A Critical Analysis of Resistance Prediction Using Regression Methods for High Speed Hull Forms

by

Michel de Vos, Brett Murrie & Viliami Siale
Faculty of Maritime Transport & Engineering
Australian Maritime College
Launceston, TAS 7250, Australia

and

Prasanta Sahoo
Australian Maritime Engineering CRC Ltd.
Launceston, TAS 7250, Australia

Summary

The aim of this work has been to look closely at the various regression methods published to-date and propose a suitable regression method to predict the resistance of high speed crafts in the preliminary design stage.

Literature review indicates a considerable amount of work in the field of resistance prediction through equations and formulas that represent model test results mathematically. There are numerous articles which provide useful information to the naval architect by which resistance of high speed craft can be predicted by use of a handful of hull form parameters. The methods illustrated in this article have been carefully selected and reviewed and their range of applicability have been presented.

This work, undertaken as part of a sub-program on "Resistance of High-Speed Marine Vehicles" of AMECRC, falls into two sections:

a) To develop and validate software to use some of the more popular regression methods available from the literature.

b) To evaluate the towing tank results of different hull forms which have been carried out at the Ship Hydrodynamic Centre of Australian Maritime College, against the various regression methods.

An extensive study of different methodologies has been provided by MacPherson (1993) clearly illustrating the advantages and disadvantages of using various methods. The above article states that all of these methodologies have been limited in one way or another, by a physical reality where the relationship of dimensional volume to water viscosity cannot be simultaneously scaled from a model's size to the full scale vessel. Attempts have been made to apply corrections and correlating factors so that full scale resistance can be predicted from models. No universal procedure has been developed, so these corrections are often applied inappropriately between methods and the accuracy of the results has suffered as a result.

Models of single chine vessels have been tested over a range of speeds considered adequate for semi-planing and planing craft and some of their results have been evaluated. A critical analysis of the main hull form parameters which have the most significant influence on the resistance has been conducted. A comparative study has been carried out to evaluate and establish the suitability of the published regression methods against the towing tank results.

1 Introduction

There are numerous methods available today by which a ship designer can obtain an estimate of the resistance of high speed craft. Studies made by various authors and the present study show that no single method is accurate enough to predict the resistance over a wide range of speeds. Investigations made over the last few years show that some of the modern regression methods are sufficiently accurate over the speed range for which they had been developed while some of the other methods have been less than satisfactory. While using regression methods designers generally tend to satisfy the non-dimensional range for their particular hullform. The most important aspect i.e., the hull shape needs to be considered bearing in mind the limitations applicable to a particular method. To ensure confidence in accuracy it is imperative to investigate the regression methods in detail and compare results of a number of vessels for whom models have been previously tested.

It is the intention of this paper to provide the designer with a reference to select the most suitable regression method applicable to their particular vessel keeping in mind the limitations of the method and the hull shape for which it had been developed. One should remember that such numerical regression methods are not attempting to eliminate model testing but provide a cost effective means of predicting resistance and are a powerful tool in the hands of the designer of what to expect in the future.

2 Influence of Hull Form Parameters

Before making a statistical analysis of data, it is necessary to decide upon the hull form parameters that should be used. The selection of the parameters or variables is quite arbitrary as stated by Fairlie-Clarke (1975). Fung (1991) points out that this selection was quite often subjected to the judgment of specific researchers' suggestions. Almeter (1993) pointed out that there would be a problem when trying to incorporate all the variables defining the hull into the equation. On the other hand, he also warned the danger of omitting too many terms which is quite preferable for the equation but cannot fully define the hull considered. However, Fairlie-Clarke (1975) suggested that the regression equation should not contain more than 10 independent variables, because the accuracy of the prediction becomes stagnant with a large number of variables. Fung (1991) also suggested the error in the prediction decreases with the increase in number of terms but after 11 to 17 terms, the errors become stagnant and additional terms produces little or no improvement at all on the error.

It is a common occurrence in the design spiral that changes are made to the shape of a hull after the initial lines have been drawn and some performance calculations made. Usually these changes will be relatively minor with the changes made due to some new information being received. These changes could be estimated displacement, waterline length, beam, transom area or any of a number of relevant hull parameters. The naval architect may also wish to explore slightly different variations of some parameters to see their effect on performance. It would be a fair assumption to say that the vast majority of designers would have a good knowledge of the effect that a change in the basic parameters would have, but to what extent would not be as common.

