"An Approximation Method for the Added Resistance in Waves of a Sailing Yacht"

by
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Abstract.

For the use in a VPP environment an easy to use calculation method for the assessment of the added resistance of a sailing yacht, when sailing in waves, is essential to be able to compare a large number of designs in the early design stage.
The method used should be able to take into account the primary design parameters of interest as far as added resistance in waves is concerned. Also the trends should be predicted correctly because these play an important role when comparing different design alternatives. In many cases these are more important than the absolute values. On the other hand in the assessment of the added resistance calculations the actual environmental conditions, i.e. the shape of the wave spectrum, may play an important role. Therefore the calculation method preferably should be capable of taking into account user defined (wind generated) wave conditions.
Different methods are available. The method presented here makes use of a polynomial expression derived from an extensive data base containing all the relevant hull data to approximate the Response Amplitude Operator (RAO) of the added resistance in waves of an arbitrary yacht. In the VPP environment this RAO can be combined with an arbitrary wave spectrum to yield the added resistance at any speed at any heading between head wind (180 degrees) and beam seas (90 degrees).
The method is described and presented in this paper. Some results are shown and the advantages over the traditional methods shown.

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1. Introduction.

Since the introduction of the influence of the seakeeping behavior of a sailing yacht in the velocity prediction in the 70's considerable attention has been paid to the subject. In particular the added resistance in the wind generated waves, which are inevitably present when sailing with wind on exposed waters, drew a lot of attention. Both the designers and the "operators" found that there were considerable gains in speed and performance to be made by proper design and operation of the sailing yacht. Noticeable papers on the subject were, amongst others, presented by Gerritsma in 1974 Ref [1] showing the influence of Length Displacement ratio and Longitudinal radius of Gyration and by Gerritsma and Keuning in 1994 Ref [2] showing also the influence of the heel and the leeway on the added resistance.
Both the experiments in the towing tanks with sailing yacht models in waves and the calculation methods for the added resistance of a sailing yacht in waves however contain deficiencies. The towing tank tests are hampered by the difficulty of towing the yacht in the proper equilibrium condition (at reasonable cost) and the absence of the sail forces. The calculation methods generally used in the Shiphydromechanics field for commercial ships are also not fully applicable. The influence of the heel causing asymmetry in the geometry of the hull, the influence of the instationaire lift on the appendages, the influence of the damping of the motions by the presence of the sails and the influence of the relatively high Froude numbers at which the yachts are sailing causes problems for the more traditional methods methods. These may also be overcome by more sophisticated methods now available, but again at considerable cost and time.
To increase the challenge also the environmental conditions in which the yachts are sailing are most of the time not precisely known. These however have a considerable influence on the result. Parameters like the exact shape of the (wave) energy distribution over the frequency range, the directional spreading in the wave spectrum and for instance the effect of the wave-current interaction have a large influence on the final outcome and are commonly not available.
So, in general this implies that there is a strong tendency in the design and evaluation process to put the most attention on the comparison between various design options and so the trend of the relation between the performance and the parameters of interest should be properly predicted.
In addition, this implies that a method should be available which is capable of assessing the added resistance in waves in a generic Velocity Prediction Program (VPP) "environment".

The most straight forward approach is the one being used in the VPP of the International Measurement System (IMS) from the Offshore Racing Congress (ORC). This method is based on the calculation of the added resistance using a 3-D potential theory panel method with forward speed on a small series of 5 systematically varied hulls. The added resistance is approximated with the Length/Displacement the Beam/Draft and the Longitudinal Radius of Gyration (k_{yy}) as prime parameters. In this assessment, a fixed relationship between the wind speed and the generated waves is assumed. The shape of the wave spectrum and the energy distribution is kept constant and only the significant wave height is varied with wind speed. This relationship is based on a limited amount of real scale measurements on one or two of the larger lakes in the USA. This is an obvious restriction of the general applicability of the method when more or all of the (major) sailing areas of the world are considered.

