Systematic Series of the IACC yacht ”Il Moro di Venezia”: Heel and Yaw analysis

D. Peri, INSEAN - Italian Ship Model Basin, Roma, Italy
F. Di Ciò, INSEAN - Italian Ship Model Basin, Roma, Italy
and M. Roccaldo, INSEAN - Italian Ship Model Basin, Roma, Italy

Abstract

”Il Moro di Venezia” was the challenger for the XXVIII edition of the America’s Cup in San Diego, 1992, and it has become the first non-English European challenger in the history of the cup. Due to the change in class rules at that time, a great effort was spent in the research of the more favorable design in terms of displacement and sail area: to this aim, a large experimental campaign has been produced. The end of the confidentiality agreement for the experimental data produced in that time allows now a deep analysis into the different designs still available at INSEAN. The large size of the models (with scale ratio of 1:3) makes this data set nearly unique in the field.

A first approach to this analysis has been produced in [1]: here the results for the unappended tests have been presented. This first data analysis has been revised in [3], and the fully appended configurations, still in upright condition, have been included. Two different strategies for the development of a correlation for the data have been also presented.

In this paper, the heeled and yawed experiments will be analyzed. A revision of the standard methodologies for the consideration of the heel and yaw angles will be performed. Than, a statistical analysis of the influencing quantities will be applied, identifying a suitable set of design parameters, and their effect on the performances of a sailing yacht.

Notation

\( S_C \) max. transverse section area
\( A_W \) water-plane area
\( B_{WL} \) waterline beam
\( C_B \) block coefficient
\( C_M \) max. transverse section coefficient
\( C_P \) prismatic coefficient
\( C_P^{\text{fore}} \) prismatic coefficient of hull forward of max. section
\( C_P^{\text{aft}} \) prismatic coefficient of hull aft of max. section
\( C_R \) residuary resistance coefficient: \( C_R = R_R/(0.5\rho v^2 S_C) \)
\( C_T \) total resistance coefficient: \( C_T = R_T/(0.5\rho v^2 S_C) \)
\( C_T^\nabla \) total resistance volumetric coefficient: \( C_T^\nabla = R_T/(0.5\rho v^2 S_C) \)
\( C_W \) water-plane coefficient
\( F_n \) Froude number, \( F_n = v/\sqrt{gL_{WL}} \)
\( L_A \) overall hull length
\( LCB \) longitudinal center of buoyancy, as fraction of \( L_{WL} \) measured from the forward extremity of \( L_{WL} \)
\( LCF \) longitudinal center of floatation, as fraction of \( L_{WL} \) measured from the forward extremity of \( L_{WL} \)
\( L_{WL} \) waterline length
\( R_n \) Reynolds number
\( R_F \) frictional resistance
\( R_R \) residuary resistance
\( R_T \) total resistance
\( S_C \) wetted surface of canoe body
\( T_C \) draft of canoe body
\( k \) form factor
\( \iota_E \) half angle of entrance at the waterline
\( v \) hull velocity
\( \lambda \) scale factor
\( \rho \) water density
\( \nabla \) volume of displacement of canoe body
\( \Delta_C \) weight of displacement of canoe body
\begin{align*}
I_{xx} & \text{ Inertia moment of the ship around the } x \text{ axis} \\
I_{yy} & \text{ Inertia moment of the ship around the } y \text{ axis} \\
I_{zz} & \text{ Inertia moment of the ship around the } z \text{ axis}
\end{align*}

1 Introduction

The systematic series produced for the design and development of "Il Moro di Venezia" is really interesting for a number of features. First of all, it was one of the most expensive and extensive campaigns ever attempted in history of the America's Cup. In fact, 5 different yachts were built for this challenge, partly based on the analysis of 20 different models, with some parametric studies on the appendages also. The syndicate was the winner of the 1988 Maxi World Championship in San Francisco. Furthermore, the third yacht, "Il Moro di Venezia III" took the first place in the first ever International America's Cup Class world championship in San Diego, 1991, while the first boat, "Il Moro di Venezia I", was third. The first yacht was build since the beginning of the experimental campaign, started in 1990. This situation gave to the designers the great opportunity to have both full scale and towing tank data (scale ratio 1:3) for at least 5 different boats. A second reason for the uniqueness of this series is the large size of the models, all built using composite materials in order to reduce deformations and improve the stability of the shape in time. Moreover, for the first ten models, longitudinal wave cuts were produced, but these data are still unanalyzed, while some seakeeping experiments were carried out, on smaller models, but these tests were rapidly cancelled.

