Resistance Prediction for Sailing Yacht Hulls Based on Systematic Towing Tank Tests

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Abstract. A regression analysis of the bare hull upright resistance of the DSYHS was presented in a previous paper. This new regression includes also tank test results of heeled and appended hulls of the DSYHS and in addition those of the US Sailing Nine Model Series.

NOMENCLATURE

A_{Stm}	Stem angle, positive forward
A_{W1}	Water plane area, forward of max. section
A_{W2}	Water plane area, aft of max. section
A_X	Area of max. section = maximum immersed area of all cross sections
ATK	Angle of attack, see text
BM	Longitudinal metacentric height
B_X	Beam in the heeled water plane at max. section
c_{keel}	Chord length of keel at root
Fn	Froude number $U_\infty / (g \cdot L_{WL})^{1/2}$
g	gravitational acceleration = 9.81 m/s^2
I_E	Incidence angle at water plane entrance
E_{wp}	Exit angle at stern of elevated waterplane
L_1	Distance from front of L_{WL} to max. section
L_2	Distance from max. section to aft end L_{WL}
Lcb	Distance front of L_{WL} to centre of buoyancy
Lcf	Distance front of L_{WL} to centre of flotation
L_{TO}	Length of transom overhang
L_{WL}	Length of the actual water line at rest with trimming moment applied
L_{WL0}	Length of the designed water line
R_{res}	Residuary resistance force
ROK	Exit angle in the heeled lateral plane
T_X	Draft of heeled canoe body at max. section
t_{keel}	Thickness of keel at root
U	Water speed at edge of boundary layer
U_∞	Ship speed
V_{attn}	Volume attenuated with depth, see [1]
V_{CB}	Displaced volume of canoe body
V_1	Part of V_{CB} forward of max. section
V_2	Part of V_{CB} aft of max. section
x, y, z	Coordinate system, x-direction from stern to bow, z-direction upwards
ρ	Density of the water
σ	Standard deviation

1. INTRODUCTION

A regression analysis of the bare hull upright resistance of the Delft Systematic Yacht Hull Series (DSYHS) was presented in a previous paper [1]. For sailing yachts it is desirable to extend this analysis and include also all tank tests with appended hulls and also those that were performed in a heeled attitude. Since the publication of the first paper [1] additional tank test results became available. In 2015 the Sailing Yacht Research Foundation (SYRF) published results of a tank test program from 2003 that was until then not available in the open literature. The tested fleet is called the US Sailing Nine Model Series [2]. This was a great opportunity to extend the database for the regression analysis.

In the original Delft-method the effect of heel is treated as an additional resistance that is added to the value of the upright resistance [3]. The method that was introduced in [1] allows the determination of the resistance at any given attitude, heeled or upright, without calculating the upright resistance as an intermediate step. With the addition of the heeled and appended models of the DSYHS and also all the USSAIL-models, the total number of interpolated towing tank results at fixed Froude-numbers increased from 1276 to 2718 experimental data points. The data points are spaced at Fn-intervals of 0.05 between Fn = 0.1 and 0.8. In the medium Fn-range each regression at a fixed Fn uses the data of approx. 250 independent test-runs (N) of different hull forms or hull attitudes. The exact numbers for N are given in table 1. No other regression analysis in the open literature is based on such a large number of different tests.

2. CORRECTION OF THE RAW DATA

According to an E-mail exchange with the researchers at Delft, the measured resistance values were only corrected for the parasitic drag of the sand strips. No corrections were applied for the blockage effects in the tank. The results published by the SYRF are raw data, without any correction, except for mechanical crosstalk. The aim of a resistance prediction is the prediction of the drag force in unrestricted waters of infinite depth. Therefore the measured drag values had to be corrected for the blockage effect and the finite depth in the towing tank. At Delft the experiments were conducted in the No.1 towing tank, which has a width of 4.22m and a depth of 2.50m [4]. The towing tank of the IMD at St. John’s is 12m wide and 7m deep [5]. Schuster’s method [6] and Tamura’s model of a Rankine Ovoid [7] were used to correct the measured speed to the equivalent speed at infinite depth. The measured force was corrected according to Tamura [7], which is especially necessary at the high Froude-numbers in the Delft-tank with its limited depth. The corrections amounted up to 10%.