This brought Gerritsma, Keuning and Versluis Ref [3] in 1993 to the introduction of a more elaborate assessment method. This method was based on the results of calculations using the, in Shiphydromechanics widely used method known as the "ordinary 2-D strip theory" and the well proven "Gerritsma-Beukelman" method for the determination of the added resistance, on a series of 8 different hulls, all part of the extensive Delft Systematic Yacht Hull Series (DSYHS). The added resistance of all hulls was calculated with three variations in the k_{yy} value, for a range of forward speeds and headings between 135 and 90 degrees. The parameters of the hulls taken into the final assessment method for the added resistance were the Length/Displacement ratio and k_{yy}.

To obtain mean values in a realistic seaway these calculations were carried out in a number of wave spectra for fully developed seas according to the well known Bretschneider formulation:

$$S_\zeta = A\omega^{-5}e^{(-B\omega^{-4})}$$

in which: $A = 173\dfrac{\overline{H}_{1/3}}{\overline{T}_1^{\,4}}$ and $B = \dfrac{691}{\overline{T}_1^{\,4}}$

with:

S_ζ wave energy spectral density [m^2s]

ω_e encounter frequency of the wave [rad/s]

$H_{1/3}$ significant wave height [m]

T_1 average period of the spectrum [s]

By doing so they enabled the introduction of both the mean wave period T_1 and the significant wave height $H_{1/3}$ as an input parameter for the assessment method.

A systematical analysis of the results obtained for the added resistance by these calculations showed that for constant wave direction, wave height, wave period and forward speed the added resistance depends for the greater part on the factor:

$$\nabla^{1/3} / Lwl * k_{yy} / Lwl$$

A typical result is presented in Figure 1 for T_1 = 4 sec. $H_{1/3}$ = 1.5 meter, Fn = 0.35 and waterline length Lwl = 10 meters.

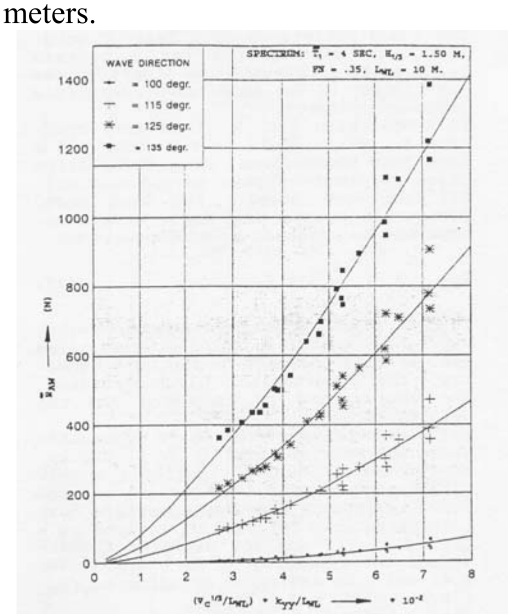

Figure 1: Dimensionless Added Resistance in Waves for one Froude number and 4 headings

All the results of these added resistance calculations have been summarized in a dimensionless form and approximated by a regression formula given by:

$$\frac{\overline{R}_{AW} 10^2}{\rho g \cdot Lwl \cdot {H_{1/3}}^2} = a\left[10^2 \frac{{\nabla_c}^{1/3}}{Lwl}\frac{k_{yy}}{Lwl}\right]^b$$

in which the coefficients a and b are presented in Ref [3] for different T1, different headings and different Froude numbers. By implementation of the actual significant wave height and selection of the appropriate coefficients for the selected $T_{1,}$, wave heading and Froude number the actual mean added resistance for a particular yacht can be assessed.

With this new method it became possible to specify (and differentiate for) the wave spectrum in which the yacht is sailing, al be it for a limited range of spectra.

After a while however it was felt that the number of parameters describing the hull geometry and used in the assessment was too restricted, since the influence of important hull shape parameters such as the Length to Beam ratio (L/B), the Beam to Draft ratio (B/T) and the prismatic coefficient Cp were not taken into account. Therefore it was decided to extend the numbers of models from the DSYHS used for the added resistance calculations in order to be able to include these hull parameters too.
So in 1997 this method was extended during a research project carried out at the Delft Shiphydromechanics Department as part of his MSc project by D Schaaf of the Haarlem Polytechnics. The results of this extension were presented in 1998 by Keuning and Sonnenberg in Ref [4].
The formula now read as follows and was based on computational results obtained for 16 instead of 8 models of the DSYHS, each again with three different values for k_{yy} and for the same number of different headings and forward speeds:

