Defence Science Journal, Vol 42, No 1, January 1992, pp. 13-2?

Estimation of Powering Characteristics of a Semi-Planing Ship

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ABSTRACT

High speed ships, especially with planing or semi-planing type of hull forms are popular amongst navies of the world. Appropriate propulsion plant configuration has to be selected to provide the desired maximum speed and quick responses. Dynamic response of the ship's propulsion plant is one of the main considerations in selection procedure. Accuracy of dynamic response obtained from computer simulation depends on the accuracy of data, especially the hull resistance and propeller characteristics.

This paper discusses the estimation of hull resistance and propeller characteristics of the ship with the help of computer programs and their comparison with full-scale trial data.

NOMENCLATURE

B	maximum molded breadth
B_{P_x}	maximum beam at the chine
B_{ref}	breadth at reference section
C_B	block coefficient
C_p	prismatic coefficient
C_v	viscous coefficient
C_F	friction coefficient for corrected displacement
C_f	Schoenherr friction coefficient
C_{wp}	waterplane area coefficient
C_m	midship section coefficient
$F_{n\nabla}$	volumetric displacement Froude number
j	advance coefficient
k_t	propeller thrust coefficient
k_q	propeller torque coefficient
P/D	propeller pitch to diameter ratio
S	wetted surface area
T	mean draft
V	speed of the ship
w	wake fraction
β	dead-rise angle
Δ	displacement
∇	volumetric Froude number
τ	trim angle
λ	wetted length to beam ratio
ν	kinematic viscosity
η_R	relative rotative efficiency

1. INTRODUCTION

The use of high speed ships, of late, has been gaining popularity amongst most of the navies all over the world. Generally hull forms of these ships are chosen to get the desired speed and sea-keeping characteristics depending on the operating area. Though the high speed round bilge displacement type of hull forms are also being considered[1,2] the planing or semi-planing type of hull forms have an edge over them in terms of maximum speed. Their sea-keeping performance is also quite comparable to that of the conventional hull forms[3].

Received 5 December 1990, revised 16 April 1991

Proper selection of an appropriate propulsion plant configuration to meet the desired maximum speed and quick responses to the given speed demand is a difficult task. If the hull form and the propellers are fixed, there is very little room left for making changes in them to improve the dynamic response of the ship. This is generally the case when one is considering the possibility of fitting the ship with a different propulsion plant configuration from the existing one.

To ensure the dynamic response of the ship's propulsion plant is better than or at least equal to that of the already existing propulsion plant configuration, one has to resort to ship simulation technique. This technique will help in predicting such responses and the evaluation of the control system provided the hull resistance and propeller characteristics are known accurately.

This paper discusses the estimation of ship's resistance and propeller characteristics with the help of computer programs developed and compares the results with those obtained from full-scale trials. The ship considered here has a semi-planing type hull and is propelled by gas turbines driving two shafts having a fixed pitch propeller.

2. PREDICTION OF RESISTANCE CHARACTERISTICS

Various methods generally available to determine the resistance characteristics of the ship are: (i) theoretical analysis, (ii) model testing of hull and propeller, (iii) statistical analysis, (iv) resistance prediction from systematic series data, and (v) full-scale trials of the ship.

Theoretical analysis requires a sound knowledge of the equations governing the hull resistance and solving them with the help of computers. The formulation of the governing equations, their computations and validation of the results is quite demanding and time consuming. Model testing could be carried out provided such facilities exist within the country. The existing facilities are not adequate enough in terms of maximum speed that could be achieved and accuracy of the results.

Statistical analysis requires a large database from model tests and full-scale ship trials. Multiple regression analysis is then performed on the database and empirical relations developed. Thus, given the hull parameters, predictions of resistance characteristics can be made. Accuracy of this prediction will be dependant on the closeness of the hull under consideration to the mean value in normal distribution of the database.

