RESISTANCE OF IDLE PROPELLERS IN MARINE MULTI-PROPELLER PROPULSION SYSTEMS

Adam Charchalis

Gdynia Maritime University, Faculty of Marine Engineering
Morska Street 83, 81-225 Gdynia, Poland
e-mail: achar@am.gdynia.pl

Abstract

The configuration of a marine propulsion system is selected with regard to the maximum power resulting from its maximum design speed and displacement. The propulsion systems of high speed vessels use three or even four propellers, and each propulsion unit may be multi-engine. High speed vessels are designed for maximum speeds, but their factual exploitation speed parameters are usually considerably lower - partial speed. In such cases particular propulsion propellers and engines need to be shut down. The idle propellers are dragged by the hull and they work in the so-called turbine work mode; they transfer torque to the shaft and generate negative thrust, i.e. additional resistance. Additional resistance contributes to reducing estimated speed of a vessel and increasing fuel consumption. What is more, torque generated on a propeller is transferred to the shaft and when friction resistance torque in shaft stuffing-boxes and bearings, transmission and, possibly, the propulsion engine is exceeded, mobile components rotate as a result, reaching considerable rotational speed values. Torque and thrust on a propeller in this work mode may be estimated on the grounds of universal hydrodynamic characteristics of propellers. Universal hydrodynamic characteristics of propellers are used as reversion characteristics in evaluating the steering properties of a vessel, and may be useful in evaluating resistance of freewheeling and locked propellers in marine multi-shaft propulsion systems. This paper presents charts of universal hydrodynamic characteristics of propellers for the full range of their rotational speed, the methodology and an example of calculating resistance of freewheeling and locked propellers for the given marine propulsion system.

Keywords: transport, high speed vessels, marine propellers, multi-propeller propulsion systems

1. Introduction

The demand for power needed for marine propulsion depends on the size (displacement) and speed of a vessel. The issue is particularly critical in the case of high speed vessels, because high speed of a vessel involves considerable propulsion power, while limited displacement, which minimizes the resistance values of a vessel, leads to limited draught of a vessel and volume inside the hull. It also affects the number, type, power and parameters of main engines and propellers. Due to the demand for power needed for high speed vessel propulsion and its poor draught, which is the reason for reducing the diameter in propeller selection, the propulsion systems of this kind of vessels are multi-engine and multi-propeller [6].

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High speed vessels show specific exploitation properties. They are designed for maximum speeds, but their factual exploitation speed parameters are usually considerably lower, which is referred to as partial speed. In such cases particular propulsion propellers and engines need to be shut down. The idle propellers are dragged by the hull and they work in the so-called turbine work mode; they transfer torque to the shaft and generate negative thrust and, consequently, generate additional resistance for the whole propulsion system [4, 12]. Additional resistance caused by idle propellers needs to be taken into consideration at the stage of designing the propulsion system and analysing its performance in particular work modes. Additional resistance contributes to reducing estimated speed

of a vessel and increasing fuel consumption. What is more, torque generated on a propeller is transferred to the shaft and when frictional resistance torque in shaft stuffing-boxes and bearings, transmission and, possibly, the propulsion engine is exceeded, mobile components rotate as a result, reaching considerable rotational speed values. In order to prevent engine or transmission gear seizure, the propulsion shaft in this type of systems is often fitted with brakes. Determining the necessary braking moment ensures proper brake operation and prevents shaft spinning. There are two cases of propeller operation in the turbine work mode: "a freewheeling propeller" and "a locked propeller". Torque and thrust on the propeller in particular work modes can be conveniently estimated on the grounds of universal hydrodynamic characteristics of propellers [1, 4, 12].

