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Author:
Helmore, Phillip; Swain, Peter

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Regression Analysis of the Ridgeley-Nevitt Trawler Series Resistance

Phillip J. Helmore
The University of New South Wales, Australia

Peter M. Swain
ADI Limited, Australia

ABSTRACT

There are few numerical methods available for the prediction of resistance of hullforms with fine entrances and broad, flat sterns, typical of tugs, trawlers and offshore supply vessels. The field narrows even further for those hullforms having high displacement/length ratios. Ridgeley-Nevitt's trawler series data caters for high displacement-length ratios up to 500, but the residuary resistance data are only available in the form of two-dimensional contour plots at each speed/length ratio, and determination is time consuming.

Data were therefore lifted from each of the contour plots and regression analyses completed, resulting in polynomial expressions for the residuary resistance at each of the speed/length ratios. The expressions are in terms of the prismatic coefficient and displacement/length ratio, giving good results compared to the contour plots and providing fast evaluation of the residuary resistance component.

1. INTRODUCTION

The prediction of resistance is important in most ships designs for the estimation of either the speed which will be achieved with a given power, or the power which will be required to achieve a given speed. It becomes particularly important if there are penalties in the contract for under-achievement of the required speed.

Over the years there have been many fine analyses of the resistance data for many different hullforms, and the range of hullforms is increasing. However, vessels with hullforms having fine entrances and broad, flat sterns have had less attention paid to their resistance characteristics than most. This hullform is typical of tugs, trawlers and offshore supply vessels, and so designers of these vessels have a harder time of it in predicting their resistance with confidence than many others.

Ridgeley-Nevitt (1967) published the final results of the tank tests of a series of high-displacement-length ratio round-bilge trawler hullforms. The results were presented as contour plots of residuary resistance coefficient, C_R, vs displacement-length ratio and prismatic coefficient at each speed-length ratio. These two parameters had been identified as being the most significant in the development of the series, while beam-draft ratio had been shown to have only a small effect. Ridgeley-Nevitt's data have been useful to designers of these hullforms ever since.

Van Oortmerssen (1971) used a regression analysis to obtain a parametric expression for the residuary resistance of a database of 93 tugs and trawlers which had been tested at MARIN (then the Netherlands Ship Model Basin). Unlike Ridgeley-Nevitt's series hullforms, these were unrelated, or random, hullforms. The parametric expression was ideally suited for use on computers and, especially, personal computers which started to become widely available about ten years later. There is no stated upper limit to the displacement-length ratio for van Oortmerssen's method. However, there were errors in van Oortmerssen's original paper and, while many of these have been resolved by correspondence with the author and with MARIN, some are still being investigated. This has not stopped the method from being widely used, but almost every known implementation gives different results for the resistance.

Calisal and McGreer (1993) published the results of a systematic series of double-chine, low length-beam ratio hullforms based on the purse-seiners on the west coast of Canada. The results were presented as tables of the residuary, frictional and total resistance coefficients obtained for the models at various Froude numbers, and as parametric expressions for the residuary resistance coefficient obtained by regression analysis. The prismatic coefficients cover about one-third of the range of Ridgeley-Nevitt's series or van Oortmerssen's data. However, the bow shape of the parent hull was modified to reduce the half-angle of waterline entrance and to remain developable. Preliminary testing had shown that reducing the half-angle of waterline entrance reduced the resistance at higher speeds, and developability was of concern to minimise construction costs. Few trawlers or tugs designed in Australia have the low half-angles of waterline entrance of this series and, as a result, the series tends to under-predict the resistance in the high-speed range.

There are other series for specialist vessels, such as the tuna purse-seiner series with bulbous bows tested at the El Pardo model basin in Madrid (O'Dogherty et al., 1985), but such series are concentrated on highly-refined hullforms.

Many tugs designed in Australia over the last ten years have had displacement-length ratios in the 700–800 range, significantly exceeding Ridgeley-Nevitt's series limit. However, trawlers tend to have displacement-length ratios towards the upper end of Ridgeley Nevitt's series, and his C_R data are still referred to. The authors are aware of one trawler designed with a displacement-length ratio of 700, for which the Ridgeley-Nevitt C_R data was extrapolated by hand to the top of the page, and the vessel made its speed on trials; a testament to the good behaviour of the data!

The problem lies in the format of the Ridgeley-Nevitt data in contour plots. This makes lifting the values for C_R at a known displacement-length ratio and prismatic coefficient at each of nine speed-length ratios a labour-intensive process, compared to the speed of numerical prediction on an office computer to which we have all become accustomed. Various empirical methods are used to allow for the fact that Ridgeley-Nevitt's series was of round-bilge hullform, whereas most trawlers being designed in Australia are of double-chine hullform.

The authors therefore decided to embark on a regression analysis of the Ridgeley-Nevitt data to provide a parametric expression for the residuary resistance coefficient, so that the data could continue to be used, without the labour intensity and at much higher speed on a computer.