Prediction of resistance characteristics is also carried out from the systematic series data of a particular type of ship. Some of the known high speed series are : planing type series[4,5] 62 and 65, high speed displacement forms series[6] 64, high speed round bottom boats series[7] 63, and high displacement length ratio trawler series[8]. In advanced countries various agencies have their own systematic series for each type of hull, viz. displacement, semi-displacement, planing, etc. Such a systematic series data for the type of vessel under consideration is not available at present in India.

There is an advantage in measuring resistance, etc from full-scale trials since the 'scale effects' are not present. However, full-scale trials present their own set of difficulties, since the environment in which the ship is being tested is uncontrolled.

In view of the above, the present study was conducted based on statistically analysed data and comparing them with the data obtained from full-scale ship trials.

2.1 Particulars of the Ship

Particulars of the ship for which resistance characteristics have been estimated are shown in Table 1.

Table 1. Particulars of hull resistance characteristics

Parameter	Value
Type of hull form	Hard chine
L_{pp}/B_{ref}	4.853
B_{ref}/T	4.6364
$S/\nabla^{2/3}$	7.5544
C_B	0.40418
C_p	0.7181
C_{wp}	0.7127
C_m	0.5628
$\beta_{midship}$	15 deg
$\beta_{transom}$	4 deg

2.2 Resistance Prediction by Holtrop's Method

A statistically analysed resistance prediction method has been proposed by Holtrop[9] and Holtrop and Menen[10]. They have carried out the regression analysis based on the results of tests on more than 300 models and full-scale test data. Empirical relations have thus been developed by them for calculation of various elements of the total resistance of the ship. Total resistance is a combination of frictional, wave, appendages, bulbous bow, transom and model ship correlation resistance.

These empirical relations/formulae are quite exhaustive and take care of differrent types of hull shapes, appendages, bulbous bow, etc. These have been implemented on a computer. Once the geometrical details of the hull, its appendages, etc are known, ship's resistance can be predicted based on these relations. A generalised computer program has been developed to do the number crunching and iterations making use of the large number of formulae given. This program has been written in Turbo C language and can be used on an ordinary PC AT. The logical/numerical errors in the program developed were corrected with the help of test input and output data[9].

2.3 Resistance Prediction by Savitsky and Brown's method

Savitsky and Brown[11] have given a resistance prediction method for the planing type of hulls for pre-planing and planing regimes separately. In the pre-planing regime they reported regression analysis carried out by Mercier and Savitsky[12] of the smooth water resistance data of seven transom stern hull series, which includes 118 separate hull forms.

The range of geometric characteristics for all the seven series has been summarized and given in the form of table[11]. The resistance prediction equation derived from the resistance data of the above mentioned 118 models, is based on the following four parameters.

$$X = \quad {}_{WL}$$

$$Z \quad \nabla / B_{P_x}$$

$$U \quad \sqrt{2 i_e} \qquad (3)$$

$$W = A_T / A_x \qquad (4)$$

The original equation had 27 terms out of which the lesser significant were eliminated to arrive at Eqn (5) which gave a reasonable fit.

$$R_T / \Delta = A_1 + A_2 X + A_4 U + A_5 W + A_6 XZ + A_7 XU + A_8 XW + A_9 ZU + A_{10} ZW + A_{15} W^2 + A_{18} XW^2 + A_{19} ZX^2 + A_{24} UW^2 + A_{27} WU^2 \qquad (5)$$

Values of the 14 terms corresponding to $F_{n\nabla}$ varying between 1.0 to 2.0 in steps of 0.1 are also given[11]. Terms for all values of $F_{n\nabla}$ may not be necessary always because each ship may move into planing regime at a different value of $F_{n\nabla}$. The values of the 14 terms in the resistance prediction equation given are applicable for a 100, 000 lbs displacement ship only. For ships having any other displacement the resistance calculated from the earlier equation can be corrected as per the following relation.

$$(R_T / \Delta)_{corr} = (R_T / \Delta)_{100,000} + [(C_F + C_A) - C_{F_{100,000}}] (1/2) (S/\nabla^{2/3}) F_{n\nabla}^2 \qquad (6)$$

where $(R_T/\Delta)_{corr}$ is the corrected value of R_T/Δ, $(R_T/\Delta)_{100,000}$ is the value of R_T/Δ for Δ (100,000 lbs seawater, from Eqn (5)), and $C_{F100,000}$ is the Schoenherr friction coefficient corresponding to Reynold number and is given by

$$C_{f100,000} = (F_{n\nabla} (L_{WL}/\nabla^{1/3}).\sqrt{(32.2 \times 100,000/64)} / \nu$$

