MEASUREMENT AND PREDICTION OF THE RESISTANCE OF A *LASER* SAILING DINGHY

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SUMMARY

This study explores the insight that can be gained into the performance of a conventional sailing dinghy from a program of tanks testing in a range of displacement and trim conditions, and further investigates the extent to which performance can be predicted using a regression approach developed for sailing yachts, with the ultimate aim of developing performance prediction tools customised for sailing dinghies.

The upright resistance of a *Laser* Dinghy is examined through tank-testing at three different displacements and with a range of trims. Results show that residuary resistance is substantially affected by displacement, and that trim can have a beneficial effect at the lower and upper extremes of the speed range. Comparison with tank test results show that the Delft sailing yacht regression approach does not predict the resistance of a *Laser* particularly accurately, substantially underestimates the weight sensitivity of a *Laser*, and cannot reliably predict the impact of trim.

NOMENCLATURE

A_w	Waterplane Area (m^2)
B_{wl}	Waterline Beam (m^2)
C_m	Section Area Coefficient
C_p	Prismatic Coefficient
c_t	Total Resistance Coefficient
KM_L	longitudinal metacentric height from the keel (m)
LCB	position of the centre of buoyancy relative to midships (positive forwards)) expressed as a percentage of the waterline length
LCB_{fpp}	Position of Centre of Buoyancy measured from forward perpendicular (m)
LCF	position of the Centre of Flotation relative to midships (positive forwards)) expressed as a percentage of the waterline length
LCF_{fpp}	Position of Centre of Flotation measured from forward perpendicular (m)
L_{wl}	Waterline Length (m)
M_θ	Trimming moment (Nm)
R_t	Total Resistance (N)
S_c	Hull Wetted Area (neglecting appendages) (m^2)
T_c	Hull Draught (neglecting appendages) (m)
V	Speed (m/s)
$\Delta R_{rc\theta}$	change in residuary resistance of the hull due to trim (N)
∇_c	Hull Volume Displacement (neglecting appendages) (m^3)
ρ	Water Mass Density (kg/m^3)

1. INTRODUCTION

The resistance of sailing yachts has been extensively studied over many years, with intensive programmes of tank testing related to design of high-profile yachts for competitions such as the America's Cup, and the Vendee Globe, as well as some well-known campaigns designed for the purposes of development of regression models for use in Velocity Prediction Programs (VPPs). The most well-known of these has been developed in Technical University of Delft with a total of over fifty models tested over a period of more than twenty-five years (Keuning & Katgert [1]). The regression methods generally give reliable results for yacht forms fitting the range of parameters tested, with results for upright resistance typically within 5% or better of the tank test results.

In contrast, relatively few tank-test studies have been carried for sailing dinghies, and little effort appears to have been expended on development of VPPs specifically with dinghies in mind. Dinghies are sufficiently small and cheap to construct that most design development programs have been based on building and sailing prototypes rather than tank testing; although VPPs are certainly used by dinghy designers, it is questionable to what extent the hydrodynamic models utilised in the VPPs are valid for high-performance hulls. It is tempting to assume that many conventional dinghies are essentially similar to small yachts and that their performance can be predicted using models derived for yachts.

However there are some particular challenges associated with performance prediction for sailing dinghies. The same hull may be sailed by crews with substantial weight variations, yielding differences in performance profiles which may well be significant in terms of the tight margins associated with elite dinghy racing. Indeed VPPs have been developed for "one-design" sailing dinghies, even though the hull shape of these boats is fixed within relatively tight tolerances, in order to identify optimum crew weight for prestigious international events such as Olympic Games.

Furthermore, with a given crew weight, a much more substantial variation in trim and heel is achievable by crew movement than with a larger yacht, placing additional challenges on the prediction of performance via a VPP. Crews naturally trim and heel the boat to give the maximum perceived performance in a given set of conditions. One relatively extreme example of this is the so-called "fourth mode" condition discussed by authors including Bethwaite [2] in which the boat is sailed with extreme bow-down trim and heel in light winds to reduce wetted area.

The present study followed from a tank-test investigation into a high-performance skiff-type sailing dinghy (the *Aura*) with a narrow hard chine form typical of many modern high performance dinghies. The study was carried out in two towing tanks, one of which was relatively small; as a consequence the model tested was sized for the smaller facility and was rather smaller than would be desirable for reliable results. A number of interesting issues specific to dinghy testing were nonetheless identified. In particular the study highlighted the importance of crew weight and trim on performance and the difficulty of predicting these variations using conventional regression formulae. It was decided that useful insight could be gained from testing a conventional moderate performance dinghy over a range of trim and displacement conditions prior to continuing an investigation of high-performance dinghies. The aim of the study is to examine how physical model testing can be used to gain insight into the performance of a sailing dinghy in realistic range of trim and displacements conditions, and to explore the extent to which the performance of the boat can be predicted using conventional regression approaches developed for sailing yacht performance.

The *Laser* dinghy was chosen for this study for a number of reasons – it is a tightly controlled one-design class; it is an Olympic class for both men (with the "standard" sail) and women (with the smaller "radial" sail); it is one of the most popular racing dinghy classes worldwide with over 200,000 boats built since 1971. The *Laser* has a relatively conventional round-bilge hull-form, which might reasonably be assumed to be suitable for prediction using a yacht-oriented VPP; in level trim conditions, all key hull-form parameters fall within the range of parameters for the Delft series regression model. It should be noted that the *Laser* is currently the subject of a legal dispute between the designer Bruce Kirby and some of the licensed builders, which may result in the class being renamed.

The study examines the upright resistance only. The upright resistance was chosen as the focus of this study since a typical regression model (such as the Delft series model) uses the upright resistance as the foundation of the calculation, and then corrects the resistance with a series of "deltas" reflecting changes in resistance due to heel, trim, and side-force. From a practical perspective, there are a sufficient number of realistic displacement and trim variations in the upright condition which can be considered to give adequate insight into the complexity of the phenomena, and the reliability of existing techniques for prediction.