$$\frac{R_{AW} \cdot 100}{\rho \cdot g \cdot Lwl \cdot H_{1/3}^2} = A_1 \cdot \frac{k_{yy}}{Lwl} \cdot \frac{\nabla c^{1/3}}{Lwl} + | A_2 \cdot \frac{k_{yy}}{Lwl} + A_3 \cdot Cp^2 + A_4 \cdot \frac{Lwl}{Bwl} + A_5 \cdot \left(\frac{Lwl}{Bwl}\right)^2 + A_6 \cdot \frac{Bwl}{Tc} + A_7 \cdot \left(\frac{Bwl}{Tc}\right)^2$$

The set of coefficients A_1 to A_7 belonging to this assessment formula is rather more extensive and presented in Ref [5].

It should be noted that the analyses mentioned are restricted to wave directions forward of the beam. In general it is assumed that the waves are coming from the direction of the true wind. So the wave angles for which the added resistance are presented ranges from 135 degrees (close hauled) till 90 degrees (beam wind). For waves aft of the beam the calculation of the added resistance in a given spectrum according to the strip theory is considered to be not reliable. However, in general the added resistance in those conditions is rather small and may even become negative in the situation of “surfing”. These effects are not included.

Still the need was felt for a more general approach in which it was possible to combine each wind with any wind generated wave spectrum. Also the inclusion of a 180 degrees wave

direction (i.e. head waves) was considered of relevance because motoring in head waves and being able to calculate the extra engine power needed was an interesting aspect for designers.
So, an approach previously investigated but abandoned for the time at that moment was taken up again. In their report in 1993 Gerritsma, Keuning and Versluis Ref [3] already mentioned the possibility of approximating the Response Amplitude Operator (RAO) for the added resistance in waves for an arbitrary yacht directly by means of a polynomial expression. If this proved to be feasible for a range of yachts, in a range of speeds and headings then calculating the added resistance in an arbitrary wave spectrum becomes possible.

This method is described in the following chapter.

2. The approximation of the added resistance in waves of an arbitrary yacht

Similar to the previous methods the calculations in the present method for the added resistance in waves have been performed with the 2-D linear ordinary strip theory method. In this method the added resistance of a ship in waves is approximated by calculating the radiated energy of the damping waves of the ship according to the well known Gerritsma-Beukelman method, i.e.:

$$R_{AW} = \frac{1}{\lambda} \int_0^{Lwl} \int_0^{Te} b' Vz^2 dx_b dt$$

in which:

λ	wave length	[m]
t	time	[s]
b'	sectional damping	[Ns/m^2]
V_z	relative vertical vel.	[m/s]
T_e	period of wave enc.	[s]
x_b	length coordinate	[m]

The vertical velocity V_z is determined for each cross section as the sum of the heave-, pitch- and orbital velocity in the incident wave.

In irregular waves, for a known wave spectrum, the mean value of the added resistance may be calculated using the linear superposition principle yielding:

$$\overline{R}_{AW} = 2\int_0^{\infty} \frac{R_{AW}}{\zeta_a^2} S_{\zeta}(\omega_e) d\omega_e$$

in which :

ζ_a	wave amplitude	[m]
R_{aw}	added resistance response	[N]
S_ζ	spectral density	[m^{2}s]
ω_e	encounter frequency	[rad/s]

In general it was shown that this method yielded quite satisfactory results for the "average" type of hulls like the parent hulls of Series1 and 2. These yachts in particular have no extreme values for parameters such as the beam to draft- and the length to displacement ratio's. Also for a considerable number of actual designs the results have been compared with measurements and in general yielded satisfactory agreement considered in the light of the difficulties encountered with the measurement and the assessment of the added resistance in waves in general.

To investigate the applicability of the 2-D strip theory based calculation method used even further a new and extensive series of towing tank experiments in waves with 5 models of DSYHS Series 4 have been carried out in head waves by M. Levadou at the Delft Shiphydromechanics Laboratory in 1994 Ref [5]. The models used for this validation experiment were model #42, #43, #44, #45 and #46 within the DSYHS and known as IMS-40 models 1 till 5. This little sub series of the DSYHS series actually contains a systematic variation in length-beam ratio (L/B) and length-displacement ratio ($L/\nabla^{1/3}$). In these new tests the influence of the beam to draft ratio (B/T) has been investigated implicitly once again, but now within a much more usual range as compared with those tested with the models 26 and 27 of DSYHS Series 2. In addition also the influence of the longitudinal radius of gyration has been investigated on model 44 (parent model DSYHS Series 4) and checked against the results of the computations.

