The “US Sailing Nine Model Series”

Abstract. The towing tank test results of the US Nine Model Series are a valuable database for the validation of computer simulations and CFD. The information supplied by the SYRF is not complete. This report tries to gather the missing data.

1. INTRODUCTION

In 2015 the Sailing Yacht Research Foundation published on its website results of towing tank tests, that were conducted at the NRC Institute for Marine Dynamics together with US Sailing between 1997 and 2003 [1]. These measurements were performed with large models and a rigid dynamometer, enabling a high degree of accuracy. The data is therefore highly valuable for the validation of computer simulations or CFD-analysis. The data provided on the SYRF website is comprehensive, but to make full usage of the data some more information is needed. This report gathers available information from other resources and estimates missing data.

2. MODEL DESIGN

IGES-files of the bare hulls are supplied for all nine models. In addition a Rhino 3D-model of the appended hull #5 can be found on the website. All hulls are drawn to full size. A 2D-drawing of #5, here depicted in Figure 1, is also displayed on the website. The designed waterline (DWL) is identical to the plane $z = 0$. The origin of the coordinate system ($x = 0$) lies at the forward end of the DWL (= forward perpendicular *FP*), positive direction towards the stern. The position and size of keel and rudder are given for model #5. One can assume, that the distance of the root of the leading edge of the keel to the *FP* is constant across all models (*xRLE* = 5400mm). The position of the rudder is not so clear. In model #5 the trailing edge of the root of the rudder coincides with the aft end of the DWL and also with station 10 at x = 12000mm. On all other models station 10 (which is always at x = 12000mm) is not at the aft end of the DWL. The position of the trailing edge of the rudder can be chosen at the aft end of the DWL or at station 10. The true position is unknown, but the easier choice seems to be the position at station 10. The scale of all tank-models is 1:2, the *DWL* is therefore roughly 6 meters for all models. For the three heavy displacement models #1,2,3 there is a remark on the datasheets “Appended with 2.3 Scale Appendages”, which would indicate, that keel and rudder are smaller by a factor of 1.15 compared to #5. The ambiguity is increased by a file called “m3a.apm” that is contained in the folder “model3”. This file displays