Two sets of variations are considered in the tank tests implemented in the first part of the study. In the first set, the sensitivity of the resistance to weight is examined, with hulls being tested at total displacements of 150, 160 and 170kg. In the second set of tests the influence of trim on the upright resistance is examined at the 160kg displacement, in order to explore the difference between a level trim and an optimum trim upright resistance curve. In the second part of the study, the tank-test results are compared with upright resistance predictions from the Delft Systematic Series in order to explore the likely reliability of a VPP constructed using such a model in predicting the performance of a conventional sailing dinghy in a range of realistic trim and displacement conditions.

2. HULL MEASUREMENT AND GENERATION

The first challenge of the proposed study was to generate an accurate 3D model of the *Laser* hull. Several CAD models of a *Laser* can be found on the internet, but quick checks of some key dimensions against a full-scale hull reveal them to be highly inaccurate.

In the current study the lines of the *Laser* were developed from scratch from a boat owned by the first author. The hull was marked out with nine sections as well as the keel-line, deck-edge, bow profile and a notional waterline. A set of points were measured along these key lines using a device constructed by the authors for the purpose, utilising the "*Qualisys*" motion capture system used at the Kelvin Hydrodynamics Lab. The device incorporates four standard 3D markers mounted on a pointer; the system is set up with a local co-ordinate system fixed to the pointer with origin at the tip of the pointer. A micro-switch is mounted in the tip, so that when the pointer is touched to the hull the position of the tip in a space-fixed global co-ordinate system can be generated. In this way a large number of points on the hull can be accurately measured very quickly. The set-up with boat, cameras and probe is shown in Figure 1.

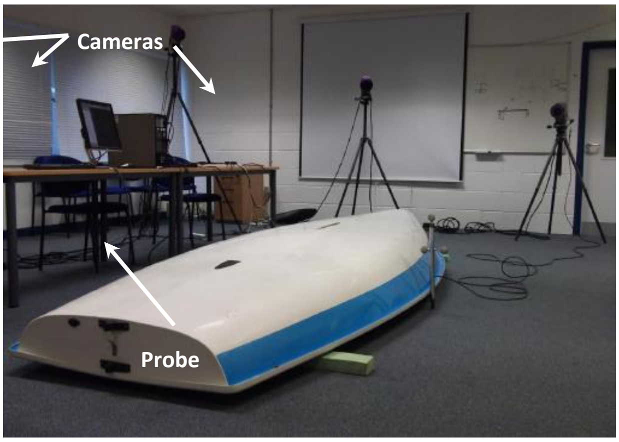


Figure 1 Hull Measurement System

The set of data points is then adjusted by simple transformation to remove any heel and trim, and the points are entered as markers into a standard CAD package *(MaxSurf*). A preliminary NURBS surface was generated automatically using the *Prefit* software, and then adjusted manually to give the best fit. The bow section, which has a relatively complex geometry, was then added manually. In the final version, the RMS error over the markers at full scale was less than 1mm. The body plan is shown in Figure 2. The geometry was exported to an IGS format and a physical model was constructed at a scale of 0.48:1 in Divinycell foam using a CNC router. Since the study only addresses upright resistance, there was no requirement for modelling lifting surfaces, and the hull was tested without centreboard or rudder in order to maximise the observed differences between conditions.

The displacements studied were chosen using available information about the class. The nominal hull weight including fittings is quoted by the manufacturer as 58kg. Added to that are the weight of the mast, boom, foils, rudder stock, tiller and extension, ropes and sail. These were weighed at approximately 22kg. The optimal weight for a standard rig *Laser* sailor is often quoted at around 80kg. Hence the benchmark displacement was chosen to be 160kg, and a variation of plus/minus 10kg represents a reasonable reflection of the weight variation of club-level standard-rig *Laser* sailors.

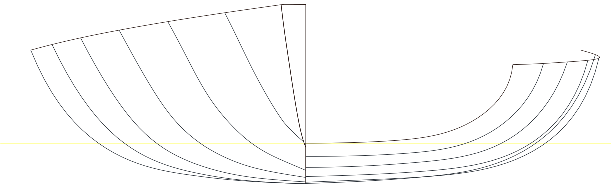
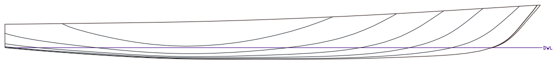
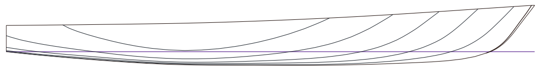


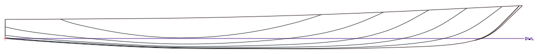
Figure 2 Laser Body Plan 80 kg nominal crew



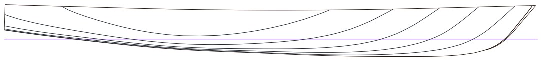
(a) 70 kg crew, level trim



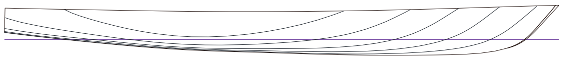
b) 80 kg crew, level trim



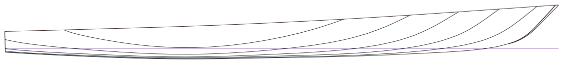
c) 90 kg crew, level trim



d) 80 kg crew extreme bow trim



e) 80 kg crew bow trim



f) 80 kg crew stern trim

Figure 3 Laser displacement and trim conditions

As mentioned previously, one of the goals of the study was to investigate the effect of trim; hence a level trim condition had to be defined, for each of the displacements. Since no well-defined waterline or baseline exists, based on experience of sailing the boat, the level trim condition for each displacement was defined as a condition in which the vessel is trimmed so that the transom stern was just touching the water surface. In this condition, the principal dimensions are shown for each of three displacements in Table 1 below. It can be seen from this that the lightweight crew will benefit from a 1.9% reduction in wetted area, whilst the heavy crew will incur a penalty of 1.8%.