It would therefore be beneficial to explore and quantify the effects that a change in parameters would have on the resistance of planing hulls over a range of speeds. This would in turn lead to findings as to which hull parameters have the most significant effect on the resistance of such vessels. By investigating the results of model resistance tests of a large number of unrelated commercially operating craft and comparing them to their respective non-dimensional hull form parameters it is hoped that general trends will be recognised that will be applicable across the entire spectrum of high speed craft. Results obtained should then be able to not only identify the effect on performance of changing the design variables but also indicate their optimum. These trends or patterns if and when identified should also enable the development of a regression equation using the most important hull form parameters. A previous effort made using this concept for high speed round bilge displacement hulls has been published by Ping-zhong et al (1980) but as yet no known effort has been made with regard to planing hulls.

In the past most of the work that attempts to identify the effect of certain hull parameters has usually been done with the use of a systematic series. These systematic series would usually involve the extensive testing of a small number of vessels whose forms have been derived by stretching or compressing the parent model. The resulting forms thus only had a number of parameters that were varied whilst others were kept strictly constant. This enabled for easy cross plotting and interpretation of results between models. Unfortunately, some of these series such as Series 50 have been based on a parent model that has been rather outdated and as such their applicability to modern vessels is somewhat limited as has been pointed out by Keuning et al (1993). There have however been a few series that represent modern practices for hull shapes and have provided some valuable information. The series data currently available has more than likely reflected a particular viewpoint of the ranges in service and are therefore sometimes further limited in their application. There is one further consideration that should be made with regard to systematic series. The effects on resistance of changing a particular parameter are normally attributed to a direct cause by the parameter in question. This may not always be the case and it is probable that it is the result of changes in a number of parameters due to the variation of the single parameter. It is normally true to say that by varying one dimension of a vessel it will change a number of others and so they are all interconnected.

To date particular interest has been centred on parameters such as L/B and LCG. For these parameters quite a lot of data exists. Clement and Blount (1963) presented a paper regarding the testing of a number of hard chine models to explore the influence of L/B and LCG positions. The L/B ratios ranged between 2 and 7. It showed that the value of R/Δ was lower for higher values of L/B. This occurred up until the volumetric Froude number was approximately 3.5-4.0 where specific resistance (R/Δ) of the higher L/B values gave higher results but the difference was much less. It also showed that the lowest value of L/B would be impractical since the resistance curve would have a rather extreme hump in the drag curve. The analysis of LCG positions was interesting but showed little that was not already known. It indicated that as the centre of gravity is moved further aft resistance decreased. There comes a point however when by moving the LCG position further aft it produces a rather undesirable hump in the resistance curve. This indicates that there is an optimum range for the position of the longitudinal centre of gravity. In fact it was stated that the optimum position for the centre of gravity for these tests was between 4 and 8 per cent aft of the centroid of the projected planing area (Ap). For high speeds the aftermost LCG position gave the best results for all models. In a practical sense these results appear to indicate that by careful arrangement of items upon a heavily loaded vessel it is possible to obtain a significant decrease in the resistance.

The effect of displacement upon the resistance of planing craft is widely known as an important parameter since one of the basic rules for craft of this type is low weight and large power. Through tests made at the Ship Hydrodynamic Centre of the Australian Maritime College some patterns are evident. These tests involve the results of some 14 hard chine models with a total of 36 test conditions. The models themselves are of boats that are currently in commercial service and as such are considered to be unrelated.