Variation	Model Nr.	Lwl/Bwl	$Lwl^3/\nabla c$	k_{yy}/Lwl
Base Hull	IMS-40-3	3.31	123	0.25
L/B ratio	IMS-40-2	2.77		
	IMS-40-4	4.16		
L^3/∇ ratio	IMS-40-1		104	
	IMS-40-5		156	
k_{yy}/L ratio	IMS-40-3			0.30

Table 1 Model Hull Variations for Added Resistance

From the results of this research project it was concluded that the prediction based on the 2-D strip theory approach yielded good results for range of the length-displacement ratio (and beam-draft ratio) and the range in the radius of gyration as tested, but for the length beam ratio the calculations showed hardly any dependency while the measurements showed a considerable lower added resistance for the high length beam ratio model.
In general the trends in added resistance with changing parameters are predicted correctly however. Therefore the general correlation between the measured and calculated values was considered good enough for an assessment of the added resistance based on these results for incorporation in a VPP.

For the development of the present approximation method however a more general use of the models constituting the DSYHS was needed. Therefore the results of the computations using this 2-D linear strip theory approach have been checked with two additional and rather more extreme models. With these models an extensive series of towing tank experiments have been carried out with two rather more radical models of the DSYHS Series 2, i.e. models #26 and #27, in head waves. The aim was to check on the accuracy of the calculations as well as on the influence of the heeling angle, the leeway and the side force production (i.e. lift) on the appendages on the added resistance. In the usual calculations these effects are not accounted for.
The results were presented in Ref. [2]. These indicated:

- The influence of the heeling angle on the added resistance was generally small except for the very low beam to draft ratio model and well within the accuracy range obtained with these type of calculations anyway and therefore the heeling angle was omitted from the further investigations. Therefore all tests and calculations have been carried out with the models in the upright condition.

- The influence of the leeway angle and the side force produced by the appendages underneath the hull on the motions and the added resistance of the yacht was also very small. Therefore all the tests and calculations to derive the approximation method are based on the results obtained for the unappended hulls only.

3. The approximation of the Response Amplitude Operator

So to yield the widest range of options available in the RAW calculation the possibility of assessing the RAO of the added resistance in waves (RAW) for an arbitrary yacht is investigated.
Because it was considered to be too complicated and CPU time consuming to incorporate a full 2-D strip theory code into the VPP and because then a full lines plan would be necessary, it was decided to investigate the possibility of assessing the RAO of the RAW of an arbitrary yacht by means of a polynomial regression formula through an extensive data base.
A first attempt was made by Reumer, Ref [6], as fulfillment of his MSc project at the Delft Shiphydromechanics Department in 1997. He carried out the strip theory calculations of the RAW for a sub series of the DSYHS models. The calculations were carried out for the full scale models, i.e. at 10 m waterline length. He compared the results of various polynomial expressions of the RAO of the RAW for the goodness of fit with the original data base results and found the following expression to be the most accurate:

$$f_3 = R_{aw} = a_1.(\frac{L}{\nabla^{1/3}}) + a_2.(\frac{L}{\nabla^{1/3}})^2 + a_3.(\frac{L}{\nabla^{1/3}})^3 + a_4.(\frac{L}{B}) + a_5.(\frac{L}{B})^2 + a_6.(\frac{B}{T}) + a_7.C_p + a_8.C_p^2 + a_9.C_p^3$$

In a later project N Homma, Ref [7], extended the data base in 2003 by using now all the models of the DSYHS for the calculations and taking into the calculations also the wave heading of 180 degrees, i.e. head waves, to extend the range of applicability. In order to make the expressions applicable to an arbitrary yacht size, the expressions were also made non dimensional. The new expression reads

$$\frac{R_{aw}}{\rho.g.L_{wl}.\zeta^2} = a_0 + a_1.(\frac{L}{\nabla^{1/3}}) + a_2.(\frac{L}{\nabla^{1/3}})^2 + a_3.(\frac{L}{\nabla^{1/3}})^3 + a_4.(\frac{L}{B}) + a_5.(\frac{L}{B})^2 + a_6.(\frac{B}{T}) + a_7.C_p + a_8.C_p^2 + a_9.C_p^3$$