2. REGRESSION ANALYSIS

2.1 Previous Analyses

The first published statistical analysis of a resistance database was the landmark paper by Doust and O'Brien (1959), who had analysed the results for some 130 trawlers which had been tested in the No. 1 tank at the Ship Division of the National Physical laboratory, UK. Results were presented as curves of factors F_1 (depending on prismatic coefficient and beam/draft ratio), F_2 (depending on prismatic coefficient and LCB), F_3 (depending on prismatic coefficient, half-angle of waterline entrance and length/beam ratio), and F_4 (depending on midship section coefficient), all contributing to the Telfer resistance criterion, $C_{RTelfer} = R_T L/\Delta V^2$ for a 200 ft (60 m) vessel at speed-length ratios from 0.8 to 1.1. The Telfer resistance criterion is not non-dimensional, and has been little-used since the 1970s.

Since then, there have been many regression analyses carried out, most of them useful, and some memorable. Mercier and Savitsky's (1973) paper was memorable as the first to investigate the pre-planing regime. Lahtiharju et al. continued the analysis up into the higher speed range. It is now a rare series which is published without a regression analysis of the resistance data. See, for example, Zips (1995) and Muller-Graf et al. (2002) on the VWS hard-chine catamaran series, and Radojcic et al. (2001) on the double-chine monohull series tested at the National Technical university of Athens.

Also memorable was Fung's (1991) paper which, in addition to publishing the results of a regression analysis of a large database of unrelated hullforms, gave an excellent review of the historical development of regression methods in ship resistance prediction and the selection of relevant parameters. He also gave an overview of regression analysis techniques in general, and the points which need consideration in conducting the analysis.

2.2 Regression Analysis

Many regression analyses in ship resistance work use a polynomial representation taking the form

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_1^2 + a_4 x_1 x_2 + a_5 x_2^2 + \ldots \qquad (1)$$

i.e.

$$y = \sum_i a_i x_1^j x_2^k \qquad (2)$$

where y is the dependent variable and x_1 and x_2 are two independent variables, for example. We can choose to take as many terms in the polynomial as we like. As shown in Equation 1 above, where all powers up to 2 are taken including cross products, there are 6 terms in the equation. For powers up to 3 there are 10 terms; for powers up to 4 there are 15 terms, for powers up to 5 there are 21 terms, and for powers up to 6 there are 28 terms. It is rare to find powers of independent variables greater than 6 in ship resistance work, and greater powers were not considered here.

If we have a number of sets of data, such as y for given values of x_1 and x_2, then each data set provides an equation. If there are as many equations (data sets) as coefficients, then we can solve the equations for the coefficients, and the resulting equation fits the data points exactly. If there are more data sets than coefficients, then we usually choose to minimise the sum of the squares of the differences between calculated values and the data sets, and this is known as a least-squares fit. i.e. we minimise

$$SSD = \sum_{i=0}^{N} (y_i - \hat{y}_i)^2 \tag{3}$$

where y_i is a data point, $\hat{y}_i$ is the value calculated from the equation. One measure of the "goodness of fit" is the correlation coefficient (or coefficient of determination):

$$R^2 = 1 - \sum_{i=0}^{N} (y_i - \hat{y}_i)^2 / \sum_{i=0}^{N} (y_i - \bar{y}_i)^2 \tag{4}$$

where $\bar{y}_i$ is the mean of the N values of y_i and N the number of data sets in the sample. If $R^2 = 1$, then the equation fits the data exactly whereas, if $R^2 = 0$ then the equation does not fit the data at all well. In ship resistance work, correlation coefficients greater than 0.99 are considered an excellent fit, and above 0.95 acceptable.

As we take more terms in the equation, the sum of the squares of the differences $\Sigma(y_i - \hat{y}_i)^2$ may not indicate when the behaviour of the polynomial between fitted points begins to predominate. In such cases the variance can be used to indicate the effect which the number of terms is having on the equation. For multiple regression analysis the variance is calculated as

$$\sigma^2 = \frac{\sum_{i=0}^{N} (y - \hat{y}_i)^2}{N - n} \tag{5}$$

where n is the number of terms in the equation, and N is the number of data points. As the number of terms increases from a low value, the variance generally decreases, and a subsequent increase means that the number of terms is not improving the goodness of fit.

3. ANALYSIS OF RIDGELEY-NEVITT DATA

3.1 Form of the Polynomial

Ridgeley-Nevitt's data was published as contours of residuary resistance coefficient, C_R, vs displacement-length ratio as the ordinate and prismatic coefficient as the abscissa in nine graphs for speed-length ratio, $V/\sqrt{L}$, from 0.7 to 1.5 in 0.1 kn/√ft increments. An example is shown for $V/\sqrt{L} = 0.9$ in Fig. 1.