Resistance in the planing regime can be calculated with the help of the following equation

$$R_T = \Delta \tan \tau + 0.5 \rho V^2 \lambda B_{P_x}^2 C_f / \cos \tau \cos \beta \qquad (7)$$

The Schoenherr friction coefficient C_f corresponds to a Reynolds number, $R_N = \lambda B_{P_x} V / \nu$

A computer program has been made to solve the various equations for predicting pre-planing resistance and calculating iteratively lift coefficient for zero dead-rise. The numerical/logical errors in the program developed were corrected with the help of test input and output data by Savitsky and Brown[11]

3. PREDICTION OF PROPELLER CHARACTERISTICS

If the geometrical details are available, the characteristics of a given propeller can be determined by one of the four methods: (i) model testing, (ii) theoretical analysis, (iii) matching with the known series data, and (iv) full-scale trials of the ship.

Model testing requires a suitable tank and a cavitation tunnel in order to determine the characteristics of the model propeller over the complete operating range which is time consuming and very expensive. Theoretical prediction is possible, but some input is still required from the model tests[13,14].

The third alternative (used in this study) is to try and match the given propeller with other well-known series by comparing their geometrical features. One to one geometrical similarity was not found between the given propeller and those generally used for high speed crafts[15-20].

The four propellers namely, Gawn series, Gawn and Burrill series, SSPA series, and Wageningen B series, whose open water characteristics (k_q, k_t, vs J), available in the form of graphs were picked up from the literature. They were then expressed as third degree polynomial curves. Thus equations were obtained for thrust and torque coefficients as functions of advance coefficient and propeller pitch (P) to diameter (D) ratio so that for a particular propeller, k_q and k_t values can be calculated for any value of J and P/D ratio.

The torque and thrust characteristics of the four propeller series are plotted for a particular P/D ratio in Figs 1 and 2. All of them exhibit similar characteristics except the B series, which is mainly used for merchant

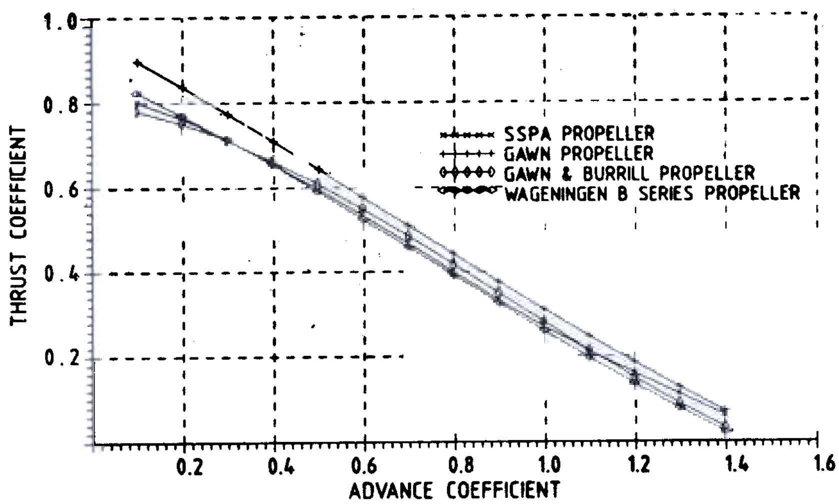

Figure 1. The relationship between thrust coefficient and advance coefficient of propellers, p/d = 1.45, 3 blades

