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CALCULATION OF SCALE EFFECT ON TORQUE AND THRUST OF SCREW PROPELLER OF SHIPS

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Abstract

The values of torque and thrust coefficients of any propeller are different from the corresponding values of its model. This difference is known as scale effect. The significant fraction of this scale effect results from the fact that the friction conditions of the model and those of the propeller are different from each other. Based on this, there is a simple method for calculation of the correction of torque and thrust coefficient of screw propeller.

Keywords: screw propeller, scale effect.

Symbols Used

D	diameter of screw propeller,
D_m	diameter of model propeller,
P/D	the pitch ratio,
Q	the torque of propeller,
T	the thrust of propeller,
k	the equivalent grain size of the propeller blade surface,
l	the length of propeller blade sections,
n	the revolution of propeller,
n_m	the revolution of model,
v_A	the speed of advance of the propeller,
z	number of blades,
φ	the pitch angle of blade section,
υ	coefficient of kinematic viscosity of water at the propeller,
υ_m	coeff. of kinematic viscosity of water at the model,
ρ	the density of water.

1. The Scale Effect

The open water test results of a propeller model are usually plotted in the conventional way with torque coefficient

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

and thrust coefficient

$$k_T = \frac{T}{\rho n^2 D^4}$$

as functions of advance coefficient

$$J = \frac{v_A}{nD}.$$

Experiences show that curves of $k_Q(J)$ and $k_T(J)$ of propeller are different from the corresponding curves of its model. This difference is known as the so-called *scale effect.*

According to the similarity law it can be assumed that the pressure distribution along the section of propeller blade and that of its model are similar to each other so that the normal force arising on the blade section and the pressure resistance can be recalculated without any correction made. It is only the frictional resistance coefficient on the surface of propeller blade which differs from that of the model.

This difference between the friction conditions can be taken into consideration with a good approximation similarly to Froude's method used in the course of determining the resistance of the ship from the results of model testing.

On *Fig. 1* are drawn the forces acting on the blade section in continuous lines in a condition of friction. The F is the resultant force of F_N normal force and the F_R resistance force. The advance component of the resultant force is T thrust, and the component perpendicular on it is the K peripheral force. If the resistance of the blade section is higher by ΔF_R, then the peripheral force increases by ΔK, while thrust decreases by ΔT.

The wetted surface of a small part of the blade is

$$dS = 2 \cdot l \cdot dr.$$

The frictional resistance on this surface is

$$F_{RF} = c_F \frac{1}{2} \rho [v_A^2 + (2\pi r n)^2] \cdot 2 \cdot l \cdot dr = c_F \cdot \rho \cdot v_0^2 \cdot l \cdot dr$$

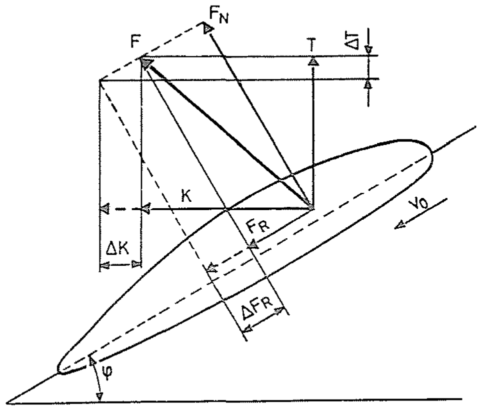

Fig. 1. Forces acting on a blade section

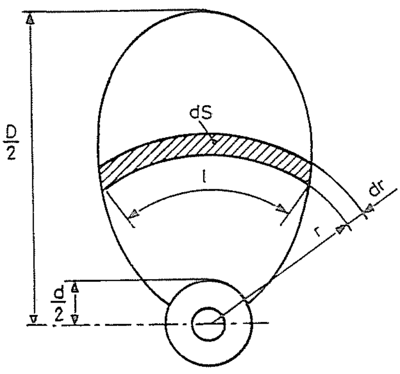

Fig. 2. Elementary surface on a propeller blade

The pressure resistance does not change, therefore the difference of the total resistance components is

$$\Delta F_R = F_{RF} - F_{RFm} = (c_F - c_{Fm}) \cdot \rho \cdot v_0^2 \cdot l \cdot dr,$$

where c_F is the frictional resistance coefficient in a frictional condition of surface, and c_{Fm} is the same in an other condition. (For example, is the frictional coefficient of the propeller blade, and c_{Fm} is the frictional coefficient of the model screw.)