3. VISCOUS RESISTANCE OF THE HULL WITH APPENDAGES

The viscous resistance is computed for the heeled hull in the same way as in the upright case [1]. The planforms and profiles of keel and rudder were taken from the CAD-models that came with the test results. 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 viscous resistance of the appendages was determined by an integration of the profile drag at 8 different sections along the span of the fin. The section drag was computed with the program XFOIL [8] as a function of the Reynolds-number. Polynomials of higher order were fitted to the drag curves, so as to enable interpolation of the profile drag for each desired Reynolds-number. The total viscous resistance of the yacht was assumed to be the sum of the viscous resistance of hull, keel and rudder, plus an interference resistance as described in [9]. The residuary resistance R_{res} is calculated by subtracting the total viscous resistance from the measured resistance.

4. SELECTION OF THE PARAMETERS

The aim of the regression analysis is the determination of appropriate coefficients for the prediction of the residuary resistance of the hull [1]. All textbooks on statistical methods stress the importance of avoiding collinearity, when selecting the dimensionless variables for the regression analysis. Therefore in the initial paper [1] a large portion was devoted to the inspection of the database and to the analysis of the problem of collinearity. The variables that were used were mostly composed of global dimensions, like total length, beam, volume etc. The dimensional analysis gave the smallest number of dimensionless variables that contained all of those global dimensions. The variables were chosen in such a way that collinearity was reduced. When the database was now increased with additional hull forms [2] it soon became evident, that the original small set of variables with only the global dimensions does not suffice to describe the resistance of a wide variety of hull forms. It seems that the resistance does not only depend on global dimensions but is also heavily influenced by local changes in hull properties like e.g. the local curvature of the hull. More than 100 new parameters were tested in the regression analysis with the hope to find variables that improve the accuracy of the predicted hull resistance. Several local angles were defined such as the flare angles at different stations and entrance and exit angles of different waterplanes. The residual mean square [10] was used to identify good parameter combinations. In the end it turned out that variables that are almost collinear are still valuable because the subtle differences between nearly collinear variables of global parameters seem to contain valuable information about local hull properties. The new strategy for finding a helpful regression did therefore not look at a possible collinearity any more, instead the residual mean square and the absolute sum of the coefficients were minimized. Under this strategy a set of 35 dimension-less variables was defined for the canoe body and two additional variables for the keel:

$$BL_1 = \frac{B_X}{L_1} \quad BL_2 = \frac{B_X}{L_2} \quad TL_1 = \frac{T_X}{L_1} \quad TL_2 = \frac{T_X}{L_2} \quad AW_1 = \frac{\sqrt{A_{W1}}}{L_1} \quad AW_2 = \frac{\sqrt{A_{W2}}}{L_2} \quad AX_1 = \frac{\sqrt{A_X}}{L_1} \quad AX_2 = \frac{\sqrt{A_X}}{L_2}$$

$$LV_1 = \frac{L_1}{\sqrt[3]{V_1}} \quad LV_2 = \frac{L_2}{\sqrt[3]{V_2}} \quad VA_1 = \frac{\sqrt[2/3]{V_1}}{A_{W1}} \quad VA_2 = \frac{\sqrt[2/3]{V_2}}{A_{W2}} \quad C_{P1} = \frac{V_1}{A_X \cdot L_1} \quad C_{P2} = \frac{V_2}{A_X \cdot L_2} \quad C_{V1} = \frac{V_1}{A_{W1} \cdot T_X} \quad C_{V2} = \frac{V_2}{A_{W2} \cdot T_X}$$

$$C_{W1} = \frac{A_{W1}}{L_1 \cdot B_X} \quad C_{W2} = \frac{A_{W2}}{L_2 \cdot B_X} \quad C_X = \frac{A_X}{B_X \cdot T_X} \quad U_{04} = \frac{U_{4\%}{}^2}{U_\infty{}^2} \quad U_{25} = \frac{U_{25\%}{}^2}{U_\infty{}^2} \quad U_{\max} = \frac{U_{\max}{}^2}{U_\infty{}^2} \quad I_E \quad ROK \quad A_{ST}$$

$$LCB = \frac{Lcb}{L_{WL}} \quad LCF = \frac{Lcf}{L_{WL}} \quad Fl_B = \left.\frac{\mathrm{d}\,y}{\mathrm{d}\,z}\right|_{Bow} \quad Fl_S = \left.\frac{\mathrm{d}\,y}{\mathrm{d}\,z}\right|_{Stern} \quad Fl_X = \left.\frac{\mathrm{d}\,y}{\mathrm{d}\,z}\right|_{\max.section} \quad BML = \frac{BM}{L_{WL}} \quad BT = \frac{B_X}{T_X} \quad E_{WP}$$

$$OVH = e^{-20 \cdot L_{TO}/L_{WL}} \quad ATK \quad t_K B = \frac{t_{keel}}{B_X} \quad c_K L = \frac{c_{keel}}{L_{WL}}$$

