INVESTIGATION OF THE SCALE EFFECT ON THE THRUST DEDUCTION OF GEOSIMS

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(Received August 8, 1968)

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Symbols

$A = \frac{D^2 \pi}{4}$	m^2	propeller disc area
B	m	breadth of ship
$C = \frac{T}{0.5 \cdot \varrho \cdot V^2 A}$		propeller load coefficient
$C_B = \frac{\nabla}{L \cdot B \cdot T}$		block coefficient
$C_F = \frac{R_F}{0.5 \cdot \varrho \cdot V^2 S}$		frictional resistance coefficient
$C_K = C \cdot C_B \frac{D}{T_a}$		critical load coefficient
$C_R = \frac{R_R}{0.5 \cdot \varrho \cdot V^2 \cdot S}$		specific residuary resistance coefficient
$C_S = \frac{S}{(2 \cdot T + B)L}$		fullness of the wetted surface of ship
$C_T = \frac{R_T}{0.5 \cdot \varrho \cdot V^2 \cdot S}$		total resistance coefficient
$C_{TT} = \frac{T}{0.5 \cdot \varrho \cdot V^2 \cdot S}$		thrust coefficient
D	m	diameter of the propeller
F_D	kp	tow rope force in propulsion test
L	m	length of waterline
L_p	m	length between perpendiculars
$Re = \frac{V \cdot L}{\cdot \nu}$		the Reynolds-number of ship
R_F	kp	frictional resistance
$R_R = R_T - R_F$	kp	residuary resistance
R_T	kp	total resistance
S	m^2	wetted surface of ship
T	m	draught (mean value)
T_a	m	draught at the after perpendicular
T	kp	propeller thrust
V	$m \cdot s^{-1}$	speed of ship
V_1	$m \cdot s^{-1}$	relative velocity in the race of propeller
k		thrust deduction coefficient
t		thrust deduction fraction
∇	m^3	displacement volume of ship
ϱ	$kp \cdot s^2 \cdot m^{-4}$	mass density of water
λ		model scale
ν	$m^2 \cdot s^{-1}$	kinematic viscosity

According to the investigation of several geosims (geometrically similar model families) the thrust deduction fractions have not the same values for the same corresponding ship speeds in cases of models made of different sizes of any ship. Therefore the calculation of the necessary thrust of ship propeller from measured data of different models will give different results if the scale effect on the thrust deduction fraction is omitted.

The precalculation of the exact value of the thrust is very important for the accurate design of a ship propeller. For this reason the investigation of the difference of the thrust deduction fractions in the cases of different model scale is of great significance.

Data measured on the Victory model families were the first to give a possibility for the investigation of the scale effect on the thrust deduction [1], [2]. The issues of this investigation are the following [3]:

1) The thrust deduction fraction depends not only on the Reynolds-number but on the roughness of the ship hull and on the propeller load too.
2) For the investigation of the scale effect it is very useful to introduce the k factor

$$k = \frac{C_{TT} - C_R}{1 + C}$$

instead of the use of the customary thrust deduction fraction

$$t = \frac{T - R}{T} = \frac{C_{TT} - C_T}{C_{TT}}$$

While in the latter formula both the thrust coefficient (C_{TT}) and the total resistance coefficient (C_T) are changing according to the model scale for the same corresponding ship speed, in the first formula only the thrust coefficient is function of the model size and the surface roughness, but the specific residuary resistance coefficient (C_R) is constant for all models at constant Froude number, i.e. at the same corresponding ship speed. When comparing different propeller loads the ship resistance augmentation is defined by the ratio

$$\left(\frac{V_1}{V}\right)^2 = 1 + C = 1 + \frac{T}{0.5 \cdot \varrho \cdot V^2 \cdot A}$$

where V_1 is the velocity in the propeller race behind the propeller in an ideal fluid.

3. For a corresponding ship speed the values of the k factor in function of C_F (frictional resistance coefficient) define a straight line:

$$k = a + b \cdot C_F$$

where a and b are constants for the rough and smooth models for any ship speed in the cases of lower propeller load of the Victory geosim. (In loaded condition from 10 to 16 knots, in light condition from 10 to 17 knots corresponding ship speed.)

The results afford us the possibility for a better extrapolation of model data to the actual ship.

