SCALE EFFECT ON THE TORQUE AND THRUST COEFFICIENTS OF SCREW PROPELLERS

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Summary

There is a difference between the revolution number of propellers, determined on the basis of model experiments and the actual revolution number. In ship experiments take this difference into account with a scale effect correction of $+1 \ldots +3\%$. This difference in case of small ship screws with high relative roughness is of different value and sometimes has a contrary sign. The paper introduces a method to determine the expected revolution number more precisely.

The expected characteristics of a ship are determined in the knowledge of the characteristic curves of three machines, the motor, the ship and the propeller. The characteristic curve of the motor, the exerted torque, as a function of the revolution number, can be determined accurately on the basis of the test bench measurement results. The characterestic curve of the ship, resistance as a function of the velocity, as well as the characteristic curve of the propeller, the torque and the exerted thrust as a function of the advance velocity can be determined from model experiments.

The results of the model experiments in a model experiment tank are calculated to the ship on the basis of similarity laws. The calculation of the resistance (R) of the ship is of satisfactory accuracy with the present methods. Because of the interaction of the ship body and the propeller, the thrust of the propeller (T) is not identical with the resistance of the ship. This deviation is taken into consideration with the thrust deduction coefficient

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

This coefficient with a good approximation is identical for the ship and the model at low propeller load. At higher propeller load a scale effect can be experienced on the thrust deduction coefficient [1, 2, 4].

Another consequence of the interaction of the propeller and the ship body is that the advance velocity of the propeller in open water condition (v_A) differs from the velocity of the ship (v). The difference is characterized by the wake fraction

$$w = \frac{v - v_A}{v}$$

Similarly to the thrust deduction coefficient, scale effect appears here, too [1, 3].

The model of the propeller is tested in open water condition. Torque coefficient

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

thrust coefficient

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

and velocity coefficient

$$J = \frac{v_A}{n \cdot D}$$

are formed from the connected values of open water characteristics, torque (Q), thrust (T), revolution number (n) and advance velocity of the propeller in open water condition (v_A). According to the similarity laws these coefficients are identical for the propeller and its model.

Experiences, however, show that there is a difference between the number of revolution calculated on basis of the open water characteristic curve of the propeller $k_Q = f(J)$ and the actual number of revolution. The scale effect coefficient, taking into account the difference, has been determined by experimental ship institutes on the basis of almost 100-years measurement experiences. According by the revolution number determined by experimental model results is to be increased by $+1 \ldots +3$ per cent [5]. Literature suggest such an increase in every case, independent by from Reynolds' number and the roughness of the propeller blade.

The majority of ships investigated in experimental institutes are medium or big seagoing ships, with low propeller load. The load coefficient, according to the usual interpretation is

$$c_p = \frac{T}{0.5 \cdot \rho \cdot v_A^2 \cdot A}$$

where A is the area of the cross-section of water jet passing through the propeller. For the ships tested its value was between 0.1 . . . 1.0.

For small ships of high propeller load built in Hungary, too, ($c_p = 20\dots30$) the revolution of propellers measured during trial runs significantly differed from the ones obtained by a ship model tank. The revolution number measured on the ship was not only higher but also lower than the value determined by model experiments.

A significant part of the scale effect comes from the fact that the friction condition of the model and the propeller (the Reynolds number and the relative surface roughness) are different. For big seagoing ships of low propeller load and small revolution number this difference is smaller than for inland-waterway vessels of high propeller load and high revolution number.

The effect resulting from the difference in friction condition can be considered with good approximation, similarly to Froude's method used to calculate the resistance of the ship. It can be supposed that the pressure distribution along the blade section of the propeller and its model is similar, thus normal force affecting the blade section and the pressure resistance of viscous origin can be recalculated without correction. Only the friction force coefficient on the blade surface is different on the propeller, as compared to its model.

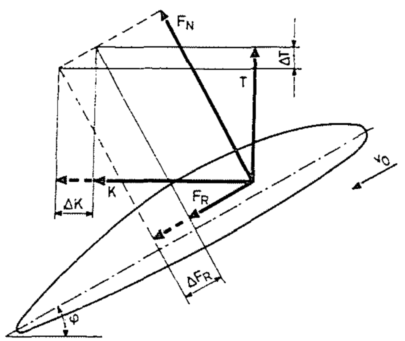

Fig. 1

Fig. 1 shows forces on a blade section. The forces drawn by a continuous line are the ones appearing on the model recalculated to the dimensions of the propeller and the dotted lines show actual forces of the propeller. The sum of the normal force (F_N) as a difference of pressure on the two sides of the aerofoil and the resistance force (F_R) is the resultant force not shown in the figure. The advance component of the resultant force is thrust (T) and the tangential component is peripheral force (K).

If the resistance of the screw propeller airfoil is higher by ΔF_R the peripheral force increases by ΔK and thrust decreases by ΔT.

Forces appearing on the screw propeller can be supposed as concentrated forces on the airfoil with a diameter of 0.75. D, in the course of our calculation [6]. Thus the resistance force is

$$F_R = 0.5 \cdot \rho \cdot v_0^2 \cdot 2 \cdot A_D \cdot (c_F + c_{VP})$$

and the resistance force increase on the propeller is

$$\Delta F_R = 0.5 \cdot \rho \cdot v_0^2 \cdot 2 \cdot A_D \cdot (c_F - c_{Fm}) = \rho \cdot v_0^2 \cdot A_D \cdot \Delta c_F$$

where $v_0^2 = v_A^2 + (0.75 \cdot D \cdot \pi \cdot n)^2$;

$2 \cdot A_D$ is the wetted surface of propeller blades;

A_D is the developed area of propeller blades;

c_F is the frictional resistance coefficient of the propeller blades;

c_{Fm} is the frictional resistance coefficient of the model propeller;

$\Delta c_F = c_F - c_{Fm}$;

c_{VP} is the coefficient of the pressure resistance (identical value for the propeller and its model).