A few remarks are necessary to clarify the definition of some variables. $U_{4\%}$ is the water speed at the edge of the boundary layer 4% of L_{WL} behind the forward end of the L_{WL}, $U_{25\%}$ at 25% of L_{WL}. U_{max} is the maximum water speed along the hull. *ROK* is the angle (rocker) between the lower line of the lateral plane and the water plane at the aft end of the L_{WL}. *Fl* is the flare angle. E_{WP}, the exit angle of a waterplane, is the difference in half beam between max. section and stern at an elevated waterplane $T_X/3$ above the designed water plane, divided by L_2. The reason that all angles are calculated from the half-beam divided by the x-distance is because the waterplanes of the heeled hull are not symmetric to the centerline. L_{TO} (transom overhang) is the distance between the aft end of the L_{WL} and the aft end of the hull. *ATK* is an angle of attack that is different from zero only in the heeled attitude. If the hull heels, the line through the half beam points is not straight but curved. The distance between this curve and the straight line from bow to stern at the position of the max. section is taken and divided by L_1 to yield *ATK*.

The denominator of the dependent variable Y_{CB} for the resistance of the canoe body is defined in three different ways. The different versions will be used for different *Fn*-ranges, as listed at the end of table 1.

$$Y_{CBI} = \frac{R_{res,CB}}{\frac{1}{2}\rho \cdot U_\infty{}^2 \cdot \frac{V_{attn,CB}}{L_{WL}}} \qquad Y_{CBII} = \frac{R_{res,CB}}{\frac{1}{2}\rho \cdot U_\infty{}^2 \cdot (A_{W1} + A_{W2})} \qquad Y_{CBIII} = \frac{R_{res,CB}}{\frac{1}{2}\rho \cdot U_\infty{}^2 \cdot \frac{V_{CB}}{L_{WL}}}$$

The residuary resistance of the keel is made dimensionless according to:

$$Y_{keel} = \frac{R_{res,keel}}{\frac{1}{2}\rho \cdot U_\infty{}^2 \cdot \frac{V_{attn,keel}}{c_{keel}}}$$

The total residuary resistance R_{res} is assumed to be composed of $R_{res,CB} + R_{res,keel}$. At each fixed *Fn* the method of full search was employed for the choice of the best subset out of the 37 variables.

5. RESULTS OF THE REGRESSION ANALYSIS

5.1 Linear regression

For the linear regression a number of 16 variables for the resistance of the canoe body and 2 variables for the keel gave the best results. Using the nomenclature that was introduced in [1] one can write for the *Fn*-range of Y_{CBI} :

$$Y_i(\mathbf{X}_i) = \beta_0 + \sum_{j=1}^{16} \beta_j X_{i,j} + \frac{V_{attn,keel}/c_{keel}}{V_{attn,CB}/L_{WL}} \left(\beta_{17} + \sum_{j=18}^{19} \beta_j X_{i,j} \right) + \varepsilon_i$$

The denominator of *Y* is the same as for Y_{CB}. For Y_{CBII} and Y_{CBIII} the denominator in front of the bracket changes accordingly. Including the two intercepts β_0 and β_{17} there are 20 coefficients that need to be determined. The variables 1 to 16 for the canoe body have to be chosen as a subset out of the 35 available variables, the variables 17 to 19 for the keel are always included for $Fn \geq 0.3$. The first condition for the choice of the best subset is a very small residual sum of squares *RSS*:

$$RSS = \sum_{i=1}^{N} \varepsilon_i{}^2$$

N is the sample size, which is listed in table 1 for each fixed *Fn*. The second condition is a small absolute sum of the coefficients. For this criteria all variables have to be centered and standardized [10], i.e. *X* and *Y* have zero means and standard deviations equal to one. The absolute sum should fulfill:

$$\sum_{j=1}^{19} \left|\beta_j\right| \quad \leq s$$

Looking at the possible subsets that are found in the full search there is always a tradeoff between a low *RSS* and a low sum of $|\beta|$. The number 10 is a good upper threshold *s* in this linear regression with 20 coefficients. In case of standardized variables the coefficients β describe the influence of the variable *X* on the prediction *Y*. If there are large coefficients with alternating signs and the absolute sum of β is too large, the prediction of the resistance will become very sensitive to small changes in the variables and the predicted values might play havoc if the hull form lies slightly outside of the database.