This large amount of data was not sufficient to win the cup: in fact, the design team explored a limited portion of the whole design space, producing a yacht with a large beam: they were probably excessively worried by the lack of lateral stability of the yacht. The evidence of the tightness of the investigated portion of the design space will be clarified in the following. Anyway, this dataset is still able to produce interesting considerations about the cross-correlation of global hull parameters and the residuary resistance of the hull. Although the number of models is not large as in a true systematic series, like the DSYS [10], some numerical experiments are able to give the perspectives of the application of statistical indicators for the identification of a good regression line for the available experimental data.

2 Available data and layout

As already recalled in [3], the experimental campaign for the "Il Moro di Venezia" challenge consisted in the experimental test of 20 different yacht models with a really large number of appendages \(^1\). At the end of the tests, only 15 models, 3 bulbs (with keel) and 1 rudder have been donated to INSEAN. The geometry of the available hulls and appendages has been obtained by using the same electro-mechanical system used for the measurement of IMS hulls [1], and a successive dedicated software has been developed for the deduction of an IGES file for each hull [3]. This operation was mandatory because the lack of the original drawings: in fact, due to the peculiarities of the adopted materials, the models have been provided by the commitment so that the lines of the models are not included in the exchanging papers between INSEAN and the design team.

Furthermore, all the papers representing the communication between INSEAN and the design team has been retrieved and carefully analyzed, gaining some more information about a number of details related to the towing tests, like the test matrix, the real displacement of the model, the correct name and type of appendages, but also about some aspects more related to the full scale yacht, like the center of effort of the adopted sailplan and the expected correlation laws for the side force estimation. In fact, for all the heeled and yawed tests, some additional forces, simulating the effects of the sailplan, have been applied to the models: these values were known, because they are clearly indicated together with the towing tank results, but no information about the origin of these data were given.

Summarizing, now for all the 14 models INSEAN was able to digitalize, a precise indication about all the test conditions is available, and the complete dataset has been rebuilt, partly from the digital copies of the datafiles, partly from the paper copy of the reports.

Using the digital geometry of the hulls, all the geometrical parameters of the hulls have been recomputed, for the upright condition and for a number of heeling angles. This operation has been repeated again because the commercial tool adopted in [1] was not completely trusted by the authors; moreover, it is preferable to produce the data in upright and heeled condition by using the same tool.

3 Experimental setup

A complete overview of the testing procedures adopted in this experimental campaign has been depicted in [3]. Here we are going to recall only a limited number of details.

There are at least two different ways for testing a sailing yacht model in the towing tank: they are called in literature free-sailing model and captive model tests. In the first way, the model is towed by the center effort of the sails. The model must to reproduce the same inertia moments of the real yacht: as a consequence, the model is more expensive to realize, because the large weight of the keel bulb require an adequate strength for the hull and the keel. A model is provided with a portion of the mast, from which the model

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\(^1\) 11 bulbs, 3 keels and 3 rudders were tested in the basin, but probably a larger number of appendages were tested in the wind tunnel only.
As a consequence, the model sails in the same condition of speed, heeling angle, drift angle and trim angle as the real yacht under the simulating conditions. The advantage underlined in [7] is the reduced number of tests to be performed for the performances predictions. On the other hand, once some variation in the sail plan are applied, the tests are no more useful because the new equilibrium condition has been not tested. Once more, in the towing tank the appendages are not working at the same Reynolds number as the real ship, and a correction for the yaw moment and side force is needed.

In a second testing strategy, the model is constrained in the most of their degrees of freedom. Heel angle and lee-way angle are fixed, as for the surge and sway motion. The model is rigidly connected to the towing carriage, allowing only for trim and sinkage. The forces and moments along the constrained degrees of freedom, as well as the trim and sinkage are measured. A cockpit is fitting the model and the dynamometers are generally located inside the test rig. The experimental setup is really compact, but the gauging and tune-up is really complex, also because the mutual interferences of the different components of the measured forces and moment are difficult to suppress. External loads are usually applied to reduce the stress on the test rig, but the deformation of the cockpit cannot be completely avoided, and its influence on the measured actions is unknown. The results of the tests must be finally evaluated by a VPP to predict all parameters in equilibrium condition.

