

*"The Influence of the Bowshape on the Performance
of a Sailing Yacht"*

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Abstract

In this paper some results of two studies carried out at the Shiphydromechanics Department of the Delft University of Technology: one on the influence of an increase of stem steepness of a sailing yacht and another, which was largely carried out by T.J.E.Tincelin as part of his master thesis at Delft University of Technology, on the effect of above waterline bowflare are presented.

To investigate the influence of bow steepness a model of the Delft Systematic Yacht Hull Series (DSYHS) has been used as a parent model of a new small subseries with two additional derivatives each with increased bow steepness. The influence hereof on both the calm water resistance and the added resistance in head waves has been investigated.

To investigate the influence of bow flair two models of a typical "Open 60" designs have been used: one "normal" and one with almost "no-flare" in the bow sections. These have been tested in calm water and in both head- and following-waves to investigate the effects of this difference in bow shape on the calm water resistance, the added resistance in waves and also on the relative motions at the bow.

The results will be presented and some comparisons with calculations made. Also some general conclusions with respect to resistance, performance and safety will be drawn

List of Symbols.

λ	=	wave length	[m]
R_{aw}	=	added resistance in waves	[N]
R'_{aw}	=	R_{aw} / ζ_a^2	[N/m ²]
R_t	=	total resistance = $R_f + R_r$	[N]
R_f	=	frictional resistance	[N]
R_r	=	residual resistance	[N]
Fn	=	Froude number = $v / \sqrt{(g \cdot Lwl)}$	[-]
ω	=	wave frequency	[rad/s]
ζ_a	=	wave amplitude	[m]

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1 – Introduction.

Stimulated by all kinds of reasons, ranging from the assumed influences of certain rating rules to design considerations driven sometimes by facts or just by fashion, there is a clear trend to be observed over the past decade to steeper and steeper stems in particular with the racing- and other high-performance yachts. The influence of this on a particular design may be found in an increased waterline-length with a constrained length-over-all, which on its turn, may lead, assuming constant displacement, to an increased fineness of the waterlines in the forepart of the yacht, i.e. a decrease in the angle which the waterlines make with the centerline of the hull (waterline entrance angle). Under the same assumption of constant displacement and overall length, there is also an effect on the prismatic coefficient (C_p decreases), the relative longitudinal position of the center of buoyancy (LCB moving aft), the centroid of the waterplane area (LCF also moving aft) and pitch radius of gyration.

The possible influence of all these changes on the performance of sailing yachts when compared in a more systematic way appeared to be not readily available in the open literature. Also this bow steepness had not been a parameter under consideration in the Delft Systematic Yacht Hull Series (DSYHS) because all the design variations investigated within the DSYHS so far were obtained by an affine-transformation technique, which implies that the bow steepness for all models originating from one parent model is more or less constant. Therefore it was decided to extend the DSYHS with two additional models, each with increasing bow steepness in comparison with their parent model, which was the parent of Subseries 4, i.e. the IMS-40.

Because part from the reasoning behind the possible benefits of the steeper stem originated from a supposed reduction in the added resistance of these ships in waves it was decided not only to test these models for their calm water resistance but to include tests in regular head waves to investigate their differences in that respect also.

Another aspect of the possible influence of the bowshape on the performance was investigated using two models not derived from a parent of the DSYHS, i.e. two model variations of a contemporary Open 60 design. This study was aimed at what the influence would be on resistance both in calm water and in waves of the amount of flare in the bowsections above the design waterline. In this case an attempt was made to keep the shape of the foreship below the waterline as identical to each other as possible and make a rather drastical change in the flare of the section above it. The philosophy behind reducing the flare of the bow sections is that here also the added resistance due to sailing in waves is reduced because sailing in (head) waves the amount of energy dissipated is reduced because less damping waves are radiated from these less volumous and beamy bow sections when these are performing large relative motions with respect to the disturbed water surface. However these less volumous bow sections will also imply a lower (nonlinear) pitch restoring moment, which in its turn could lead to higher relative motions at the bow. If this is the case this then could be particularly hazardous when sailing in following waves conditions where broaching (or even pitch poling) could occur due to (increased) deck submergence (bow diving). Therefore in that particular research project also tests in waves have been performed and well both in head- and following waves. In these tests the added resistance has been measured and also the heave-, pitch- and relative motions at the bow.

So information is now presented on the influence of (increasing) stem steepness and bow fineness below the design waterline whilst keeping the deck profile more or less constant and on the flare of the bow sections keeping the underwater part and bow profile more or less constant. Albeit on different boats.

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2 - The Experiment

2 - 1 The Models.

As explained above two different sets of models have been used for the two different parts of this project:

The first set is composed of a parent model and two systematic variations thereof. The parent model of this set is the parent model of Subseries 4 of the DSYHS (model # 44) and is known as the IMS-40. The two additional models are designed with increasing stem steepness in two equal steps. The changes in the hull lines, originating from the changes in the stem steepness, have been restricted to the front half of the models only, i.e. from stern (ordinate 0) to midship (ordinate 5) all three models are exactly identical. This choice implied that the waterline length of the three models increases significantly with stem steepness, because the overall length has been kept constant, and this again results in small changes in volume of displacement, C_p , etc. The two newly derived models are introduced into the DSYHS as models # 51 and # 52. The lines of these three models are presented in Figure 1.