2. Universal hydrodynamic characteristics of vessels

The hydrodynamic characteristics of propellers concern the ahead motion of a vessel, i.e. when the rotational speed of the propeller is positive and forward speed of the propeller is positive, the advance coefficient $J=v_p/Dn$ is also positive. Here, the coefficient values of thrust K_T and torque K_Q are positive. In such cases thrust generated by the propeller, torque and power provided by the engine and necessary for the proper functioning of the propeller are as follows, respectively:

$$T = K_T \rho n^2 D^4,$$ (1)

$$Q = K_Q \rho n^2 D^5,$$ (2)

$$N = 2\pi Q n = 2K_Q \rho n^3 D^5.$$ (3)

An example of hydrodynamic characteristics of a propeller working behind a hull of a vessel is illustrated in Fig. 1[10].

When a vessel is exploited, advance, thrust or torque coefficients may have negative values. For instance:

1. halting a vessel during the ahead motion $v_p> 0$, $n<O$, then $J<0$ and $K_T<0$,
2. halting a vessel during the astern motion $v_p< 0$, $n>0$, then $J<0$ and $K_T<0$,
3. astern motion $v_p<O$, $n<0$, then $J>0$ and $K_T<0$,
4. dragging an idle propeller $v_p> 0$, $n > O$, then $J>J1$ /advance coefficient for which the propeller thrust $=0$/,/ and $K_T< 0$ /additional resistance of a vessel/,
5. dragging a locked propeller $v_p> 0$, $n = O$, then J approaches the infinity and $K_T< 0$ /additional resistance of a vessel/.

The above cases of atypical propeller operations indicate that in order to comprehensively evaluate the propulsion system of a vessel it is necessary to know the performance of a propeller in the whole operational range within the exploitation framework. That is why so-called universal hydrodynamic characterstics of idle propellers [1, 4, 12] have been formulated. An example of the characteristics for one H/D propeller pitch is illustrated in Fig. 2.

Universal hydrodynamic characteristics of propellers are used as reversion characteristics in evaluating the steering properties of a vessel, and may be useful in evaluating resistance of freewheeling and locked propellers in marine multi-shaft propulsion systems.

3. Resistance of idle – both freewheeling and locked propellers

It is often the case in marine multi-propeller propulsion systems that one or more propellers are not operating, i.e. engines do not transmit torque to them. These propellers are then dragged by the moving vessel. An idle popeller can be locked e.g. with a brake on a shaft and then it either does not rotate or it rotates freely and transmits torque from the propeller to the engine. The propeller works like a water turbine in these situations and may give propulsion to an idle engine through the shaft line.