Here the captive model tests have been performed, with one more degree of freedom: here the heel angle is free. The model is connected to the carriage by two vertical beams, well aligned on the model. Longitudinal and transverse actions are here measured. The required heel angle is obtained by moving a sliding ballast, who is also responsible for the sail force simulation. Inclinometers are measuring the effective heeling angle, and the position of the ballast is acquired. Since we have one more degree of freedom, the forces acting on the test rig are smaller, but the heel angle has to be obtained by adjusting the position on the ballast during the run, increasing the difficulties for a correct experimentation.

## 4 Experimental data analysis

Also in this case, we refer to [1] and [3] for a detailed description of the general methodology. Here we are only describing the logic of the temperature data correction, needed because the different reasons in which the tests have been performed. By the way, this methodology is replicating the main assumptions enforced in the general case of the hull resistance prediction.

For displacing ship, a consolidated methodology is available, founded on the hypothesis that is possible to express the total resistance as the sum of two different function, one depending from the Froude number only, one form the Reynolds number only.

\[
R_T(Re, Fr) = R_R(Fr) + R_F(Re)
\]

The first is the so-called residuary resistance, while the second one is the frictional resistance. Temperature is affecting both the water density and the water viscosity. As a consequence, the Reynolds number is also changing with the temperature. The usual procedure asks to compute the residuary and frictional resistance coefficients, using the water qualities at the testing temperature. Frictional resistance coefficients can be provided by the ITTC’57 relationship

\[
C_f = \frac{0.075}{(\log_{10}(Re) - 2)^2}
\]

Then, the frictional resistance coefficient is also computed by using the Reynolds number for the reference temperature (usually 15 Celsius), it is substituted to the corresponding value, and the new water density is applied in order to compute the dimensional value of the total resistance.

Here, the yacht is a compound of different objects, with a different reference length each. As a consequence, we can define a non-dimensional quantity for each part of the yacht. Usually some semi-empirical expressions are applied for the determination of the resistance of the appendages: in this case, the viscous resistance of the isolated appendages have been estimated by producing a number of numerical simulations on the real shapes of the appendages. For the keel and the rudder, an open source 2D code has been utilized [16]: this is a well assessed code, freely available, and can be used in order to reproduce the same procedure. The position of the transition point has been aligned with the adopted turbulence stimulators. Computations have been conducted for different values of the Reynolds number and the angle of attack, according to the test conditions.

The correction factor for the consideration of the 3D effects is provided by [1]

\[
C_L = \frac{C_L}{1 + \frac{C_I}{\pi AR}} \quad C_I = \frac{C^2_L}{\pi AR}
\]

where \(C_L\) is the lift coefficient, \(AR\) is the aspect ratio, defined as the ratio between the planview surface and the span, and \(C_I\) is the induced drag, to be added to the computed viscous resistance. According to [7], the aspect ratio of the appendage has been doubled, because of the mirror effect of the canoe body on the appendages. The reference length of the canoe body is here assumed to be the waterline length. This choice is motivated by the fact that since the waterline length is clearly influencing the wave pattern of the yacht, it is correct to compute the Froude number on the basis of this length. As a consequence, since it is preferable to have a single reference length, we have not considered different options suggested in the literature, like the use of a fraction of the full waterline (sometime 70%).

For the bulb, a set of fully 3D RANS simulations [4] have been provided. Also in this case, computations have been
performed for a number of Reynolds numbers and yaw angles.

A polynomial expression has been derived for each appendage, in order to reproduce easily the resistance coefficients in the different testing conditions: in fact, bulbs of different length have been used during the tests so that for the same model speed we can have different Reynolds number for two different appendages. For the canoe body, the ITTC’57 regression line has been applied. The appendages are supposed to contribute to the frictional resistance only: we can derive the following expression for the frictional resistance of the full yacht $C_f$:

$$C_f = C_f^c \frac{S^c}{S_y} + C_f^k \frac{S^k}{S_y} + C_f^b \frac{S^b}{S_y} + C_f^r \frac{S^r}{S_y}$$

where $S^u$ is the full yacht surface, $S^c$ is the canoe body surface, $S^k$ is the keel surface, $S^b$ is the bulb surface and $S^r$ is the rudder surface; the frictional resistance coefficients of the different parts of the yacht are indicated using the same style for notation. For the canoe body, the surface in upright condition has been selected as reference surface.