Recently measured data of two other geosims have been published. Some deductions could be drawn for the cases of higher propeller load by investigating these data.

One of these geosims is the "Meteor" model family and the other the model family of a tanker-type [4], [5]. The trial results of the ship "Strinda" have also been published, Strinda being one of this tanker-type. Thus the second geosim will be denoted Strinda-family. The principal dimensions of these two ships are compiled in Table 1. For sake of comparison we give the data of the Victory ships too, in loaded and light condition (using the letter A for the loaded and B for the light condition).

Table 1

The main dimensions of the investigated geosims

		Victory A	Victory B	Strinda	Meteor
Length between perpendiculars	L_p (m)	135.045	135.045	168.0	72.8
Length of waterline	L (m)	135.562	133.177	172.0	77.30
Breadth	B (m)	18.898	18.898	22.7	13.50
Mean draught	T (m)	8.687	6.809	9.42	4.80
Draught of the after perpendicular	T_a (m)	8.687	7.919	9.42	4.80
Displacement	∇ (m^3)	15019	11370	26769	2650
Wetted surface of ship	S (m^2)	3687	3164	5665	1200
Diameter of propeller	D (m)	5.3	5.3	5.7	2.9
Block coefficient	C_B	0.6876	0.6575	0.728	0.563
Fullnes ratio of the wetted surface	C_S	0.750	0.731	0.792	0.6725
Ratio of length to breadth	L_p/B	7.04	7.04	7.40	4.40
Ratio of length to diameter	L_p/D	25.1	25.1	29.5	24.1

The paraffin models of the Strinda geosim made to 25, 35, 45 and 55 model scale were investigated by the Versuchsanstalt für Wasserbau und

Schiffbau, Berlin (VWS). There was built also a concrete motorboat "Hedwig Kloess" as the biggest model of the Strinda geosim to a model scale of 7.5. Her resistance tests were carried out on a lake near Berlin. Propulsion tests of this motor boat was investigated only in self-propelled condition. The paraffin models were tested in three different conditions in the towing tank:

a) Self-propelled condition. The resistance and its augmentation was counterbalanced only by the propeller thrust:

$$T = \frac{R}{1 - t}$$

b) A tow rope force as the half value of the usual frictional deduction (according to the Froude method) and the propeller thrust balanced the resistance. Thus the propeller thrust of the models was:

$$T = \frac{R - 0.5\, F_D}{1 - t}$$

c) The propulsion tests were carried out with a tow rope force equal to the whole frictional deduction too. In this condition the propeller thrust was:

$$T = \frac{R - F_D}{1 - t}$$

The Meteor geosim was investigated also by the VWS Berlin. The paraffin models of the research vessel Meteor made to scales 13.75, 19 and 25 were tested in the same three propeller load conditions as the models of Strinda.

In the course of our investigation we calculated the frictional resistance coefficient according to the ITTC 1957 formula:

$$C_F = 0.075\, (\lg Re - 2)^{-2}$$

The motor boat "Hedwig Kloess" has a relatively higher frictional resistance coefficient than that of the hydrodynamically smooth surface. The analysis of the resistance test points to a roughness allowance of about $0.09 \cdot \cdot 10^{-3}$. Thus the viscous resistance coefficient of the motor boat was calculated by the following formula:

$$10^3 \cdot C_F = 75\, (\lg Re - 2)^{-2} + 0.09$$

These frictional resistance coefficients and the measured values of C_{TT} and C_T had been applied to calculate the values of k