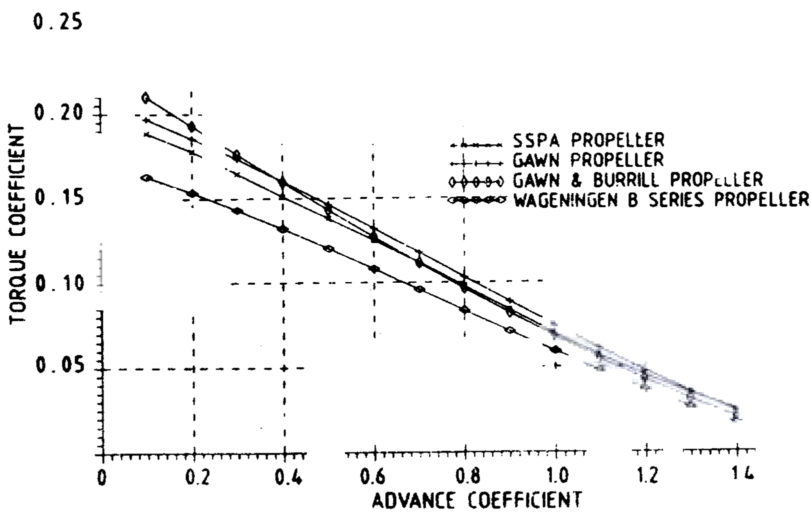

Figure 2. The relationship between torque coefficient and advance coefficient of propellers, p/d = 1.45, 3 blades

ships. This implies that characteristics of any one of them can be considered for initial powering calculations. Later this can be modified suitably based on the full scale trials on the ship or model testing of the propeller. However, this is true only under non-cavitating conditions of the propeller. But in actual practice all propellers used for high speed crafts are generally cavitating types especially in the higher speed range. The authors had access only to the open water characteristics of Gawn and Burrill series propellers for 6 different cavitation numbers. These curves were digitised for P/D ratios of 1.4 and 1.6 and stored in the program as a look-up table. A program was written for the interpolation of these characteristics for $P/D = 1.45$. The results are shown in Figs 3 and 4. These have been used for the powering predictions in this paper.

The last technique available is to conduct full-scale trials. This requires a ship adequately instrumented for measuring thrust, torque and rpm of the propeller shaft and conducting trials on it to derive the partial or complete open water charateristics.

4. PROPULSIVE FACTORS

Propulsive factors of the ship namely, wake fraction, thrust deduction fraction and the relative rotative efficiency, can be statistically predicted. To predict the powering characteristics in this study these factors have been taken from two different sources.

Holtrop[10] has given a generalised formula for these parameters for a twin screw arrangement :

$$w = 0.3095\, C_B + 10\, C_V\, C_B - 0.23\, D/\sqrt{BT} \qquad (8)$$

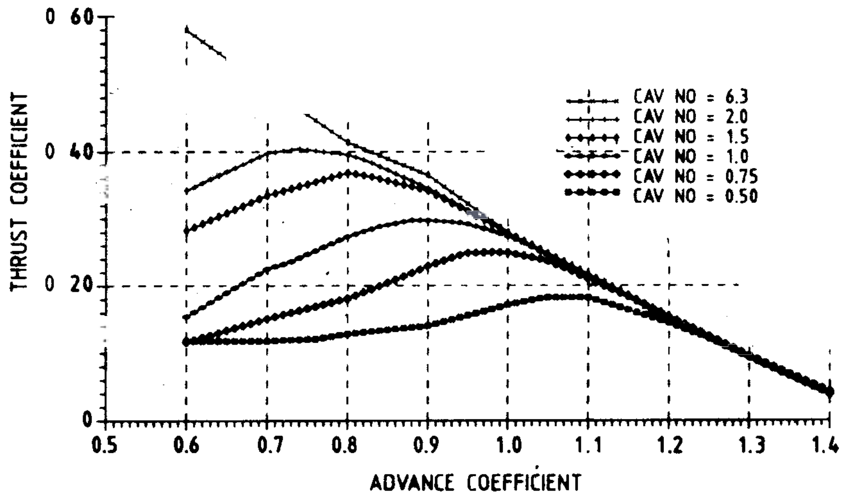

Figure 3. The relationship between thrust coefficient and advance coefficient of Gawn and Burrill propeller, $p/d = 1.45$.

