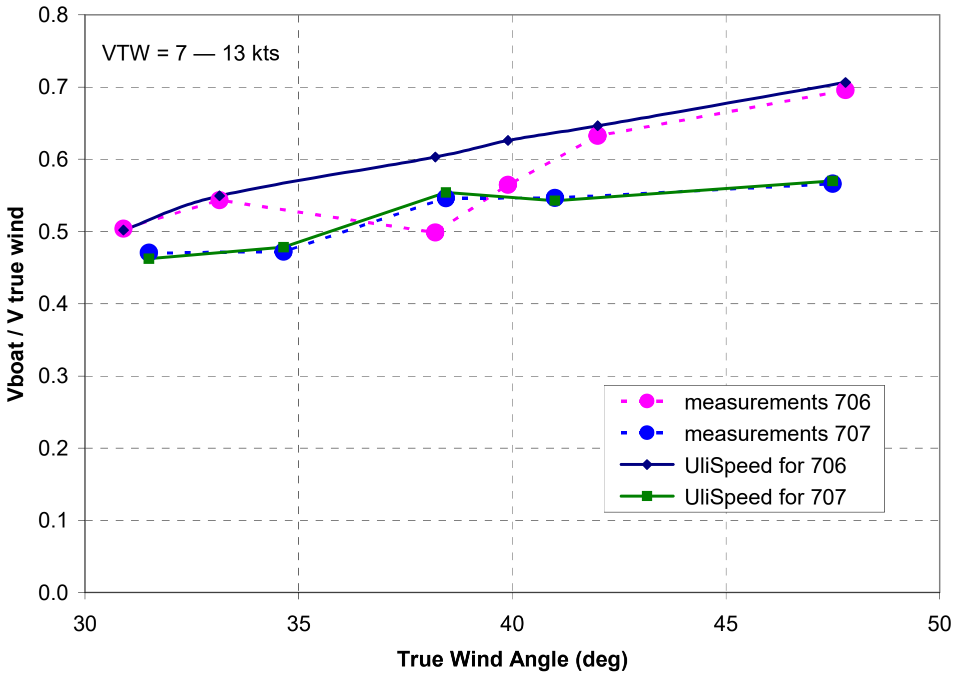

figure 2: measured and calculated boat speed

Each measurement point is the average of 250 instrument recordings during steady sailing conditions. The agreement between tests and predictions is good, except for to points, where the trim of Dyna was most likely not optimal.

5 CONCLUSION

UliSpeed is a reliable VPP that is very sensitive to changes of the geometry of the boat and changes of the environmental parameters. It is possible to determine the optimal sail shape for a condition that takes into account all these parameters. Depending on the starting values for the trim parameters, several optima can be found that do not differ much in the achieved boat speed. This indicates that there is not the one and only best trim, instead different sail cuts and sail trims can lead to similar results.

As final remark it must be kept in mind, that the optimized shape of the sails is the flying shape of the loaded sail. If the sailmaker requires the shape of the unloaded sail, a finite-element program is required that determines the deflection of the sails.

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