$$k = \frac{C_{TT} - C_T + C_F}{1 + \frac{S}{A} C_{TT}}$$

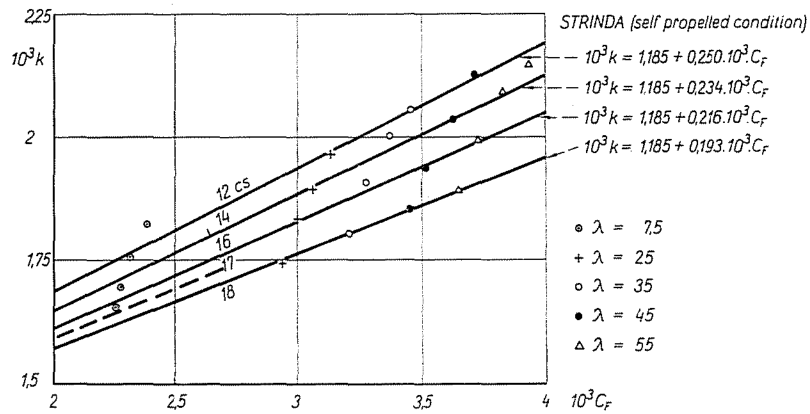

Fig. 1. The values of k for the Strinda geosim

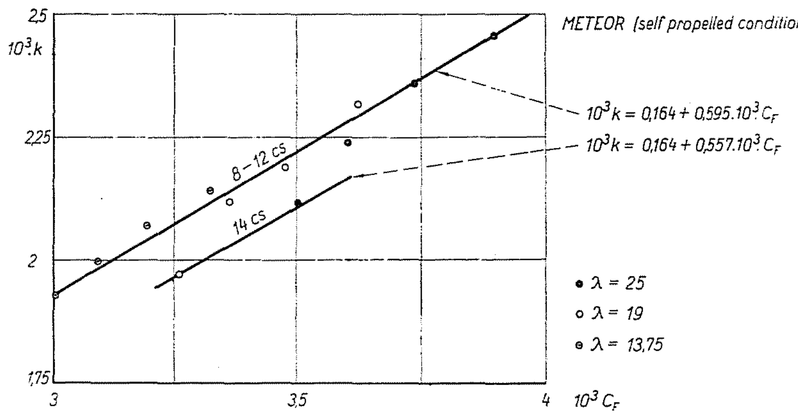

Fig. 2. The values of k for the Meteor geosim

and the values of the thrust deduction fractions (t). These are shown in Tables 2 and 3 in function of the corresponding ship speed for the three different conditions (a, b, c).

In Figs 1 and 2 we plotted the values of k against the C_F in self-propelled condition (a). The points for the same Froude numbers for the same corresponding ship speeds define a straight line with a good approximation. These straight lines are designed by the corresponding ship speeds.

For the Strinda family the k values of the motor boat deviate from the points determined by the straight lines. According to the test description there emerged several difficulties during the tests of the motor boat of 22.9 m length (swinging of the tow rope etc.) [6].

Therefore, we can assume more errors in the results of the measurements than in the cases of the paraffin models tested in towing tank. In Table 4 the k values of the motor boat are compiled, as calculated by the equation

$$k = a + bC_F$$

Table 2

The values of k and t calculated from data measured on the Strinda-family

Sign of the towing condition	Ship speed (knots)	Model scale									
		55		45		35		25		7.5	
		$10^3 \cdot k$	$10^3 \cdot t$	$10^3 \cdot k$	$10^3 \cdot t$	$10^3 \cdot k$	$10^3 \cdot t$	$10^3 \cdot k$	$10^3 \cdot t$	$10^6 \cdot k$	$10^3 \cdot t$
	12	2.15	150	2.12	164	2.050	168	1.960	175	1.82	262
	14	2.09	156	2.03	162	2.000	172	1.890	175	1.75	259
a	16	1.99	154	1.93	162	1.905	167	1.832	175	1.695	255
	17	—	—	—	—	—	—	—	—	1.636	252
	18	1.895	158	1.85	160	1.800	169	1.742	175	—	—
	12	2.40	170	2.36	186	2.23	179	2.095	188	—	
b	14	2.33	180	2.26	182	2.15	184	2.020	180	—	—
	16	2.21	180	2.13	181	2.06	184	1.940	183		
	18	2.06	175	2.00	174	1.94	176	1.810	184		
	12	2.72	212	2.62	219	2.44	197	2.240	190		
c	14	2.63	219	2.51	212	2.34	195	2.160	188	—	—
	16	2.46	208	2.35	202	2.12	192	2.060	190		
	18	2.27	195	2.17	195	2.06	190	1.920	187		