### 5 Methodology for resistance splitting

Once all the tests have been translated up to the same temperature, we are ready for the full data analysis. Our ultimate purpose is the determination of a regression line for the residuary resistance coefficient of a sailing yacht obtained basing uniquely on geometric data. This operation is in accordance with other applications, like [7]. In the translation of experimental data from a temperature to another we have observed the splitting of the total resistance of the yacht into a number of different components. Here we are now going to define a more complete splitting of all the terms following a possibly logic approach. The linear superimpositions approach is obviously the most easy and intuitive method to model by means of a simple linear correlation. If we are interested in the correlation among the parameters. In a word, we stay a step behind the utilization of regression techniques like multiple linear or non linear regression, trying first to understand and rank the influence of the parameters.

The authors believe that the utilization of a regression equation as a fine-tuned resistance predictor of a broad range family of hulls is intrinsically prone to tricky exploitations and distortions, as put in evidence by the last generations of IMS yachts. Following this guideline, in [1] a statistical analysis has been presented, identifying not only the weight, but mainly the existence of a correlation between some geometrical parameters and the resistance of a yacht, also avoiding the consideration of parameters that are correlated each other. Here our attention was focused not on the prediction properties of the resulting equation, but on the properties of correlation among the parameters. In a word, we stay a step behind the utilization of regression techniques like multiple linear or non linear regression, trying first to understand and rank the influence of the parameters.

Here the general idea of the correlation analysis is recalled, and it is applied on the different quantities we need to model by means of a simple linear correlation. If we are

### 6 Statistical analysis of a systematic series

In [1] we already recalled a number of examples of studies regarding regression analysis for resistance, power prediction, hydrostatic analysis [14, 8, 13, 6, 9]. Among them, Fairlie-Clarke [5] with his paper posed a sound basis on the regression technique applied to the naval architecture domain, presenting both the theoretical background and some examples of its application.

We have some simple analytical approximation for 1, 3, 4 and 5. As a consequence, we are going to produce a number of regressions for the terms 2, 6 and 7. To do that, we have to identify a number of geometrical parameters that are influencing the quantity we are going to model.
interested in reproducing a functional by means of a simple analytical structure, a large number of indicators able to trace if a linear correlation between a dependent and independent variables exists: a list of the much common indicators is reported in [2]. We have to remember how these criteria are defined for a single variable at a time and under some assumptions regarding the data distribution. Anyway, they are able to trace a linear correlation only, but if we apply a transformation of the variables, under certain hypothesis, the same criteria are useful to trace nonlinear correlations. In order to identify a correlation, we are going to apply the Pearson’s $r$, the $t$-Student test, the $z$-Fisher transformation, the Spearman’s test, and the Kendall’s test, whose description has been provided extensively in [1]. The importance of the application of a correlation test is double: first of all, by performing a correlation analysis on the design variables we are able to identify all the variable showing a mutual correlation. Some design parameters are correlated by definition, and it is quite simple to identify these situations also without the application of the suggested indicators. But a couple of design parameters may show correlations in the analyzing dataset, simply because this situation occur for the actual hull family, i.e. due to the construction strategy. The use of a couple of correlated variables in building a regression is a situation to be avoided: it means that we are not using an orthogonal base in describing our data, so that we are wasting a parameter. A second advantage comes from the fact that in this way we are identifying an orthogonal base whose components are the more correlated ones with the dataset.