An idle propeller is the source of additional resistance and causes a number of difficulties, such as the necessity to use a brake with considerable brake torque on the shaft line.
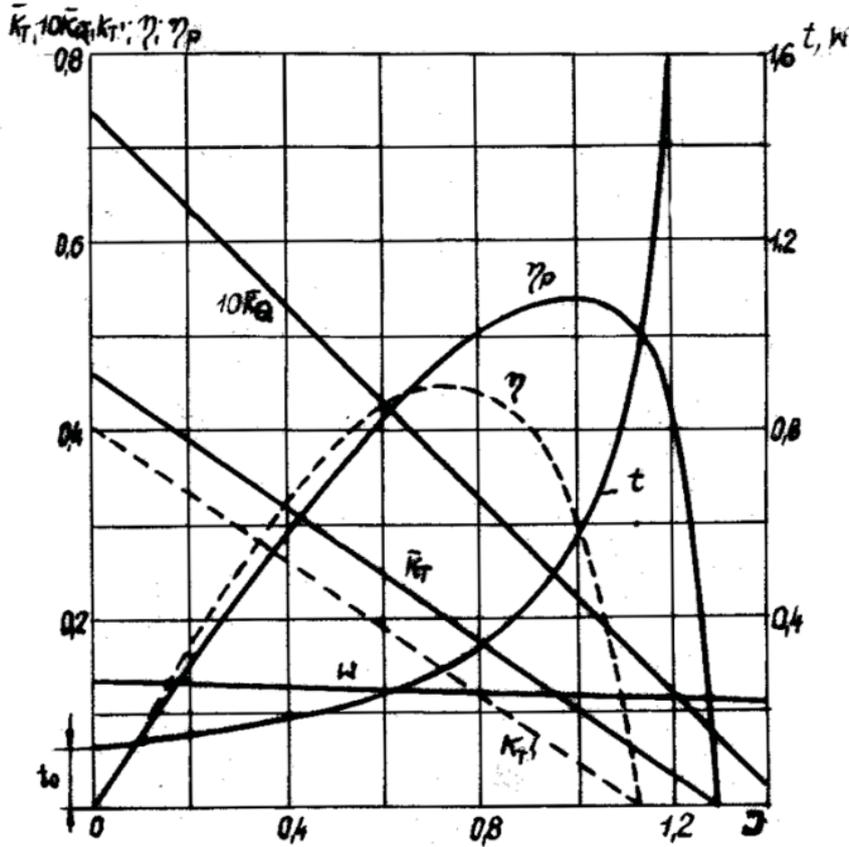
Fig. 1. *Characteristics of a propeller working behind a hull of a vessel where: KT - thrust coefficient, KQ - torque coefficient, ηp - efficiency of an idle propeller, t - suction coefficient, w - wake fraction , ηh - efficiency of a propeller working behind a hull*
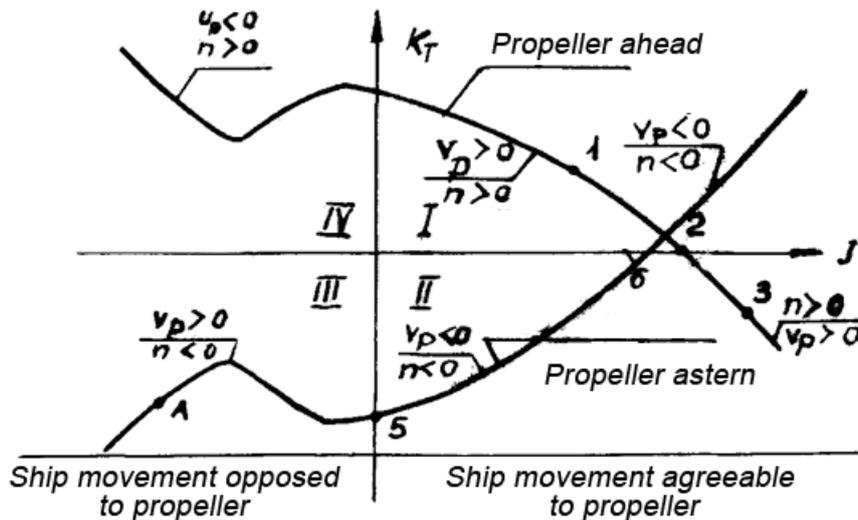
Fig. 2. *Universal characteristics of a propeller for H/D = idem*

3.1. A dragged locked propeller

When a propeller is not operating, it is dragged and is not rotating, and then the frictional torque in the shaft line, transmission gear (possibly engine or brake) is larger than the torque developed by the propeller in its turbine work mode. During the ahead movement $v_p>0$ and with a locked propeller $n=0$, advance coefficient $J=v_p/Dn$ approaches infinity. That is why hydrodynamic

characteristics of propellers were developed for the cases in which n→0, i.e. when J→∞. The method involved replacing advance coefficient J with its converse $J_0 = 1/J = Dn/v_p$ on the x-axis. Then $J_0=0$ is in the centre of coordinate system in the case of a locked propeller.