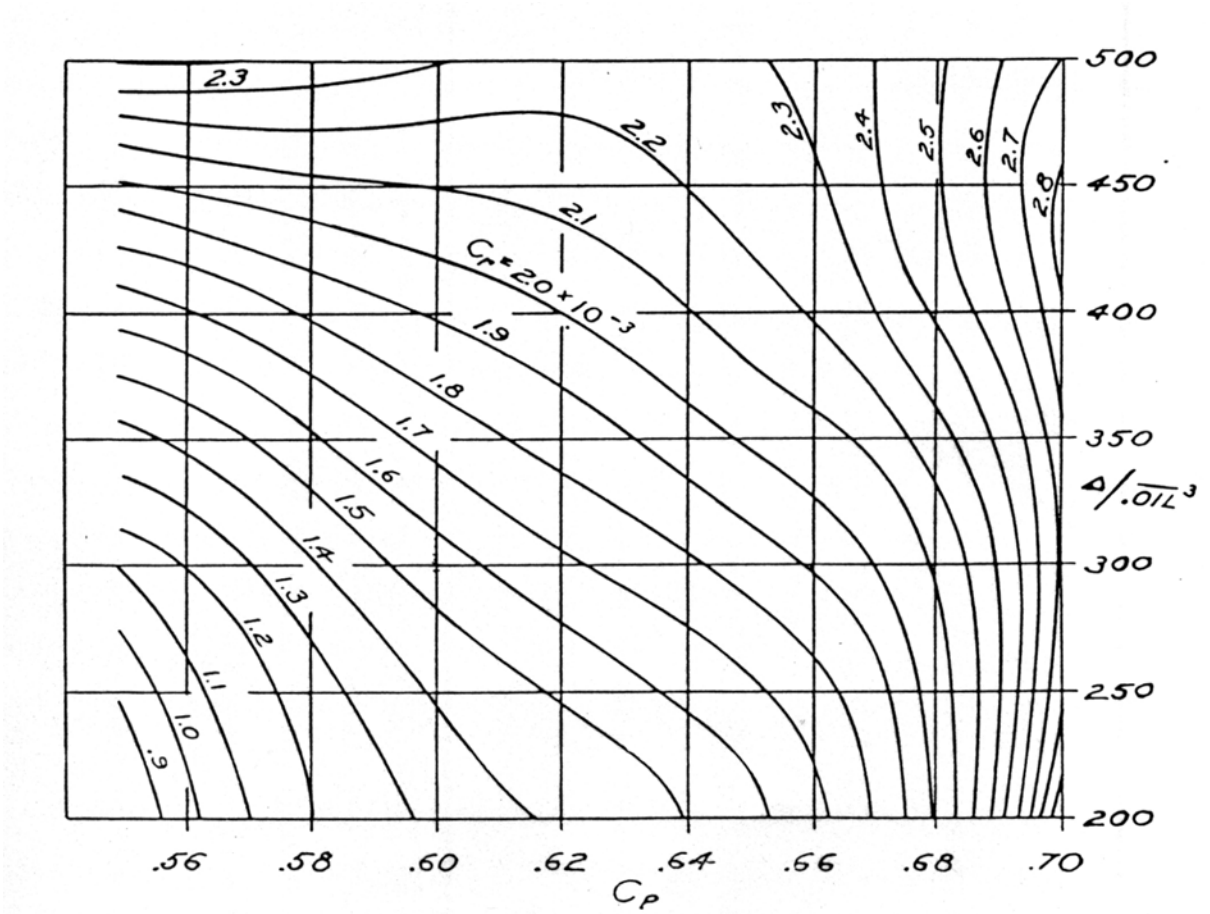

Figure 1 Residuary Resistance Coefficient for $V/\sqrt{L}$ = 0.9 (from Ridgeley-Nevitt 1967)

The independent variables have already been chosen by Ridgeley-Nevitt to be the prismatic coefficient, C_P, and the displacement-length ratio, $\Delta/(0.01L)^3$. Reasons for so doing are outlined in the development of the series.

Consideration was given to whether the regression analysis should be speed dependent (fitting the data at each of the given speed-length ratios), or speed independent (fitting the data with speed as an independent variable). Fung (1991) advises that step-wise regression over discrete speed regimes was preferable for reproduction of the humps and hollows in the resistance curve, and that a speed-dependent analysis will ensure smoothness of the predicted resistance curve. We have therefore analysed each speed-length ratio separately.

So, in the form of Equation (2), we take y as the residuary resistance coefficient, $C_{R;}$ x_1 as the prismatic coefficient, $C_{P;}$ and x_2 as the displacement-length ratio, $\Delta/(0.01\mathrm{L})^3$, giving:

$$C_R = \sum a_i C_P^j \left(\frac{\Delta}{(0.01L)^3} \right)^k \qquad (6)$$

The task is to find the number of terms to take in this equation at each speed-length ratio to maximise the goodness of fit.

3.2 Data Collection

The data was lifted from Ridgeley-Nevitt's published curves by measuring, as accurately as possible, the prismatic coefficient or displacement-length ratio for each value of residuary resistance coefficient. The spacing of data points was determined mainly by the intersections of the C_R contours with the gridlines. Data was lifted at each of the nine speed-length ratios from 0.7 to 1.5. Table 1 shows the number of data sets lifted at each speed-length ratio.

Table 1 Data Sets at Speed-length Ratios

$V/\sqrt{L}$	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
N	137	185	229	186	159	183	148	134	141

The higher numbers of data sets correspond to those speed-length ratios in which the contours of C_R are more closely spaced. This is a total of 1502 data sets, giving an average of 167 sets per speed-length ratio, compared to the maximum number of terms in the equation being considered as 28.

3.3 Regression Analysis

A regression-analysis program was available at UNSW, and a modified copy of this program was used to test the initial data. However, the program was written in single-precision, and could not provide all the information that we would have liked. So, after initial testing, the second author wrote his own regression-analysis program in C^{++}, with all variables in double precision and more comprehensive output. Results from the new program were tested against the available program and data prepared for the purpose to ensure that it was delivering correct results.