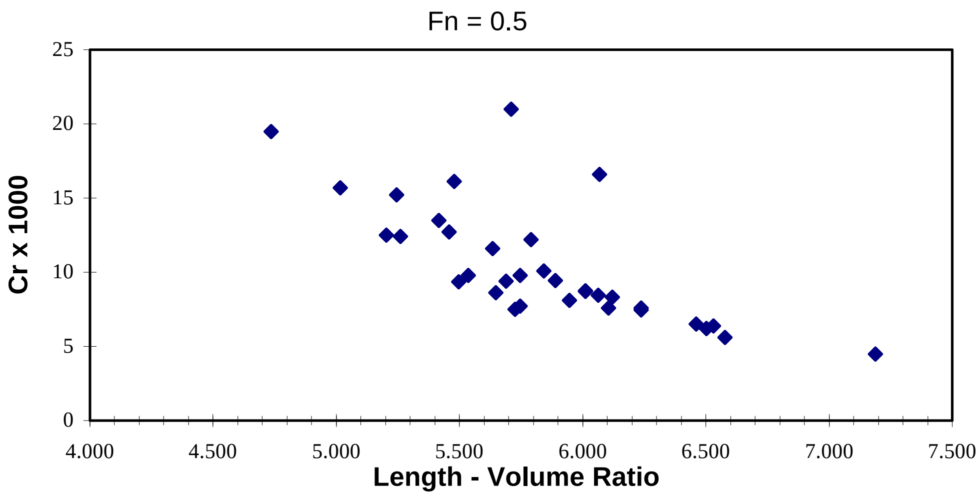

Figure 1: Variation of Residual Resistance with Length-Volume Ratio ($L/\nabla^{1/3}$).

Presented in Figure 1 are values of residual resistance coefficients plotted against length-volume ratio at a Froude number of 0.5 which corresponds to that of hump speed. This plot is typical of those that have been found throughout the range of Froude numbers encountered. There is a distinct band in which the majority of points lie. This is as would be expected with the lower residual resistance coefficients corresponding to the higher length-volume ratios. It is also indicated that for a change in displacement the residual resistance coefficient changes much less at high Froude number than at hump speed which correlates with the fact that a heavy vessel requires a much higher engine power in order to enter the planing mode.

Deadrise angle is considered as an important parameter characteristic of almost all planing hulls. Du Cane (1974) has rightly said that the use of deadrise angle stems from seakeeping considerations but only marginally influences resistance. Increasing deadrise decreases the vertical component of lift and therefore the efficiency of the vessel as a lifting surface. There is also an inherent increase in wetted surface with deadrise and since wetted area is an important component of high speed resistance then so is deadrise. There are however, certain arguments pertaining to the use of a deep deadrise hull to give the best performance in smooth water at high speed as Levi (1990) has suggested.

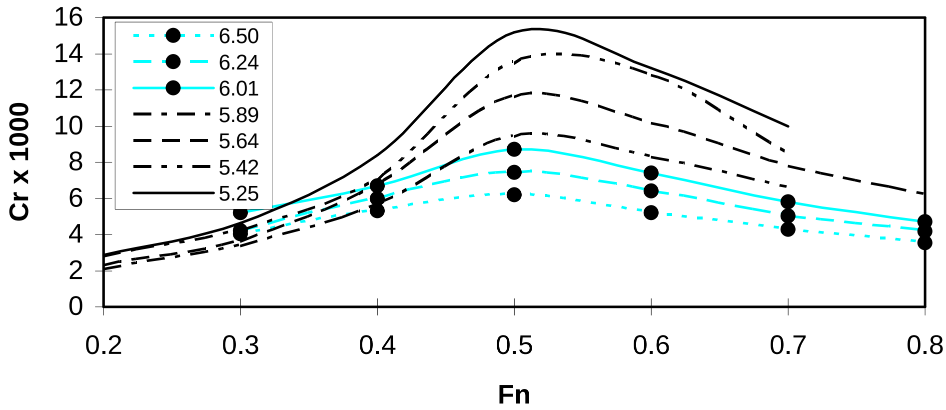

Figure 2: Influence of $L/\nabla^{1/3}$ ratio on Cr values at constant 17º Deadrise Angle.

Unfortunately no conclusive evidence is forthcoming from the investigations made regarding the model test data of the 14 models. Figures 2 and 3 show a large variation of residual resistance coefficients for some hulls of equal deadrise. The curves appear to be more dependant upon the $L/\nabla^{1/3}$ ratio than upon deadrise itself. This suggests that deadrise may have a very subtle effect which could only be investigated through either a much larger number of independant vessels or through systematic tests with vessels of similar form.