Table 1 Hull dimensions and form coefficients for displacement variation

Notional Crew Weight	∇_c	L_{wl}	B_{wl}	T_c	S_c	A_w	C_p	C_m	$\frac{LCB_{fpp}}{L_{wl}}$	$\frac{LCF_{fpp}}{L_{wl}}$
	(m^3)	(m)	(m)	(m)	(m^2)	(m^2)				
Light	0.150	3.763	1.095	0.089	2.904	2.813	0.546	0.755	0.535	0.565
Standard	0.160	3.791	1.103	0.094	2.959	2.859	0.552	0.757	0.532	0.565
Heavy	0.170	3.812	1.111	0.099	3.012	2.901	0.558	0.759	0.529	0.565

Table 2 Hull dimensions and form coefficients for trim variation

Trim Condition	∇_c	L_{wl}	B_{wl}	T_c	S_c	A_w	C_p	C_m	$\frac{LCB_{fpp}}{L_{wl}}$	$\frac{LCF_{fpp}}{L_{wl}}$
	(m^3)	(m)	(m)	(m)	(m^2)	(m^2)				
Level	0.160	3.791	1.103	0.094	2.959	2.859	0.552	0.757	0.532	0.565
Extreme Bow Trim	0.160	3.379	1.066	0.124	2.653	2.504	0.630	0.738	0.509	0.571
Bow Trim	0.160	3.455	1.076	0.117	2.711	2.572	0.631	0.740	0.513	0.570
Stern Trim	0.160	3.603	1.116	0.094	2.910	2.827	0.552	0.764	0.592	0.582

The trim variation study was carried out for the default displacement of 160kg. Trim conditions were chosen based on experience, and can be regarded as indicative rather than definitive. Two bow-down trim conditions, which are typically utilised in low-speed (light-wind) conditions, were investigated, along with one stern trim condition, which might be expected to be utilised in stronger wind conditions when the boat is planing. It is possible to estimate where the crew would have to sit longitudinally to generate these trims; however this value is not necessarily reflective of the sailing situation since such a calculation neglects the aerodynamic trimming moment generated by the sails. The trim conditions are illustrated in Figure 3 and the hull dimensions in these conditions are shown in Table 2.

The bow down trim condition yields a reduction in wetted area of over 8% compared to the level trim case, whilst the extreme bow down trim yields over 10% reduction. The stern trim has 1.7% less wetted area than the level trim case.

3. TANK TEST PROCEDURE

The tests for the current study were carried out in the test tank of the Kelvin Hydrodynamics Laboratory in Glasgow. The tank measures 76m (L) x 4.6m (W) x 2.5m (D); for the current tests the water depth was set at 2.15m. The carriage can travel at more than 4.0m/s with a high level of accuracy in speed control and regulation. The tank is equipped with a modern high-performance multi-flap active absorbing wave-maker.

The model was towed purely in the upright condition, and no appendages were fitted during the tests. The experiment procedure in general conformed to the standard ITTC procedures for model making and resistance testing. One minor variation, common in testing of sailing yachts, was to fit turbulence stimulation studs at 20% of the design waterline length from the bow perpendicular in the benchmark condition of level trim at 160kg displacement, rather than according to the ITTC standard for merchant ships. The model was free in heave, pitch and roll; the towing point, attached at the benchmark LCG for level trim, is capable of transmitting only a horizontal towing force.

3.1 INSTRUMENTATION

The resistance was measured using a proprietary tension-compression load cell, with excellent linearity characteristics. Carriage speed was measured using an encoder mounted on a trailing wheel. Running attitude was measured with two linear variable displacement transformers (LVDTs). Data was logged on a 16-bit data acquisition system with a sampling rate of 137 Hz.

3.2 TEST MATRIX

The model was tested in the three displacement conditions over a speed range corresponding to full scale speeds between 2.0 knots and 9 knots, at 0.5 knot increments. The bow-down trim conditions were tested from 2.0 knots to 5.0 knots, whilst the stern trim condition was tested from 4.0 knots to 9.0 knots.

3.3 SCALING

Resistance results are scaled to full scale using the standard ITTC procedure, with the ITTC 1957 friction line, and all results scaled to fresh water at 15.0 degrees Celsius. It should be noted that there are some challenges associated with this scaling procedure, common to scaling of planing craft. In particular, the wetted area was here assumed to be constant at the value obtained at the static waterline for each condition. Since the vessel does adopt some dynamic trim, the resulting change in wetted surface will introduce a small error in scaling.

3.4 UNCERTAINTY

A full investigation of the uncertainty involving multiple installations and ballasting of the model was not carried out with these tests. However calculation based on uncertainty components identified as dominant in previous studies in this facility using this towing arrangement and dynamometer suggested that the bias limit on the total resistance coefficient at model scale is of the order of 0.25%. Even them it should be noted that the dominant sources of bias do not in any case affect comparisons between tests such as resistance changes between the model with and without interceptors. Multiple repeat tests carried out indicate that the corresponding precision of the total resistance coefficient was around 0.4%. Hence the total uncertainty is estimated at around 0.5%.

4. EXPERIMENT RESULTS

4.1 INTRODUCTION

Many of the results are presented here in terms of full-scale drag area (in m^2) plotted against full-scale speed (in knots). Drag area is defined as:

$$\text{Drag Area} = R_t \Big/ \left(\frac{1}{2} \rho V^2 \right) = c_t S_c \qquad (1)$$

Drag Area is used in preference to the conventional metric of total resistance coefficient since both wetted area and displacement vary substantially between the conditions; it is thus possible that a condition with a higher resistance coefficient may have a lower resistance, making the comparison of resistance coefficient potentially confusing. On the other hand, simply plotting total resistance tends to mask the subtle changes present in some conditions.

4.2 VARYING DISPLACEMENT

The variation of drag area with speed for the three level trim conditions is shown on Figure 4 below. A consistent trend can clearly be seen, with a major hump in drag area at around 6.5 knots for all displacements; a small hump can also be seen around 3.5 knots. Dynamic sinkage and trim were found to be almost identical for all three cases; results are shown in Figure 5. In this plot sinkage is defined as positive downwards and trim is positive bow up. It can be seen that the sinkage starts to become negative as the boat starts to plane at around 6.5 knots at which point the drag area starts to reduce and the rate of increase of trim starts to level off.