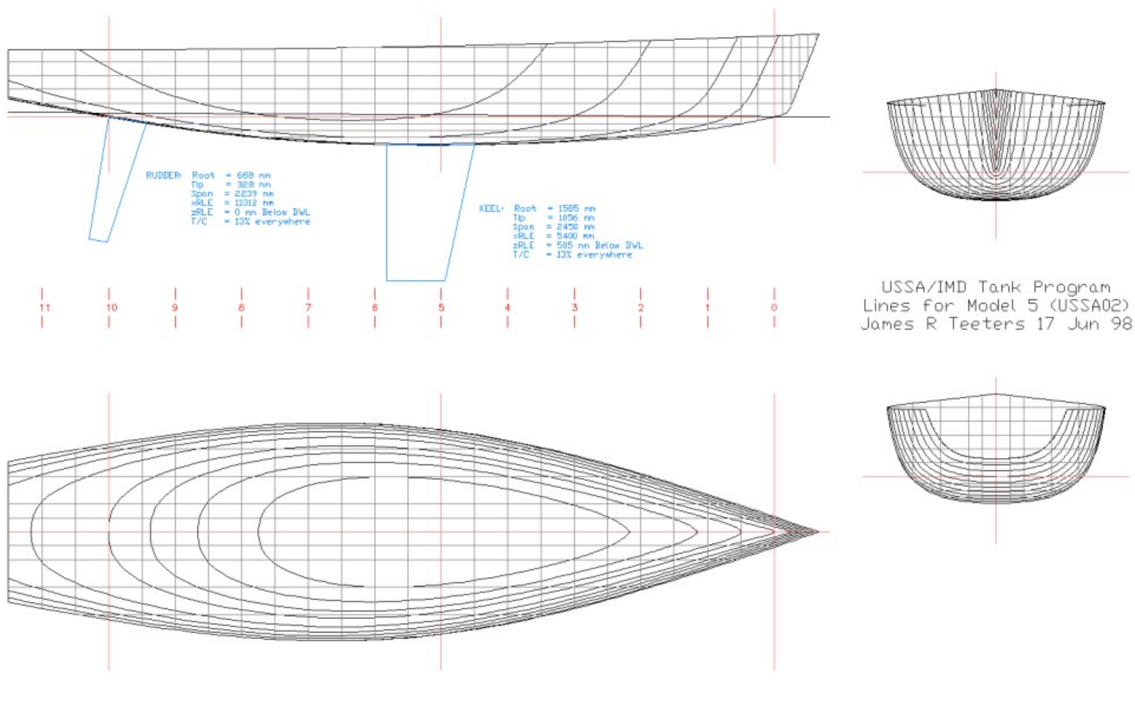

Figure 1. Drawing of hull #5, as published

different dimensions for the rudder. The following dimensions at model scale in *mm* incorporate the different scales and the different rudder:

	keel span	keel root	keel tip	rudder span	rudder root	rudder tip
# 1,2,3	1065	689	459	979	347	183.5
# 4-9	1225	793	528	1119	344	164

The sweep angle of the quarter chord line is 9.2° for the keel and 15.8° for the rudder. Thickness is 13% of the chord. When these values were analyzed with the program UliTank [4] the models #4-9 gave accurate results for the side-force, whereas the measured side-force for the models #1-3 was about 20% higher than the results of the simulation. UliTank is a virtual towing tank that uses the proven theory of hydrofoils for the prediction of the side-force. The results are accurate within a few percent. It is therefore questionable, if the remark in the raw-data sheets "Appended with 2.3 Scale Appendages" is correct. Since it is not possible to clarify this discrepancy 20 years after the tests were performed, only the results for the bare hulls of the models #1-3 are used.

3. THE TRIMMED WATERLINE AT REST

In figure 1 the red line marks the DWL at $z = 0$, but in addition there is another waterline visible, that is inclined to the DWL by *0.33 deg*. The grid of waterlines and sections is parallel to the axes of the coordinate system. The additional waterline seems to indicate an initial trim that describes the attitude of the hull at rest prior to moving the trim weights. In the excel-sheets with the test results there are two columns that are marked *TM(Nm)* and

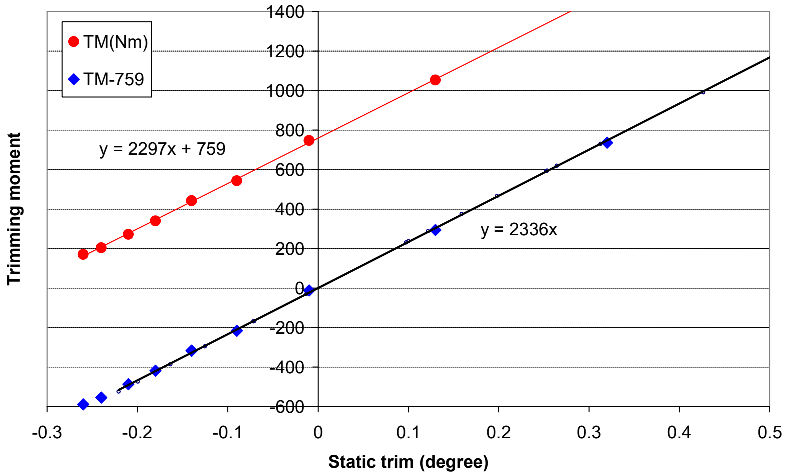

Figure 2. Trimming moment required for given static trim
positive values for bow down
appended hull #5

TrimI, indicating the applied trimming moments and the initial trim angles at rest. For the appended hull #5 these points are marked in figure 2 as red dots. The sign of *TrimI* is reversed in comparison to the excel-sheet, to make *TM* and *TrimI* both positive for a bow down trim. It is obvious, that trim weights, creating a trimming moment of *759 Nm*, are needed to level the boat at zero trim. With the trim weights in their neutral position the centre of gravity of the boat lies behind the centre of buoyancy and the boat is trimmed *0.33 deg*. bow up, equivalent to *759 Nm*. The supplied 3D-CAD data allow calculating the dependence of trim angle and trimming moment. The function is depicted by the black line in figure 2. If *759 Nm* are subtracted from the trimming moment *TM*, the points (blue diamonds) fall on the CAD-trim function. If the CAD-models are used to calculate trim angles, it is advisable to take the applied trimming moment as *TM-759 Nm* and place the centre of gravity at the centre of buoyancy at zero trim. Such a trim analysis has to be performed for each model separately in the upright condition, because the initial trim differs between the models.