Since

$$v_0^2 = v_A^2 + (2\pi r n)^2 = n^2 D^2 [J^2 + (x\pi)^2],$$

where

$$x = \frac{2r}{D}$$

the difference of the resistance forces is

$$\Delta F_R = \rho n^2 D^2 (c_F - c_{Fm})[J^2 + (x\pi)^2] \cdot l \cdot dr.$$

Hence using the symbol

$$G = (c_F - c_{Fm}) \cdot [J^2 + (x\pi)^2] \cdot l$$

the following relationship is yielded:

$$\Delta F_R = \rho \cdot n^2 \cdot D^2 \cdot G \cdot dr.$$

The decrease of total thrust is

$$\Delta T = z \int_{d/2}^{D/2} \Delta F_R \cdot \sin\varphi = z\rho n^2 D^2 \int_{d/2}^{D/2} G \cdot \sin\varphi \cdot dr$$

and the increase of torque is

$$\Delta Q = z \int_{d/2}^{D/2} \Delta F_R \cdot r \cdot \cos\varphi = z\rho n^2 D^2 \int_{d/2}^{D/2} G \cdot \frac{D}{2} \cdot x \cdot \cos\varphi \cdot dr,$$

where z is the number of blades, and

$$\varphi = \text{arctg}\left(\frac{P/D}{\pi \cdot x}\right).$$

The decrease of thrust coefficient is

$$\Delta k_T = \frac{\Delta T}{\rho n^2 D^4} = \frac{z}{D^2} \int_{d/2}^{D/2} G \cdot \sin\varphi \cdot dr$$

and the increase of torque coefficient is

$$\Delta k_Q = \frac{\Delta Q}{\rho n^2 D^5} = \frac{z}{2D^2} \int_{d/2}^{D/2} G \cdot x \cdot \cos\varphi \cdot dr.$$

The corrected coefficients are

$$k_{Tcorr} = k_T - \Delta k_T \quad \text{and} \quad k_{Qcorr} = k_Q + \Delta k_Q$$

If the surface of the propeller blade is smooth, then $c_F < c_{Fm}$, because the Reynold's number of the propeller is larger than that of its model, and so $\Delta k_T < 0$ and $\Delta k_Q < 0$. But if the propeller blades have rough surfaces, then may be $c_F > c_{Fm}$ and in this case $\Delta k_T > 0$ and $\Delta k_Q > 0$.

2. The Method of Calculation

To determine frictional resistance coefficients the Reynold's numbers used are

$$Re = \frac{v_0 l}{v} = \frac{nDl}{v}[J^2 + (x\pi)^2]^{0.5} \quad \text{and} \quad Re_m = \frac{n_m D_m l_m}{v}[J^2 + (x\pi)^2]^{0.5}$$

The model propeller has a hydrodynamically smooth surface, thus

$$c_{Fm} = \frac{0.075}{(lgRe - 2)^2}.$$

Coefficient c_F of the propeller can be determined from the curves of the frictional resistance coefficient of planes as a function of Re and l/k, where l is the length of blade section and k is the equivalent grain size of the blade surface (*Fig. 3*).

