STATISTICAL DATA FOR THE EXTRAPOLATION OF MODEL PERFORMANCE TESTS

by

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1. Introduction

In view of an adequate extrapolation of model performance test results a statistical analysis of results of towing tank experiments and full-size speed trials has been made. This analysis covers not only the derivation of the correlation factors that account for the scale effects that are present in the model-test results, but also the separation of the resistance into components of different origin with emphasis on the determination of the form factor from either low-speed resistance measurements or from a statistical formula. Some of these results have been published in a previous paper [1]. In that article, however, the extrapolation method has not been described in detail.

2. Analysis of resistance tests

The extrapolation method employs a separation of viscous and wave-making resistance components using the form-factor concept. According to this method the form resistance is expressed as a fraction of the resistance of a flat plate having the same length and wetted surface as the ship and moving with the ship's speed. With this adaptation of the original Froude method the total viscous resistance of a ship model can be written as:

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

with ρ the mass density of water, V the speed, 1+k the form factor, C_F the coefficient of frictional resistance and S the total wetted surface. In the method the plate-friction coefficients are calculated from the ITTC-1957 formula:

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

in which the Reynolds number R_n is based on the length on the waterline.

From low speed resistance measurements the form factor 1+k can be determined provided the boundary layer is turbulent during the measurements and the Froude-dependent resistance components vanish at low Froude numbers.

For the form-factor determination the method proposed by Prohaska is often followed. This method is equivalent to the determination of 1+k by means of a curve-fitting process in which as regression equation is used:

$$R = (1+k)R_F + c.V^6$$

It has been observed that in many cases, especially for models having a bulbous bow, at ballast draught the exponent 6 is not appropriate. Therefore, the use of regression formulae of a more general type for the determination of the form factor can be useful.

In several cases reliable form factors have been obtained using the formula:

$$R = (1+k)R_F + c(V - V_o)^n$$

with

$$V_o/\sqrt{gL} = 0.1$$

In the application of this formula the exponent n is systematically varied.

Another regression formula that can be employed for the determination of the form factor is:

$$R = (1+k)R_F + c.\exp(m_1 \,.\, F_n^{-0.9})$$

in which F_n is the Froude number. The coefficient m_1 is a function of the length-breadth ratio and the prismatic coefficient:

$$m_1 = -4.8507B/L - 8.1768C_P + 14.034C_P^2 + \\ - 7.0682C_P^3$$

The formula for the coefficient m_1 has been derived from the resistance curves of more than 100 ship models.

A statistical analysis, in which form factors determined by means of the last mentioned method were compared with those derived from Prohaska's method, revealed that the method employing an exponential representation of the wave-making resistance has to be preferred.

A statistical support of the determination of the form factor from low speed measurements is often desired. In that case the following approximative formula with a standard deviation of σ = 4.6 per cent can be used:

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

T = average moulded draught

L = length on waterline

B = moulded breadth

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L_R = length of the run
C_P = prismatic coefficient based on the waterline length
lcb = position of the centre of buoyancy forward of 0.5L as a percentage of L.

The length of the run L_R is approximated by:

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

On the full size the total resistance R_s is considered to be composed of the viscous resistance, a component associated with the induction of waves and the model-ship correlation resistance R_A. The correlation resistance is defined as:

$$R_A = ½\rho V^2 SC_A$$

The model-ship correlation allowance C_A was determined from the analysis of 106 full-size speed-trial measurements made on board 53 new-built ships.

In Figure 1 the obtained C_A values are given as a function of the ship's length. The height of the columns corresponds with the maximum deviation found between the results at different trial speeds of one ship or a number of sister ships. An average value