Table 3

The values of k and t calculated from data measured on the Meteor-family

Sign of the towing condition	Ship speed knots	Model scale					
		25		19		13.75	
		$10^3 \cdot k$	$10^3 \cdot t$	$10^3 \cdot k$	$10^3 \cdot t$	$10^3 \cdot k$	$10^3 \cdot t$
	8	2.46	191	2.32	170	2.14	131
a	10	2.36	185	2.19	160	2.07	145
	12	2.24	176	2.12	159	2.00	157
	14	2.13	172	1.97	149	1.93	170
	8	2.67	230	2.44	176	2.27	145
b	10	2.53	212	2.34	168	2.19	156
	12	2.41	206	2.24	167	2.12	172
	14	2.27	198	2.11	168	2.05	192
	8	2.88	249	2.64	184	2.05	167
c	10	2.71	224	2.51	182	2.10	190
	12	2.57	219	2.38	186	2.16	206
	14	2.42	217	2.26	195	2.18	218

This linear equation was defined only by the k values of the paraffin models. The tabulated values of the thrust coefficient had been calculated as

$$C_{TT\,\text{cal}} = \frac{C_R + k}{1 - k\dfrac{S}{A}}$$

where the specific residuary resistance coefficient C_R is of the same value for each model. For comparison's sake there are to be seen in the table the measured values of the thrust coefficients of the motor boat (C_{TT}) and the percentage of difference from calculation have also been tabulated. The maximum difference of about 3 per cent is lower than the usual measurement errors and so it means that the thrust coefficients of the motor boat can be determined by linear extrapolation from the k values of the paraffin models with a good approximation. We may say that this method is exact enough and usable for the Strinda geosim as well as in the cases of the Victory geosims.

Table 4

The thrust coefficients of motor ship "Hedwig Kloess"
(values calculated from k and the measured values)

V (knots)	$10^3 \cdot C_F$	$10^3 \cdot k$	$10^3 \cdot C_{TTcal}$	$10^3 \cdot C_{TT}$	Difference %
12	2.37	1.78	3.79	3.91	−3.17
14	2.30	1.72	4.03	4.16	−3.22
16	2.26	1.67	4.52	4.60	−1.77
17	2.24	1.64	5.00	5.06	−1.20

Table 5

The thrust coefficients of motor ship "Hedwig Kloess"
(values calculated from t and the measured values)

V (knots)	$10^3 \cdot t$	$10^3 \cdot C_T$	$10^3 \cdot C_{TTcal}$	$10^3 \cdot C_{TT}$	Difference %
12	219	2.88	3.69	3.91	−5.63
14	212	3.08	3.91	4.16	−6.00
16	202	3.43	4.30	4.60	−6.52
17	(198)	3.73	4.65	5.06	−8.10