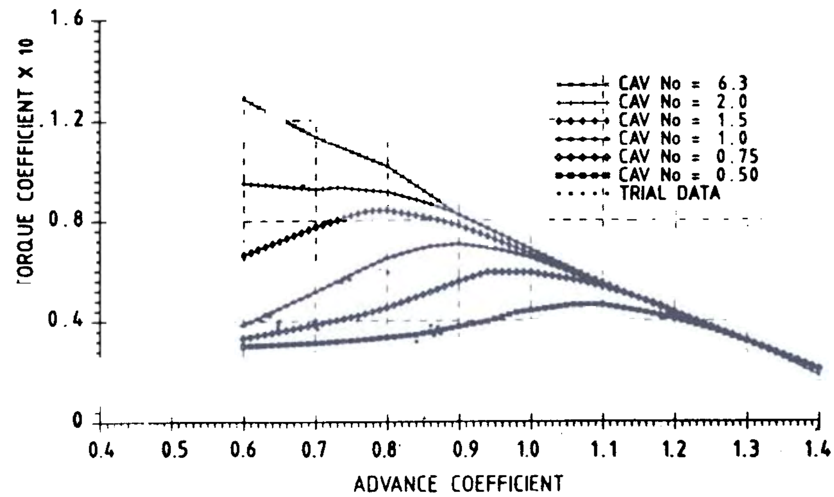

Figure 4. The relationship between torque coefficient and advance coefficient of Gawn & Burrill propeller, $p/d = 1.45$.

$$t = 0.325\, C_B - 0.1885\, D / \sqrt{BT} \qquad (9)$$

$$\eta_R = 0.9737 + 0.111\ (C_p - 0.225\, lcb) - 0.06325\, P/D \qquad (10)$$

Blount and Fox[21] have presented similar data in a graphical form showing their variations with Froude number based on volumetric displacement specifically for planing vessels. The source for these data has once again been the large number of model and full-scale experimental data for a twin screw craft. The graphs are shown in Fig. 5.

5. FULL-SCALE TRIALS

To compare the predictions made for the hull and propeller characteristics, full-scale trial of the ship was carried out. The ship was equiped to measure propeller shaft torque (torsionometer) and speed (shaft speed tachometer), ship's speed over the ground and position (decca trisponder), and wind speed and direction (anemometer) with the help of a computer-based data acquisition system. Current was estimated by allowing the ship to drift for five seconds at the trial site just before the commencement of the trials.

6. ANALYSIS OF RESULTS

6.1 Propeller Characteristics

From the propeller shaft torque values recorded for various steady ship's speed during full-scale trial, the torque coefficients were determined. The water vapour pressure was determined at sea water temperature recorded during trials. Density of sea water at trial site was measured and was used for determining torque coefficients. Percentage difference in the values of the torque coefficient determined from Gawn and Burrill series and those evaluated from trials data at the same cavitation number and advance coefficient were calculated. These values have been plotted in Fig. 6 with respect to cavitation number. The percentage difference is increasing with cavitation number and could be attributed to the following reason[22].

Although it is usual to assume that the cavitation will occur when the pressure has fallen to the vapour pressure of water, this view is too optimistic. The vapour pressure of fresh distilled water is very small at the average temperature of sea water, only some 0.25 psi absolute and is also very sensitive to temperature. But sea water contains much dissolved and entrained air and many minute nuclei of other kinds which encourage