The weight of the tank model is given in the excel-sheet. With input of the temperature of the fresh water it is possible to calculate the immersed Volume. The CAD-model enables to determine the sinkage for the given trim angle. The sinkage at station 0 for Model #5 is *3.5 mm* at *0.33 deg*. trim. In the original (.dwg) drawing of figure 1 the value for the black waterline at St.0 is *3.0 mm*. This discrepancy is within the tolerance band of *1.5 mm* that is defined in [2] for the setup of the model. An unknown tolerance for the machined dimensions of the boat compared to the CAD-model is also attributing to the discrepancy.

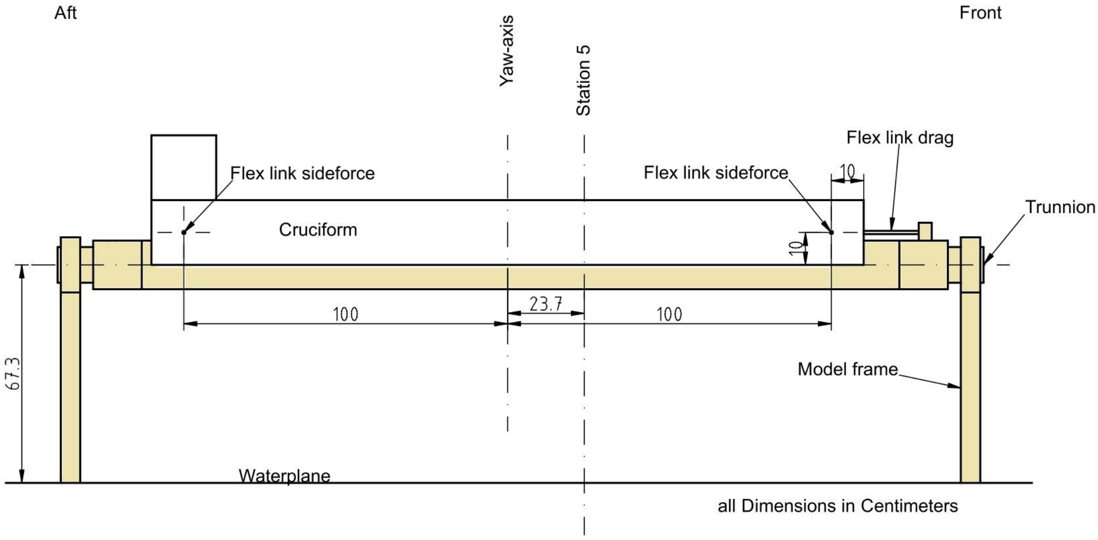

Figure 3. Lever arms of the dynamometer forces, model #5

4. GEOMETRY OF THE DYNAMOMETER

To calculate the equilibrium of forces and moments requires the exact dimensions of the lever arms of the measured forces relative to a reference point on the tested model. The geometry of the dynamometer is described in [2]. An extract of the required dimensions is given in figure 3. The distance of the heel axis (trunnion) above flotation and the distance between yaw axis and station 5 are listed for each model in the excel-sheets. The negative signs should be ignored, since the positive directions are nowhere defined. The missing dimensions are estimated from the drawing in [2]. The listed *Lift (N)* is the sum of the two side forces, and the yaw-moment *YawM (Nm)* is the moment relative to the yaw axis created by the two side forces that are 200 cm apart. The moment *YMcor (Nm)* is the moment relative to station 5. The hydraulic side force at its center of effort is balanced by a theoretical force "*Lift*" at station 5 and a moment "*YMcor*".