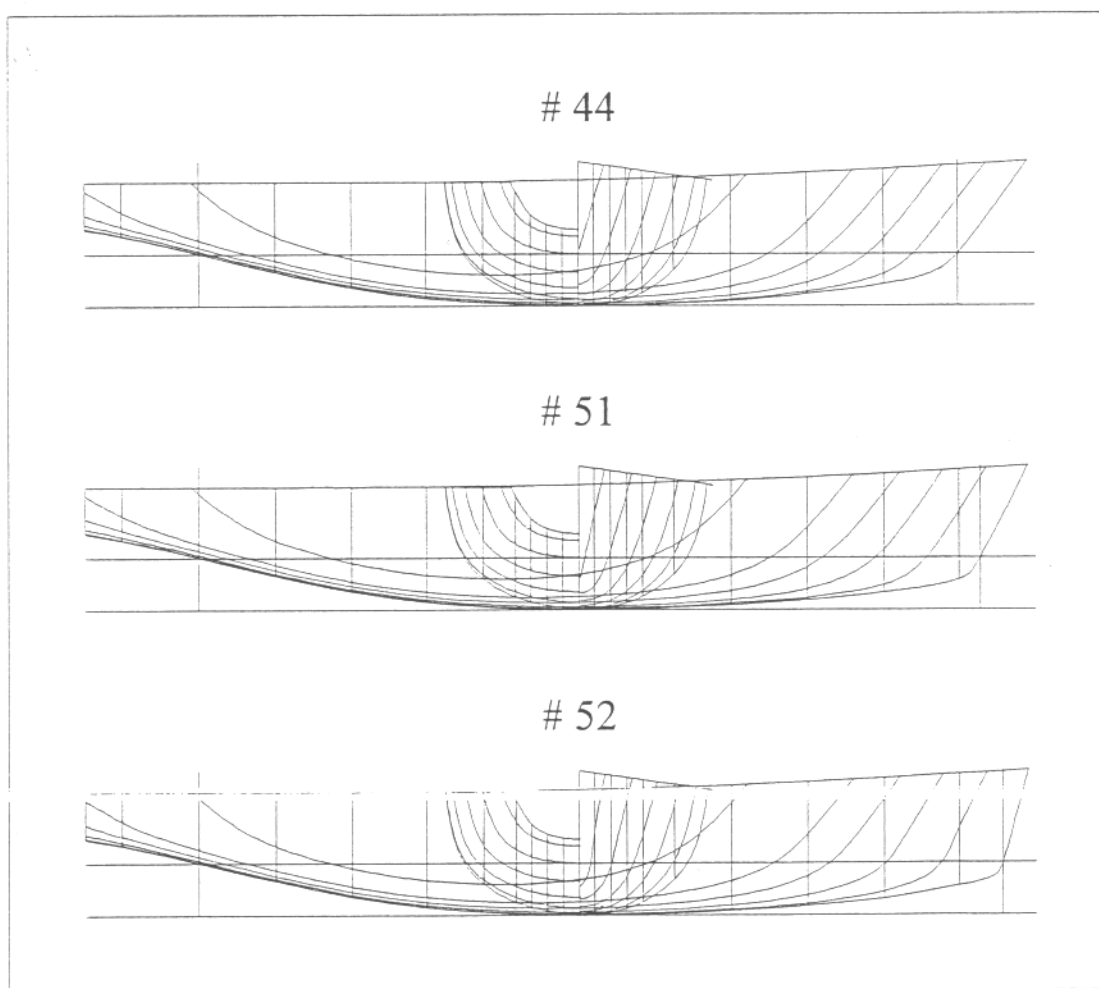


Figure 1 Linesplans of the bow steepness variations within the DSYHS, i.e. the models # 44, # 51 and # 52

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From these lines it becomes immediately obvious how the forebody shape between these three models changes when the stem is steepened, in particular it is leading to hollow waterlines with the steepest stem (model # 52) and since the deck profile is maintained also some flared sections forward. The main particulars of these three DSYHS models are presented in the Table 1 below:

TABLE 1

Model number DSYHS		# 44	# 51	# 52
Length over all	(m)	12.31	12.50	12.43
Length on the waterline	(m)	9.98	10.27	10.53
Beam on the waterline	(m)	3.02	3.02	3.02
Canoe body draft	(m)	0.68	0.68	0.68
Volume of Displacement	(m ³)	8.08	8.21	8.28
Waterplane area	(m ²)	20.3	20.5	20.6
Wetted Area canoe body	(m ²)	23.8	24.3	24.5
LCB (1/2 Lord)	(m)	-0.32	-0.25	-0.21
LCF (1/2 Lord)	(m)	-0.63	-0.58	-0.50
Prismatic Coefficient	(-)	0.558	0.551	0.543
Pitch Radius of gyration	(%Loa)	20	20	20

From the data presented in this Table 1 the differences between the three models, originating from the choices made with regard to the transformation process, are obvious.

The second set consists of two models used for the investigation on the effect of bow flare and are derived with the aid of Groupe Finot from Paris (France) along the lines of an Open 60. The basis design is with the "usual" flare in the bow sections and the second design is with no flare in the bow sections. Although this may not be a totally realistic design it was used for making the possible effects more significant. Great emphasis was placed on keeping the underwater part as identical as possible without creating an unrealistic design. The linesplans of the two models are presented in Figure 2. The main particulars of the two models are presented in Table 2.

TABLE 2

Model #		60-1	60-2
Length over all	(m)	18.28	18.28
Length on the waterline	(m)	16.97	16.97
Beam on the waterline	(m)	3.89	3.91
Canoe body draft	(m)	0.41	0.41
Volume of Displacement	(m ³)	11.02	10.95
Waterplane Area	(m ²)	45.0	44.2
Wetted Area	(m ²)	47.1	46.5
Long..Pos.Centre Bouyancy	(m)	-0.17	-0.18
Long.Pos. Centr. Waterplane Area	(m)	-0.75	-0.82
Prismatic Coefficient Cp	(-)	0.57	0.57
Pitch Radius of gyration	(%Loa)	22	22

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As may be seen from this Table 2 the two models are almost identical as far as the hydrostatic parameters of their canoe bodies are concerned. The difference between the two models are found in the above water part of the hulls as becomes apparent from the linesplans and the bodyplans of the two models as these are presented in Figure 2.