The chosen variables and the coefficients for the standardized variables are listed in table 1. Because all variables are centered, all β_0 are equal to zero. The choice of the variables is of course arbitrary. A different set of variables could give similar results. The physically "right" parameters are disguised in the "noise" created by the measurement errors.

		fore body														*mid ships*				
Fn	N	C_{P1}	BL_1	TL_1	AW_1	LV_1	VA_1	C_{W1}	C_{V1}	AX_1	I_E	U_{04}	U_{25}	Fl_B	A_{Stm}	C_X	Fl_X	BT	U_{max}	ATK
0.10	151				-0.20	-0.14				-0.21		0.52	0.03		0.50		0.07	-0.40		0.15
0.15	180				-3.81	-1.63				2.32		0.45	0.01		0.37		-0.28	1.14		0.29
0.20	215				-2.39	-0.67				1.10		0.34	0.03		0.42		-0.25	0.94		0.27
0.25	245				-1.37	-0.20				0.26		0.28	0.07		0.34		-0.20	0.84		0.23
0.30	250	0.15		-1.31					0.29				0.71	0.14		1.46				0.19
0.35	254	0.24	0.50	-1.04							-0.06		0.24				-0.13		0.76	0.11
0.40	254	0.13		0.76	0.46		0.59		1.19				-0.27						0.71	0.05
0.45	254	0.17	1.54							-1.04			-0.43	-0.40			-0.31	0.37	0.77	0.19
0.50	216		0.94						1.20				-0.32	-0.30				0.73	0.26	0.11
0.55	186		0.48	-0.37					0.93	0.78	-0.06		-0.12	-0.15						0.06
0.60	164		0.49	-0.49					1.16	1.02	-0.06		-0.10	-0.16						0.07
0.65	116		0.20					-0.07	0.71	1.10	-0.20			-0.15					-0.51	0.07
0.70	92		0.27					-0.05	1.12	1.29	-0.20			-0.14					-0.65	0.05
0.75	79		1.22		-1.11			-0.31			-0.23	-0.23	0.14	-0.08				-1.27		0.06
0.80	62		1.32		-1.20			-0.29			-0.21	-0.17	0.24	-0.06				-1.44		0.05

	entire hull			*after body*												*keel*			
Fn	LCF	LCB	BML	C_{P2}	BL_2	TL_2	AW_2	LV_2	VA_2	C_{W2}	C_{V2}	AX_2	ROK	Fl_S	E_{WP}	OVH	β_{17}	t_KB	c_KL	Y_{CB}
0.10	1.01	-0.81		-0.40	0.37				-0.72		0.16		0.80							Y_{CBI}
0.15	-1.09	-0.57		0.46	1.07				-2.08		-0.25		0.12							Y_{CBI}
0.20	-0.30	-0.84		0.22	0.88				-1.39		-0.24		0.67							Y_{CBI}
0.25	0.08	-0.86		0.14	0.62				-0.82		-0.21		0.92							Y_{CBI}
0.30			-0.26	0.78		0.88				-1.42	-0.99		0.72	0.22	-0.16	0.09	-0.35	-0.50	0.97	Y_{CBII}
0.35			0.41				-0.61	-0.76		-0.28	-0.09		0.76		-0.44	0.04	-0.21	-0.25	0.63	Y_{CBII}
0.40	-1.58	1.31							-0.43		-0.45	-0.89	0.18	-0.01		0.00	-0.05	-0.14	0.33	Y_{CBII}
0.45	-0.61	0.43			-1.12			-0.95			-0.39		0.34			0.03	-0.42	-0.43	1.13	Y_{CBIII}
0.50	-2.02	1.34			-0.32	0.45				0.50	-0.59		0.18	-0.70		0.04	-0.11	-0.03	0.31	Y_{CBIII}
0.55	-1.22	0.92		0.07		0.55		0.35			-0.39		0.29			0.08	-0.11	0.04	0.22	Y_{CBIII}
0.60	-1.43	1.12		0.11		0.63		0.48			-0.47		0.18			0.07	-0.13	0.00	0.29	Y_{CBIII}
0.65	-0.94	0.78						0.55			-0.32	0.93	0.22	0.19		0.07	0.03	0.15		Y_{CBIII}
0.70	-1.24	1.23						0.71			-0.50	0.97	0.22	0.14		0.08	0.13	0.09		Y_{CBIII}
0.75	-0.82		0.47	0.27					-0.38			1.17		1.10		0.11	0.32	-0.05		Y_{CBIII}
0.80	-0.73		0.50	0.23					-0.35			1.00		1.24		0.07	0.35	-0.08		Y_{CBIII}