The set of coefficients is quite extensive. The coefficients have been determined for all combinations of:

- Froude numbers 0.20, 0.25, 0.30, 0.35, 0.40 and 0.45
- Angle of wave incidence 100, 120, 140, 160 and 180 degrees
- Radii of gyration 0.20, 0.25 and 0.30 times Lwl
- Wavelength/ship length ratio starting at 0.5, 0.6 …….till 4.0

The sets of coefficients are available in a digital format.

4. Validation of the expressions

The results of the polynomial expressions have been validated against the database to check on the accuracy of the predictions. In general the goodness of fit with the database results is very good.

A more interesting comparison however is with a number of boats ***not*** belonging to the database, so models not belonging to the DSYHS.
This has been done for a number of different hulls. Some typical result will be shown here. The result is shown in the Figures 2, 3 and 4 for a yacht with a 7.5 meter waterline length and a yacht with a 15.0 meter waterline length. It should be realized that the comparison made is between the polynomial approximation and the actual results obtained with a 2-D linear strip theory calculation.

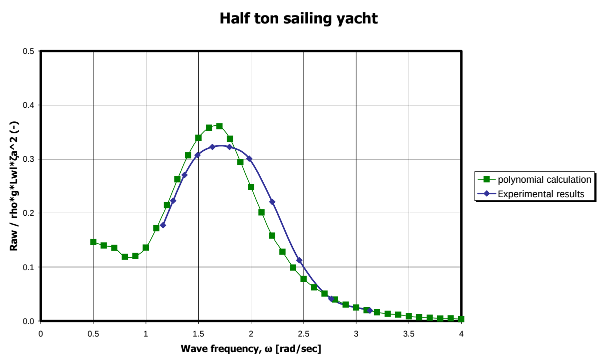

Figure 2: Comparison between the calculated and the approximated RAO for a half ton yacht with 7.5 meter waterline length

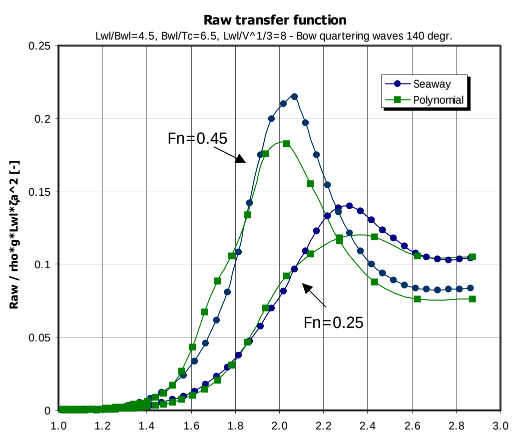

Figure 3: Comparison between calculated and approximated RAO at 180 degrees Yacht is 15.0 meter Lwl at Fn. = 0.25 and Fn. = 0.45.

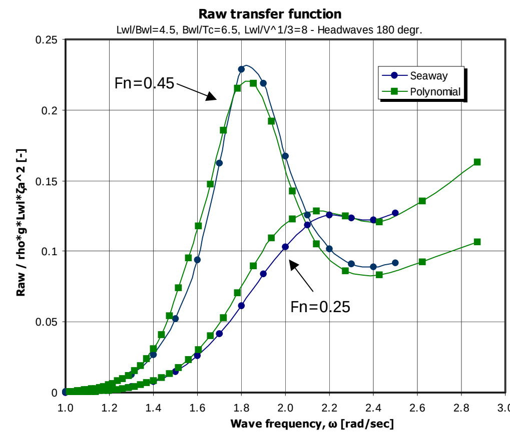

Figure 4: Comparison between calculated and approximated RAO at 140 degrees Yacht is 15.0 meter Lwl at Fn. = 0.25 and Fn. = 0.45

It should be noted that the large yacht, for which the results are presented, is already "on the edge" of the range of applicability of the present method, when its hull parameters, in particular the L/B (4.5) and Length Displacement ratio (8.0), are concerned.
These results are more or less typical for all the comparisons made. From these it may be concluded that the approximation method is as accurate as the original calculations using the entire ship motions- and added resistance in waves calculation routine for a wide range of ship lengths.