3.4 Determination of Number of Terms in the Equation

At each speed-length ratio, the program was run with varying numbers of terms in the equation, including the complete cubic (10 terms), quartic (15 terms), quintic (21 terms) and sixth-order (28 terms) polynomials. Least-squares coefficients were determined for each and, for each of the resulting equations, the values for the sum of squares of the errors, the correlation coefficient and the variance were examined.

As an example, Fig. 2 shows how the variance, σ^2, varies with number of terms in the equation for several speed-length ratios.

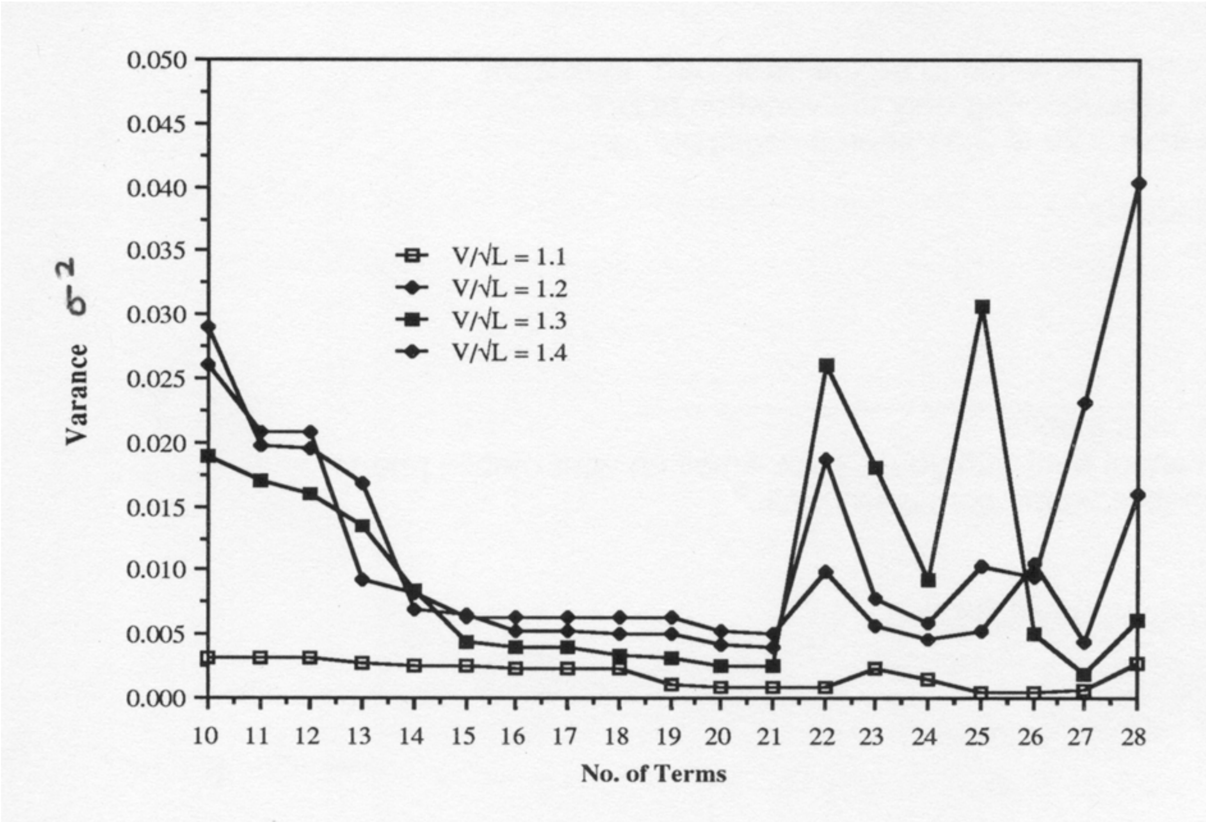

Figure 2 Variation of Variance with Number of Terms in Equation

This figure shows that it is beneficial to include all terms up to quartic (15 terms). It is also beneficial to include all terms up to quintic (21 terms), as there is a small but worthwhile increase in accuracy. It is definitely not of benefit to include any of the sixth-order terms, as the variance increases, thereby decreasing the accuracy. The corresponding figure for speed-length ratios 0.7–1.0 shows the same trends.

It was therefore decided to use the quintic version of the equation, with all powers up to 5, including cross products, and giving 21 terms.

3.5 Goodness of Fit

With the number of terms decided, the goodness of fit was examined more closely. Table 2 shows the correlation coefficients and a summary of the errors for each speed-length ratio.

The correlation coefficients are all above 0.99, and can be regarded as showing an excellent fit for all speed-length ratios. Subsequent columns show that there are some single locations where the equations do not represent the data well. However, 95% of the points show errors of less than 2.7% (most less than 2%), and the overall average errors at each speed-length ratio are all less than 1%.

Table 2 Goodness of Fit for Quintic Equation

$V/\sqrt{L}$	R^2	Maximum single error (%)	95% of errors are blow (%)	Overall average error (%)
0.7	0.997	4.2	2.5	0.82
0.8	0.996	5.0	2.7	0.97
0.9	0.999	4.6	1.7	0.57
1.0	0.999	3.4	1.7	0.67
1.1	0.999	6.5	1.7	0.73
1.2	0.998	13.3	2.2	0.95
1.3	0.999	1.6	1.0	0.49
1.4	0.999	1.6	0.9	0.34
1.5	0.999	2.9	2.0	0.73

3.6 Testing

As a further test on the accuracy of the polynomials, a number of points were chosen at each speed-length ratio, and new values of C_R at specified values of $V/\sqrt{L}$ and $\Delta/(0.01L)^3$ lifted manually. The same values of $V/\sqrt{L}$ and $\Delta/(0.01L)^3$ were then fed into the equation, and the value of C_R calculated for comparison.