7 Application of the statistical indicators to a systematic series

As previously recalled, the definition of a systematic series is usually performed without a completely clear knowledge about the relationship between hull performances and hull shape. Moreover, in order to derive a universal correlation, able to define the performance of a new unit basing on some simple geometrical parameters, a regression equation for the produced dataset is searched. As a consequence, the set of independent variables adopted in the regression equation could be different than the ones adopted for the design of the models of the series, and the distribution of the independent variables over the design space could result not uniform. This is not the ideal situation for the definition of a good regression equation: when we are trying to mimic the behavior of a function whose determination is complicated or expensive, the uniform spacing of the data on the design space is crucial for the outcoming approximated model. Ideally, the correlated independent variables are known a priori, and the hulls of the series are designed in a perfect, uniformly spaced way in this space. In example, the actual series was designed mainly thinking about a set of 1:1 comparisons between hull characteristics like the bow shape, the overhang angle, displacement, and other features not clearly addressed to a single global parameter. Using this strategy, the variation of the parameter is obtained by producing a couple of hulls, while all the others maintain the same value for this parameter. Consequently, if we trace a couple of parameters, they are not covering the design space, but they are concentrated in a single region, with a couple of exceptions: this is not a good situation if we want to produce a regression. A practical example is reported in figure 1. Here is clear how all the data are concentrated around a very small region, with only two exceptions.

In order to make a correct choice of the parameters for the regression line, a statistical tool has been developed in order to identify the existence of a correlation between dependent and independent variables. The knowledge of the independent variables really affecting the data could be helpful in designing new hulls to be added to the original series, improving the uniformity of the hull distribution, that will result in a more reliable regression equation.

All the previously described statistical indicators have been applied, and a correlation is identified if all the statistical indicators agrees. Each available independent variable has been tested against the dependent variable, and only the correlated independent variables will all contribute to the final regression equation.

7.1 Dataset selection and main characteristics

Using the available hull lines, the classical $C_B$, $C_D$ etc. to other interesting ratios, i.e. $L_{WL}/V^*_{C}$ or $S_{BP}/V^*_{C}$, for a total of 34 possible independent variables have been computed by using a dedicated analysis software. The results of the correlation tests, adopting all the statistical indicators described above, are reported in table 1. We recall that, when the absolute value of the ratio between the statistical indicator and its limit value is greater than one, a correlation between the

![Figure 1: The available dataset represented in terms of $L_{WL}/B_{WL}$ over $T_C$. A clearly uneven spaced dataset is shown.](image)
variables is found. Moreover, if it is positive, the correlation is linear with a positive slope, while if it is negative, the correlation is linear with negative slope. The independent variables in the table are sorted by the value of the sum of the modulus of $\tau$, in descending order from top to bottom, left to right. As a consequence, on top of the table the most correlated coefficients are reported. To this variables, we have to add all the variables for which a correlation with the others is not found. For these variables, the correlation is zero, and are not reported in table 1: they will be added in the following table.

By using table 1, we can identify the family of the uncorrelated variables, that are the most efficient to apply for a regression line, because we are not duplicating any design variable. Furthermore, since some of the global parameters in the top of the list are correlated with other global parameters in the table, this list will be further reduced. The result is the final table 2: here the most correlated variables are deleting less correlated ones, in order not to have mutually correlated variables in deriving a regression line. To these variables, the completely uncorrelated variables are added. For the last ones, lack of correlation can be also determined by a large sparsity of the variable: the significance with respect to the modelling quantity will tell if the variable is useful or not.

### 7.2 Modelling the wetted surface variation with heel angle

Once the set of mutually uncorrelated parameters has been identified, we need to select, among them, the most correlated parameters with respect to a specific quantity we need to model. As a first step, we have to derive a regression line for the variation of wetted surface with respect to the heeling angle. To do this, we have to apply the same correlation indicators to the dataset with respect to the uncorrelated parameters from table 2. The wetted surface has been computed for all the available models for three different heeling angles: 0, 20 and 30 degrees. Than, the difference between the upright condition and the heeled condition has been computed, producing the difference, that is the quantity to be modelled.

Using these data, the correlation between the global hull parameters and the wetted surface variation has been computed, and only two design parameters have been found to show a correlation, that is, the ratio $\frac{A_W}{\sqrt{C}}$ and $A_W$. Adopting this choice, the following regression equation comes up

$$\Delta S = a_0 + a_1 \frac{A_W}{\sqrt{C}} + a_2 A_W \quad (1)$$

Coefficients for the regression line derived by using equation 1 is reported in table 3, while the behavior of the surface variation at the angle of 30 degrees with respect to the parameter $\frac{A_W}{\sqrt{C}}$ is presented in figure 2.

We can see from the picture 2 how there is not a complete linear correlation between the dependent and independent variable, but we can argue clearly an alignment of the data, with a global tendency to reduce while the independent variable is increasing.