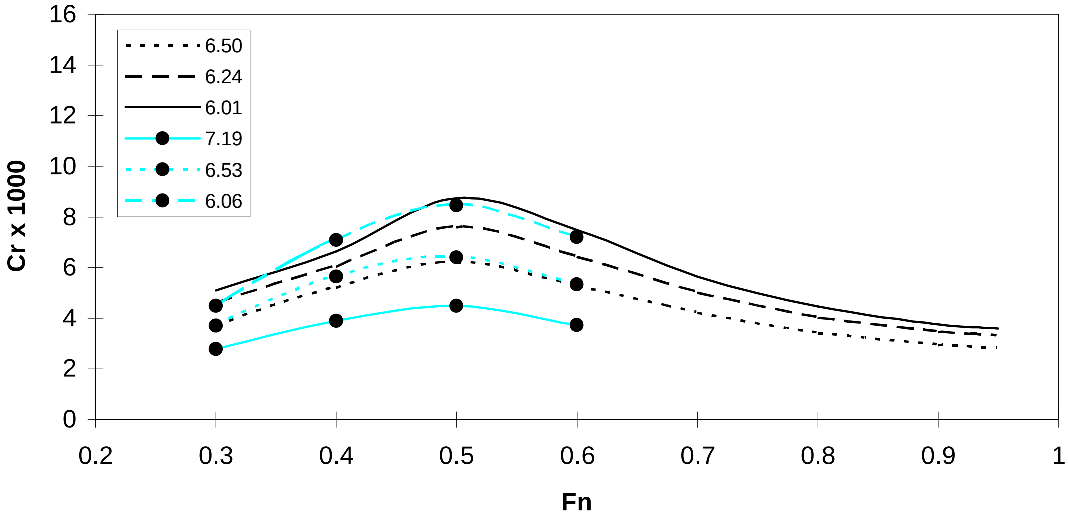

Figure 3: Influence of $L/\nabla^{1/3}$ ratio on Cr values at constant 15º Deadrise Angle.

The previous statements have been made using data that exists for hard chine vessels in smooth water only and as such may not correspond to experiences in conditions that are less than perfect.

3 Analysis of Resistance Prediction Methods

As previously mentioned the accurate prediction of the resistance of a vessel is of extreme importance, and thus any prediction method should give accurate results over the whole range of the method's validity. Studies have shown that there are numerous methods which have been developed encompassing a vast array of ship types and as such the selection of which method to use for a particular vessel is of fundamental importance. Four methods applicable to high speed hull forms were developed into computer programs. These programs were then used to validate the methods by comparing the results to the model results of three completely independent hull forms corresponding to full scale vessels. The salient features of the four methods that have been discussed here are as follows:

Prediction method of Keuning et al (1993)

Clement and Blount (1963) presented a now well known systematic series planing hull forms with a deadrise angle of 12.5°. In this paper by Keuning et al (1993) the results have been presented for a similar 25° deadrise angle series which are coupled with results of a 30° deadrise angle series to develop a regression model for total resistance, trim and rise of centre of gravity. The total resistance of the vessel is calculated by interpolating the (R_T/Δ) fitted to separate datasets containing the model resistance scaled to different volume of displacements. Table 1 summarises the application boundaries of this method.

Table 1: Parameters and range of validity as per Keuning et al (1993)

Parameters	Lp/Bpx, LCG, $Ap/\nabla^{2/3}$ & β
Constraints	β=12.5°-30°
Speed Range	$F_{n\nabla}$=0.75-3.00

Prediction method of Almeter (1989,1993)

This paper uses the virtually ignored large Soviet BK and MBK planing hull series to develop a resistance prediction technique for low deadrise, hard chine stepless planing hulls. The prediction method is based on test results of 29 systematic models of the BK and MBK series over a range of loading conditions and longitudinal centres of gravity. The resistance of any hull is predicted by calculating the resistance of an equivalent BK or MBK model that has the same β_m and dimensionless values $C_{\Delta,}$ LCG/Lp and Lp/Bm as the ship and then scaling the total resistance to full scale. The BK series is based on planing vessels such as patrol boats, supply craft and high speed motor yachts, whilst the MBK series is oriented towards smaller planing craft. The main features of the two resistance prediction methods are shown in Table 2.