It was important that the points selected were not in the data set used for determination of the coefficients of the equation. Sixteen points were selected at each speed-length ratio, giving a spread of prismatic coefficient and displacement-length ratios. Figure 3 shows the location of the selected points on each graph.

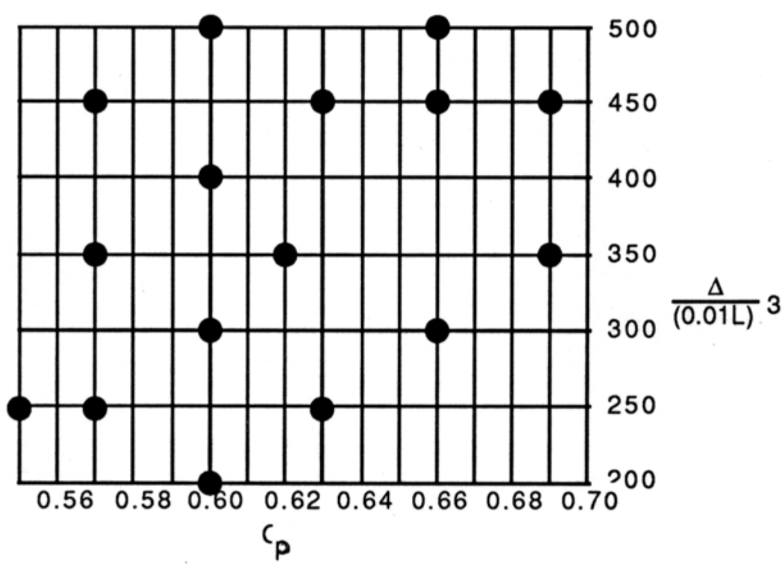

Figure 3 Location of Measured Points

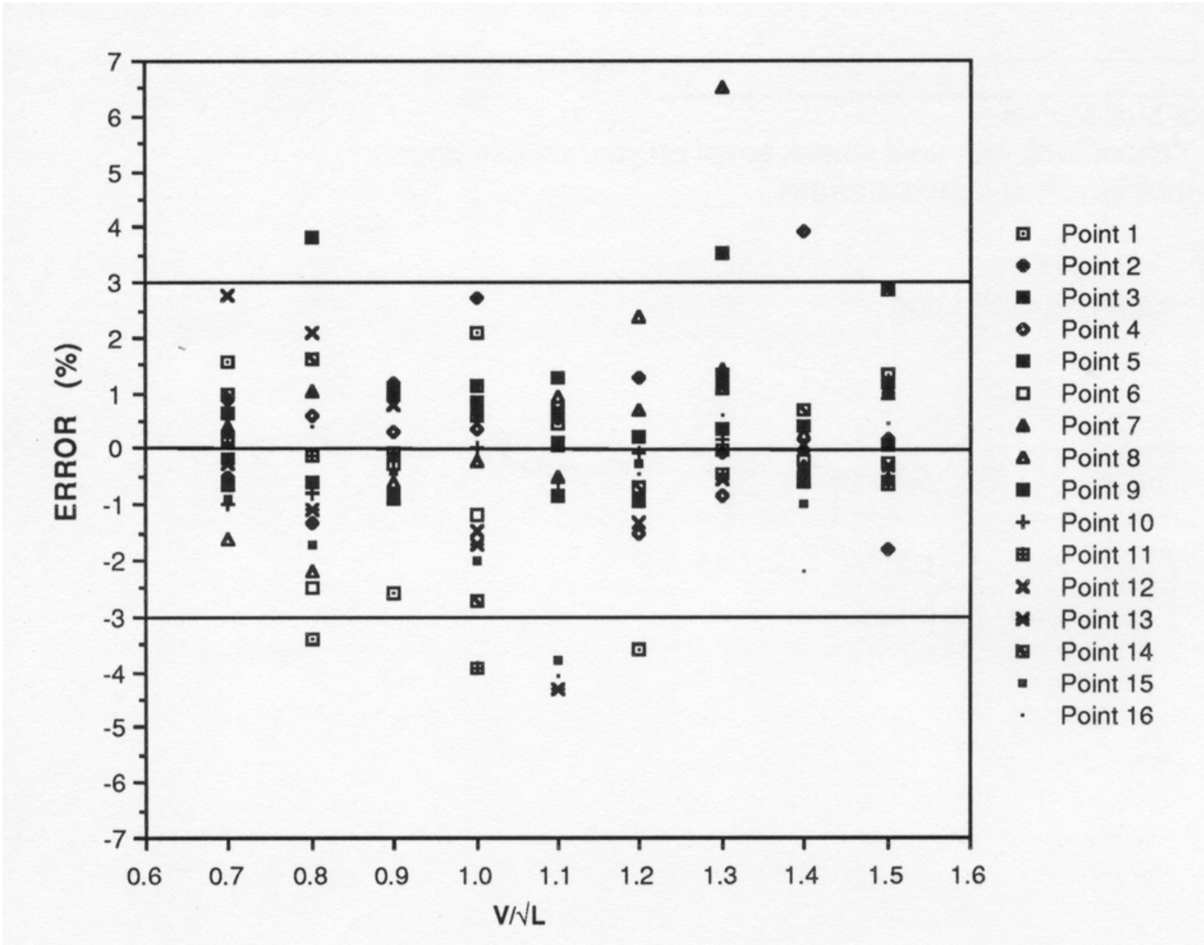

Figure 4 Test Percentage Error vs Speed-length Ratio

The differences between the calculated and measured values were then expressed as a percentage error, and plotted against speed-length ratio in Figure 4.