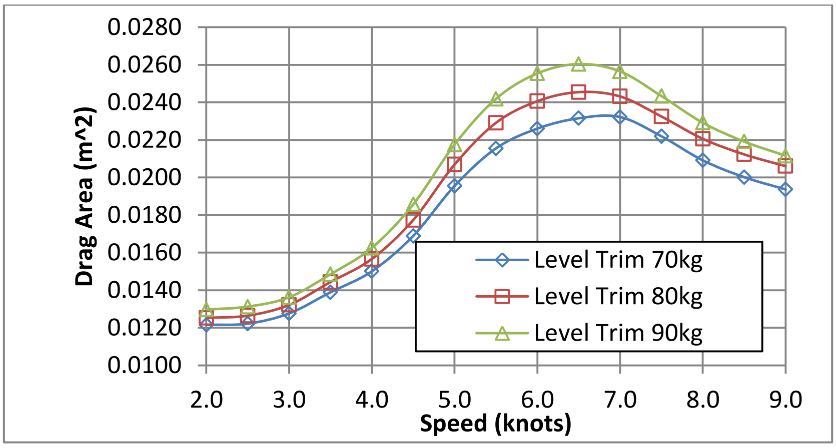


Figure 4 Drag Area for differing displacements in level trim

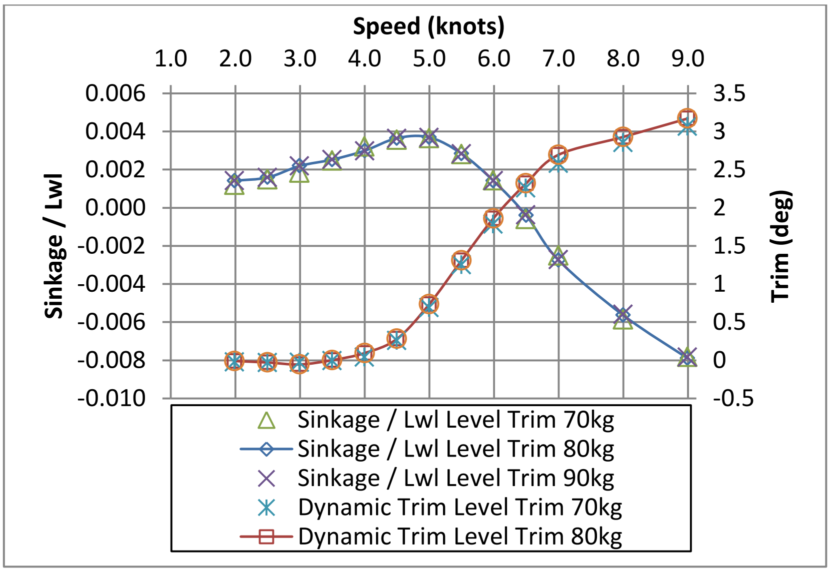


Figure 5 Sinkage and trim for different crew weights

From the point of view of the sailor, the key factor is the difference (or delta) in resistance from the optimum displacement. In the measured data the target speeds for each condition were the same, but some very small differences (within the ITTC recommended tolerances) were observed between measured speeds for corresponding tests. For the purposes of calculating the deltas, the results were therefore interpolated onto the exact target speeds using cubic spline interpolation. The deltas are plotted in Figure 6.

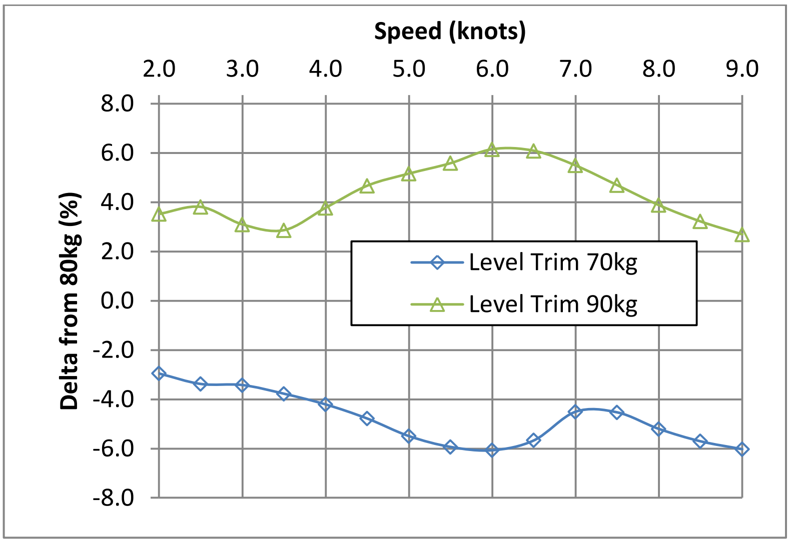


Figure 6 Difference in resistance from 80kg crew weight

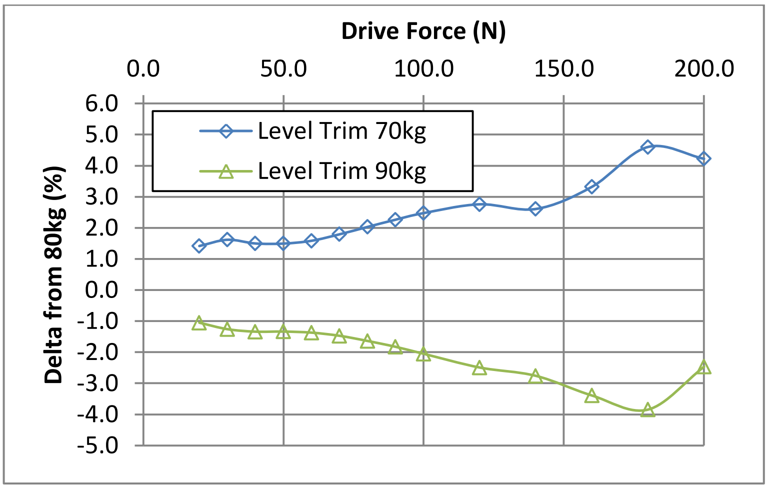


Figure 7 Difference in speed from 80kg crew weight

It should be remembered that since the results in Figure 6 are calculated from the differences between two sets of measurements they are expected to give higher uncertainty than single measurements.

