A STATISTICAL POWER PREDICTION METHOD

by

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1. Introduction

In a previous paper, [1], a numerical representation of resistance properties and propulsion factors was presented that could be used for statistical performance prediction of ships. After more than a year of experience several fields for improvement of the derived prediction method can be indicated:

- the formula for the wave-making resistance does not include the influence of a bulbous bow; this implies that especially the resistance of ships with large bulbous bows is over-estimated by the original formula.
- the resistance of fast naval ships appeared not to be represented accurately enough by the statistical formula; more in particular the wave-making resistance of ships with a large waterplane-area coefficient is over-estimated by the previous formula.
- it appeared that the accuracy of the formula for the thrust deduction fraction for slender single-screw ships is insufficient.
- the wake fraction and the model-ship correlation allowance are not properly represented by the formulas for full ships at ballast draught.

Focussed on the above-mentioned points for improvement of the prediction method a new statistical analysis was made. The presented revised formulas for statistical power prediction are based on more experimental results than the original equations given in [1].

2. Re-analysis of resistance data

The total resistance of a ship is generally subdivided into components of different origin. In the numerical representation of the total resistance the following components were considered:

- equivalent flat plate resistance;
- form resistance of the hull;
- viscous drag of appendages;
- wave-making and wave-breaking resistance;
- resistance of a (not fully immersed) bulbous bow;
- model-ship correlation allowance.

In the present statistical study each component was expressed as a function of the speed and hull form parameters. The numerical constants in the regression equations were obtained from random model test data.

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The first, second and third mentioned component were described using the form-factor concept:

$$R_V = \tfrac{1}{2}\rho V^2 C_F (1+k) S_{tot}$$

in which ρ is the mass density of the water, V the speed, C_F the coefficient of frictional resistance, (1+k) the form factor and S_{tot} the projected wetted surface including that of the appendages.
The coefficient of frictional resistance was determined using the ITTC-1957 formula:

$$C_F = \frac{0.075}{(\log R_n - 2)^2}$$

with the Reynolds number R_n based on the waterline length L. The form factor (1+k) can be divided into the form factor of the single hull $(1+k_1)$ and a contribution of the appendage resistance $(1+k_2)$:

$$1+k = 1+k_1 + \{(1+k_2)-(1+k_1)\} S_{app}/S_{tot}$$

In Table 1 tentative values of $(1+k_2)$ are given.

Table 1
Appendage factor $1 + k_2$

Appendage configuration	$1 + k_2$
rudder - single screw	1.1 - 1.5
rudders - twin screw	2.2
rudders + shaft brackets - twin screw	2.7
rudders + shaft bossings - twin screw	2.4
stabilizer fins	2.8
bilge keels	1.4
dome	2.7

The form factor for the bare hull $(1+k_1)$ can be approximated by the formula:

$$1+k_1 = 0.93+(T/L)^{0.22284}(B/L_R)^{0.92497}$$
$$(0.95-C_P)^{-0.521448}(1-C_P+0.0225\ lcb)^{0.6906}$$

In this formula T is the average moulded draught, L is the length on the waterline, C_P is the prismatic coefficient and lcb is the longitudinal position of the centre of buoyancy forward of 0.5L as a percentage of the waterline length L. L_R is the length of the run and is approximated by:

$$L_R/L = 1-C_P+0.06C_P lcb/(4C_P-1)$$

The projected wetted surface of the bare hull was correlated with the data of 191 ship models. The following statistical formula involving a standard deviation of $\sigma = 1.8$ per cent was deduced:

$$S = L(2T+B)\sqrt{C_M}(0.453+0.4425C_B-0.2862C_M+$$
$$-0.003467B/T+0.3696C_{WP})+2.38A_{BT}/C_B$$

In this formula C_M is the midship-section coefficient, L the length of the waterline, T the average moulded draught, B the breadth, C_B the block coefficient, C_{WP} the waterplane coefficient and A_{BT} is the transverse sectional area of the bulb.