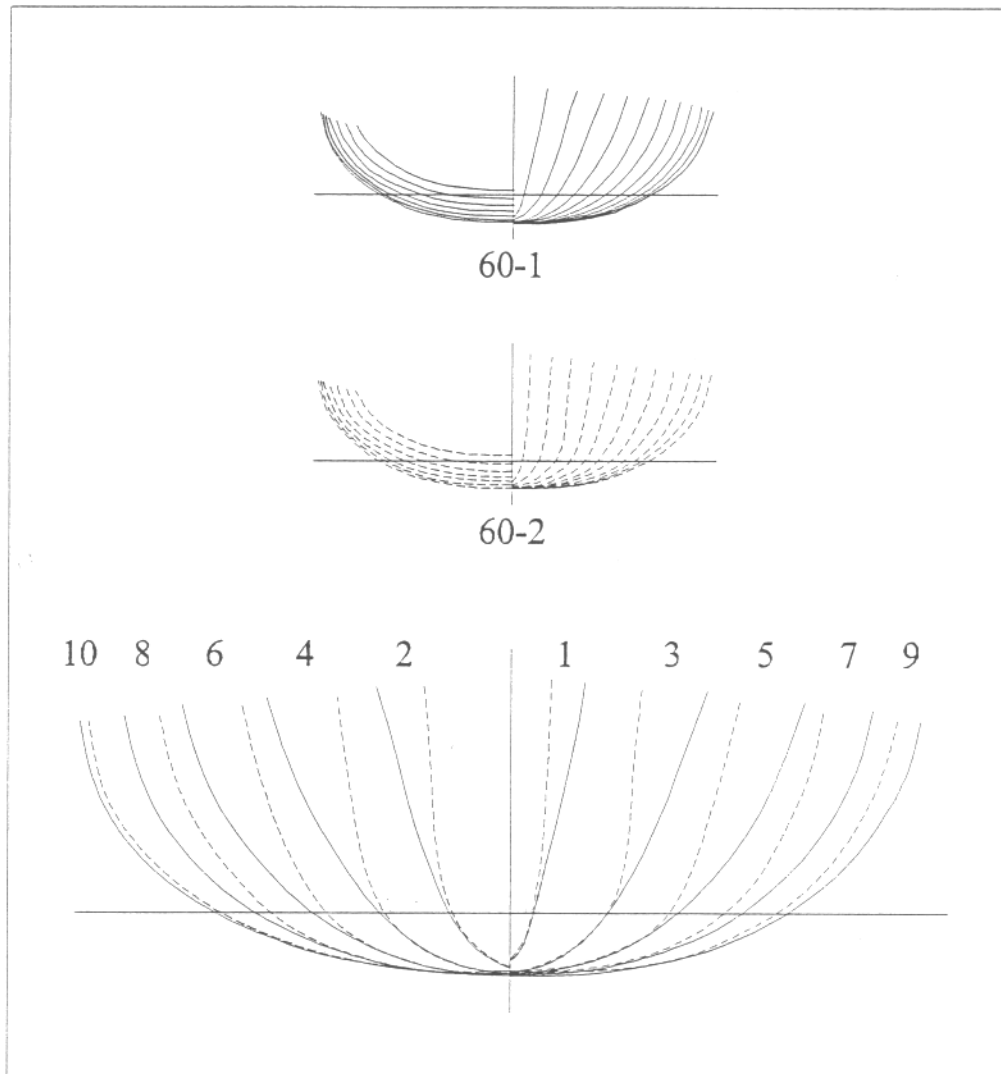


Figure 2 The linesplans and body plans of the bowflare models

2-2 The Measurement Setup and Scheme

All tests have been performed in the large towing tank of the Delft Shiphydromechanics Laboratory. The dimensions of this tank are: Length 145 meters, width 4.5 meters and maximum attainable waterdepth 2.5 meters. The towing carriage is capable of reaching speeds up to 8 m/sec. At one side the tank is equipped with a hydraulically activated wavemaker capable of generating regular and irregular waves.

During the tests all models were connected to the towing carriage in such a way that they were free in pitch and heave but restrained in all other modes of motion. This was established using the so-called "nutcracker" device customary for seakeeping tests, which connects the model to the carriage solely through the exact position of the Center of Gravity of the model. For the DSYHS this is not the way in which the calm water resistance is measured normally.

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Therefor model # 44 has been remeasured in the scope of the present study to make sure that all models have been measured using exactly the same procedure for each of them.

The standard procedure of the Delft Shiphydromechanics Laboratories with regard to turbulence stimulation has been used in these experiments also, i.e. the performing the measurements with both three half- and three full width carborundum stripes on the forepart of the model. The extra resistance caused by these stripes has been determined by taking the difference between the measured resistance using the half and full width and subtract this difference twice from the measured model resistance with the full width stripes to yield the desired measured model resistance. During the tests in waves the waves were measured using three double strings type waveheight measurement devices and the motions of the models were measured using an optical six degrees of freedom tracking device.

For the tests in following waves the models were lifted out of the water to make sure that the generated waves could pass underneath the model prior to the measurement without being disturbed by the presence of the model.

The measurement scheme used for the three DSYHS models was:

- 1 calm water resistance in the Froude range from $Fn = 0.15$ to $n = 0.60$ with half and full width of the carborundum strips.
- 2 Added resistance measurements at two different forward speeds corresponding to $Fn = 0.265$ and $Fn = 0.325$ with regular head waves ranging in length from $\lambda = 0.7 Lwl$ to $\lambda = 3.5 Lwl$ and with wave amplitudes yielding two different wave steepness values i.e. $\lambda / 2\zeta_a = 30$ and $= 40$ respectively.

The measurement scheme for the two Open 60 models was:

- 1 calm water resistance tests in the Froude range from $Fn = 0.15$ to $Fn = 0.75$ with both half and full width of the carborundum strips
- 2 Motion and added resistance measurements in regular head waves at $Fn = 0.35$ (typical upwind condition) with wave ranging from $\lambda = 0.7 * Lwl$ to $\lambda = 3.0 * Lwl$ and a wave steepness between $\lambda / 2\zeta_a = 20$ and $\lambda / 2\zeta_a = 50$
- 3 Motions and added resistance measurements in regular following waves at $Fn = 0.65$ and $Fn = 0.75$ (typical reaching conditions) with waves ranging from $\lambda = 1.2 * Lwl$ and $\lambda = 2.1 * Lwl$ and wave steepness between $\lambda / 2\zeta_a = 20$ and $\lambda / 2\zeta_a = 40$

The measurements with the Open 60 models have been carried out with and without correctional trimming moments for the sail (driving) forces and at both 0 and 20 degrees of heel (no leeway).

For the extrapolations of the measurement data to full scale Froude's extrapolation method has been used together with the ITTC-57 formulation for the extrapolation coefficient C_f . No formfactor has been applied with the DSYHS models because they turned out to be below 0.04 and not using them is consistent within the procedure adopted in DSYHS.

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3 - Discussion of the Results

3 - 1 Calm water results

In Figure 3 and Figure 4 the results of the extrapolation to full scale of the calm water residual upright resistance of the three DSYHS models are presented. The difference between the two plots originates from a different way of comparing these three models: i.e. Figure 3 is plotted on basis of identical forward speeds in m/sec for all models, taking the waterline-length of the model # 44 as the benchmark to determine the Froude number, so no correction is applied for their difference in actual waterline-length and in Figure 4 the same results are presented but now on a basis of the corrected Froude number based on the actual waterline-length of each model.