Table 2: Parameters and range of validity as per Almeter (1989,1993)

	BK	MBK
Parameters	Lp/Bm, LCG/Lp, C_Δ & b_m	Lp/Bm, LCG/Lp, C_Δ & b_m
Constraints	Lp/Bm=3.75-7.00 LCG/Lp=0.35-0.45 C_Δ=0.427-0.854 b_m=12°-21°	Lp/Bm=2.50-3.75 LCG/Lp=0.25-0.45 C_Δ=0.158-0.352 b_m=7°-18°
Speed Range	$F_{n\nabla}$=1.00-4.50	$F_{n\nabla}$=1.00-4.50

Prediction method of Radojcic (1984,1985,1990)

In attempting to minimise the hydrodynamic resistance of a vessel the quasi propulsive efficiency (QPE) may be decreased by a reduction of hull efficiency. Radojcic (1984,1985 & 1990) aimed to reduce the power rather than minimise the resistance or maximise propeller efficiency as is normally done. A resulting equation for resistance for a 100,000 lb vessel was produced accompanied by a similar equation, but with different coefficients for dynamic trim. In addition equations for wetted surface and mean length were developed to facilitate the scaling of the 100,000 lb to that of the actual vessel. Table 3 gives a summary of the method.

Table 3: Parameters and range of validity as per Radojcic (1984,1985,1990)

Parameters	$Ap/\nabla^{2/3}$, Lp/Bpa, LCG/Lp, & b_m
Constraints	Lp/Bm=2.36-6.73 LCG/Lp=.30-.448 $Ap/\nabla^{2/3}$=4.25-9.5 b_m=13°-37.4°
Speed Range	$F_{n\nabla}$=1.00-3.50

Prediction method of Lahtiharju et al (1991)

This paper investigates the resistance and seakeeping characteristics of fast transom stern hulls. The author found that there was a requirement for a systematic series of shallow draft and wide transom hull forms to accommodate the modern use of waterjet propulsion. The two resistance equations for a 100,000 lb vessel were developed, one for hard chine and the other for round bilge forms, enabling the comparison of the effect of changing from round bilge to hard chine whilst keeping the other parameters equal. In order to scale the results to the actual vessel in question correction factors have been provided. A summary of the method is shown below in Table 4.

Table 4: Parameters and range of validity as per Lahtiharju et al (1991)

	Round Bilge	Hard Chine
Parameters	LWL/Bx, Bx/T, Cx, At/Ax, $LWL/\nabla^{1/3}$ & B^3/∇	LWL/Bx, Bx/T, At/Ax & $LWL/\nabla^{1/3}$
Constraints	LWL/Bx=3.33-8.21 Bx/T=1.72-10.21 Cx=0.567-0.888 At/Ax=0.16-0.82 $LWL/\nabla^{1/3}$ =4.47-8.3 B^3/∇=0.68-7.76	LWL/Bx=2.73-5.43 Bx/T=3.75-7.54 At/Ax=0.43-0.995 $LWL/\nabla^{1/3}$ =4.49-6.81

Speed Range	$F_{n\nabla}$=1.80-3.20	$F_{n\nabla}$=1.80-3.20

Description of Vessels

Three models, all hard chine were used to validate the various methods. As previously stated these models are completely independent and are models of full sized ships. When expanding the model results to full scale, full use was made of the ITTC '57 friction line as well as applying a ship-model correlation allowance of 0.0004. All the numerical methods thus were extended to include the facility of choosing a correlation allowance ensuring continuity of model/numerical results. A summary of each vessel's features is shown below in Table 5.

Table 5: Hull form parameters of the vessels.

	Vessel 1-A	Vessel 2-A	Vessel 3-A
Lp/Bpx	3.63	4.32	3.98
Lp/Bm	3.78	4.66	3.75
$A_p / \nabla^{2/3}$	0.28	0.71	0.25
LCG from Cap (%Lp)	-2.28	-2.74	-3.71
b_m	20.00	18.5	14.00
LCG/Lp from transom	0.41	0.40	0.427
LWL/Bx	4.02	3.78	3.54
Bx/T	4.59	4.89	6.36
At/Ax	0.95	0.62	0.611
$LWL / \nabla^{1/3}$	4.93	5.38	5.66

4 Discussion of Results

Figures 4 through 6 are graphical representations of model results compared against the results obtained from the four prediction methods. The results have only been presented for volumetric Froude numbers against R_T/Δ corresponding to the available model data.