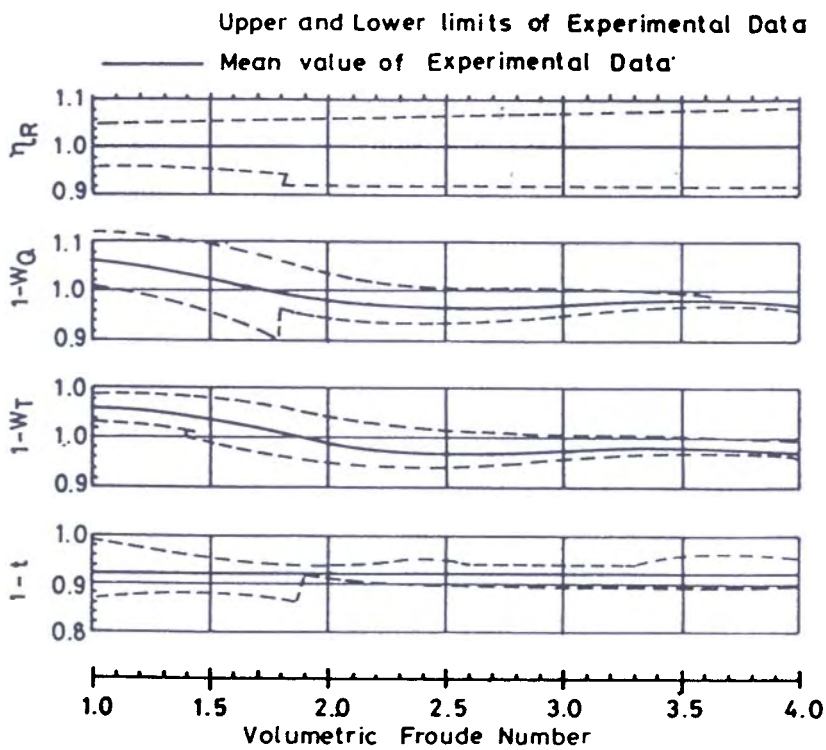

Figure 5. Twin-screw propulsive data.

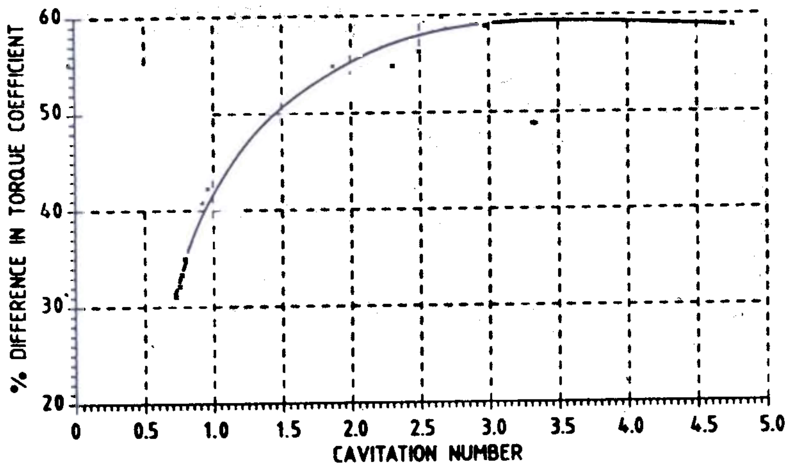

Figure 6. Comparison of trial data with estimated data.

earlier formation of cavities or bubbles and cavitation may occur at local pressures as high as 2.5 psi.

This implies that the propeller thrust break down would occur at higher cavitation numbers, and hence the shaft torque values measured during trials would be less than what they should be. This would lead to lower torque coefficient at the same advance coefficient and cavitation number compared to that evaluated from the series data.

6.2 Holtrop's Method

Figure 7 shows the shaft horsepower for different speeds of the ship calculated using Gawn and Burrill cavitating propeller characteristics. Resistance data was obtained from Holtrop[9]. The trial data has also been superimposed in this figure. There appears, in general, a good agreement between the trial results and predicted power upto 40 per cent of the maximum speed of the vessel. The difference between the two becomes larger at higher speeds of the ship. This can be attributed to the following two reasons.

(a) The relationship between propeller rpm and ship's speed has been considered to be linear through out the operating range of the ship in the above powering prediction program. Figure 8 is an actual plot of the propeller rpm versus ship's speed, which clearly indicates the nonlinear relationship between these two parameters. This may be attributed to the vessel's semi-planing type and the propellers are highly cavitating.