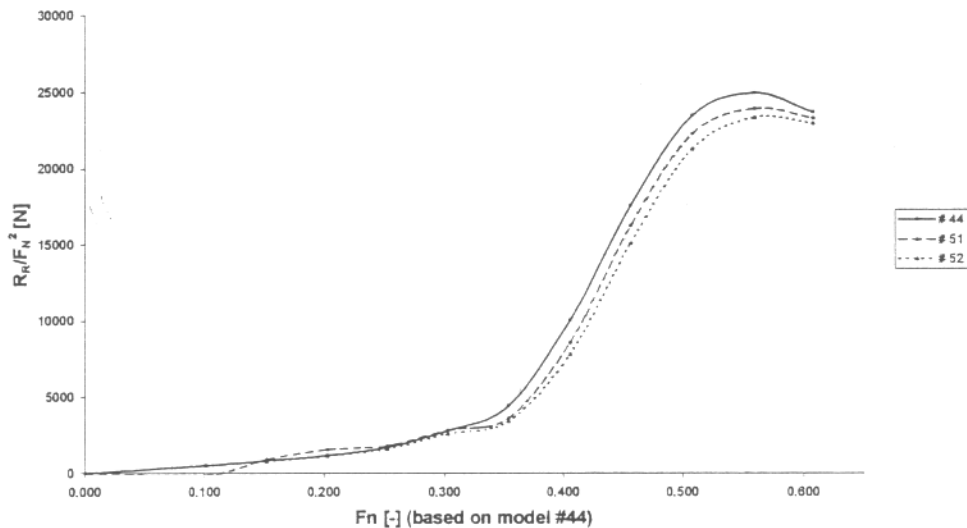


Figure 3 Residuary resistance of the DSYHS models for identical speeds

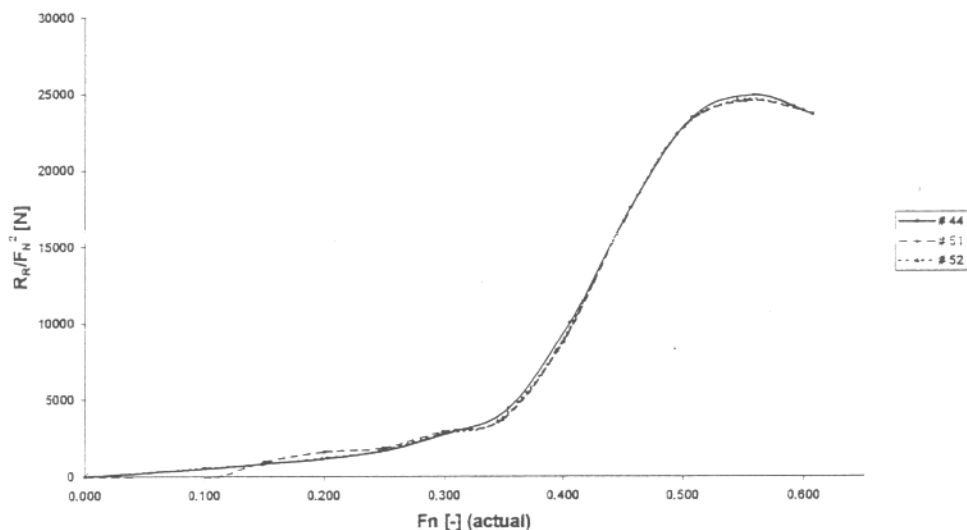


Figure 4 Residuary resistance of the DSYHS models for actual Froude numbers

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The differences in Figure 3 are rather obvious: the longer waterline yacht performs better for a given speed. So increasing waterline-length within the constraint of a constant length over all makes sense. Compared on basis of their actual waterline-length and correct Froude numbers however the differences in the residuary resistance between these three design variations become very small. However in the speed range from $Fn = 0.35$ to $Fn = 0.40$ (critical speed) and then again above $Fn = 0.50$ there appears to be an increasing small benefit for the models with the finer sections forward.

In Figure 4 also the results of an approximation for the residuary resistance are presented using the polynomial expression based on the overall results of the DSYHS as it is presented in [Figure 5](#), [Figure 6](#) and [Figure 7](#).

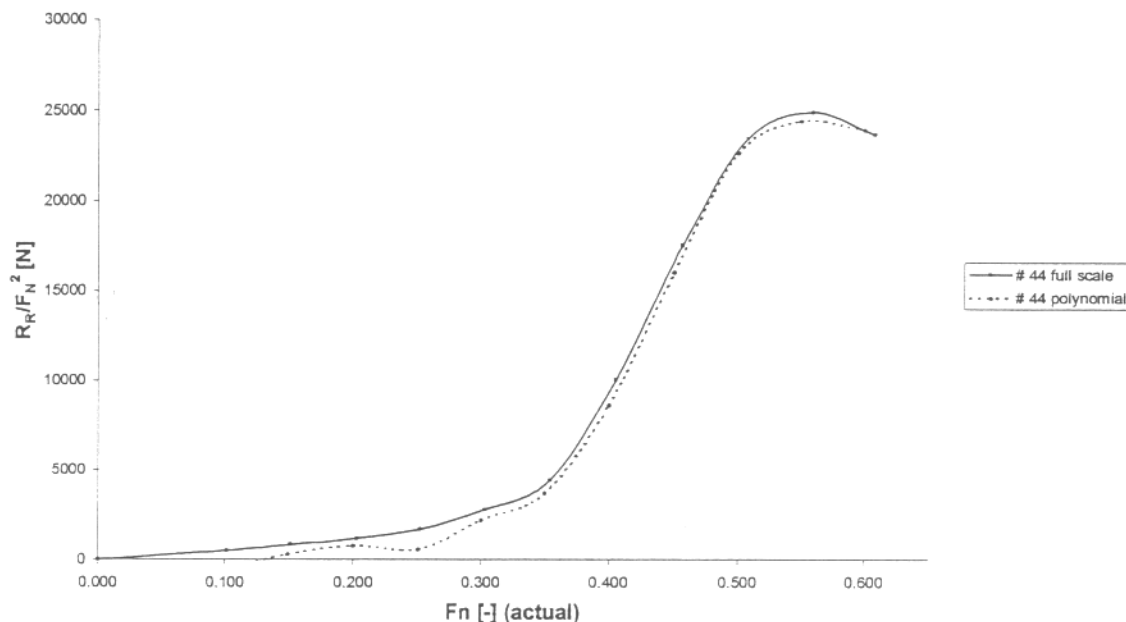


Figure 5 Comparison with DSYHS model #44 and polynomial nov. 1998.

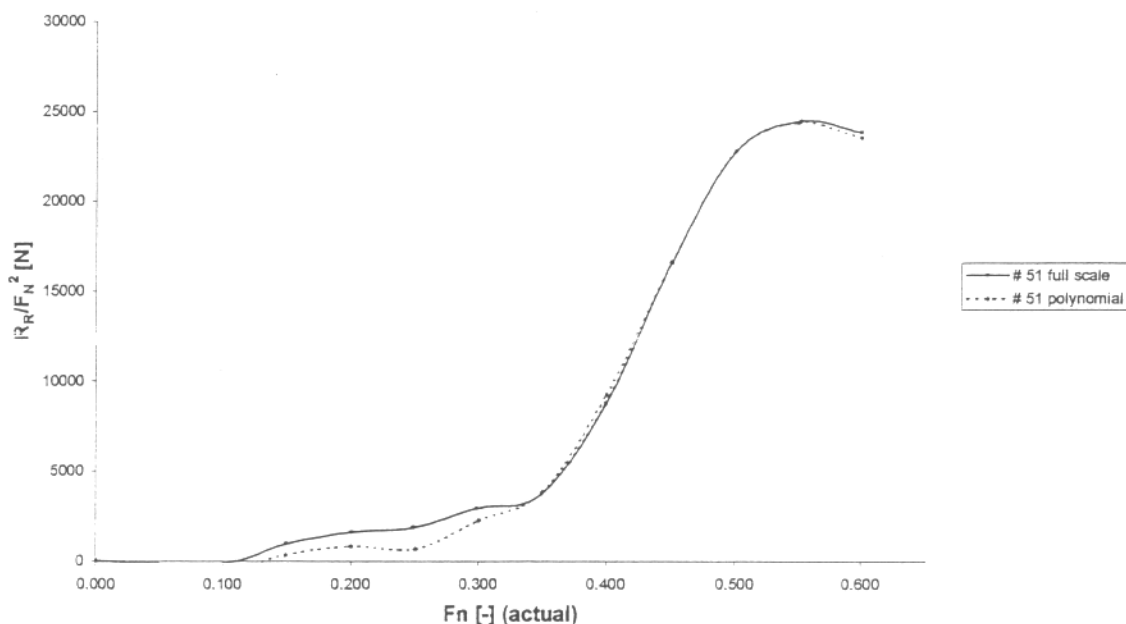


Figure 6 Comparison with DSYHS model #51 and polynomial nov. 1998.