It can be seen that the magnitude of the difference in resistance for both light and heavy crew varies in the range of 2.7-6.2%, compared to the reduction in wetted area of around 1.9% for light crew, and increase in wetted area of around 1.8% for heavy crew. This discrepancy shows that the variation in weight has a substantial impact on residuary resistance as well as frictional resistance.

Whilst the normal presentation for the yacht designer is to plot resistance against speed (or deltas of resistance against speed), from the perspective of the sailor, the change in speed for a given driving force is of more interest, as it relates more closely to the observed performance. Since the tests for different displacements were run at defined speeds, rather than at defined towing forces, this calculation involves more extensive interpolation than that involved in the resistance deltas so that speeds corresponding to specified values of towing force can be estimated and compared; hence results must be viewed with a little caution. Results are shown in
Figure 7.

As would be expected from an approximately quadratic relationship, the results for speed deltas are typically around half the values observed for resistance deltas. Nonetheless the range of values of speed deltas indicated between around 1.4% and 4.6% are very significant in terms of dinghy racing, in which races may be won and lost by a few boat lengths after a race lasting of the order of an hour.

4.3 VARYING TRIM

In light winds and at low speeds it is common for Laser sailors to sit forward of the cockpit trimming the bow down and heeling to leeward. The aim is to lift the stern clear of the water and reduce wetted area, whilst also allowing the weight of the sail to help maintain its shape. Since the present study concentrates on upright resistance, no heel is implemented in the present study; nonetheless trimming the bow down in the upright condition allows identification of the trade-off between reduced wetted area and change in residuary resistance.

The impact of bow-down trim on drag area is shown in Figure 8. It can be seen that the reduction in wetted area, and hence frictional resistance, is more than offset by increase in residuary resistance at three knots and above. The crossover occurs at around two and a half knots; at two knots, the bow-down and extreme bow-down trim conditions show reductions in drag area of 2.2% and 3.6% respectively.

The corresponding results for stern-down trim are shown in Figure 9.

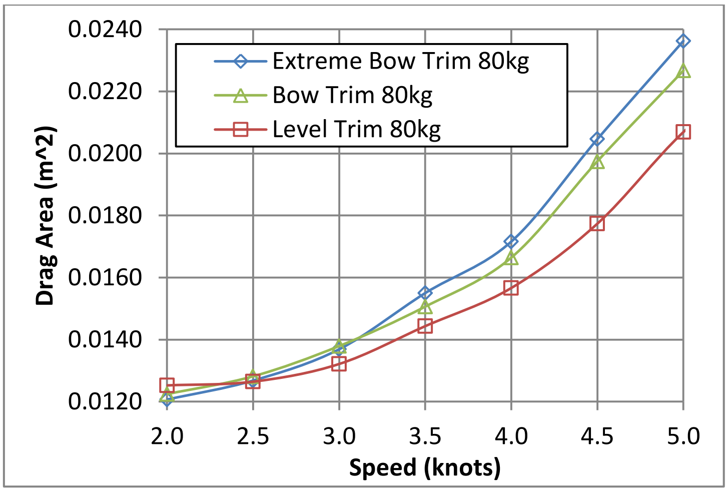


Figure 8 Drag Area for Laser with bow-down trim

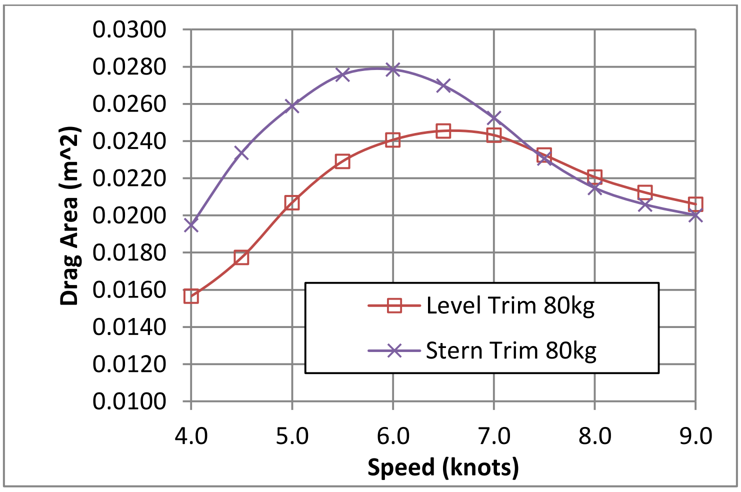


Figure 9 Drag Area for Laser with stern-down trim

The stern trim in which the transom is immersed is hugely disadvantageous at moderate speeds with over 30% penalty in resistance at 4.5 knots. This emphasises the critical importance of maintaining correct trim in moderate wind conditions.

However as the boat starts to plane around 6.5knots the penalty reduces substantially, and once the boat is planing quickly at 8knots and above, the stern trim reduces resistance by around 3%.

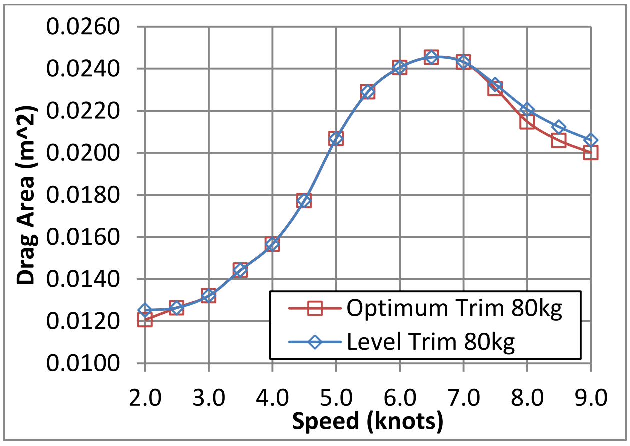


Figure 10 Drag Area for Laser in optimum trim

The results are summarised in Figure 10, showing the differences between the resistance curve for level trim and those based on the best trim out of the four conditions tested.