In table 3, we have reported the coefficients of the regression line. The mean difference between the predicted and the real value of the wetted surface is less than 1%. This value is largely lower than the one coming from the regression line suggested in [9]: this is partly due to the fact that this regression line is obtained using the same models for which we are testing the accuracy. Anyway, it could be interesting to produce the same study on a larger dataset as in [9].

### 7.3 Modelling the residuary resistance of the canoe body under heel and yaw

As previously recalled, a numerical estimation of the viscous resistance addressable to the appendages has been performed by using two different numerical tools, one for each specific problem. Using these information, the measured
Table 2: Significance value of the various coefficients. Only uncorrelated parameters are here presented. The sum of all the positive correlation indicator (SOC) is presented in the first column, while the mean value (MC) is reported in the second column. Sum of correlations is connected with the number of correlated parameters, mean correlation gives a measure of the strength of the correlations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>SOC</th>
<th>MC</th>
<th>Variable</th>
<th>SOC</th>
<th>MC</th>
<th>Variable</th>
<th>SOC</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{NC}{\sqrt{C_L^{2/3}}}$</td>
<td>13.50</td>
<td>1.35</td>
<td>$\frac{A_{aw}}{\sqrt{C_L^{2/3}}}$</td>
<td>12.36</td>
<td>1.32</td>
<td>$A_{W}$</td>
<td>6.76</td>
<td>1.35</td>
</tr>
<tr>
<td>LCF</td>
<td>1.75</td>
<td>1.75</td>
<td>$C_M$</td>
<td>0.00</td>
<td>0.00</td>
<td>$L_{WL}$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$I_{xx}$</td>
<td>0.00</td>
<td>0.00</td>
<td>$I_{yy}$</td>
<td>0.00</td>
<td>0.00</td>
<td>$A_0$</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$C_{Fore}$</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
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</tr>
</tbody>
</table>

values of the total resistance of the model under different conditions can be depurated by the contribution of appendages to total resistance obtaining

$$C_{LR}^T = C_{total}^T - C_{Keel}^T - C_{bulb}^T - C_{rudder}^T - C_{F}$$

Theoretically, if a simple linear superimposition of the effects would be applicable, the value of the residuary resistance coefficient $C_{LR}^T$ computed by using the here described approach will be the same as the one coming from the unappended tests ($C_R^T$). But this hypothesis is obviously far from reality. In fact, the flow in which the appendages are immersed is not uniform, and it is influenced by the canoe body and the other appendages. Moreover, the sinkage and trim of the model are changing with the presence of the appendages. As a consequence, in order to obtain the final value of the fully appended hull, we need to model also what is here called the *interference effect*, that is, the difference between $C_{LR}^T$ and $C_R^T$ in upright condition. Furthermore, if we want to obtain the value of total resistance under heel and yaw, we have also to produce a regression line for the difference between the values of $C_{LR}^T$ in the required condition and in the upright condition. If the hull is heeled, the previous regression line for the wetted surface variation can be further applied.

Summarizing, the elements we need for the computation of the total resistance under heel and yaw are:

1. A regression line for the unappended hull.
2. The total resistance of the appendages.
3. A regression line for the variation of the wetted surface under heel.
4. A regression line for the interference terms.

Point 1 has been depicted in [1]. Point 2 can be obtained by CFD tools, or by other approximations described in [7]. Point 3 has been provided previously. We are here going to produce point 4 of this list. It will be split into two different parts: upright interference and heeled/yawed interference.

In order to derive the new regression line, we have firstly to identify the most influencing parameters, as previously described. Also in this case, the statistical analysis of correlation has been produced. The available dataset has been divided by the leeway angle and speed: since three different leeway angles are available from the towing tank data, say 0, 2 and 4 degrees, as well as three different values of the speeds (8, 9 and 10 knots), nine different regressions have been attempted. The same methodology already applied for the identification of the most correlated parameters for the wetted surface variation has been adopted. Unfortunately, the small number of available experimental data becomes here crucial, and the correlation between the data and the variables appears here very poor. For each dataset, sometime only three parameters show a correlation, and this number is here demonstrated to be not sufficient for the determination of an useful regression line, since the obtained accuracy is rarely less than 10%. Following the indications of the correlation indicators, but lowering the limit for accepting a correlation up to 0.2, we have a maximum of 5 correlated variables. Also in this case, the quality of the correlation is reported in figure 3. Here values of the experimental data of the interference factor, no matter about the drift and heel.
angle, is reported against the interpolated value. If the interpolation was perfect, the interpolated value is the same as the experimental one: as a consequence, all the points lay on a straight line at 45 degrees in this graph. In figure 3 we can see a clear misalignment of the data: all the points are in between the two other lines reported in the graph. The aperture of these two lines is around ± 0.5 against a variation of the experimental data in between -1 and +3: this indicates an average error of about 12.5%.