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Although the results are in general in quite close agreement with the measured data it is interesting to note that these expressions yield a reverse trend for the three models in the speed range around $F_n = 0.40$. It should be noted that in this polynomial expressions no explicit parameter like the waterline entrance angle is present and the differences in forebody shape are only taken into account using an implicit approach through L/B and C_p etc.

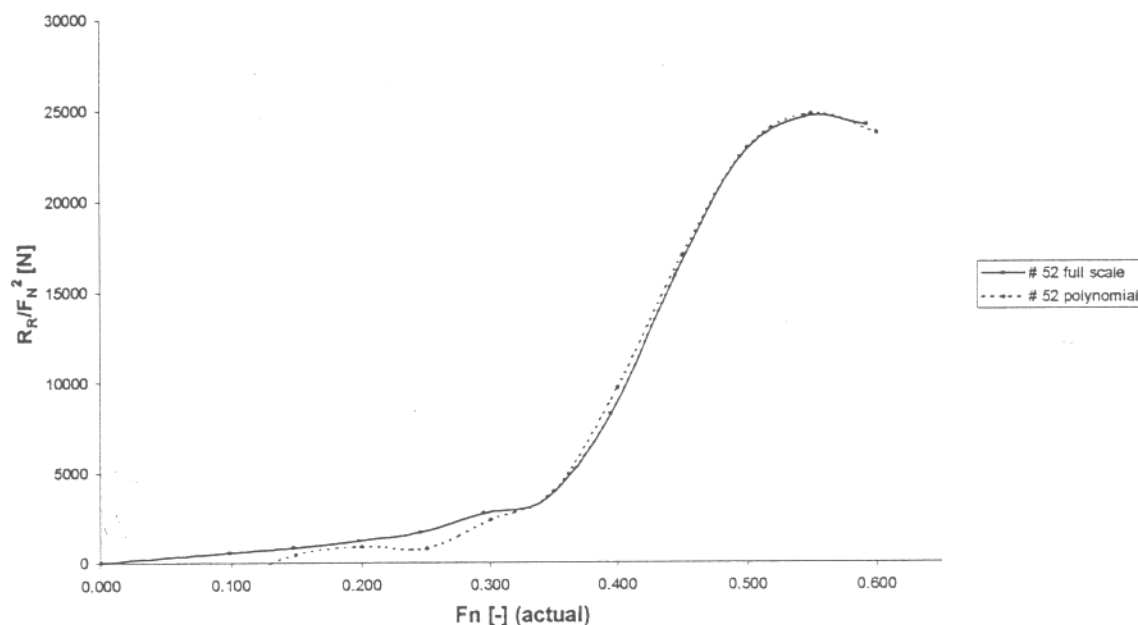


Figure 7 Comparison with DSY model #52 and polynomial nov. 1998.

The extrapolated results for the upright total resistance of the two Open 60 designs are presented in [Figure 8](#) for the condition during the measurements in which no correction moment was applied for the trimming moment exerted by the driving force generated by the sails. In this extrapolation to full scale a form factor of around $k = 0.11$ (and slightly higher for model 60-1) has been used. This value for the form factor was derived from the measurements by using a so-called Prohaska plot.

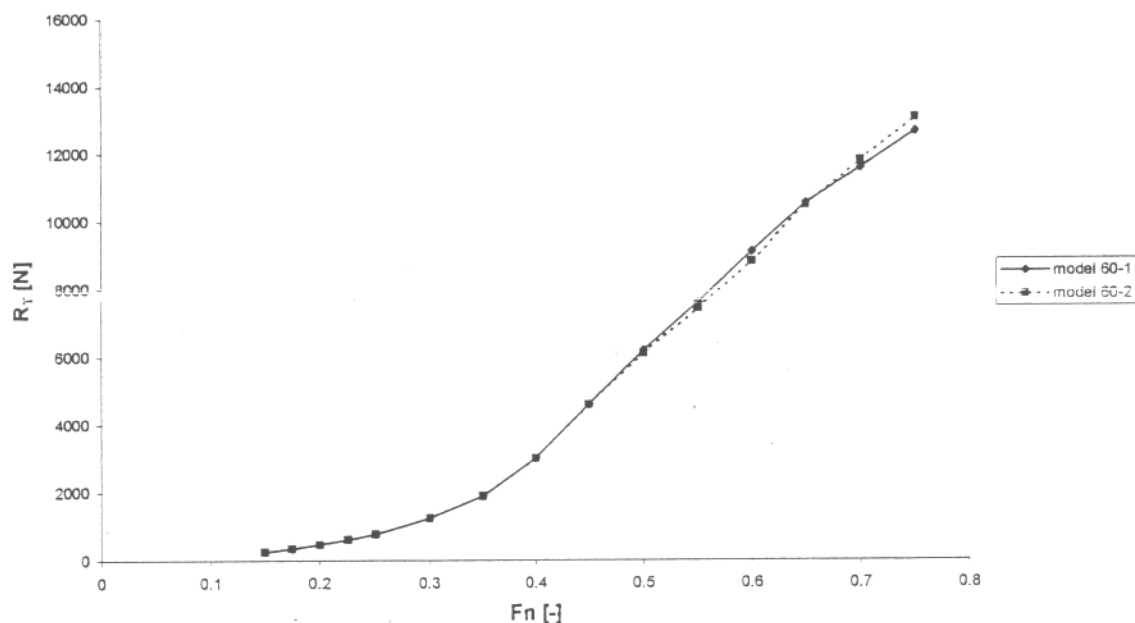


Figure 8 Upright resistance of model 60-1 and 60-2 without trim moment

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As may be seen from this Figure 8 the differences between the two designs are very small although model 60-2 appears to have in general a reduction on total resistance of around 1.2% compared to 60-1. This is to be expected because of the close similarity of the models up to the design waterline and the small difference will be induced by the slightly lower displacement and wetted area of the model 60-2.