5. The application of the present method.

The method presented above has been incorporated in the in house VPP of the Delft Shiphydromechanics Laboratory. This VPP is largely based on the published results of the DSYHS and the wind force model from the ORC- IMS VPP as published by various authors.
The advantages of the present method, i.e. the freedom of input of the wave spectrum in the calculations, show at best when a comparison is made of the speed loss suffered by one particular sailing yacht when sailing at different sea areas under the same true wind conditions are compared.

When considering the effect of the added resistance in waves on the performance of a sailing yacht it should be realized that a sailing yacht of “regular” dimensions, i.e. somewhere between the 7 and 24 meters length overall, is on average sailing in relatively very long wind generated waves. This means that the ship length to wave length ratio is small. Because the added resistance in waves is determined in the “overlap” between the RAO and the wave spectrum this has two important effects:

- The RAO of the RAW of the yacht at speed is multiplied with the short end tail of the wave spectrum. In general this is the part of the wave spectrum that is not very well defined by the usual formulations for the energy distribution over the frequency range. This is so because for commercial vessels this part of the spectrum in general is of little or no real interest.
- Even a relative small change in the position in the frequency range of the peak of the RAO or the energy range of the wave spectrum, i.e. change in peak period of the spectrum, may lead to very large differences in the overlap between the two and so in the average added resistance.

The importance of this may be seen when considering the change in energy distribution over the frequency range of the wave spectrum in a typical North Sea environment with a change in wind strength as shown in Figure 4. To be able to visualize the effect and the importance of this the RAO for a 40 feet IMS yacht is shown in the same graph on the horizontal scale. Of importance for the actual magnitude of the averaged added resistance in waves is the area where both plots overlap!! It should be noted that the horizontal axes in these plots is the wave length over ship length ratio and **not** the theoretical more correct and usual wave frequency of encounter. This has been done for the sake of the better demonstration of the fore mentioned effect, but it has a distortional effect on the plots! This implies that the area of the spectrum does not correspond to the significant wave height.
The importance of the possibility of a proper introduction of the actual wave spectrum may be obvious. Using a constant energy distribution over the frequency range, irrespective of the wind strength, is obviously not a valuable approach for all the sailing areas around the world.

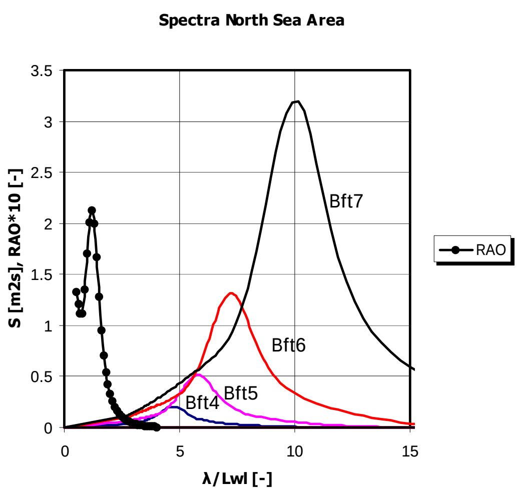

Figure 5: Different spectra for increasing wind speeds on the North Sea and the RAO of the RAW of a typical IMS-40 design. On wave length scale!

Another area of interest for the application of the present method arises when the effect on the performance of a sailing yacht in different sailing areas are concerned. As mentioned before the actual wave spectrum will be strongly dependent on parameters such as the wind speed, the fetch of the wind, the water depth, the presence of a lee shore and possibly even current effects.
To show the influence for this particular example three different wave conditions are used:

- Typical Ocean waves environment
- Typical North Sea environment
- Typical waves on semi sheltered and limited depth Estuary environment

The corresponding wave spectra, to go with the chosen true wind speed of 10 m/s, have been determined using "wave statistics data". This implies a Pierson Moskowitz spectrum (PM) for the Ocean Area, a JONSWAP spectrum for the North Sea Area and a Measured Spectrum (MS) for the Estuary.
To investigate the differences that arise when these are used for the calculation of the performance of a sailing yacht, a VPP calculation has been made using one particular yacht in one particular situation with respect to the true wind strength and true wind angle but sailing in these different areas.
The results of these calculations are shown in Figure 7 for the differences in the full-scale added resistance in the upwind conditions and for the attained speed (relative to the calm water speed) of the yacht upwind in Figure 8.