5. PREDICTION OF *LASER* RESISTANCE USING REGRESSION METHOD

5.1 DELFT REGRESSION METHOD

The most widely used regression method for yacht-like hulls is the approach derived from the Delft systematic yacht hull series, described in its most recent version by Keuning and Katgert (2008). The approach is based upon tests of over fifty yacht hulls over a period of over twenty-five years.

The method utilises a conventional prediction of the frictional resistance of the hull according to the ITTC 1957 friction line with the only non-standard feature being the utilisation of 70% of the waterline length in the calculation of the Reynolds Number.

The residuary resistance is given by the following expression:

$$\frac{R_{rc}}{\nabla_c \cdot \rho g} = a_0 + \left(a_1 \cdot \frac{LCB_{fpp}}{L_{wl}} + a_2 \cdot C_p + a_3 \cdot \frac{\nabla_c^{2/3}}{A_w} \right) \cdot \frac{\nabla_c^{1/3}}{L_{wl}} + \left(a_4 \cdot \frac{B_{wl}}{L_{wl}} + a_5 \cdot \frac{LCB_{fpp}}{LCF_{fpp}} + a_6 \cdot \frac{B_{wl}}{T_c} + a_7 \cdot C_m \right) \cdot \frac{\nabla_c^{1/3}}{L_{wl}} \qquad (2)$$

The coefficients $a_0 - a_7$ are tabulated for Froude Numbers between 0.15 and 0.75, which correspond for the Laser to speeds of between around 1.8 – 8.8 knots depending on the displacement and trim condition.

In order for the regression to yield reliable results it is necessary (but not sufficient) for the hull parameters of the vessel of interest to fall within the range of parameters tested in the derivation of the equation. These are summarised in Table 3.

Table 3 Delft Series Parameters

Condition	$\frac{LCB_{fpp}}{L_{wl}}$	C_p	$\frac{\nabla_c^{2/3}}{A_w}$	$\frac{B_{wl}}{L_{wl}}$	$\frac{LCB_{fpp}}{LCF_{fpp}}$	$\frac{B_{wl}}{T_c}$	C_m	$\frac{\nabla_c^{1/3}}{L_{wl}}$
Level Trim 70 kg	0.535	0.546	0.100	0.291	0.946	12.262	0.755	0.141
Level Trim 80 kg	0.532	0.552	0.103	0.291	0.941	11.755	0.757	0.143
Level Trim 90 kg	0.529	0.558	0.106	0.291	0.937	11.234	0.759	0.145
Extreme Bow Trim 80 kg	0.509	0.630	0.118	0.315	0.890	8.586	0.738	0.161
Bow Trim 80kg	0.513	0.631	0.115	0.311	0.899	9.195	0.740	0.157
Stern Trim 80 kg	0.592	0.552	0.104	0.310	1.018	11.842	0.764	0.151

Delft Series Min	0.500	0.521	0.079	0.170	0.930	2.460	0.646	0.120
Delft Series Max	0.579	0.580	0.265	0.366	1.002	19.380	0.790	0.230

The *Laser* falls outside the range of the prismatic coefficient C_p for the two bow trim conditions, whilst the ratio of LCB to LCF, included as a measure of hull distortion falls outside the range for all three trimmed condition. Hence it is not reasonable to expect reliable results in these trimmed conditions. However it can be seen that the *Laser* falls within the parameter range in all three level trim conditions.

An alternative approach is potentially possible for the bow-down trim conditions; in an earlier version of the method Keuning and Sonnenberg [3] give a formula for calculating the resistance delta due to bow-down trim. This was intended for investigating the relatively small bow-down dynamic trim which results in sailing yachts from the aerodynamic trimming moment in cases where moving crew weight cannot compensate for the trimming moment. The formula given is:

$$\frac{\Delta R_{rc\theta}}{M_\theta / KM_L \tan\left(1^\circ\right)} = T_0 + T_1 \frac{L_{wl}}{B_{wl}} + T_2 \frac{B_{wl}}{T_c} + T_3 \frac{A_w}{\nabla_c^{2/3}} + + T_4 \cdot LCB + T_5 \cdot LCF \qquad (3)$$

The coefficients $T_0 - T_5$ are tabulated for Froude Numbers between 0.25 and 0.6, which correspond for the Laser to speeds of between around 3-7 knots depending on the displacement and trim condition. The formula is applied to the vessel in level trim condition to yield a correction in the residuary resistance.

5.2. COMPARISON OF DELFT PREDICTIONS WITH TANK TEST RESULTS

Using the formula (2) above in conjunction with the wetted area and the related friction coefficient the total resistance and the drag areas were calculated for the three level trim conditions. A comparison of the drag area measured in the tank and the Delft prediction for the baseline case of 80kg crew in level trim is shown in Figure 11. It can be seen that the general agreement is quite good, especially in the region between 5.0-8.0 knots. However the agreement in the critical region of 3-5 knots (a common speed range for a *Laser*) is not so good, with an error of over 8% at 4.0 knots.

The discrepancy between the Delft series and the tank results for all three level trim conditions is shown in Figure 12. In order to make the comparison the Delft values are interpolated onto the speeds used for the tanks tests. This is achieved using a cubic spline fit to the Delft prediction, which is the approach commonly used in VPPs. The trends are very similar for each displacement, but the errors increase slightly as the displacement increases, with peak error of over 9% for the 90kg crew.