The difference in the above water shape between these two models becomes only significant when the results of the resistance measured with the longitudinal trimming moment is applied during the measurement, i.e. the moment that is exerted on the boat due to the driving force (equal to the resistance at that speed) in the center of effort of the sails. These results are presented in Figure 9

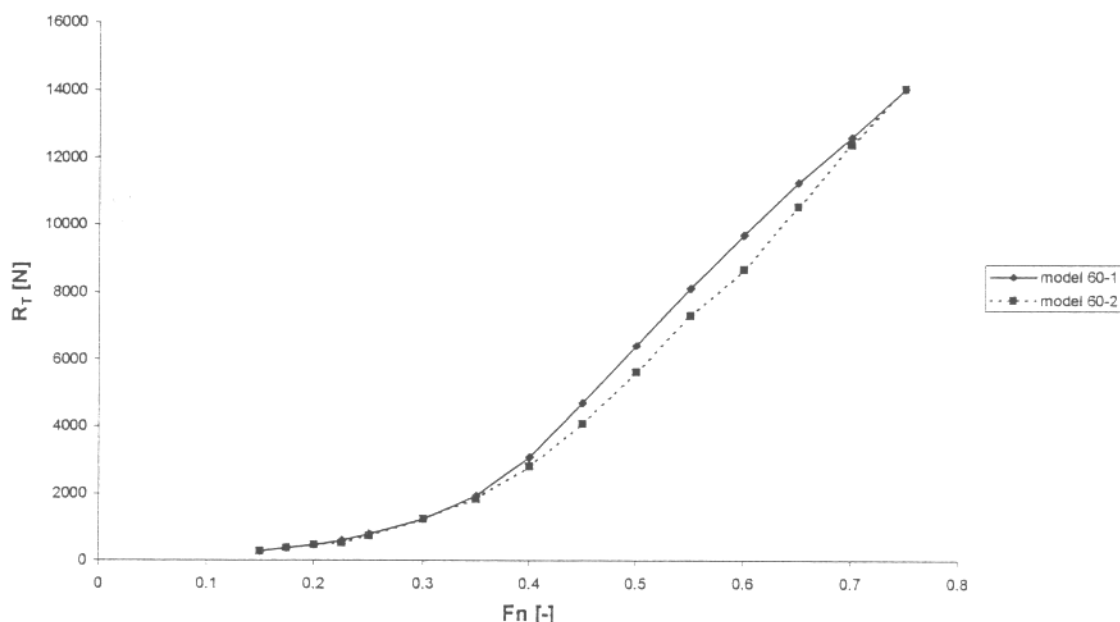


Figure 9 Total resistance of models 60-1 and 60-2 with trimming moment applied

From these results it can be seen that the model 60-2 has a definite advantage over the 60-1 in particular when this trimming moment becomes substantial, i.e. at speeds above $F_n = 0.30$. In the entire speed range of 10 to 15 knots model 60-2, with the "low volume bow", has circa 8% less resistance. This difference in resistance is caused by the differences in sinkage and running trim: the sinkage of model 60-2 is significantly less and the running trim, which can be quite substantial for these kinds of yachts (i.e. 1.5 – 2.0 degr.), is lower at the higher speeds. At the highest speeds the bows are clear of the water and the differences diminishes. These results will undoubtedly be influenced by the designs under consideration, i.e. the Open 60. The trends observed on the resistance of these models however will probably also be valid, albeit to a smaller extend, on other designs.

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3 - 2 Head waves added resistance

Some results of the added resistance measurements in head waves with the three DSYHS models are presented in the Figure 10 and Figure 11 as being typical for all other results also. In these figures only the results of R'_{aw} for one forward speed are presented at two different values for the wave steepness, i.e. $\lambda/2\zeta_a = 30$ and $\lambda/2\zeta_a = 40$.

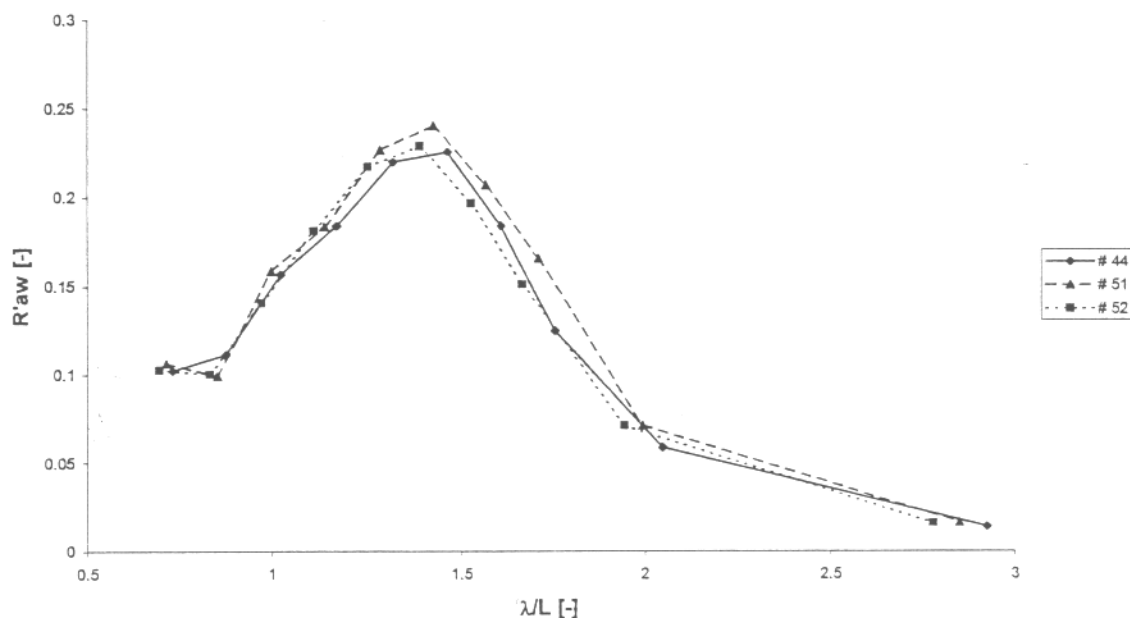


Figure 10 Added resistance in head waves at $F_n = 0.325$ and $\lambda/2\zeta_a = 30$