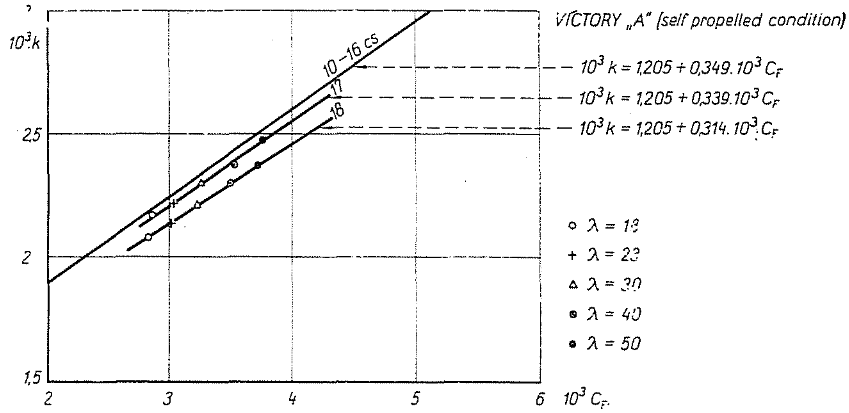

Fig. 3. The values of k for the Victory A geosim

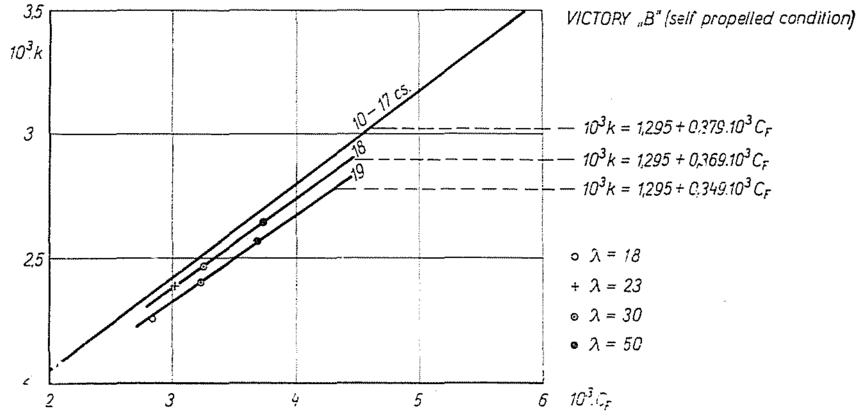

Fig. 4. The values of k for the Victory B geosim

As a further comparison in Table 5 are written: the thrust deduction fractions (t) of the model made to scale 45 in condition c (giving the best results with this calculation method), the total resistance coefficient (C_T) of the motor boat (calculated from the measured resistance); the calculated values of the thrust coefficient

$$C_{TTcal} = \frac{1}{1-t} C_T$$

the values of C_{TT} from the measured thrust of the motor boat. Higher difference percentages would result from total resistance coefficients calculated from the measured results of paraffin models (e.g. scale 25 or 35). Thus the thrust coefficients calculated from the thrust deduction fraction would be more erroneous than from the k factor.

In Figs 3 and 4 the straight line of $k(C_F)$ obtained from the measured values of Victory geosims for lower ship speeds [3] and the k points for higher ship speeds have been plotted. These points determined also straight lines for the corresponding ship speeds.

For the Strinda family (Fig. 1) different straight lines arise for each ship speed. In the case of the Meteor geosim (Fig. 2) only the 14 knots ship speed has a line of its own, the other ones (8, 10, 12 knots) lie on a common line. The Victory models produce a common line for the ship speeds below 16 knots in loaded condition and below 17 knots in light condition. For each higher speed, separate straight lines can be drawn.

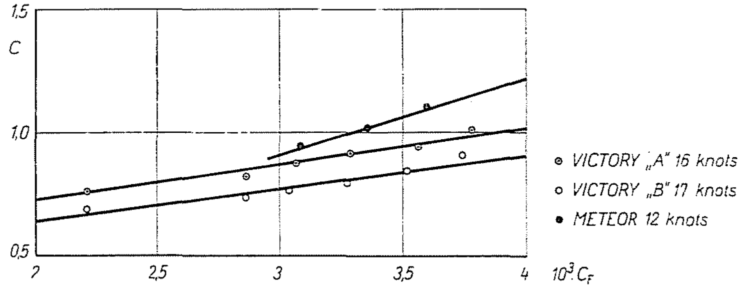

Fig. 5. The values of the propeller load coefficients for the critical corresponding ship speed

Consequently the effect of the Froude number appears only for higher speeds. The results support the assumption that for lower speed (that is for lower propeller loads) only the viscous component of the resistance has changed in consequence of the action of propeller and practically the residuary resistance component is unchanged.

In Fig. 5 the propeller load coefficients of the geosims are shown. For the geosim Victory A they refer to 16 knots ship speed; for Victory B to 17 knots and for Meteor to 12 knots ship speed. For this corresponding ship speed and for lower speeds the k values change only in function of the specific frictional resistance coefficient (C_F)

Thus it can be stated for propeller load coefficients lower than given in Fig. 5 that the picture of the waves is the same in towing condition as in self-propelled condition of ships. These "critical" propeller load coefficients have different values for different ship hull and for different sizes of propeller. For higher values of the block coefficient of the ship (C_B) or the diameter of the propeller (relative to the draught of ship at the after perpendicular) greater differences can be assumed in the wave system behind the ship between towed and self-propelled condition, even for lower critical propeller load coefficients.

Therefore the values of

$$C_K = C \cdot C_B \cdot \frac{D}{T_a}$$

have been calculated for the three investigated geosims and plotted in Fig. 6 in function of C_F. In this figure the values of C_K determine a straight line with a ± 5 per cent error.