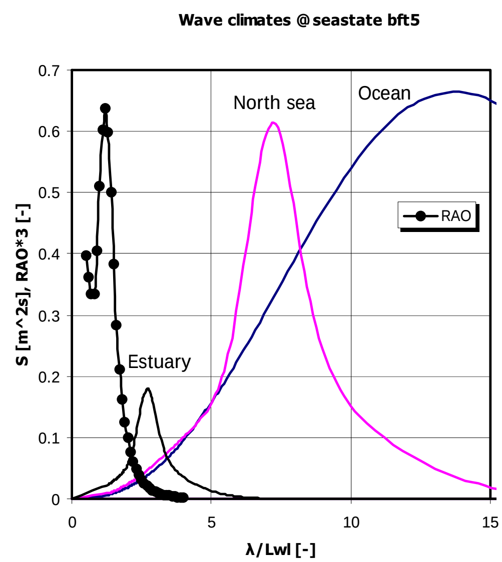

Figure 6: Different wave spectra use for the three different sailing areas under the same true wind conditions. With RAO of RAW of an IMS-40 design.

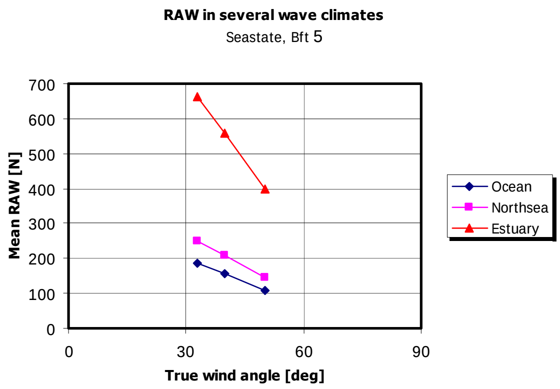

Figure 7: Full scale added resistance of an typical IMS-40 in different sailing areas.

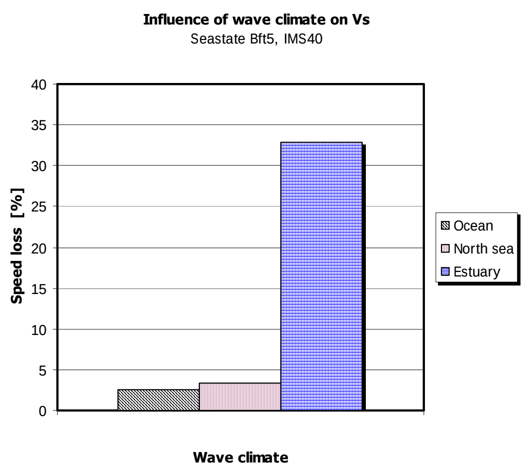

Figure 8: The effect of different sailing areas with same true wind speed on the speed loss of a sailing yacht.

6. Conclusions

Based on the results found so far it seems that a quite user friendly method has been formulated which allows the designer to make performance comparisons between various sailing yacht designs in the actual wave spectra they encounter. The mutual comparison between different designs may certainly depend on the environmental conditions under consideration.

The inaccuracies introduced in the assessment method due to the use of a 2-D linear strip theory method are most likely exceeded by far by the uncertainties introduced due to the lack of detailed information about the exact environmental conditions.

The method was proven to be capable of handling a large variety in yacht sizes. The designers should be strongly aware of the calculation methods used to acquire the mean added resistance in waves and the particular points of interest when dealing with small ships in long waves.

The fact that a considerable amount of racing takes place in short fetched, (semi) sheltered areas with limited depth (much like the Estuary) will have a strong influence on the actual importance of the added resistance in waves of “regular” sailing yacht. Maybe there is no “one added resistance for all”.

7. Acknowledgement

The authors wish to gratefully acknowledge their appreciation for the work carried out in this project by J Reumer and N Homma.

8. References

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