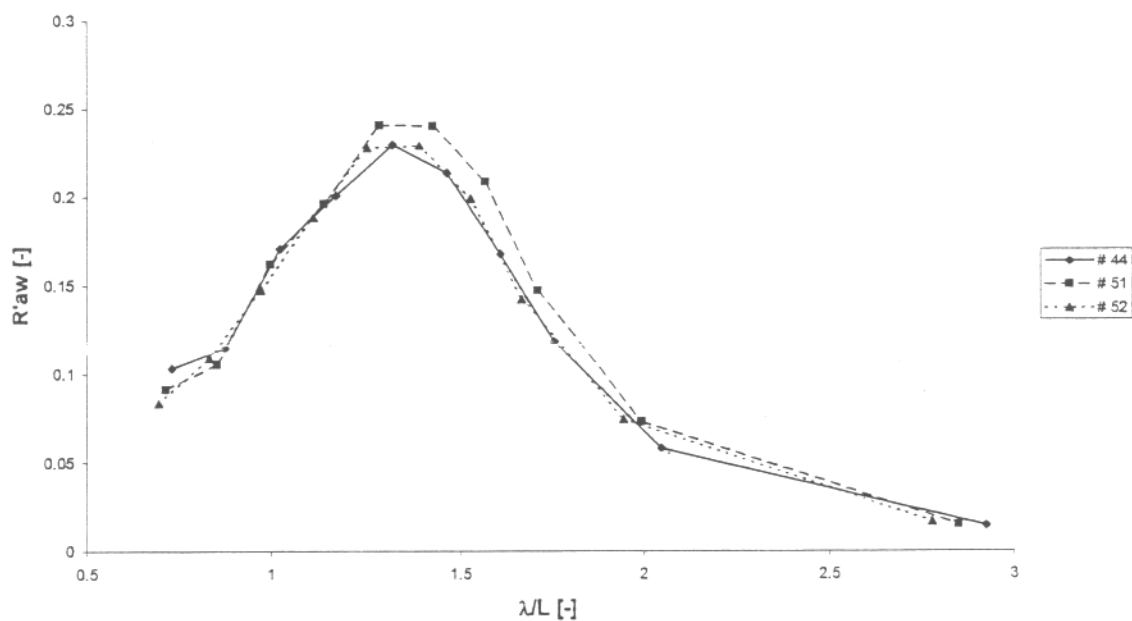


Figure 11 Added resistance in head waves at $F_n = 0.325$ and $\lambda/2\zeta_a = 40$

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These results are in contradiction maybe to what was expected; i.e. the model with the finest bow (i.e. # 52) has the lowest added resistance in waves. The difference between the three models appears to be small however, in particular when an accuracy band around the measured values is considered, then no significant difference may be found. There is inevitably some inaccuracy in these R_{aw} measurements because this "added resistance in waves" is obtained by subtracting two rather large quantities: i.e. the calm water resistance at the forward speed under consideration and the averaged time integrated (higher) resistance in waves at the same speed. This later quantity on its turn is determined by integrating and averaging a rather oscillatory force signal over a large number of wave encounter periods. So the trend between the added resistance differences between the models is not very consistent.

What may be observed from the results also, and this has been found before by other authors such as Hirayama for an IACC yacht in head waves (Ref [4]), is that there appears to be a dependency of the added resistance RAO on the wave steepness in such a way that the added resistance in waves RAO, i.e. $R'_{aw} = R_{aw} / \zeta_a^2$, decreases with an increasing wave steepness, i.e. increasing ζ_a for a given λ . This nonlinearity in R_{aw} , which may be introduced by the changes in displaced volume of the bowsections which is brought into contact with the water whilst the bow is performing large relative motions. In this respect the three DSYHS models have a contradictory trend with respect to their bow fineness, i.e. the underwater part (and so the waterlines) are "stretched" with increasing bow steepness but in the same time the flare of the sections above the waterline is increased, because the deck profile has been kept more or less constant. This may be seen from the body plans of these models as presented. Also the tests for all three models have been performed on exactly the same model speed, which actually implies a somewhat lower Froude number for the longer models.

This phenomenon is maybe even more clearly demonstrated by the results obtained from the tests with the two Open 60 models in head waves as presented in Figure 12, because between these models only the flare of the bow sections has been changed.

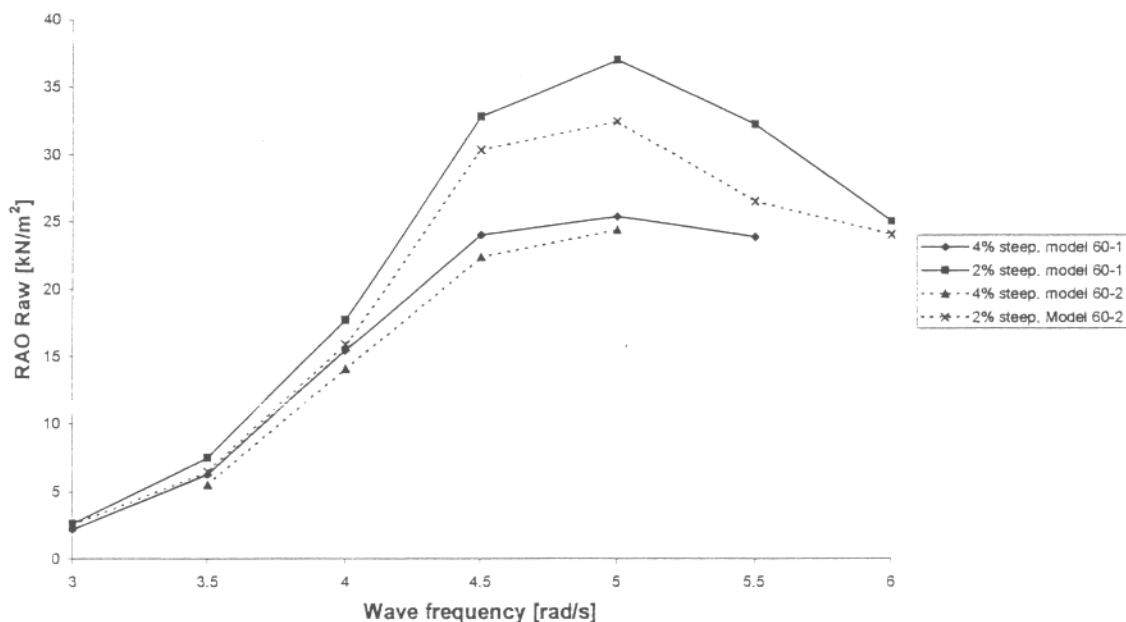


Figure 12 Added resistance in head waves at $F_n = 0.35$ of model 60-1 and 60-2

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From Figure 12 it is obvious that almost over the entire frequency range investigated the added resistance in waves of model 60-1 is higher than the added resistance of model 60-2. Although the RAO's are (again) strongly reduced with increasing wave steepness the difference between these two models increases also with increasing wave steepness and the maximum difference in the RAO may become as large as 20% for certain wave lengths. The effect on the added resistance of a larger increase in the momentary submerged (sectional) volume at the bow of model 60-1 while performing large relative motions apparently overrules the effect of the larger relative motions at the bow of model 60-2 because these were found to be significantly larger for model 60-2 when compared to model 60-1. This was confirmed by analysis of the time history of the resistance/surge force signal from the transducers. The larger relative motion for 60-2 was conform expectation. It should be noted though that no deck submergence occurred during these tests with either of the two models. The amount of water on deck however was considerably larger for model 60-1 than for model 60-2 possibly due to significant difference in the dynamic swell-up and spray generated.