Thus the decrease of thrust is

$$\Delta T = \Delta F_R \cdot \sin\varphi = \rho \cdot v_0^2 \cdot A_D \cdot \Delta c_F \cdot \sin\varphi$$

where

$$\varphi = \mathrm{arc\,tg} \frac{P}{0.75 \cdot D \cdot \pi}$$

P is the pitch of the propeller.

The increase of the torque is:

$$\Delta Q = \Delta K \cdot 0.75 \cdot \frac{D}{2} \cdot = \Delta F_R \cdot 0.75 \cdot \frac{D}{2} \cdot \cos\varphi =$$

$$= \rho \cdot v_0^2 \cdot A_D \cdot \Delta c_F \cdot 0.75 \cdot \frac{D}{2} \cdot \cos\varphi$$

As a result the open water characteristics, the thrust coefficient k_T and the torque coefficient k_Q, can be corrected in the function of velocity coefficient J. The decrease of the thrust coefficient:

$$\Delta k_T = \frac{\Delta T}{\rho \cdot n^2 \cdot D^4} = \frac{\rho \cdot \Delta c_F \cdot A_D}{\rho \cdot n^2 \cdot D^4} \cdot [v_A^2 + (0.75 \cdot D \cdot \pi \cdot n)^2] \cdot \sin\varphi =$$

$$= \frac{\pi}{4} \cdot \frac{A_D}{A_0} \cdot \Delta c_F \cdot [J^2 + (0.75 \cdot \pi)^2] \cdot \sin\varphi$$

where $A_0 = 0.25 \cdot D^2 \cdot \pi$.

The increase of the torque coefficient

$$\Delta k_Q = \frac{\Delta Q}{\rho \cdot n^2 \cdot D^5} = \frac{\rho \cdot \Delta c_F \cdot A_D}{\rho \cdot n^2 \cdot D^5} \cdot [v_A^2 + (0.75 \cdot D \cdot \pi \cdot n)^2] \cdot 0.75 \cdot \frac{D}{2} \cdot \cos \varphi$$

$$\Delta k_Q = \frac{\pi}{4} \cdot \frac{A_D}{A_0} \cdot \Delta c_F \cdot [J^2 + (0.75 \cdot \pi)^2] \cdot 0.375 \cdot \cos \varphi.$$

To determine the friction coefficient, airfoil cord length 1 and velocity v_0 can be taken at diameter $0.75 \cdot D$ according to the proven method used in other kinds of investigations. So the significant Reynolds number

$$\mathrm{Re} = \frac{v_0 \cdot 1}{\nu}$$

and the reciprocal of relative roughness

$$\frac{1}{k}$$

can be calculated. These figures show the coefficient friction value for a screw propeller and its model from the curve of frictional resistance coefficient valid for planes.

With the usual big screw propellers the relative roughness of the blade surface is so small that the frictional coefficient of the propeller is smaller than that of the model screw. In this case the torque coefficient of the propeller decreases compared to the model propeller, i.e. the number of revolutions will be higher than the value determined from a direct recalculation of the results of model experiments. The frictional coefficient of a small size screw propeller can be higher than the frictional resistance coefficient of its model. Thus the torque coefficient of the propeller will be higher, too. That is why the number of revolutions decreases compared to the value calculated from model experiments.

On the basis of the method the number of revolutions of propellers for ships of different propeller load was determined. The results obtained for a river pushboat are given as an example.

The diameter of the screw propeller is 1.60 m, its pitch is 1.60 m, the developed area ratio is 0.70, the advance velocity of the propeller in open water condition 2 $\mathrm{m \cdot s^{-1}}$. The torque in open water condition is 14942 $\mathrm{N \cdot m}$.

The frictional coefficients are $c_F = 5.4 \cdot 10^{-3}$ $c_{Fm} = 4.7 \cdot 10^{-3}$. For the open water propeller characteristic curves determined on the basis of model experiments (Fig. 2) $k_T = 0.371$ and $k_Q = 0.056$ can be read for value $J = 0.25$.

The corrected coefficients are $k_{T\,corr} = k_T - \Delta k_T = 0.371 - 0.0008 = 0.3702$
$k_{Q\,corr} = k_Q + \Delta k_Q = 0.056 + 0.0007 = 0.0567$

On the basis of a torque coefficient without correction the number of revolutions of the propeller is 5.044 s^{-1}. The expected value given by the ship model tank with a usual scale effect correction of +2 per cent was 5.15 s^{-1}. The

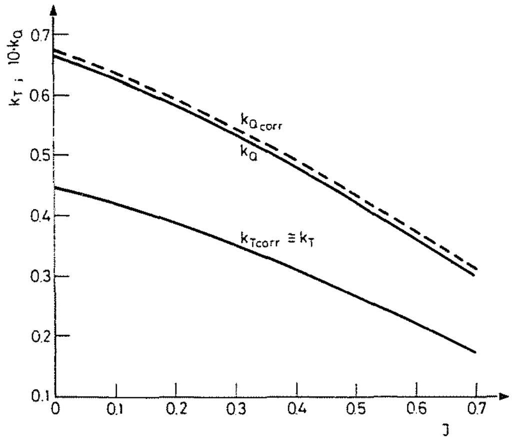

Fig. 2

value determined by a curve corrected on the basis of the introduced method is 5.013 s^{-1}, which corresponds well with the value 301 $min^{-1} = 5.016$ s^{-1} measured in the course of the trial run of the ship.

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