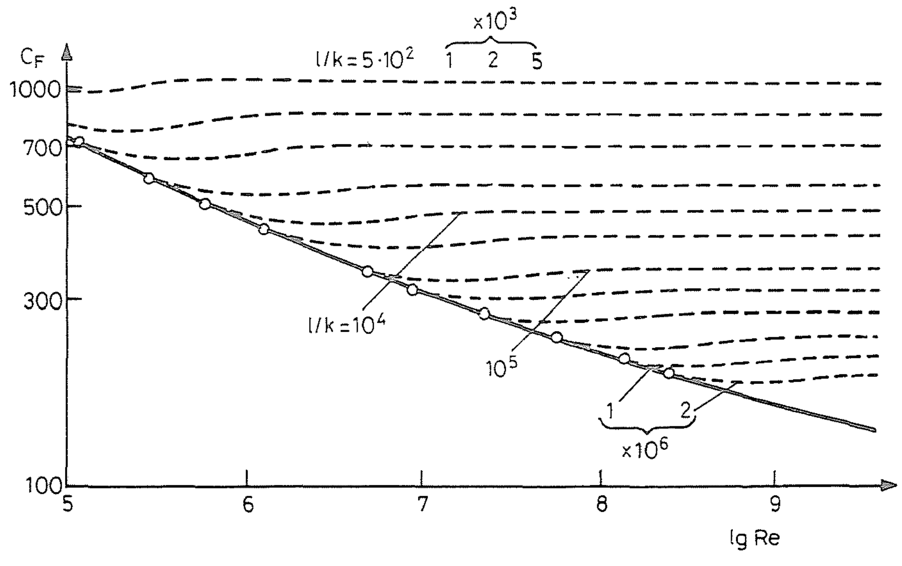

Fig. 3. The frictional resistance coefficient of planes

For the possibility of numerical calculation to be ensured instead of using diagram, it is necessary to determine two approximate equations:

1. It requires to know the critical value of relative roughness $(l/k)_0$ as a function of Reynold's number, where in case of l/k larger than that, the surface is considered as hyrodynamically smooth.

2. We need an approximative polynomial $c_F = f(Re, l/k)$ valid for the hydrodynamically rough surface.

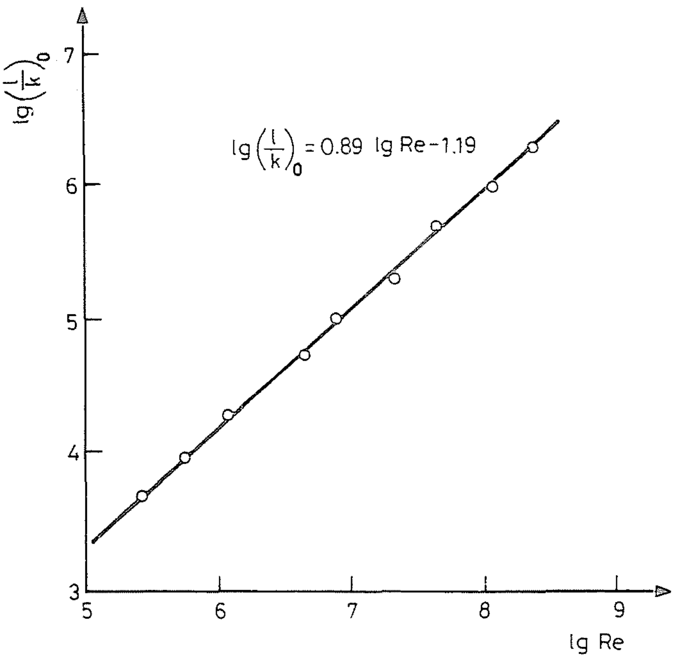

Fig. 4. The critical values of (l/k)

On the diagram (*Fig. 3*) the connection points between the different curves with $l/k =$ const. and the curves of c_F valid for hydrodinamically smooth surface are indicated by small circles. The values of Re and l/k read off in these points are plotted by a logarithmic diagram (*Fig. 4*). The points determine a linear relationship:

$$lg(l/k)_0 = 0.89 lg Re - 1.19$$

If actually $l/k > (l/k)_0$ is in force, then the surface is hydrodynamically smooth, and the formula of ITTC 1957 can be used in the calculation of c_F.

From the diagram $c_F = f(Re, l/k)$ the values of c_F along the horizontal section of the curves with $l/k =$ const. can be read off (*Fig. 3*). These values are plotted as a function of $lg(l/k)$ in the diagram shown in *Fig. 5.*