Table 1. Coefficients of the selected variables in the linear full search

The relative error for the prediction of the resistance R_{res} is depicted in figure 1. The standard deviation σ is divided by $\bar{Y}$, the average of Y_i for i = 1 to N. The denominator under the root sign represents the degrees of freedom of the error vector. At low Froude-numbers the residuary resistance $\bar{Y}$ is very small, therefore the relative error increases as Fn decreases.

$$\frac{\sigma}{\bar{Y}} = \frac{\sqrt{\dfrac{RSS}{N-20}}}{\bar{Y}}$$

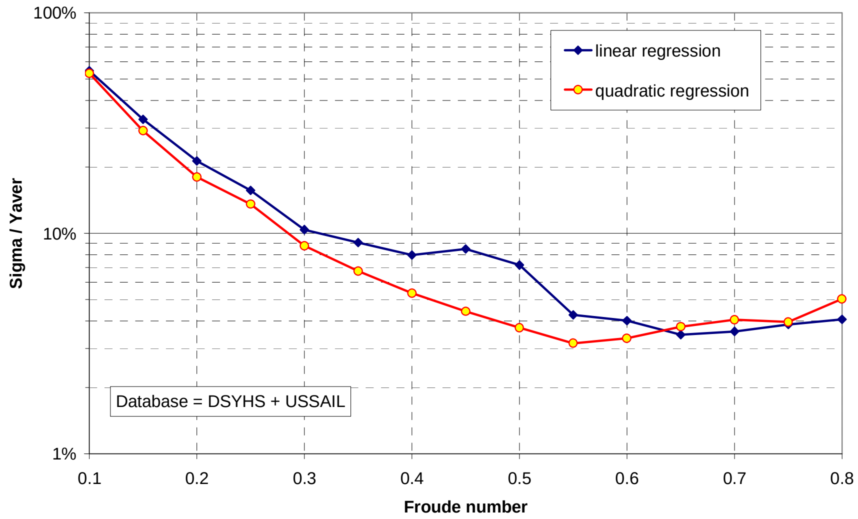

Figure 1. Relative standard deviation for the prediction of R_{res}

For some readers it might be surprising that the selection of variables differs significantly from that one of the upright case as described in [1]. This can be explained by the collinearity of the variables. The inclusion of the heeled and appended test runs requires additional variables and increases the measurement noise. In such a case the variable selection by full search is driven to a certain degree by random errors.

5.2 Quadratic regression

For the quadratic regression 8 variables for the resistance of the canoe body and 2 variables for the keel gave the best results. Using the nomenclature that was introduced in [1] one can write for the *Fn*-range of Y_{CBI} :

$$Y_i(\mathbf{X}_i) = \beta_0 + \sum_{j=1}^{44} \beta_j X_{i,j} + \frac{V_{attn,keel} / c_{keel}}{V_{attn,CB} / L_{WL}} \left(\beta_{45} + \sum_{j=46}^{47} \beta_j X_{i,j} \right) + \varepsilon_i$$

The 44 $\beta_j X_{ij}$ for the canoe body are made up from 8 linear, 8 quadratic and 28 mixed terms. Together with the two intercepts and the two keel variables a sum of 48 coefficients have to be determined in the full search. Again the choice is guided by a low *RSS* and a low sum of $|\beta|$. The absolute sum of the coefficients varied from 5 to 15. The chosen variables are listed in table 2, Y_{CB} differs from the linear case. The relative error for the prediction of the resistance R_{res} is depicted in figure 1. From this figure it is obvious that the quadratic regression is only beneficial in the medium *Fn*-range. At low and high Froude-numbers the residuary resistance can be described sufficiently by linear functions.