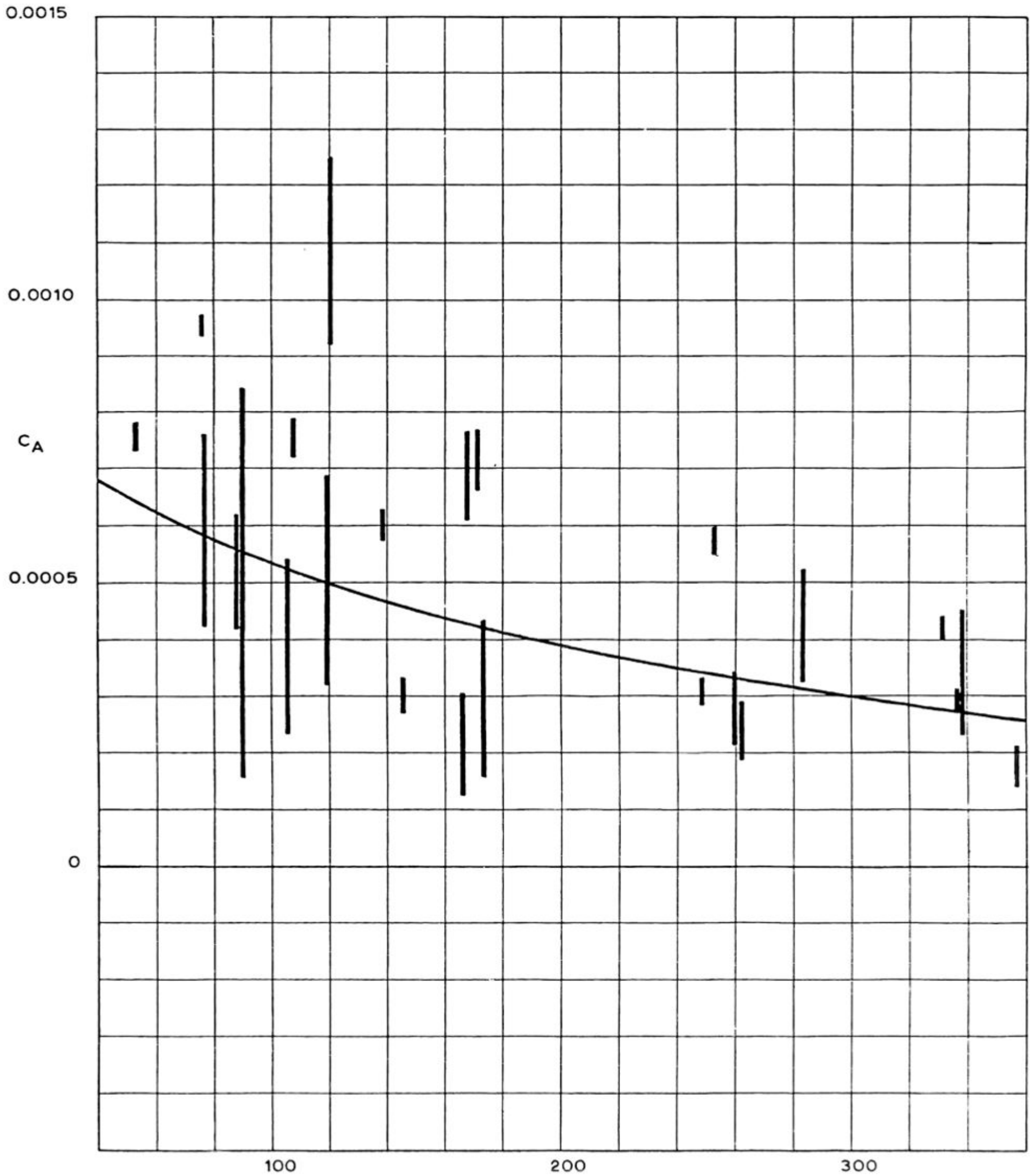

Figure 1. Correlation allowance C_A as function of length.

of C_A is given by the statistically determined formula with a standard deviation of $\sigma = 0.00021$:

$$C_A = 0.00675(L+100)^{-.33} - 0.00064$$

From the test results there appeared no obvious difference between the C_A-values of single and twin-screw ships.

It appeared that for full ships at ballast draught C_A-values are approximately 0.0001 higher. A possible reason for this difference cannot be solely the greater air resistance of the ships in ballast condition. A more probable explanation can be given if the wake of the breaking bow wave interacts with the relatively thick boundary layer on the hull on model scale. According to this assumption the difference in C_A value will be present only if in full-load condition breaking is absent whereas it is supposed to occur at the ballast draught.

3. Analysis of the effective wake

The wake fraction is assumed to be composed of both a viscous fraction w_v and a potential wake fraction w_p. For this reason the effective wake fractions, determined from model propulsion tests as well as full-size trial measurements, were correlated with both a characteristic boundary-layer variable as well as geometrical parameters. As boundary-layer parameter the quantity

$$D_v = \frac{D}{L\,(C_T - C_W)}$$

was used. In this definition, D is the propeller diameter, L is the waterline length and C_T and C_W are coefficients of total and wave-making resistance. The parameter D_v was obtained by considering the propeller to be placed at the trailing edge of a flat plate with length L and having the same viscous resistance as the actual hull form. From an integration of the velocity over the screw disk it followed that the wake fraction is directly dependent on D_v, provided the propeller radius is less than the boundary-layer thickness. Although the latter condition is not always fulfilled, especially not at the full size, D_v proved to be significant in the regression analysis. For single-screw configurations the following prediction formula for the effective wake was obtained with a standard deviation of $\sigma = 0.041$:

$$w = 0.177714B^2/(L - L.C_p)^2 - 0.577076B/L + $$
$$+0.404422C_p + 7.65122/D_v^2$$