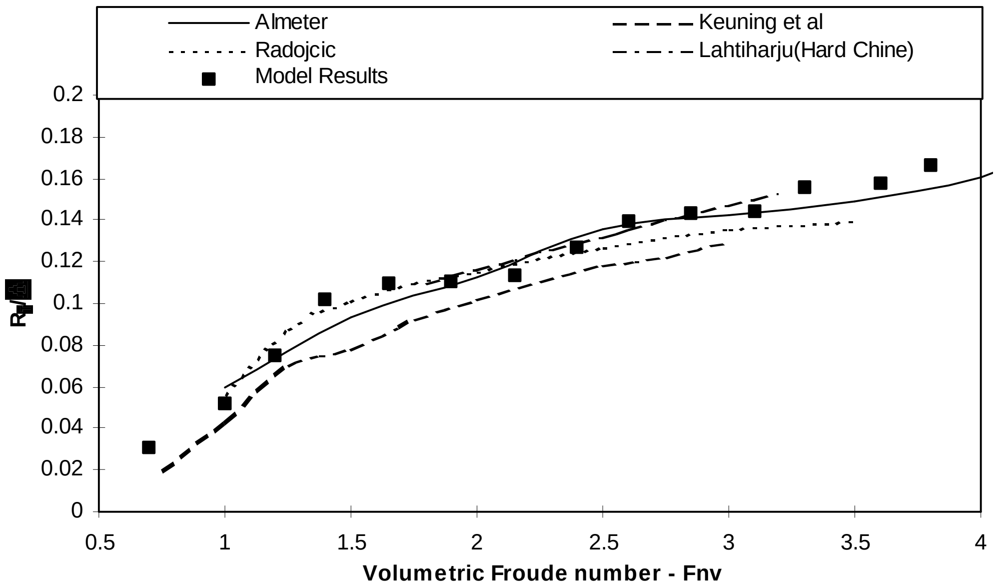

Figure 4: Predicted versus Model Results Vessel 1-A

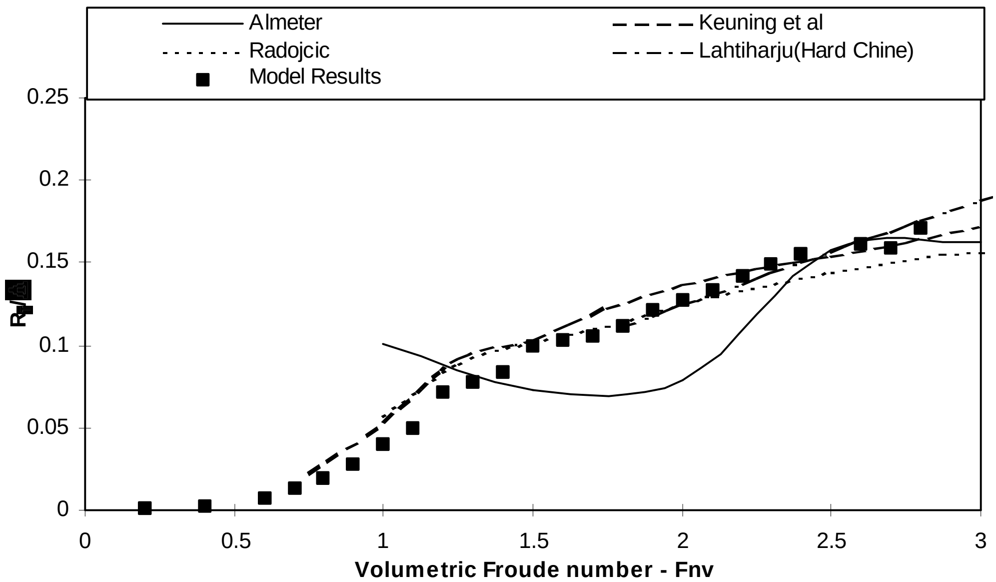

Figure 5: Predicted versus Model Results Vessel 2-A

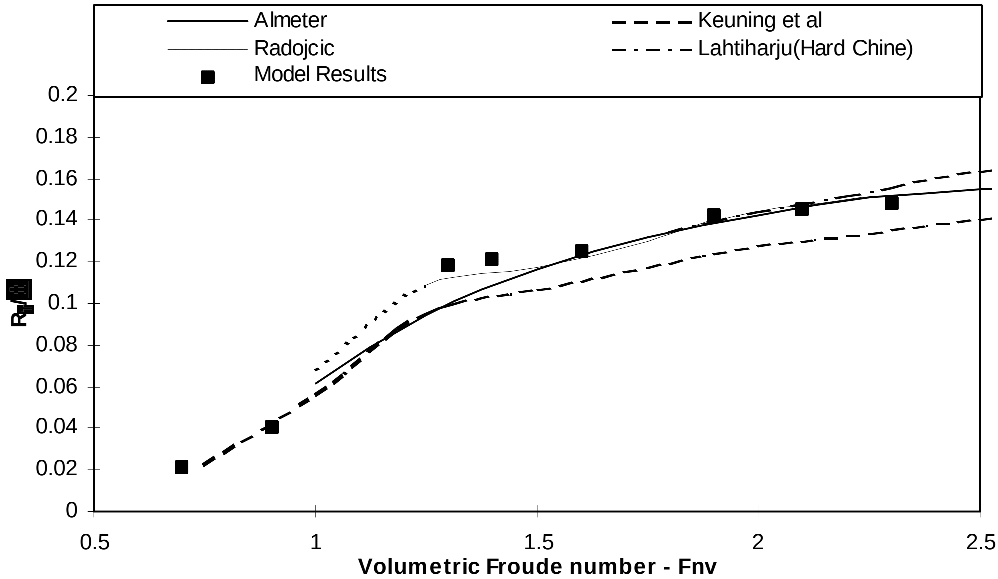

Figure 6: Predicted versus Model Results Vessel 3-A

It is obvious that in some cases each method provides results of sufficient accuracy to be useful during the preliminary stages of ship design. Observing the prediction method by Almeter(1993), it is immediately evident that for vessel 2-A some very erratic results occur in the range $F_{n\nabla}$=1.00-2.5. Although this vessel is within the range specified for BK series unsatisfactory results were obtained and further comparisons of model test results against the prediction method of BK series need to be carried out before any conclusive remarks can be made. The results for the other two vessels provide reasonable correlation with model results. No general trends in over or underprediction are evident from such a small range of results and further testing is to be performed before any additional conclusions can be made. Focusing on the method of Keuning et al (1993), it is evident that although this method does give very good results it seems to underpredict over the entire speed range for all vessels especially at higher values of $F_{n\nabla}$. It has been suggested by Keuning et al (1993) that by utilizing a worm screw function ζ, a dramatic improvement in accuracy could be achieved. It is therefore concluded that this method is of sound nature and could make a suitable tool for resistance prediction not only in the initial stages of ship design but also in the more demanding final stages. The method of