		fore body														*mid ships*				
Fn	*N*	C_{P1}	BL_1	TL_1	AW_1	LV_1	VA_1	C_{W1}	C_{V1}	AX_1	I_E	U_{04}	U_{25}	Fl_B	A_{Stm}	C_X	Fl_X	*BT*	U_{max}	*ATK*
0.10	151	X			X							X			X		X	X		X
0.15	180	X	X											X	X			X		X
0.20	215	X												X	X	X		X		X
0.25	245	X												X	X	X		X		X
0.30	250												X							X
0.35	254	X				X			X									X		X
0.40	254							X			X								X	X
0.45	254		X					X			X		X						X	X
0.50	216									X	X		X					X		X
0.55	186																			X
0.60	164																			X
0.65	116			X							X									X
0.70	92			X				X												X
0.75	79				X			X	X		X									X
0.80	62				X				X		X									X

	entire hull			*after body*													*keel*			
Fn	LCF	LCB	BML	C_{P2}	BL_2	TL_2	AW_2	LV_2	VA_2	C_{W2}	C_{V2}	AX_2	ROK	Fl_S	E_{WP}	OVH	β_{45}	$t_K B$	$c_K L$	Y_{CB}
0.10				X																Y_{CBI}
0.15						X				X										Y_{CBI}
0.20		X							X											Y_{CBI}
0.25		X							X											Y_{CBI}
0.30		X				X						X	X		X	X	X	X	X	Y_{CBII}
0.35				X		X										X	X	X	X	Y_{CBI}
0.40		X					X				X					X	X	X	X	Y_{CBI}
0.45									X							X	X	X	X	Y_{CBIII}
0.50			X										X			X	X	X	X	Y_{CBIII}
0.55																X	X	X	X	Y_{CBIII}
0.60																X	X	X	X	Y_{CBIII}
0.65		X					X									X	X	X	X	Y_{CBIII}
0.70		X			X						X					X	X	X	X	Y_{CBIII}
0.75				X		X										X	X	X	X	Y_{CBIII}
0.80				X				X								X	X	X	X	Y_{CBIII}

Table 2. Selected variables in the quadratic full search

Above Fn = 0.6 the number of hull-variables was reduced from 8 to 7 because the smaller sample size N would cause an overprediction with the initial 48 variables.

6. PREDICTED VS. EXPERIMENTAL RESISTANCE

Figure 2 compares the predicted and experimental values of the total resistance for the new linear regression and for the Delft-method. The linear regression is used, because it is even applicable if the hull form of interest does not match exactly the hull forms of the database. The quadratic regression would give much better results for the database, but here we examine the less favorable case. The Delft-method uses 24 regression coefficients, including the effects of trim and heel. Y_{tot} in the diagrams is defined in the following equation. R_{tot} is either the measured total resistance or the sum of viscous and residual resistance.

$$Y_{tot} = \frac{R_{tot}}{\frac{1}{2}\rho \cdot U_\infty{}^2 \cdot \frac{V_{CB}}{L_{WL0}}}$$

In the ideal case all points would be lying on the diagonal line. A high value of the kurtosis is a clear sign that the distribution is peaked and not normal (Gaussian). The red dashed lines in figure 2 indicate the 2·σ bands. In case of a normal distribution of the errors, the ± 2·σ band would contain 95% of all test points. Because of the high kurtosis the distribution is not normal. With a sample size of 3518 it is possible to determine the quantiles empirically by counting. The results (94%) are in both cases almost identical to the values of the normal distribution. The statistic evaluation shows that in the new formula the standard deviation and also the error band are reduced by a factor of 2.2 compared to the Delft-method.