In a similar way a prediction formula for twin-screw ships with a standard deviation of $\sigma = 0.041$ was determined:

$$w = 0.4141383C_p^2 - 0.2125848C_p + 5.769/D_v^2$$

The Reynolds scale effect on the wake fraction can be determined using the following prediction formulas for the viscous wake fraction:

$$w_v = 7.65122/D_v^2 \qquad \text{(single screw)},$$

$$w_v = 5.769/D_v^2 \qquad \text{(twin crew)}.$$

The scale effect on the wake, Δw, can be calculated from

$$\Delta w = 7.65122(C_{Tm} - C_{Ts})\,(C_{Tm} + C_{Ts} - 2C_W)\,L^2/D^2 \qquad \text{(single screw)}$$

$$\Delta w = 5.769\,(C_{Tm} - C_{Ts})(\,C_{Tm} + C_{Ts} - 2C_W)\,L^2/D^2 \qquad \text{(twin screw)}$$

In Figure 2 the viscous component of the effective wake fraction w_v is presented as a function of the boundary-layer parameter D_v. In these diagrams both the results of trial measurements and corresponding model tests are given. The effective wakes determined from the full-size measurements have been based on open-water characteristics which have been corrected for average blade roughness and Reynolds effects according to the method proposed by Lindgren [2]. The blade roughness, however, has been put equal to 30 μm instead of 50 μm in accordance with correlation studies carried out by the ITTC in a later stage.

4. Outline of the extrapolation method

In a model propulsion test the propeller thrust T, the torque Q and the residuary towing force F that acts on the model are measured for a number of speeds. From these measured values, the resistance and the open-water characteristics of the propeller model, the propulsion factors are determined.

The thrust-deduction fraction is defined as:

$$t = 1 + (F - R_m)/T,$$

The wake fraction w_m is determined using thrust identity which means that the advance coefficient J, defined as $V(1-w)/nD$, is determined from $K_T = K_{To}$, in which K_T and K_{To} are the thrust coefficients for the behind and open-water condition respectively, n the number of revolutions of the propeller and D the propeller diameter. The open-water efficiency η_o and the relative-rotative efficiency η_R are defined as:

$$\eta_o = \frac{J.K_{To}}{2\pi K_{Qo}} \quad \text{and } \eta_R = K_{Qo}/K_Q$$

in which the torque coefficient is given by:

$$K_Q = \frac{Q}{\rho\, n^2 D^5}$$

In the extrapolation to the full size a scale effect on

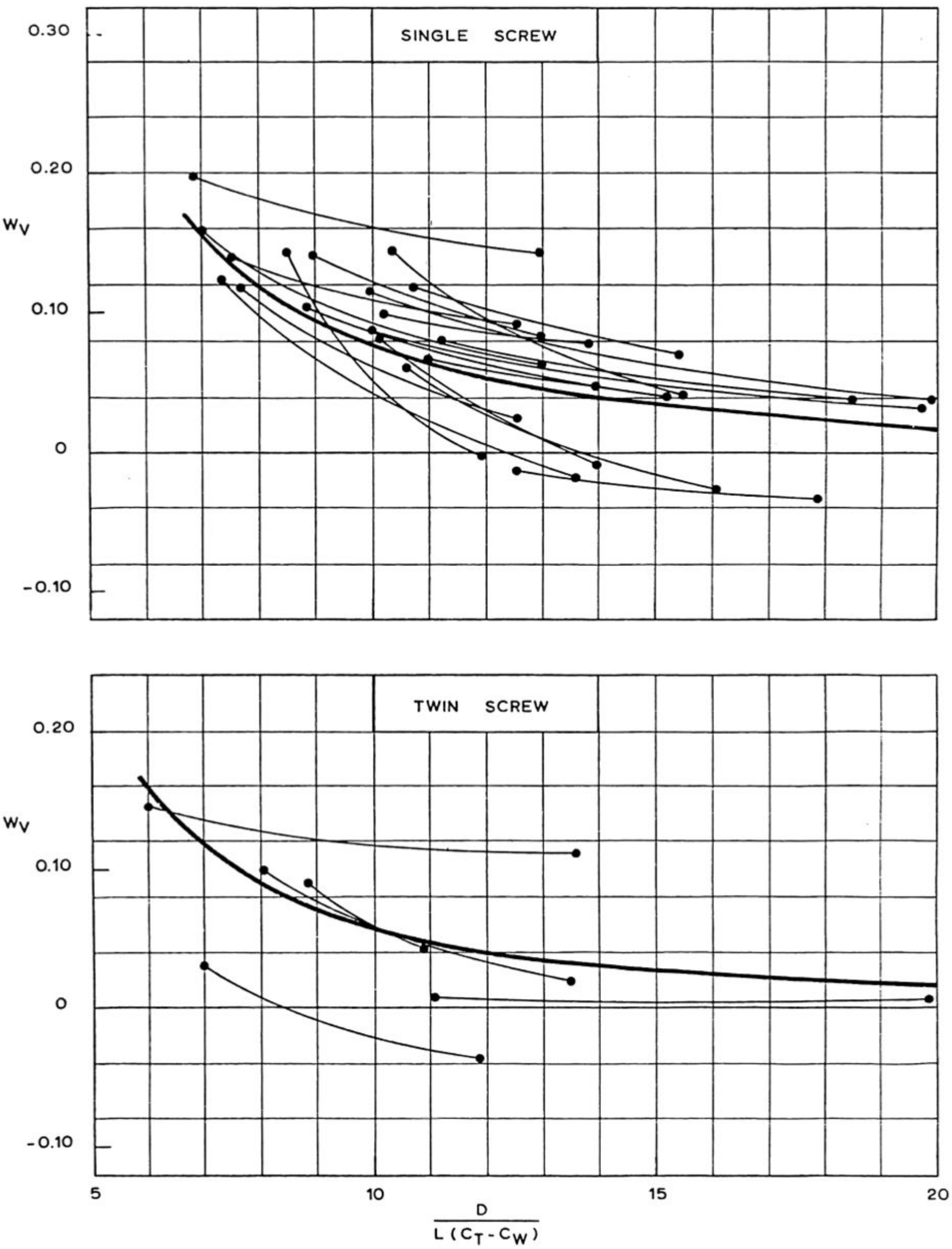

Figure 2. Viscous part effective wake fraction.

the wake fraction, being Δw, is considered present, whereas the thrust deduction and the relative-rotative efficiency are assumed to be equal for model and ship.

The analysis of the model test results proceeds along the following lines:

i from the resistance test the full-size resistance is determined:

$$R_s = (R_m - F_D)\lambda^3 \rho_s / \rho_m$$

in which F_D is the scale effect on resistance with:

$$F_D = \tfrac{1}{2}\rho_m V_m^2 S_m \{(1+k)(C_{Fm} - C_{Fs}) - C_A\}$$

ii the scale effect on the wake is estimated and the full-size wake fraction is determined:

$$w_s = w_m - \Delta w$$

iii the full-size propeller load is calculated from:

$$(K_T/J^2)_s = \frac{R_s}{(1-t)(1-w_s)^2 V_s^2 D_s^2 \rho_s}$$

iv the open-water characteristics are corrected for Reynolds and blade-roughness scale effects using the method proposed by Lindgren [2].

v interpolation in the full-size open-water curves with $(K_T/J^2)_s$ yields J_s and K_{Qos}.

vi the full-size rate of rotation of the propeller is calculated from:

$$n_s = V_s(1-w_s)/J_sD_s$$

vii the power delivered to the propeller is determined from:

$$P_D = \frac{2\pi \rho_s n_s^3 D_s^5 K_{Qos}}{\eta_R}$$

viii the power supplied to the shafting system is assumed to be 1 per cent more in view of friction losses in the stern tube:

$$P_S = P_D/0.99$$

5. Final remarks

With the presented method scale effects on ship performance can be determined. The method can be applied when the performance properties of a ship are to be predicted from model experiments. The derived system of correlation factors will be refined further. More specific attention will be paid to the relation between the propeller loading and the propulsion factors.

Other fields for investigation are the scale effects on the form factor and other resistance components. The method is employed in the facilities of the Netherlands Ship Model Basin and will be used more and more for standard application.

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 method based on theoretical considerations", 13th International Towing Tank Conference, Berlin and Hamburg, 1972.