Radojcic (1984,1985 & 1990) provides good correlation with model results over most of the speed range. There is some underprediction at and above $F_{n\nabla}$=2.5 for vessels 1-A and 2-A. These errors are of such a small magnitude that they could almost be ignored, resulting in the conclusion that this method is sufficiently accurate to be used as prediction of resistance for all phases of the ship design. The method developed by Lahtiharju et al (1991) shows the best correlation against model results for the speed range over which this method is valid. There seems to be no under or overprediction at any speed. It is hereby emphasized that this method along with Radojcic's method are extremely reliable. Conclusions just made are based on just three independent vessels and many more vessels must be analysed before any firm conclusions can be drawn regarding under or overprediction for any $F_{n\nabla}$ range.

Conclusions

This paper endeavours to present the validity range of some of the regression methods developed within the last few years. An attempt has been made to establish the degree of accuracy and confidence one would encounter while using any one of the methods illustrated in the preceding paragraphs. One should bear in mind that confidence level would be reduced if the validity range is violated. The hull shape, which is of equal importance, should be carefully considered while selecting a particular regression method. It is the view of the authors that the methods developed by Lahtiharju et al (1991) and Radojcic (1984,1985 & 1990) provide reasonable degree of accuracy not only for the initial stages of ship design but also for more rigorous analysis in the later stages.