$$YMcor\ (Nm) = YawM\ (Nm) - 0.237m \cdot Lift\ (N)$$

If *YawM* is positive, the true center of effort of the hydraulic side force is forward of the yaw axis, for negative values it is aft. The pitching moment relative to the water plane for a leveled boat at zero trim is:

$$PM\ (Nm) = Drag\ (N) \cdot (0.673m + 0.1m)$$

In chapter 13.2 of [2] there is a description of the deflection of the dynamometer caused by the yaw moment. The deflection increases the true yaw angle δ compared to the measured angle δ_{measrd} according to:

$$\delta = YawM / 1200Nm \cdot\ 0.03° + \delta_{measrd}$$

This small correction can easily be applied to the values listed in the excel-sheets.

5. THE BOUNDARY LAYER TRIP

The boundary layer along the hull and the appendages is always turbulent at the full size boat. To guarantee fluid dynamic similarity, the boundary layer at the model is tripped. For the Nine Models the trip is made of cylindrical studs, mounted on a strip. These studs create an additional drag that must be subtracted from the measured resistance of the towed model. The dimensions of the studs can be found in [3], the distance between individual studs can be calculated from the number of studs given in the excel-sheets and the length of the keel span.
The results are listed in the table.

diameter	0.125 inch
height	0.1 inch
distance (pitch)	1 inch

There are three strips placed on the hull, the position is given in file 3385CB70 as Stn 0.5, Stn 1.5 and Stn 2.5. The number of submerged studs can be calculated from the pitch and the girth length at these stations in the trimmed position. The number of studs on the appendages is given in the excel-sheets.

6. POSITION OF THE CENTER OF GRAVITY

The model in the tank is free to pitch and heave. The pitch angle during the run and therefore also the resistance depends on *GM*, the height of the longitudinal metacenter above the center of gravity. The position of the cog in the model should be similar to the full size boat to guarantee similar pitching angles. The static trim-curve of figure 2 allows the calculation of the distance *GM* from:

$$Trimming\ moment = Displacement \cdot\ g \cdot\ sin(pitch) \cdot\ GM$$

The distance of the metacenter above the keel point *KM* can be calculated from the geometry of the CAD-model. The distance *KG* is obviously the difference *KM-GM*. This distance is depicted in figure 4 for the bare and the appended hull #5.

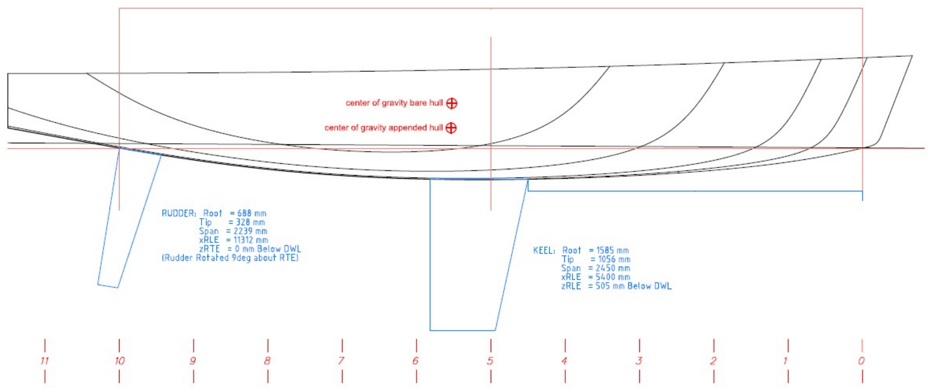

Figure 4. Position of the center of gravity, hull #5

7. CONCLUSION

With the additional information in this report, the test parameters in the excel-sheets [1] can be used as input for a VPP and the measured forces and moments can be compared to the predictions from the VPP. A regression analysis of the residuary resistance of the whole fleet will lead to an improvement of the VPP [4]. For questions I can be reached at ulrich@remmlinger.com.

8. REFERENCES

1. Teeters, J., Pallard, R., Muselet, C., "US Sailing Nine Model Series", 2003, [Online]. Available: http://sailyachtresearch.org/resources/us-sailing-nine-model-series
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4. http://www.remmlinger.com/UliTank.html