Conclusions drawn from data of Strinda and Meteor geosims support our findings in the investigation of the Victory geosims:

1. The propeller action alters both the frictional and the wave making resistances of the ship. Denote by ΔC_F the augmentation of the viscous resistance coefficient and by ΔC_R the augmentation of the specific residuary resistance coefficient, then the thrust coefficient of any ship can be written as

$$C_{TT} = C_R + \Delta C_R + C_F + \Delta C_F$$

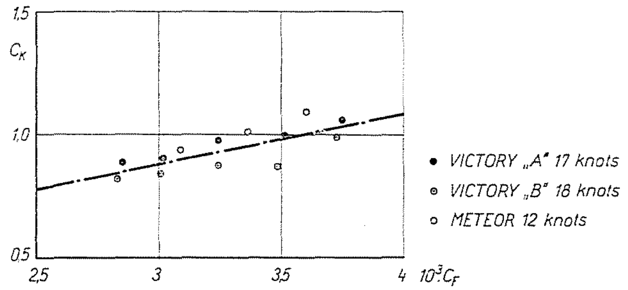

Fig. 6. The values of the critical propeller load coefficients

where ΔC_F depends on the propeller load and on the Reynolds number and on the roughness of the hull, and ΔC_R depends on the Froude number and on the propeller load, in the case of geometrically similar ship hulls.

For the same corresponding ship speed, the value of the specific residuary resistance coefficient is constant, therefore the difference of forces

$$C_{TT} - C_R = \Delta C_R + C_F + \Delta C_F$$

best lends itself to examine the scale effect on the resistance augmentation. The introduced k factor

$$k = \frac{C_{TT} - C_R}{1 + C}$$

determines a straight line for each corresponding ship speed in the function of C_F. *Thus, from factors k obtained from data measured on two models (made of the same size with different roughness or made of different sizes but equal hydrodynamical smoothness) the factor k for the ship of different surface roughness can be linearly extrapolated.* With this k factor and with the specific residuary resistance coefficient the thrust coefficient is

$$C_{TT} = C_R + (1 + C)\,k = \frac{C_R + k}{1 - k\dfrac{S}{A}}$$

In addition the results of the investigation of the model tests on the four geosims permit to make the following statements:

2. *For lower propeller load* when the value of the propeller load factor (C) is lower than a critical value, the effect of the Froude number is negligible. The augmentation of the specific residuary resistance coefficient can be assumed to be zero. Therefore the k values determine the same straight line for any ship speed:

$$k = a + b_0 \cdot C_F$$

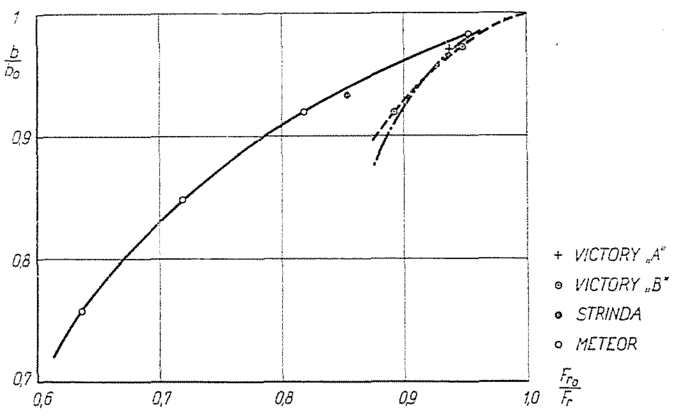

Fig. 7. The values of b/b_0 in function of Fr_0/Fr

3. *For higher propeller load* the ΔC_R is not negligible. Thus the value of factor k depends on the Froude number too. In tests on geosims the values of k were found to determine different straight lines for each Froude number. In the formula

$$k = a + b \cdot C_F$$

the value of a is the very same as it appeared for the lower propeller load but the b is different for all corresponding ship speeds.

From these equations $k = a + bC_F$ of the straight lines for the tested geosims, we obtained the b values. These appeared to decrease for higher ship speeds, i.e. to be dependent on the Froude number. When ship sp eedis higher then b is lower. We give the fractions of b/b_0 for different Fr_0/Fr to plot the function $b = f(Fr)$ (Fig. 7). In the Fr_0 there is substituted the highest ship speed for which b_0 is constant (below these ship speeds the function $k(C_F)$

gives the same straight line). For the Strinda geosim we assumed that this ship speed was about 11.5 knots according to the extrapolation mentioned above.