This figure shows that, for the data points tested, the maximum single error was 6.5%, 95% of the points had errors of less than 3%, and the average error was less than 1%. These are very similar results to those found for the equation on the original data, except that the maximum single error has been halved.

3.7 The Final Equation

The final equation is similar to Equation 6, but with the number of terms now determined, and a factor of 1000 inserted on the left-hand side for convenience:

$$1000C_R = \sum_{i=0}^{20} a_i C_P^j \left(\frac{\Delta}{(0.01L)^3} \right)^k \tag{7}$$

The a_i coefficients are given in Appendix 1.

Table 3 Principal Particulars of Vessels Analysed

Item	Units	20 m Prawn Trawler	40 m Survey Vessel
Length BP	m	18.42	35.78
Displacement	m	120	376
Prismatic coefficient		0.5607	0.6159
$\Delta/(0.01L)^3$	tons/ft^3	535	229

4. APPLICATIONS

4.1 Vessels Analysed

For purposes of illustration, two vessels for which tank-test results were available were selected for use with Ridgeley-Nevitt's method, and comparison with van Oortmerssen's method and the UBC low length-beam ratio series. The vessels both have double chines, one being a 20 m prawn trawler, and the other a 40 m survey vessel. Details of the two vessels are shown in Table 3.

The displacement-length ratio for the 20 m prawn trawler is slightly above the 500 upper limit of the Ridgeley-Nevitt series. However, the C_R values returned by the polynomial are of the right order when compared to the lines of the original curves. The results appear to be well-behaved in this area, showing a general increase in C_R with displacement-length ratio.

The Ridgeley-Nevitt calculation using the polynomials for the survey vessel is shown in Appendix 2.

4.2 Results

Tank-test results were extrapolated to full size using a correlation allowance $C_A = 0$, and the same allowance has been used for each of the prediction methods for the purpose of comparison. The resistance predictions for the 20 m prawn trawler and the 40 m survey vessel are shown in Figures 5 and 6.

For the prawn trawler, all predictions (Ridgeley-Nevitt, van Oortmerssen and UBC) are slightly low when compared to the tank-test data up to a speed of 9.5 kn. Above that speed, both the Ridgeley Nevitt and van Oortmerssen prediction follow the tank-test data up to the highest speed tested of 10.4 kn, and then show some divergence. The UBC data under-predicts at the higher speeds.

For the survey vessel, all predictions are slightly low when compared to the tank-test data up to a speed of 10 kn. Above that speed, the van Oortmerssen prediction follows the tank-test data more closely, while the Ridgeley-Nevitt and UBC predictions under-predict but are close to each other up to about 13 kn. Above 13 kn, the Ridgeley-Nevitt prediction picks up and is the best predictor at 16 kn, while the UBC data under predicts at the higher speeds.