The wave-making and wave-breaking resistance components were described using the following representation for the dependency on the speed:

$$\frac{R_W}{\Delta} = c_1 c_2 \exp\{m_1 F_n^d + m_2 \cos(\lambda F_n^{-2})\}$$

In this equation, in which R_W/Δ is the Froude-number dependent resistance per unit displacement and F_n the Froude number based on the waterline length. The coefficients c_1, c_2, m_1, d, m_2 and λ are functions of the hull form.
The coefficient λ can be determined from:

$$\lambda = 1.446C_P - 0.03L/B$$

From a regression analysis using the above-mentioned equation for the wave-making resistance with the exponent

$$d = -0.9$$

the following formulas for the coefficients c_1, c_2, m_1 and m_2 were derived:

$$c_1 = 2223105(B/L)^{3.78613}(T/B)^{1.07961}(90-0.5\alpha)^{-1.37565}$$

$$c_2 = \exp(-1.89\sqrt{c_3})$$

$$m_1 = 0.0140407L/T - 1.75254\nabla^{1/3}/L - 4.79323B/L+$$
$$-8.07981C_P+13.8673C_P^2-6.984388C_P^3$$

$$m_2 = -1.69385C_P^2\exp(-0.1/F_n^2)$$

The coefficient c_3, that accounts for the reduction of the wave resistance due to the action of a bulbous bow, is defined as:

$$c_3 = 0.56A_{BT}^{1.5}/\{BT(0.56\sqrt{A_{BT}}+T_F-h_B-0.25\sqrt{A_{BT}})\}$$

In the above given formulas 0.5α is the angle of the waterline at the bow in degrees with reference to the centre plane neglecting the local shape at the stem, ∇ is the displacement volume, A_{BT} is the transverse area of the bulbous bow, h_B is the position of the centre of area A_{BT} above the base and T_F is the draught on the forward perpendicular. The half angle of entrance can be approximated by:

$$0.5\alpha = 125.67B/L-162.25C_P^2+234.32C_P^3+$$
$$+0.155087\left(1cb+\frac{6.8(T_A-T_F)}{T}\right)^3$$

With respect to the resistance of a bulbous bow which is close to the water surface a tentative formula was deduced using the results of only a few model tests. From inspection of these test results it was concluded that the relation to the speed could be represented well by:

$$R_B = c\,F_{ni}^3/(1+F_{ni}^2)$$

In which F_{ni} is the Froude number based on the immersion:

$$F_{ni} = V/\sqrt{g\,i+0.15V^2}$$

with

$$i = T_F - h_B - 0.25\sqrt{A_{BT}}$$

In the definitions above:

- V = speed
- g = acceleration due to gravity
- T_F = draught forward
- h_B = position of centre of area A_{BT} above base
- A_{BT} = transverse area of the bulb at the position where the still water plane intersects the stem.

As a measure for the emergence of the bulbous bow from the still water surface the coefficient p_B was introduced with:

$$p_B = 0.56\sqrt{A_{BT}}/(T_F-1.5h_B)$$

It appeared that the resistance of a bulbous bow could be described fairly well according to:

$$R_B = 0.11\exp(-3p_B^{-2})F_{ni}^3A_{BT}^{1.5}\rho g/(1+F_{ni}^2)$$

With respect to the model-ship correlation resistance R_A it was observed that the correlation allowance C_A with

$$C_A = R_A/(½\rho V^2 S_{tot})$$

for full ships in ballast condition is about 0.0001 higher than at the loaded draught.

A possible explanation for this difference can be found in the interaction of the wake of the breaking bow wave with the relatively thick boundary layer on the hull on model scale.

According to this explanation the difference in C_A value will be present only if in fully loaded condition wave breaking is absent, whereas it is supposed to occur at the ballast draught. Based on the results of 108 measurements made during the speed trials of 54 new ships the following formula for C_A having a standard deviation of $\sigma = 0.0002$ was deduced:

$$C_A = 0.006(L_S+100)^{-0.16} - 0.00205 + \\ + 0.003\sqrt{L_S/L_M}\, C_B^4\, c_2\,(0.04 - c_4)$$

with $c_4 = T_F/L_S$ if $T_F/L_S \leq 0.04$ or

$c_4 = 0.04$ if $T_F/L_S > 0.04$.

In this formula L_S is the length on the waterline of the ship, L_M the similar value for the ship model, C_B the block coefficient and T_F the draught forward. The coefficient c_2 accounts for the influence of a bulbous bow on the wave-breaking resistance. For calculating full-size resistance values for ideal trial conditions the above given formula can be used employing a typical model length of L_M = 7.5 metres.

Application of the afore-mentioned statistical resistance formulas showed a standard deviation of 5.9 per cent of the total model resistance values.

3. Statistical data for propulsion factors

New formulas for the thrust deduction fraction, the effective wake fraction and the relative rotative efficiency were derived for single-screw ships. The thrust deduction fraction, defined by

$t = 1 - R/T$,

in which R is the total resistance and T the propeller thrust, can be approximated by:

$$t = 0.001979L/(B - B\,C_P) + 1.0585B/L - 0.00524 + \\ - 0.1418D^2/(BT)$$

In this formula B is the moulded breadth, T the average moulded draught, D the propeller diameter and C_P the prismatic coefficient.