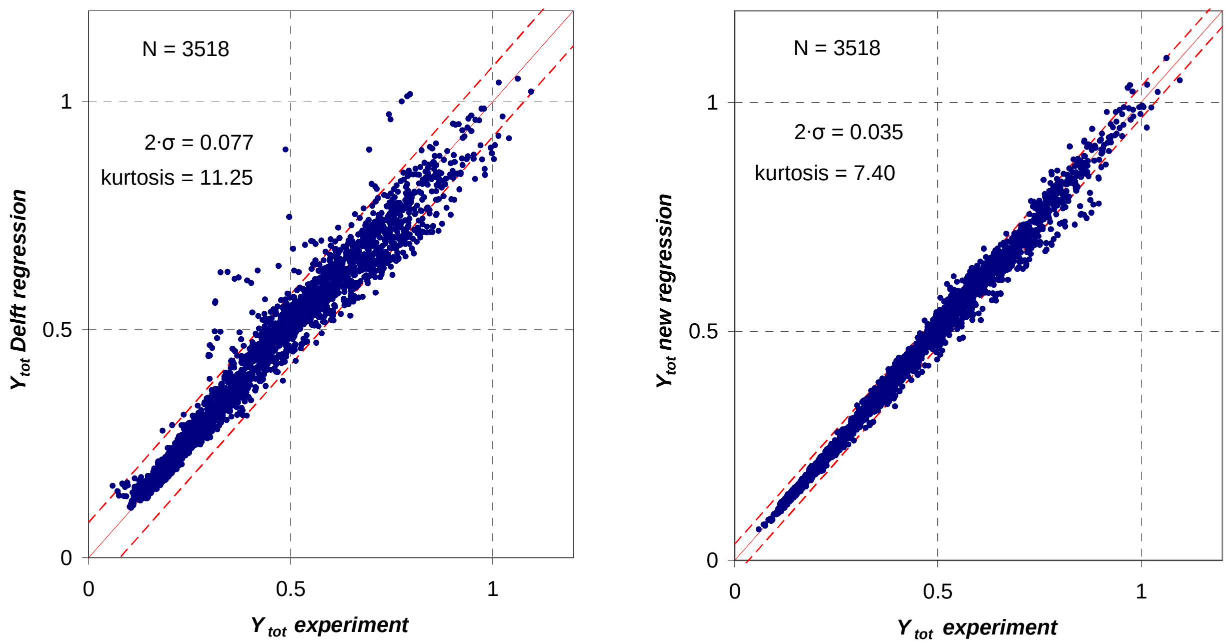

Figure 2. Total resistance coefficients for all experiments 0.1 < *Fn* < 0.8

The relative error of the predicted total resistance is depicted in figure 3. The prediction error is calculated from

$$Y_{error} = Y_{tot}\,predicted - Y_{tot}\,measured.$$

The ± 2·σ band is reduced with the new method from ± 20.4% to ± 7.2%. The relative error is obviously larger at the low end for small *Fn*. This trend is more pronounced in the Delft regression than in the new one. The reduction of the errors is significant. It must be pointed out, that these errors are only valid for models that are not too different from the tested models. For models far outside of this database the error will be larger because of the selection bias in the regression analysis. On the contrary, for the models that are part of the database the quadratic regression can be used. In this case the 2·σ band is only 5.5%.