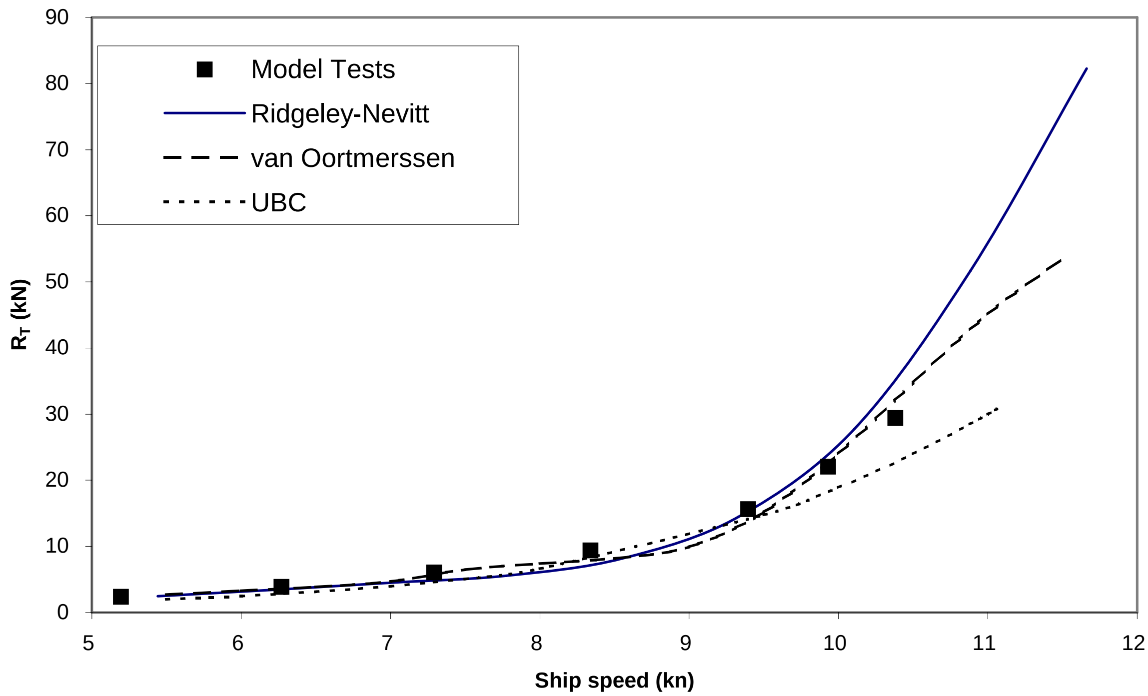

Figure 5 Resistance Predictions for 20 m Prawn Trawler

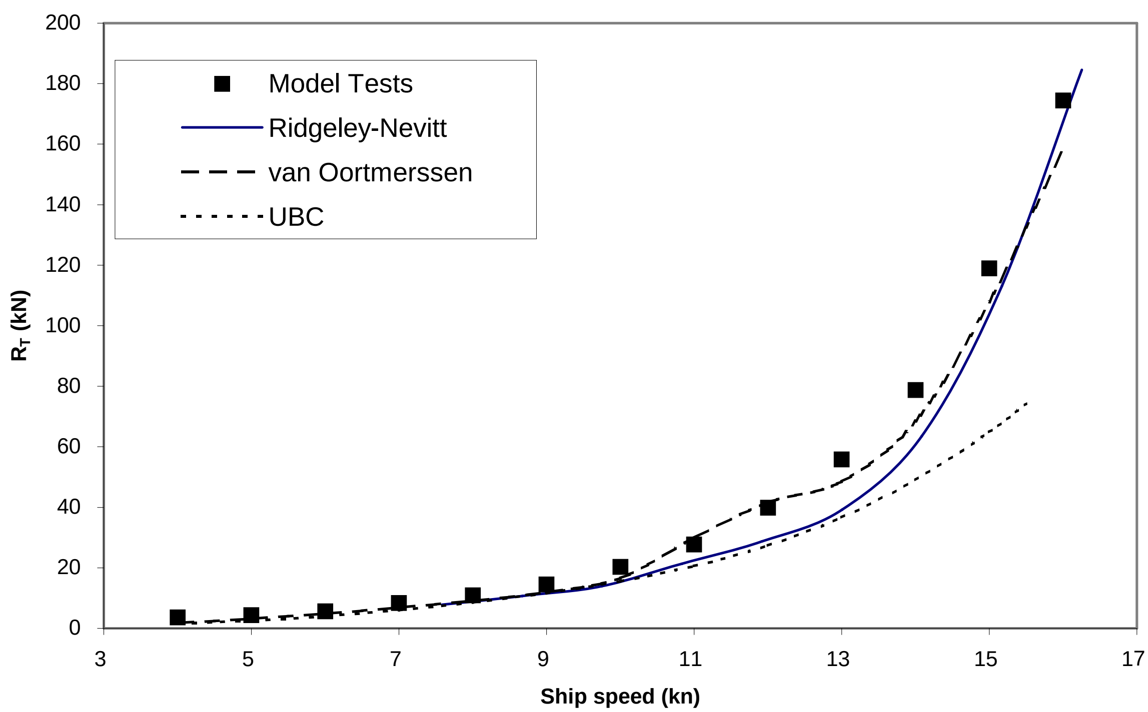

Figure 6 Resistance Predictions for 40 m Survey vessel

5. CONCLUSION

Data have been lifted from the contour plots of residuary resistance coefficient vs displacement-length ratio and prismatic coefficient published by Ridgeley-Nevitt for his trawler series. The data have then been analysed using regression analysis, and polynomials found at each of the nine speed-length ratios to give the residuary resistance coefficient in terms of the displacement-length ratio and prismatic coefficient.

The polynomials have been used to predict the resistance of two vessels, and the predictions compare well with the results of tank tests. It is also shown here that, for the vessels analysed, van Oortmerssen's method is another good predictor, while the UBC low length-beam ratio series tends to under-predict at high speeds.

It is the author's hope that the formulation of the polynomials will provide the Ridgeley-Nevitt data with a further lease of life.

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APPENDIX 1
Coefficients for the Ridgeley-Nevitt Trawler Series Polynomial

$$1000\ C_R = \sum_{i=0}^{20} a_i C_P^{\,j} \left(\frac{\Delta}{(0.01\,L)^3} \right)^k$$