4. The values of a in self-propelled condition can be determined by the following formula:

$$a = 10^{-4} \cdot \frac{F}{C_B \cdot C_S} \cdot \left(\frac{L_p}{B}\right)^2$$

where $F = 125$ for both Victory geosims (A and B) and for the Strinda geosim, and $F = 21.3$ for the Meteor model family. In [7] there is a picture of the stern construction of the investigated ship types. The Victory and the Strinda are seen to have the same stern construction, but the Meteor has a very different one. Therefore it can be assumed that the value of F depends on the stern construction and the relative position of the propeller on the ship.

5. For lower than critical propeller load coefficient we can write in self-propelled condition the following formula:

$$b_0 = \frac{32}{C_B \cdot C_S} \cdot \frac{B}{L_p} \cdot \frac{D}{L_p}$$

giving a fair approximation for any of the four geosims.

Table 6

The values of a and b_0 in self-propelled condition

Model family	From Figs 1 to 4		Calculated values	
	a	b_0	a	b_0
Victory A	1.205	0.349	1.205	0.350
Victory B	1.295	0.379	1.295	0.377
Strinda	1.185	0.254	1.185	0.254
Meteor	0.164	0.595	0.164	0.625

Table 6 includes the values of a and b_0. The first two columns contain the values corresponding to the straight lines in Figs 1 to 4 determined by the values of k, and in the second two columns there are the values calculated by means of the empirical formulae in paragraphs 4 and 5. For the Strinda geosim the b_0 is extrapolated for 11.5 knots ship speed from the b values for 12, 14, 16, 18 knots ship speed ($b = .250\ .234\ .216\ .193$).

6. In other conditions (different from the self-propelled condition) when tow rope forces helped the thrust of model propeller (the tow rope forces being the half and the whole value of the "frictional correction force"), the

calculated values of k determine also straight lines in the function of C_F. In these conditions a is constant for any ship speed [8]. Because such tests were only made on two geosims (Strinda and Meteor) and the stern construction of these two geosims were very different, it could be rather uncertain to find some empirical formula for the determination of a and b_0.

7. Since the value of a is constant for any ship speed (for any propeller-load) i.e. it is independent from C_F we can assume that the potential component of the resistance augmentation (thrust deduction) can be calculated. Namely in a perfect fluid the C_F is zero and so the k equal to a. Thus in ideal stream the difference of the thrust and resistance coefficients (the potential part of this difference in a real fluid) is

$$[C_{TT} - C_T]_{\text{pot}} = a\left(1 + \frac{S}{T} C_{TT}\right)$$

According to the paragraphs 2 through 7 it can be stated: When the theoretical investigations give us a practical method for the exact determination of the potential component of the thrust deduction, the thrust deduction of any ship can be extrapolated from the testing results on a single model by means of the straight line of $k(C_F)$. Extrapolation from data measured on a single model is possible with a similar safety, if test series on further geosims can be applied to support our empirical relationship for the value of a, or to deduce for it a relationship of a more general validity.

Summary

The results of the investigations on several geosims prove that the values of

$$k = \frac{C_{TT} - C_R}{1 + C}$$

determine a straight line in the function of the specific frictional resistance coefficient. By means of these straight lines the necessary thrust of any ship (for different roughnesses) can be calculated from the results of model experiments without any scale effect.

References

1. van Lammeren, W. P. A., van Manen, J. D., Lap, A. J. W.: Trans. I.N.A. **97**, 167 (1955).
2. Lap, A. J. W., van Manen, J. D.: Trans. I.N.A. **104**, 23 (1962).
3. Benedek, Z.: Periodica Polytechnica M **10**, 141 (1966).
4. Modellfamilienversuche für das Forschungschiff Meteor. VWS Bericht Nr. 321/1965. Berlin.
5. Modellfamilienversuche für einen 20 000 tdw Tanker. VWS Bericht Nr. 280/1964. Berlin.
6. Grothues-Spork, H.: Trans. I.M.E. **77**, 259 (1965).
7. Benedek, Z.: Periodica Polytechnica M **12**, 27 (1968).
8. Benedek, Z.: I.S.P. **15**, 78 (1968).

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