Principal Nomenclature

$A_p / \nabla^{2/3}$ = Load Coefficient
Ap= Projected planing bottom area
Ax= Maximum section area
At= Transom area
B= Breadth
Bm= Midship chine beam
Bpx= Maximum breadth over chines
Bx= Maximum beam
C_Δ= Load coefficient, $\Delta/(rgBm^3)$
Cr = Residual resistance coefficient
Fn= Froude Number
Fnv, $F_{n\nabla}$= Volumetric Froude number
L= Length
$L/\nabla^{1/3}$ = Length volume ratio
LCG= Longitudinal Centre of Gravity
Lp= Projected chine length
R_T= Total resistance
V= Speed
ζ = Worm screw function
β= Deadrise
b_m= Midship deadrise
Δ= Displacement
ρ= Mass density of fluid
∇= Volume of displacement

Acknowledgements

This paper describes the work carried out as part of a sub-program of AMECRC. The authors are greatly indebted to AMECRC for providing the facilities and resources to publish the results. Last but not the least the authors would like to thank all their colleagues for their valuable suggestions and help during the course of their work without which this paper would not have materialised.

References

1. MacPherson, D.M. (1993): " Reliable Performance Prediction: Techniques Using A Personal Computer", *Marine Technology,* Vol 30, No. 4, pp. 243-257, October.

2. Fairlie - Clarke, A.C (1975): " Regression Analysis of Ship Data", *International Shipbuilding Progress*, Vol 22 , No. 251, pp 227 - 250.

3. Fung, Siu . C . (Am) (1991): " Resistance and Powering for Transom Stern Hull forms during Early stage Ship Design", *Society of Naval Architects and Marine Engineers*, Transaction Vol 99 , pp 29 - 84.

4. Almeter, John .M (1993): " Resistance Prediction of Planing Hulls ; State of the Art", *Marine Technology*, Vol 30 , No.4 , pp 297 - 307,October

5. Ping-zhong, J., Ba-ying, S. & Zhong-kai, T.(1980): "A Parametric Study On High-Speed Round Bilge Displacement Hulls", *High Speed Surface Craft*, pp 6 - 13, September.

6. Keuning, J.A., Gerritsma, J. & Van Terwisga, P.F(1993): " Resistance Tests of a Series Planing Hull Forms With 30 Degree Deadrise Angle, and a Calculation Model Based on this and Similar Systematic Series", *International Shipbuilding Progress*.,Vol 40, No.424 , pp.333-385

7. Clement, E.P. & Blount D.L.(1963): "Resistance Tests of a Systematic Series of Planing Hull Forms", *Society of Naval Arcthitectures and Marine Engineers,* pp 491-561

8. Du Cane, P.(1974): " *High Speed Small Craft*", David & Charles (Holdings) Limited, Abbot, England

9. Levi, S.(1990): "*Dhows to Deltas*", 2nd Ed., A&A, Milano, Italy.

10. Almeter, M.(1989):"Resistance Prediction and Optimization of Low Deadrise, Hard Chine, Stepless Planing Hulls",*Society of Naval Arcthitectures and Marine Engineers*, Spring Meeting/STAR Symposium, pp S1-4-1 to S1-4-23, April.

11. Radojcic, D.(1984):"A Statistical Method for Calculation of Resistance of the Stepless Planing Hulls",*International Shipping Progress*.,Vol 31, No.363, pp.272-276, November

12. Radojcic, D.(1985):"An Approximate Method for Calculation of Resistance and Trim of Planing Hulls",*Ship Science Report*, No 23, University of Southhampton, Dept of Ship Science, pp 1-28, December.

13. Radojcic, D.(1990):"An Engineering Approach to Predicting the Hydrodynamic Performane of Planing Craft using Computer Techniques",*RINA Transaction*, pp 251-267.

14. Lahtiharju, E., Karpinen, T., Hellevaara, M and Aitta, T.,(1991) "Resistance and Seakeeping Characteristics of Fast Transom Stern Hulls with Systematically Varied Form", *SNAME Transaction*, Vol 99, pp 85-111