V/√L	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	j	k
a_0	-3.367375e+02	-1.131821e+03	-7.987487e+02	-5.495031e+03	-1.959839e+04	-1.115782e+04	2.059093e+04	2.304725e+04	-7.627116e+03	0	0
a_1	4.510132e+03	1.144315e+04	9.444859e+03	4.470873e+04	1.493976e+05	8.523455e+04	-1.731665e+05	-1.955533e+05	4.808621e+04	1	0
a_2	-2.775423e+00	-3.882796e+00	-3.483028e+00	1.564857e+00	1.681544e+01	1.849773e+01	2.205332e+01	3.151908e+01	3.469430e+01	0	1
a_3	-1.987067e+04	-4.485211e+04	-4.197684e+04	-1.456501e+05	-4.581927e+05	-2.644082e+05	5.757648e+05	6.541129e+05	-1.214046e+05	2	0
a_4	3.177310e-03	1.619355e-03	-3.433895e-03	-5.242900e-03	-1.998867e-02	-1.415517e-02	-1.540912e-02	-1.849526e-02	-3.897304e-02	0	2
a_5	1.446973e+01	2.396460e+01	2.701334e+01	-5.754920e+00	-8.572638e+01	-9.764750e+01	-1.198054e+02	-1.740689e+02	-1.779765e+02	1	1
a_6	3.985281e+04	8.628761e+04	8.957297e+04	2.389184e+05	7.071299e+05	4.166109e+05	-9.472197e+05	-1.081178e+06	1.522179e+05	3	0
a_7	-1.867135e-07	-2.357607e-06	-1.407289e-06	-7.488554e-06	6.922887e-06	8.127120e-06	2.900006e-06	3.533519e-06	3.380046e-05	0	3
a_8	-2.707036e+01	-5.796037e+01	-7.847958e+01	-4.786991e+00	1.564267e+02	1.897987e+02	2.395678e+02	3.598812e+02	3.511918e+02	2	1
a_9	-1.456770e-02	-3.138204e-03	1.990320e-02	3.921751e-02	8.683298e-02	5.600747e-02	6.901450e-02	7.832233e-02	1.320576e-01	1	2
a_{10}	-3.789170e+04	-8.217560e+04	-9.282566e+04	-1.980407e+05	-5.492796e+05	-3.330532e+05	7.723279e+05	8.855386e+05	-9.382871e+04	4	0
a_{11}	-1.315193e-09	-5.818228e-10	-4.243546e-10	4.816011e-09	-3.834599e-10	-2.601107e-10	4.158014e-09	8.372639e-09	-1.410815e-08	0	4
a_{12}	2.195102e+01	6.604912e+01	1.010491e+02	3.097721e+01	-1.186469e+02	-1.621401e+02	-2.119516e+02	-3.349618e+02	-3.143636e+02	3	1
a_{13}	1.967615e-02	-4.658654e-03	-3.834695e-02	-7.706417e-02	-1.235117e-01	-6.819438e-02	-9.199182e-02	-9.559278e-02	-1.513725e-01	2	2
a_{14}	3.612058e-06	9.631851e-06	5.787269e-06	1.384514e-05	-2.169403e-05	-2.669033e-05	-2.003295e-05	-2.838143e-05	-7.478212e-05	1	3
a_{15}	1.396810e+04	3.113467e+04	3.762746e+04	6.649705e+04	1.718026e+05	1.076942e+05	-2.502245e+05	-2.882853e+05	2.229106e+04	5	0
a_{16}	5.394199e-13	6.850379e-13	6.363168e-13	-1.303861e-12	-3.314301e-13	1.490808e-12	-1.001611e-12	-2.939132e-12	2.759353e-12	0	5
a_{17}	-6.775294e+00	-2.957850e+01	-4.841819e+01	-2.445800e+01	3.014213e+01	5.325358e+01	7.217284e+01	1.203924e+02	1.083748e+02	4	1
a_{18}	-7.769878e-03	7.400768e-03	2.370982e-02	4.635973e-02	5.801611e-02	2.059287e-02	3.407026e-02	3.211705e-02	5.570532e-02	3	2
a_{19}	-4.040588e-06	-6.911744e-06	-3.989399e-06	-6.791872e-06	1.560512e-05	2.717004e-05	2.285796e-05	2.826415e-05	4.573017e-05	2	3
a_{20}	7.782022e-10	-1.132617e-09	-1.005605e-09	-4.154611e-09	1.681804e-09	-4.044971e-09	-4.386360e-09	-5.550756e-09	1.295067e-08	1	4

Appendix 2
Ridgeley-Nevitt Resistance Prediction for 40 m Survey vessel

RIDGELEY-NEVITT TRAWLER SERIES RESISTANCE ver 1.3

Length BP	35.78 m		
Displacement volume	366.8 m^3		
Prismatic coefficient	0.6159	0.55-0.70	Allowable range
Wetted surface area	317.3 m^3		
Water density	1.025 t/m^3	1.0250 at 19°C	
Water viscosity	1.07854 X 10^{-6} m^2/s	1.07854 x 10^{-6} at 19°C	
Correlation allowance	0		
Displacement	375.9 T		
$\Delta/(0.01L)^3$	228.6	200-500	Allowable range

$V/\sqrt{L}$	V	$10^{-6}Rn$	10^3C_F	10^3C_R	10^3C_T	R_T	P_E
	kn		ITTC'57			kN	kW
0.7	7.58	129.5	2.008	1.168	3.175	7.9	31
0.8	8.67	148.0	1.970	1.321	3.291	10.6	47
0.9	9.75	166.4	1.938	1.466	3.404	13.9	70
1.0	10.84	184.9	1.910	2.324	4.234	21.4	119
1.1	11.92	203.4	1.885	2.827	4.712	28.8	177
1.2	13.00	221.9	1.862	3.528	5.391	39.2	262
1.3	14.09	240.4	1.842	5.594	7.436	63.5	460
1.4	15.17	258.9	1.824	9.588	11.411	113.0	882
1.5	16.25	277.4	1.807	14.432	16.239	184.6	1543