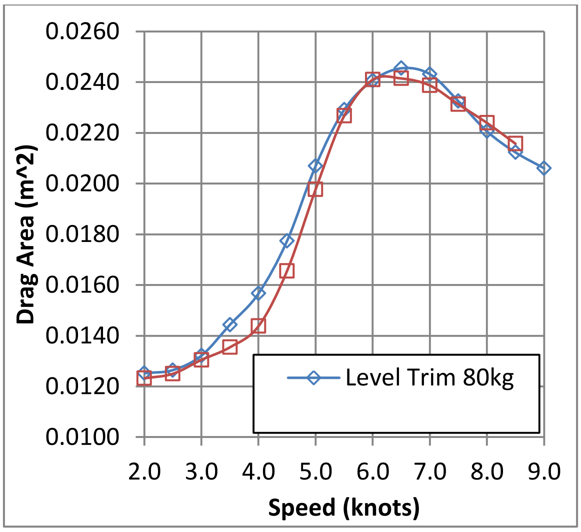


Figure 11 Tank data and Delft prediction for level trim 80kg crew

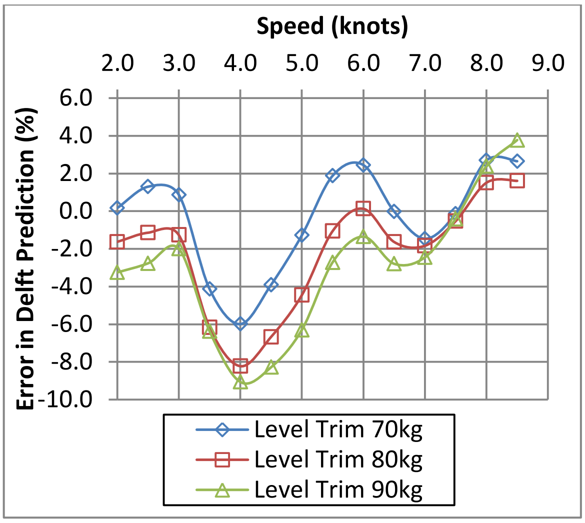


Figure 12 Delft prediction errors for three level trim cases

These results show that the Delft method underestimates the residuary resistance of the *Laser* hull, particularly in the 3.0-5.0 knot speed range, corresponding to Froude Numbers in the region of 0.25 - 0.425.

Figure 13 shows Delft method predictions for the resistance deltas related to the change in crew weight corresponding to Figure 6. It can be seen that the Delft method underestimates the weight sensitivity of the boat substantially, underestimating the impact of the 10kg variation from the benchmark 80kg crew by a factor of more than three in the worst cases.

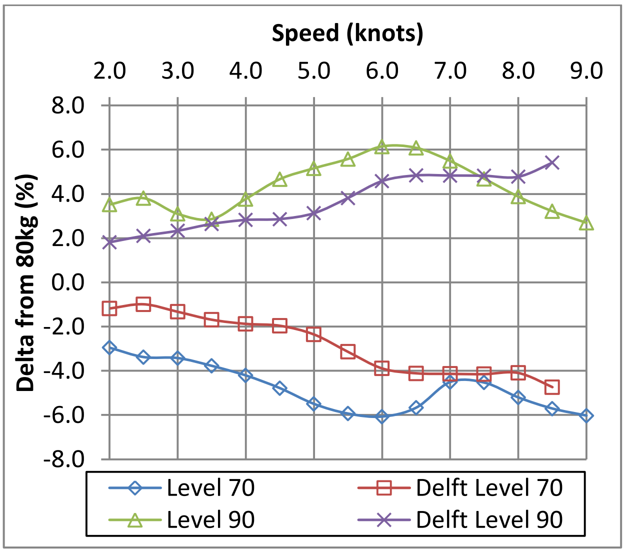


Figure 13 Delft prediction of weight sensitivity for three level trim cases

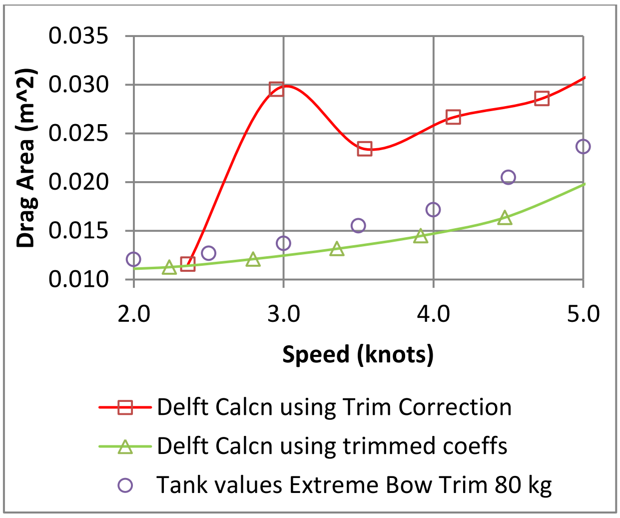


Figure 14 Delft predictions of Extreme Bow Trim Case

Figure 14 shows the results of attempts to predict the resistance in the extreme bow trim case using the Delft approach. The method using equation (3) above was tried first. In this approach, the residuary resistance in level trim is first calculated using equation (2); then the bow-down trimming moment is calculated from the longitudinal shift in the LCB compared to the level trim case. The correction to the residuary resistance is then calculated using equation (3) and the resulting residuary resistance is combined with the frictional resistance calculated using the parameters for the bow-down trim case. This approach dramatically overestimates the residuary resistance correction due to the large bow-down trim; indeed the predicted correction to the residuary resistance is very substantially larger than the residuary resistance in level trim at low speeds.

For comparison a calculation is carried out using equation (2) with the form coefficients for the trimmed vessel, although it is expected that this will not produce reliable results since the hull falls outside the range of coefficients tested in the series. In contrast this substantially under-predicts the resistance of the trimmed vessel. It is therefore concluded that the impact of bow-down trim on a *Laser* dinghy cannot be reliably predicted using the Delft approach. A similar conclusion may be reached for the stern trim case, for which no correction formula corresponding to equation (3) is given.