For the effective wake fraction based on thrust identity the following formula was derived:

$$w = \frac{BSC_V}{DT_A}\left(\frac{0.0661875}{T_A} + \frac{1.21756C_V}{D(1-C_P)}\right) + \\ + 0.24558\sqrt{\frac{B}{L(1-C_P)}} - \frac{0.09726}{0.95-C_P} + \frac{0.11434}{0.95-C_B}$$

In this formula C_V is the viscous resistance coefficient, determined from:

$C_V = (1+k)C_F + C_A$

S is the total wetted surface, T_A is the draught aft and D is the propeller diameter. The above-mentioned formula has been derived from the results of model experiments and speed trials. The full-size wake fractions were determined using the following calculation procedure:

a. The measured trial speed, rotation rate and shaft power were corrected for ideal trials conditions:
   - no wind, waves and swell
   - deep sea water of 15 degrees centigrade and a mass density of 1025 kg/m^3
   - a clean hull and propeller

b. The open water torque coefficient was determined from these values assuming a shafting efficiency of η_S = 0.99 and using the relative-rotative efficiency from the model test.

c. The open-water characteristics of the propeller were determined from the results of the open-water test with the model propeller by correcting for the proper Reynolds number and the average full-size blade roughness according to the method proposed by Lindgren, [2].

d. The effective wake fraction then followed from:

   $w = 1 - JnD/V$

   in which J is the advance coefficient, n the rotation rate of the propeller and V the speed.

The relative-rotative efficiency can be approximated by

$\eta_R = 0.9922 - 0.05908A_E/A_O + 0.07424C_{PA}$

In this formula A_E/A_O is the expanded blade area ratio and C_{PA} is the prismatic coefficient of the afterbody. C_{PA} can be approximated by:

$C_{PA} = C_P - 0.0225\,\text{lcb}$

With respect to twin-screw ships only tentative formulas are presented:

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

$t = 0.325\,C_B - 0.1885D/\sqrt{BT}$

$\eta_R = 0.9737 + 0.111\,(C_P - 0.0225\,\text{lcb}) - 0.06325P/D$

In these formulas C_V is the viscous resistance coefficient, D is the propeller diameter and P/D is the pitch-diameter ratio.

4. Application in preliminary ship design

The numerical description of the resistance components and propulsion factors can be used for the determination of the propulsive power of ships in the preliminary design stage. In this stage the efficiency of the propeller has to be estimated. To this purpose a propeller can be designed using the characteristics of e.g. the B-series propellers. Polynomials for the thrust and torque coefficient of this extensive propeller series are given in [3]. The calculation procedure for determining the required power proceeds along the following lines:

- for the design speed the resistance components described in Section 2 are determined.

- for a practical range of propeller diameters the thrust deduction and the effective wake fraction are calculated.
- the required thrust is determined from the resistance and the thrust deduction.
- the blade area ratio is estimated.
- for a practical range of rotation rates the pitch ratio as well as open-water thrust and torque coefficient are determined from the polynomials given in [3].
- the scale effects on the propeller characteristics are determined from the method described in [2].
- the shaft power is calculated for each combination of propeller diameter and rotation rate using the statistical formula for the relative-rotative efficiency and a shafting efficiency of $\eta_S = 0.99$.
- that combination of rotation rate and propeller diameter is chosen that yields the lowest power; further optimization of the propeller diameter and rotation rate, employing e.g. the embedded search technique can then be carried out.

5. Final remarks

The presented formulas for the resistance and propulsion properties constitute an appreciable improvement with respect to the previously given formulas in [1]. Especially, the incorporation of the influence of a bulbous bow in the numerical description of the resistance is considered important.

Apart from the application in preliminary ship design, where the presented method can be used for parameter studies, the method is also of importance for the determination of the required propulsive power from model experiments. The given formulas for the model-ship correlation allowance and the effective wake, from which the wake scale effect can be easily deduced, can be employed in the extrapolation from model test results to full-size values.

References

1. Holtrop, J., "A statistical analysis of performance test results", International Shipbuilding Progress, Vol. 24, No. 270, February 1977.
2. Lindgren, H., "Ship model correlation based on theoretical considerations", 13th International Towing Tank Conference, Berlin and Hamburg, 1972.
3. Oosterveld, M.W.C. and Oossanen, P. van, "Representation of propeller characteristics suitable for preliminary ship design studies", International Conference on Computer Applications in Shipbuilding, Tokyo, 1973.