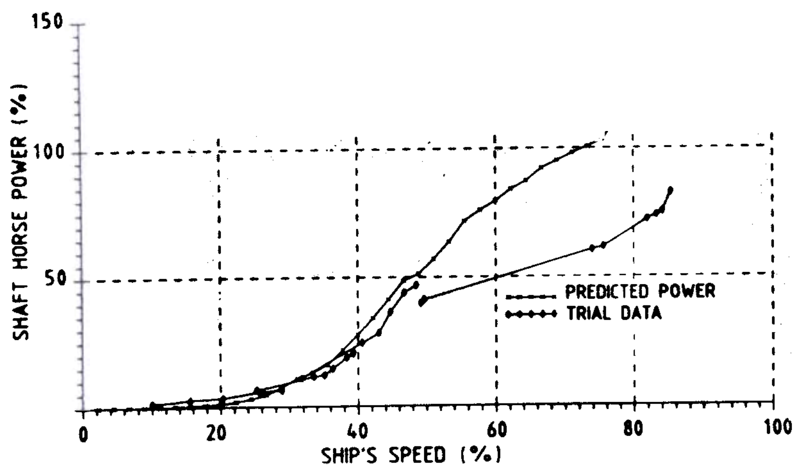

Figure 7. Comparison of predicted power by Holtrop's method and trial data.

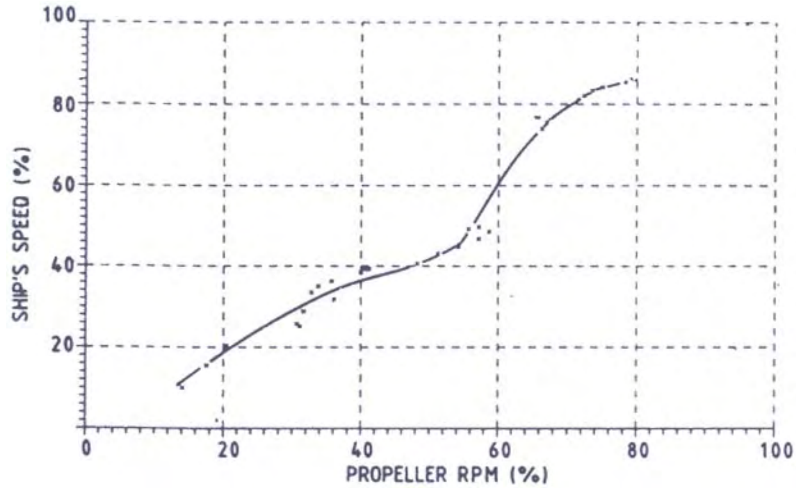

Figure 8. Trial data showing relation between propellor rpm and ship's speed.

(b) Holtrop's paper does not specify the range of applicability of the empirical relations in terms of geometrical parameters of the hull. It appears that these empirical relations would be more applicable for a displacement type of a vessel as seen from Fig.7.

6.3 Savitsky and Brown's Method

It may be observed from Fig. 9 that the resistance estimated making use of Savitsky and Brown's method compares well with that obtained from the trials. There can be many reasons for this :

(a) The database from which the 14 terms have been evaluated are specifically for high speed transom stern hull series, which presumably contain large number of planing hulls.

(b) In the planing regime, theoretically derived hull resistance equations have been used.

(c) The values of the propulsive factors are taken from Blount and Fox[21], which are again the mean values taken from a large number of planing craft model test data.

(d) Geometric characteristics of the hull under consideration fall very well within the range covered by the models. Various graphs have been given by Savitsky and Brown[11] to confirm applicability of the Eqn (5) to the hull form under consideration.

However, certain differences between the predicted and trial data can be observed from Fig. 9 which may be explained as follows:

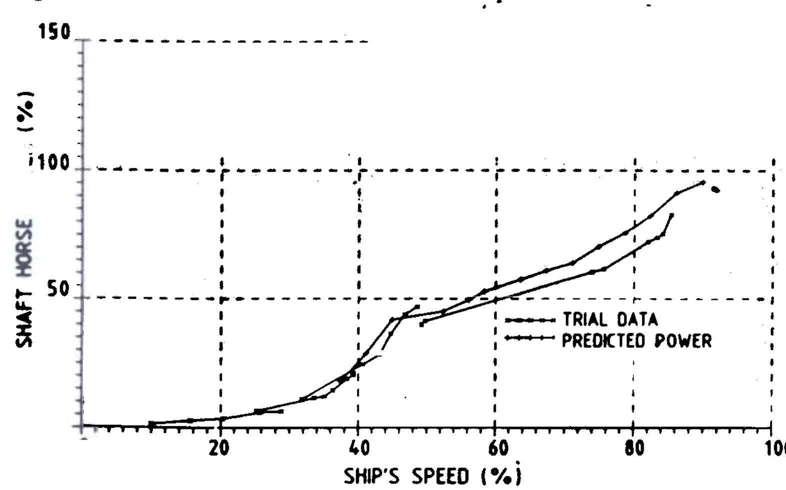

Figure 9. Comparison of predicted power by Savitsky & Brown method and trial data.

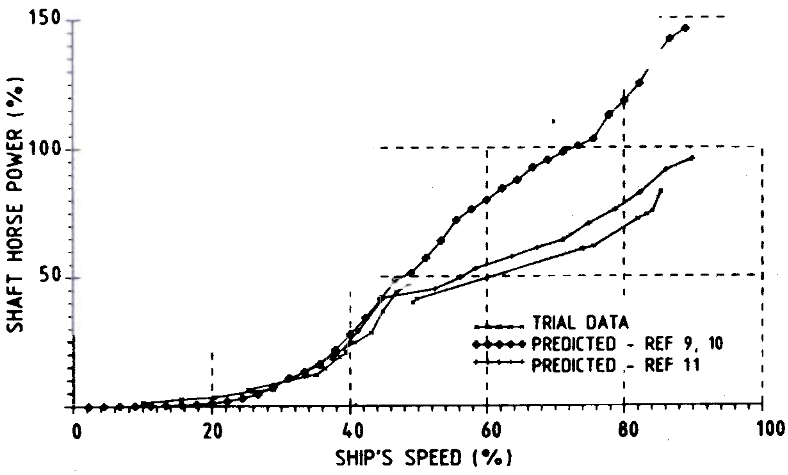

Figure 10. Comparison of predicted power by Savitsky and Brown[11] Holtrop method[9,10] and trial data.

(a) The Gawn and Burrill propeller is a flat faced one, whereas the ship's propeller under consideration is cambered. Such a propeller will have better cavitation characteristics[17] and hence higher propeller efficiency when operating at lower cavitation numbers. It is expected that when the actual propeller data is used, the shaft power required to propel the ship will be less and hence the difference in predicted power and trial data will become less.

(b) The trial data shows discontinuities in the recorded power vs speed curve. The most predominant discontinuity occurs at approximately 50 per cent of maximum ship's speed probably due to (i) semi-planing and planing type of vessel exhibit a hump in their power vs speed curve, and (ii) there is a changeover from two-engine configuration to four-engine configuration with a resultant difference in the transmission losses.

(c) The trial data covers a speed range of 10–90 per cent of maximum ship's speed which corresponds to $F_{n\nabla}$ between 0.267 and 2.28. But as mentioned in Section 2.3, resistance prediction equation used is valid only in the $F_{n\nabla}$ range of 1.0 and 2.0.

7. CONCLUSION

Software packages have been developed for computing resistances of a ship from the known geometrical characteristics by two different methods. One is specifically good for predicting resistance for displacement type of hulls, whereas the second could be used only for a planing hull, since the resistance prediction equations have been developed based on the database of the transom stern high speed ship only. Comparison between full scale trial results with predicted data regarding ship's resistance observed to be satisfactory.

Figure 10 gives a plot of ship's speed vs power, measured power and power predicted by Holtrop's method, and Savitsky and Brown's methods. From this figure it can be seen that for $F_{n\nabla} < 1.0$ Holtrop's method can be used for predicting power required even for a semi-planing ship.

ACKNOWLEDGEMENTS

The authors wish to convey their thanks and appreciation to Mrs Anila Rana for the help rendered by her in digitising the propeller characteristics, data entry and typing the manuscript.

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