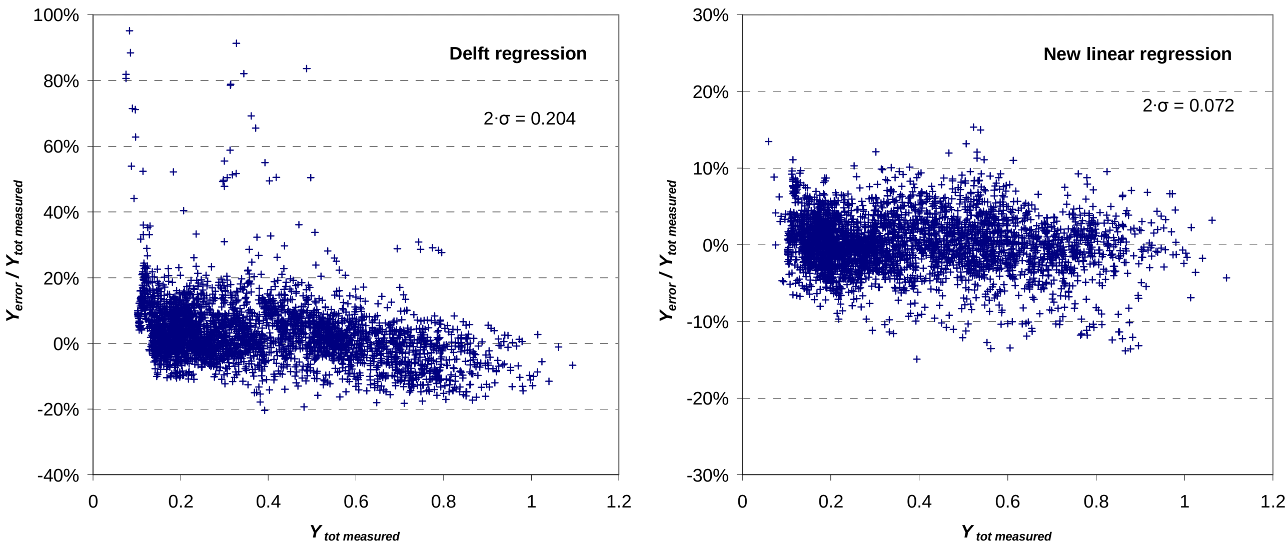

Figure 3. Total relative resistance error for all experiments 0.1 < *Fn* < 0.8

The kurtosis of the final selection is still high and the distribution is not normal. It is therefore interesting to have a look at the statistical distribution of the prediction errors for the new regression. The deviation from the normal distribution with a peak at the mean and missing values at medium distance to the mean is clearly visible in figure 4. Another way to look at this picture is the assumption of a normal distribution caused by the measurement errors and on top a superposition of a random error caused by an unknown parameter. Figure 5 depicts this hypothesis by assuming a smaller standard deviation for the normal distribution.

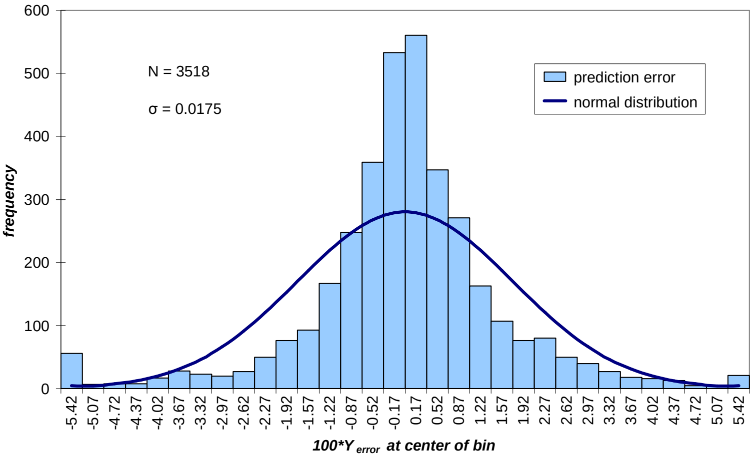

Figure 4. Distribution of the prediction error and comparison with normal distribution of equal standard deviation

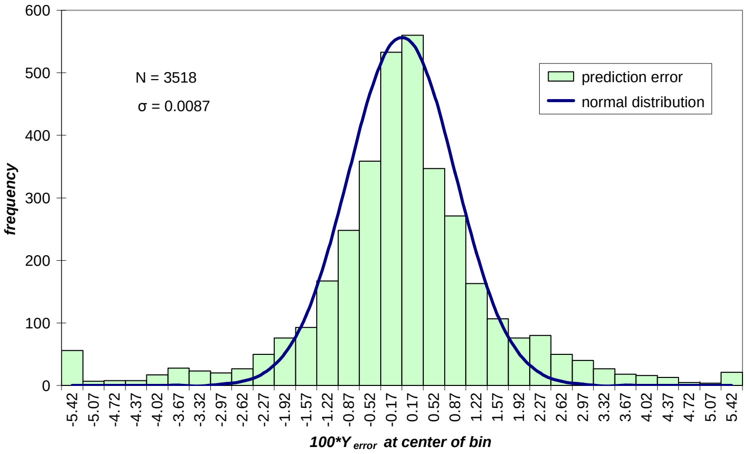

Figure 5. Distribution of the prediction error and comparison with a normal distribution of reduced standard deviation

The unknown parameters that cause additional randomly distributed small and large errors are to a minor extent the quadratic terms that are left out in the linear model, but in addition it might be a hull parameter that was not yet considered or it could also be the influence of the towing tank set up. The roughness strips are changed between the test runs, this could have an influence. Normally the measured resistance is time dependent and an averaging process is employed, which is unknown. Without a detailed knowledge of the experimental process and ideally the inspection of the raw data, a further analysis is not possible and the current error must be accepted.

7. CONCLUSION

The new regression model improves the prediction of the resistance of the hull of a sailing yacht compared to the Delft-method. Future comparisons will tell, if the improvements will consistently appear also with different and new designs. To enable this necessary feed-back, the new prediction-software "UliTank" was developed and is available online [11].

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