6. DISCUSSION

The tank results show that the effect of weight on upright resistance of a Laser is substantial, with between 2.7-6.2% changes in resistance for a 10kg change in weight from the nominal total weight of 160kg. The corresponding change in wetted areas is around 1.9% for the 10kg reduction and 1.8% for the 10kg increase, thus suggesting that the majority of the change in resistance is due to residuary rather than frictional resistance. These changes in resistance can be re-interpreted by interpolation as suggesting changes in speed at constant drive force of 1.4-4.6%.

It must be stressed that speed deltas at constant drive force do not by any means tell the whole story of the influence of crew weight on boat performance. One key effect is that heavier crews can generate substantially more righting moment than lighter crews. As wind speed increases, the speed of the boat sailing upwind will become limited to some extent by available righting moment, and lighter crews have to depower the rig more than heavier crews in order to reduce heeling moment. This depowering in turn reduces driving force, whilst also affecting aerodynamic side-force and hence hydrodynamic induced drag. In such conditions, heavier (and taller) sailors will start to be at an advantage sailing upwind, which will offset to some extent the speed loss in downwind sailing, for which righting moment is less likely to be an issue. Thus the relationship between sailing performance around a racecourse and crew weight is complex. However, it should be remembered that the results do directly reflect the impact of other weight components on the boat, such as an overweight hull, additional equipment such as a compass or a bottle of water, or the presence of water in the cockpit.

Even in light wind conditions, when the righting moment is not an issue for lighter crews, the impact of boat speed on apparent wind speed and hence driving force is neglected in this simple comparison. In order to address these matters correctly, a velocity prediction program (VPP) would be required reflecting the full aero-hydrodynamic performance of the boat. Nonetheless, the results shown still give a strong indication of the significance of the impact of the crew weight on performance.

Trimming the boat by the bow does show small beneficial effects in low speeds corresponding to light winds, as expected. The impact of stern trim, giving an increase in resistance at moderate speeds is also expected, but the scale of the resistance penalty is quite surprisingly large at up to 30%. This emphasises the importance of correctly trimming the boat.

The comparison between tank results and Delft regression predictions in the level trim condition show that the Delft method substantially underestimates the resistance in the 3-5knot speed range, and dramatically underestimates the impact of weight on resistance by as much as three times. It should be stressed that these comments are not intended as a criticism of the Delft method, which is known to give excellent results for sailing yachts, and which was not intended for these purposes. However the results show that resistance regression formulae derived for sailing yachts should be treated with great caution if they are to be used to create VPPs for use in dinghy design or for assessment of optimum crew weight.

It is speculated that one reason for the discrepancy in the present case might be related to the shape of the *Laser* forebody, which is somewhat different from that of a typical yacht. The *Laser* bow has quite a high volume and low freeboard compared to the bow of a sailing yacht. The *Laser* was originally designed to be a dinghy which could be carried on the roof of a car, and it has been suggested that the bow shape was driven by the need to prevent the boat nose-diving in waves without adding freeboard, so that the boat could be easily lifted onto a car roof. However this full bow may contribute to additional residuary resistance compared to a conventional sailing yacht hull with similar form parameters.

Nonetheless the *Laser* is still arguably more similar to sailing yachts than modern high-performance hard-chine skiff dinghies such as the Olympic *49er* and *49er FX* classes, and hence it is possible that discrepancies between predictions using regression methods derived for yachts and tank-test results may be even higher for boats of this type.

Results for the trimmed condition show the importance of realistic modelling of trim in the context of VPPs if they are to predict performance correctly at the extremes of the speed range. Perhaps unsurprisingly, the Delft method, derived for the small trim angles likely to occur in a sailing yacht at low speed, cannot cope at all with the large trim angles achievable at most speeds in a small sailing dinghy by longitudinal movement of crew weight.

In conclusion, the study shows that tank-testing can contribute useful insight into the performance profile of a moderate-performance dinghy. Whilst the broad conclusions of the study would not come as a great surprise to anyone familiar with sailing a *Laser* dinghy, the magnitude of the sensitivity of resistance and speed to weight is larger than might be expected. Furthermore, the challenges of predicting the performance of the boat using a standard regression approach are much greater than was anticipated at the outset, emphasising that methods derived for yachts must be treated with caution when applied to sailing dinghies.

There are a number of avenues for future study here. Some preliminary tank-tests of high performance dinghies including a *49er*-like hull have been performed by the authors, and more tests are planned to provide a further insight into phenomena similar to those described in the present study, including the effect of heel as well as trim.

In a parallel development, it would be beneficial to be able to build up an understanding of sailing dinghy resistance without having to go to the expense of building scale models and tank-testing. Hence the development of a reliable full-scale measurement technique, for example following the work described by Watin [4], would be of some interest. This would also allow an interesting comparison between physical measurements at large model scale and full-scale as well comparison between measurements, regression methods and hydrodynamic approaches. This approach is currently being pursued by the authors.

Finally, it is planned that the data generated in the present study will be incorporated into a velocity prediction program (VPP) so that the trade-off in crew weight between resistance and righting moment may be studied in more detail.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Keuning J. A. & Katgert M. "*A Bare Hull Resistance Prediction Method derived from the Results of the Delft Systematic Yacht Hull Series Extended to Higher Speeds*" Paper 3, International Conference on Innovation in High Performance Sailing Yachts (Innov'Sail 2008) Lorient France 29-30 May 2008

2. Bethwaite, F. "*High Performance Sailing*" Waterline Books, Shrewsbury UK 1993

3. Keuning J. A. & Sonnenberg U. B. "*Approximation of the Calm Water Resistance on a Sailing Yacht Based on the Delft Systematic Yacht Hull Series*" Proc. 14th Chesapeake Sailing Yacht Symposium, Annapolis MD USA January 29-30 1999

4. Watin, S. "*49er performance enhancement*", downloaded from http://9eronline.com/library/49er%20Performance%20Enhancement%20Report%20by%20Simon%20Watin.pdf August 2013