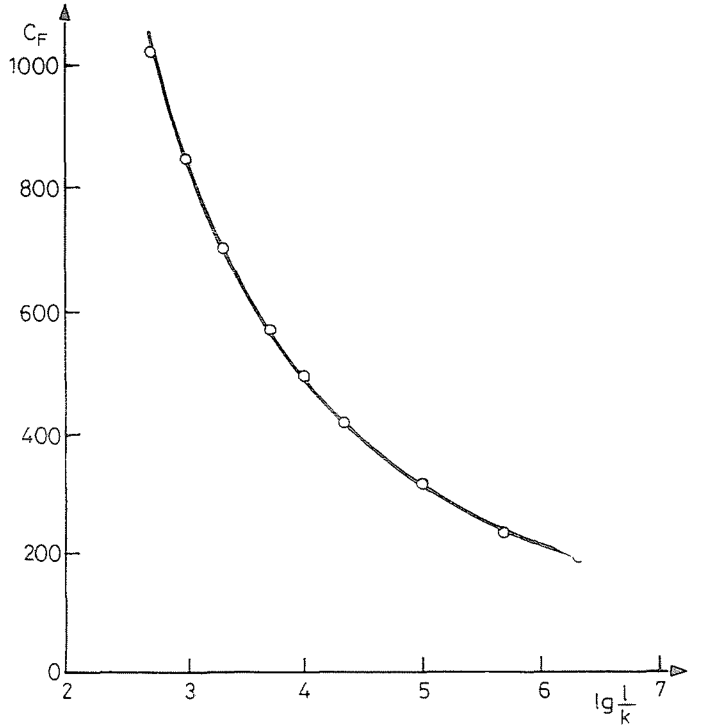

Fig. 5. Frictional resistance coefficient of rough surface

The approximate polynomial of the curve determined by these points is:

$$c_F = 0.06850074 - 0.04460449L + 0.01213810L^2 -$$

$$0.00154034L^3 + 0.00007478L^4$$

where $L = lg(l/k)$.

If the actual value of $l/k > (l/k)_0$ (i.e. the surface is hydrodynamically rough then the value of c_F can be calculated from this polynomial.

3. Example

The necessary initial data: $D, n, D_m, n_m, z, l_i, \frac{P}{D}, \frac{A_D}{A_0}, k, v_A, v, v_m, \rho$

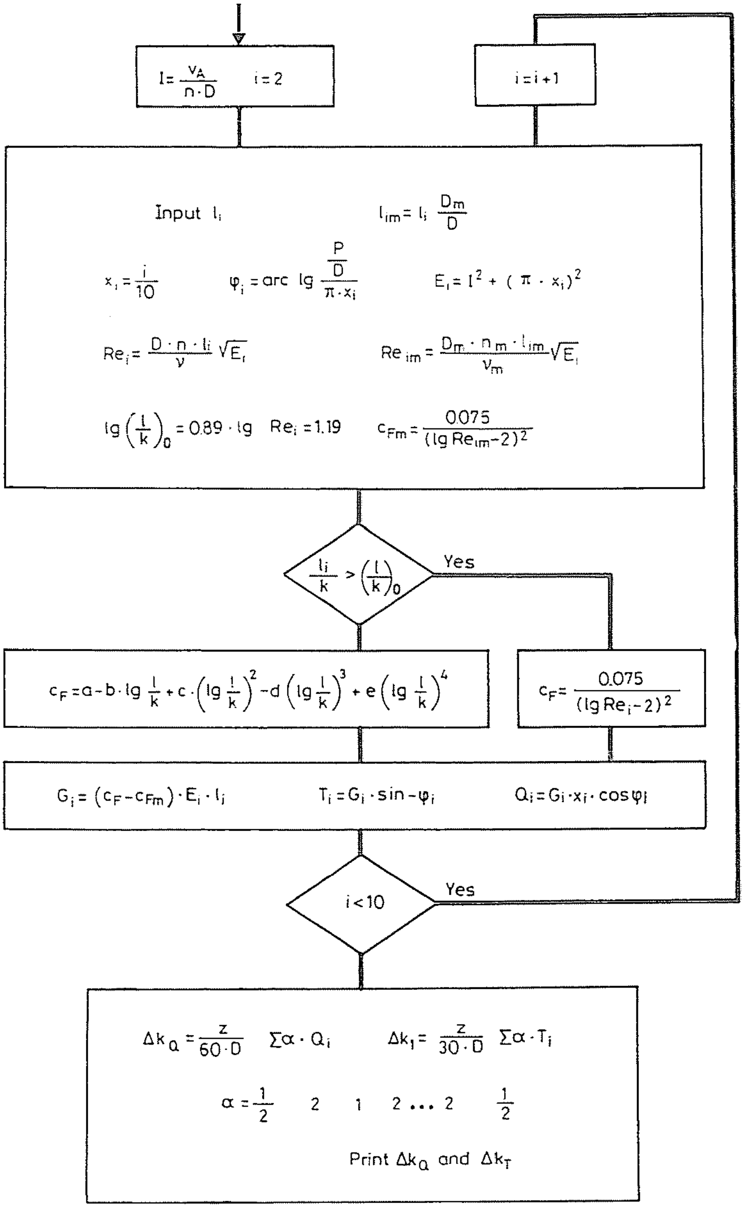

Fig. 6. The block diagram of the calculation