In figure 4, the effect of the heeling angle on the residuary resistance for all the available models is reported. Here we have plotted the variation of the residuary resistance of each model with respect of the upright condition for the two available heeling angle. We can see how not all the models have been tested in all the heel and leeway conditions: model M4 dataset is really poor. Furthermore, we can observe how we have both an increase and a decrease of the residuary resistance for the most of the models, while for some of them the variation of the residuary resistance is substantially positive or negative. We are particularly interested in the behavior of two models, M9 and M10, since they show opposite geometrical qualities. M10 is the most extreme for the midsection shape, presenting a squared section: the model is the largest and less deep in the family. On the contrary, M9 has the smaller beam and the larger draught. From the analysis of

1. the number of available experimental data is not sufficient for the correct determination of the correlated variables: this phenomenon is probably depending from a large number of variables, higher than the number of available models.

2. The observed phenomenon is too complex to be described by a simple ensemble of global hull parameters.

Some further considerations can be drawn from the simple observation of the experimental data regarding the increase or decrease of the bare hull resistance in heeled and yawed conditions.

In figure 5, the effect of the heeling angle on the residuary resistance for all the available models is reported. Here we have plotted the variation of the residuary resistance of each model with respect of the upright condition for the two available heeling angle. We can see how not all the models have been tested in all the heel and leeway conditions: model M4 dataset is really poor. Furthermore, we can observe how we have both an increase and a decrease of the residuary resistance for the most of the models, while for some of them the variation of the residuary resistance is substantially positive or negative. We are particularly interested in the behavior of two models, M9 and M10, since they show opposite geometrical qualities. M10 is the most extreme for the midsection shape, presenting a squared section: the model is the largest and less deep in the family. On the contrary, M9 has the smaller beam and the larger draught. From the analysis of
figure 5, the effect of the squared section looks positive for the heeled conditions, since we have a reduction of the residuary resistance. On the contrary, yachts like M9 are good in upright, but they suffer a deterioration in the performances under heel. Obviously, we have to check, case by case, if the increase of the resistance is such that also the total resistance becomes higher.

Figure 5: Experimental data of the variation in bare hull residuary resistance at 20 degrees of heel with respect to the upright condition reported against the variation in bare hull residuary resistance at 30 degrees of heel with respect to the upright condition. The data are reported in different graphs, each representing a single hull model.

We can split the dataset by the speed, and also in this case some important features are evident. We are here observing only model M2, since for this model we have the larger amount of data: we cannot identify a precise tendency for the experimental data. The full dataset of model M2, split by speed, is reported in figure 6. Here we can observe how the tendencies become clear: in the low speed range, the effect of the heeling angle is positive, reducing the upright bare hull residuary resistance. On the contrary, at higher speeds this tendency is reversed, and the bare hull residuary resistance is increased under heel.

Figure 6: Experimental data of the variation in bare hull residuary resistance at 20 degrees of heel with respect to the upright condition reported against the variation in bare hull residuary resistance at 30 degrees of heel with respect to the upright condition. The data are reported in different graphs, each representing a single speed value for the model M2 only.

8 Conclusions

A study regarding the heeled and yawed resistance of 14 models belonging to the “Il Moro di Venezia” systematic series has been presented.

The application of statistical tools for the determination of the most correlated parameters has been already demonstrated to be of great utility, helping the researchers in discovering the really influencing parameters for the available dataset.

This experimental database is presently used for validation of numerical tools, with the aim of using these codes alone or included in optimization methods [11, 12] applied to sailing yacht problems.

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References


Table 3: Regression coefficients for the equation of the wetted surface variation with respect to the heeling angle (1).

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