Resistance Prediction for Sailing Yachts, Appended with Leeway, Based on a Regression Analysis of Towing Tank Tests

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Abstract. The regression analysis for the appended and heeled hull, but without leeway, was presented in previous papers. This paper extends the analysis to towing tank tests with leeway and side force.

1. INTRODUCTION

This paper is an extension of a previous analysis [1] that includes now the effect of leeway and side force on the resistance of sailing yacht hulls. The database consists of the Delft Systematic Yacht Hull Series [2], the US Sailing Nine Model Series [3], the SYRF Wide-Light Project [4] and the Delft 372 model [5]. For each Froude-number in the medium speed range there are now more than 400 independent test runs in the towing tank available. The regression analysis covers therefore a wide range of hull forms and hull attitudes.

In the DSYHS the appendages carried sand strips as a boundary-layer trip very close to the leading edge. Even at moderate leeway angles the stagnation point moves into this sand strip and the flow separates from the foil. This is a well-known phenomenon from wind-tunnel tests with ice accretion on airfoils. No test runs of the DSHS with leeway could therefore be used. The appended models of the DSYHS sailing upright with zero leeway were used with a correction for resistance of the sand strips. Also the appended models #1-3 of the USSAIL-series had to be excluded from the database, because the scale of the appendages is unknown [6].

2. THE GENERATION OF SIDE FORCES

The hull of a sailing yacht needs to generate a side force to counterbalance the side force component that is generated by the sails. This side force on the hull is proportional to the leeway, i.e. the angle between the direction of travel and the centreline of the hull. The side force is the sum of the forces generated by the keel, the rudder and the canoe body. The generation of side forces will also result in an additional drag. When applying the theory of the airplane to the modern keel, the side force of the keel is equivalent to the lift of the wing.

3.1 Side forces of keel and rudder

The lift and drag characteristics of a hydrofoil section can be calculated with the program XFOIL [7] as a function of the angle of attack and the Reynolds-number The DSYHS uses the profile NACA 63_2A015 for the keel and NACA 0012 for the rudder. USSAIL-models have profiles NACA 64_2A013 for both keel and rudder. The lift and drag of the keel was determined by integration of 8 different sections along the span of the fin. Polynomials of higher order were fitted to the polar curves, so as to enable interpolation of the profile drag for each desired Reynolds-number. The effect of the finite span, which is a function of the aspect ratio, was computed using Küchemann's method [8]. The interference between hull and keel is covered in the next chapter. The forces on the rudder were calculated following the proposals of Whicker & Fehlner [9]. The downwash behind the keel that changes the angle of attack for the rudder was calculated using Hoerner's equations [10].

3.2 Side force generated by the hull

There are two different ways in which the hull can generate a side force. First, the hull alone, without appendages will experience a side force under leeway. The hull can be regarded as a lifting body with a very small aspect ratio. In this case the method of R. T. Jones [10] will give a first approximation of the side force. Depending on the sharpness of the forebody a correction factor should be applied. A second source of side force is the carry over of the pressure field generated by the keel onto the hull. This pressure field on the hull results in an additional side force and is part of the interference between keel and hull. The method of conformal mapping allows calculating the interaction between the keel and the hull. This transformation yields as result the change of the flow over the keel and therefore the change in lift created by the keel and also the induced lift on the hull. The method is described by Johanna Weber in [11].

The big difference between the flow described by airplane theory and the flow around the hull of a yacht is the influence of the free surface of the water plane. The effective aspect ratio of the lifting surfaces depends on the Froude-number, the leeway angle and the draft. The experiments of van den Brug [12] are valid for the vertical flat plate, but the results can be modified and applied to the calculation of the forces on the hull.

3. INFLUENCE OF THE PITCH ANGLE

The pitch angle of the model at speed is composed of the inclination of the water plane and the trim angle. The trim angle is a hydrostatic reaction to the trimming moment, caused by the pulling force on a lever arm. The inclination of the water plane can be calculated by adding the hydrostatic trim angle (positive bow down) to the measured pitch angle under speed (positive bow up). This angle of inclination is a function of Froude-number and hull form. It is possible to perform a regression analysis and develop a prediction formula for this angle. If the yacht is heeled and travels with a pitch angle, the appendages will be inclined to the incoming flow and this angle of attack creates a side force, even for zero leeway. For accurate predictions this side force has to be taken into account and therefore a rough estimate of the pitch angle must be included into the analysis. Let φ be the heel angle, δ the leeway angle and ψ the pitch angle, then the angle of attack for the appendages is:

$$AoA = \delta \cdot \cos\varphi + \psi \cdot \sin\varphi$$

4. REGRESSION ANALYSIS

In the previous papers the quadratic regression was recommended because it gave the smaller standard deviation and the predicted resistance was close to the measured value. The drawback of the quadratic regression is the failure if the investigated hull form or attitude is different from the tested models. Especially if the goal of the design process is the optimization of the hull form, a robust estimation of the resistance is needed that gives plausible results, even if the hull form is outside of the database that was used for the determination of the regression coefficients. The analysis was therefore restricted to the linear regression and the maximum number of parameters in the regression was limited to 11. The total resistance of all models could be predicted within ± 10% and the method is stable with unconventional hull forms. The relative standard deviation for the residuary resistance only is depicted in figure 1.

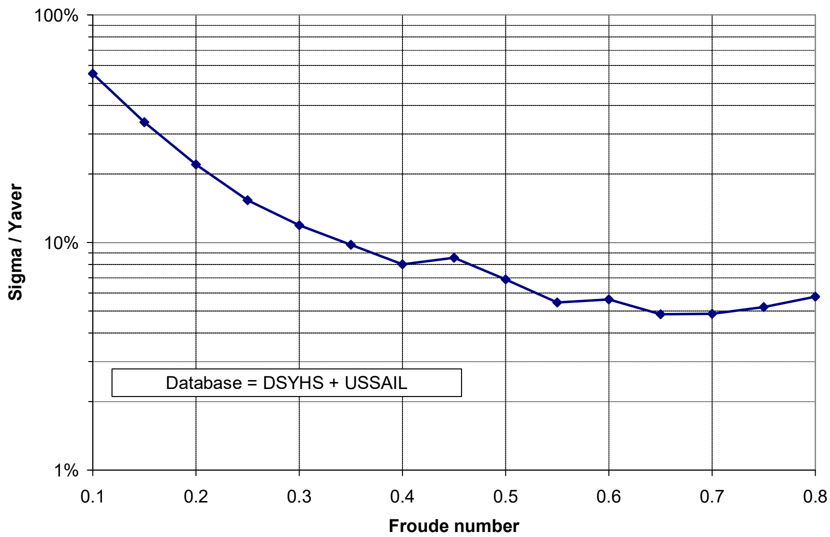

Figure 1. Standard deviation in % of the average residuary resistance for the linear regression

A set of 15 regression coefficients each at intervals of 0.05 between Froude-number = 0.1 and 0.8, altogether 180 coefficients, is used to calculate the residuary resistance of the hull based on 33 parameters that describe the geometry of the hull in the heeled and trimmed attitude.

5. CONCLUSION

With the inclusion of side force and leeway the hydrodynamic resistance of a sailing yacht hull can now be predicted at all attitudes. The prediction-software "UliTank" incorporates the computation of all the described resistance components and is available online [13]. It can be regarded as a virtual towing tank, but can also predict directly the resistance of a full size yacht.

6. REFERENCES

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