3 - 3 Following waves

The added resistance in following waves has been measured with and without the correctional trimming moment to simulate the longitudinal moment caused by the driving forces on the sails. Without this correction the differences in added resistance are generally small, although again increasing with the wave steepness similar to the head waves condition. With the longitudinal correction moment applied the differences between the two models become more significant. This is probably largely due to the differences in resistance between the two models when the bow is being trimmed down, i.e. the model with bow flare (60-1) suffers more than the model without (60-2) Results are presented in Figure 13.

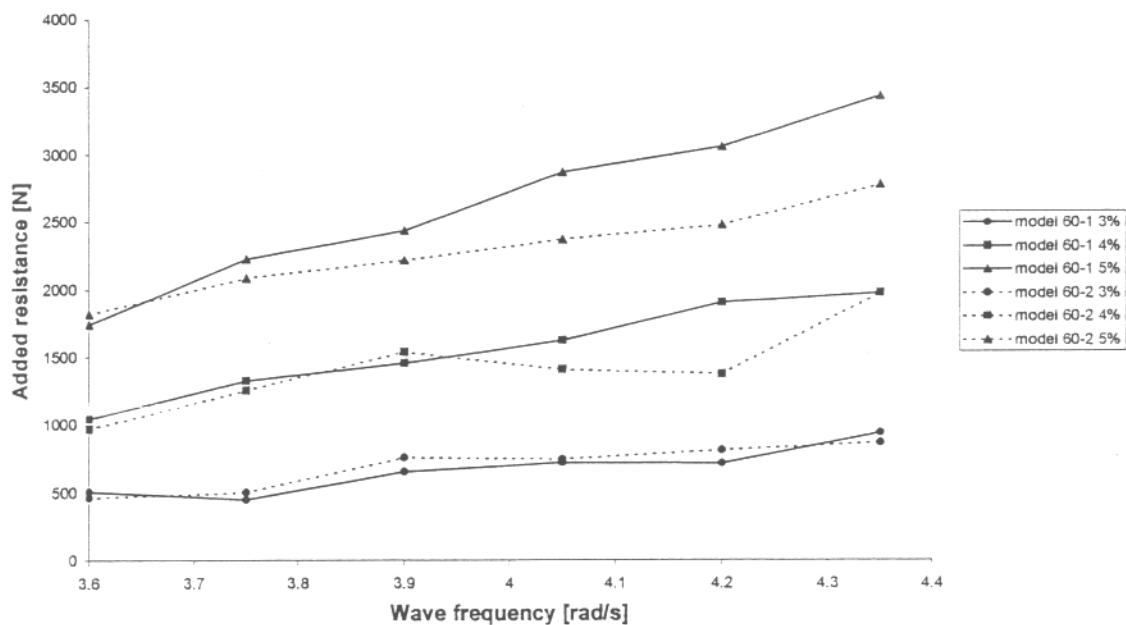


Figure 13 Added resistance in following waves at $F_n = 0.65$ model 60-1 and 60-2

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Although these results are not presented here the tests in following waves at the highest speed, i.e. $F_n = 0.75$ showed even larger differences between the two models.

As far as the safety of the yacht is concerned the results of the vertical displacement of the bow for the two models in following waves is presented in Figure 14. From this Figure it is obvious that the bow of model 60-2 at higher speeds is almost 10 cm deeper in the water than the flared bow of model 60-1. Although this may seem a small difference in steep following waves this made a tremendous difference in the likelihood of bow diving and green water on deck.

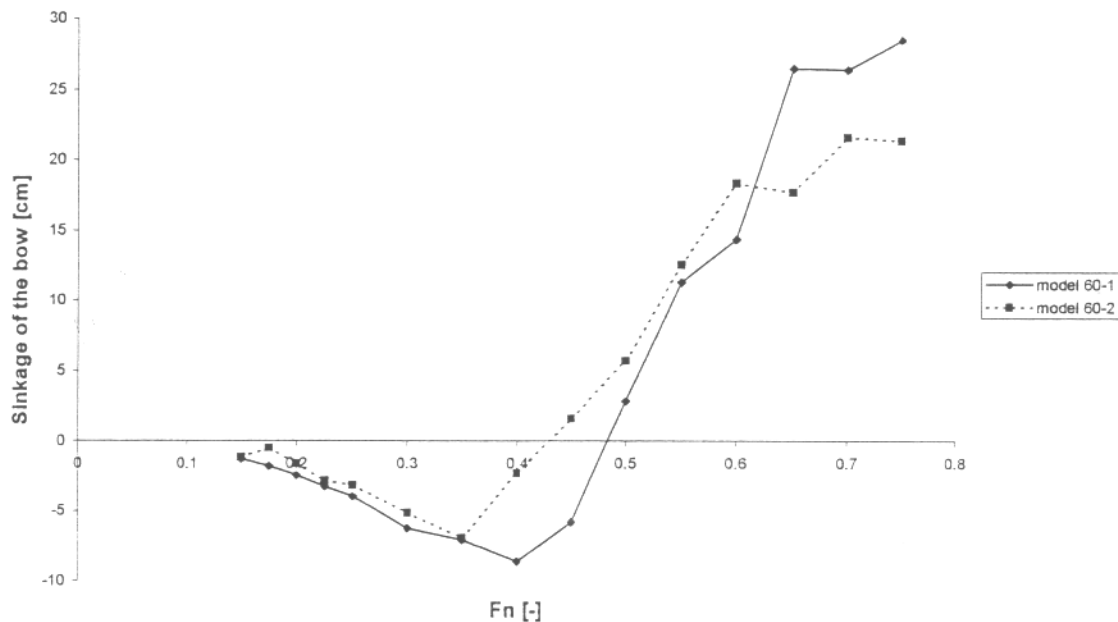


Figure 14 Bow sinkage in following waves with trim moment applied.

In the speed range from 8 to 17 knots the model with the thinner bow (model 60-2) performed some 15 to 20% larger relative motions at the bow compared to the flared bow (model 60-1) in particular for the longer and the steeper waves.

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3 - 4 Conclusions

As a conclusion of both studies reported here it could be stated that increasing the stem steepness implying stretching the waterlines in the underwater part of the hull while keeping the above water part of the bow more or less constant does not seem to have a large influence on the calm water resistance as long as the lengthening of the waterline is being taken into account properly. The fine waterline entry does not influence the added resistance due to waves to a large extent because the relative large relative motions at the bow make the shape of the bow above the still waterline at least as important as the shape below it. Reducing the flare in the bow sections creates a significantly larger difference in added resistance, both in head and in following waves. But with respect to the safety of the yacht the increase of the relative motions at the bow may cause an increased probability of deck submergence.

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