Examples of universal hydrodynamic characteristics of propellers in the K'$_T$ and K$^{'}_Q$ system are illustrated in Fig. 3, 4 [2, 4, 12]. In order to determine resistance or torque of a locked propeller, thrust and torque coefficients need to be determined first on the K'$_T$ –f(J_0) graph in the beginning of the coordinate system ($J_0=0$) for the appropriate pitch ratio H_1/D. In this case, the negative thrust of a locked propeller, i.e. additional resistance amounts to:

$$R_{zast} = T' = K_T^t \rho n^2 D^4.$$ (4)

Frequently, in order to design a brake, the value of the necessary minimum frictional torque needs to be known. It is determined in the following way:

$$Q_{tr} = K_Q^t \rho v_p^2 D^2.$$ (5)

3.1. A dragged freewheeling propeller

When a vessel is in motion and the propeller is not operating, but being dragged and the torque it develops in the turbine work mode is larger than frictional torque in the shaft line, then the propeller starts rotating. Rotational speed a propeller reaches depends on the relation between frictional torque in the shaft line and on the propeller and torque developed by the propeller. Both frictional torque and torque a propeller develops are a function of its rotational speed, which, in turn, is derived from torque balance $Q(n) = Q_{so}(n, v_p)$. When the resistance of a freewheeling propeller is calculated, the rotational speed value is not known for a propeller. That is why, what needs to be estimated first is torque in the shaft line, followed by frictional torque coefficient balanced by torque of a propeller working in the turbine mode, i.e. providing propulsion to the shaft.

$$Q_{tlw} = Q_{so},$$ (6)

$$Q_{so} = K_Q \rho n^2 D^5.$$ (7)

Because the rotational speed value is not known, $n = v_p/DJ$ is entered, so: K$^{'}_Q$ = K$_Q$/J

$$Q = K_Q^t \rho v_p^2 D^3.$$ (8)

4. Calculating the resistance of freewheeling and locked propellers

Exemplary calculation of resistance for idle propellers was conducted for a marine propulsion system which uses three propellers, is equipped in three-bladed propellers of constant pitch $H_1/D=1.175$, diameter D=1.15m, blade area coefficient $S_0/S=1.1$. Engine torque is 25 kNm. The assumed water was $\rho=1026 kg/m^3$, for $t=15^{\circ}C$.

For a locked propeller ($v_p=0$, $J_0=0$) with an assumed $H_1/D=1.175$, thrust coefficient is K$^{'}_T$=0.32, and torque coefficient K$_Q$=0.057.

That is why the resistance of a locked propeller and the torque necessary to halt the propeller are as follows:

$$R_{repl} = K_T^{'} \rho\, v_p^2 D^2 = 434.2\, v_p^2,$$

$$Q = K_Q^{'} \rho\, v_p^2 D^3 = 88.94\, v_p^2.$$

It is crucial to determine torque in the shaft line for a freewheeling propeller because it affects the rotational speed of a propeller, which is generated by means of balancing frictional torque in

the rotating elements of the propulsion system and torque produced by the propeller working in the turbine mode and transmitted to the shaft.

Frictional torque in the shaft line is the function of its rotational speed and shaft length; it also depends on whether the engine is declutched or propulsed by a propeller. The longer the shaft, the larger the number of bearings, stuffing boxes and poorer the efficiency of the shaft line. The following relations may be used for determining frictional torque:

$$Q_{ttw} = \left(a + b\frac{n_x}{n}\right)Q , \tag{9}$$

$$Q_{tlw} = cQ\left(\frac{n_x}{n}\right)^{\frac{1}{2}} , \tag{10}$$

where:

$a = \frac{1}{2}c; b = \frac{2}{3}c; c = 0.02 - 0.05$ (smaller values for shorter shafts),
$x = 1 - \eta_{lw}$,
Q - nominal torque developed by the vessel,
n_x - nominal rotational speed of a shaft.

The relations above may be used if rotational speed of freewheeling shafts is known e.g. thanks to specific measurements. In computational estimation certain authors [WW] recommend assuming that frictional torque does not depend on rotational speed and then

$$Q_{tlw} = (1 - \eta_{lw})Q , \tag{11}$$

where:

η_{lw} = 0.96 - 0.98 - shaft line efficiency; it is assumed that η_{lw} = 0.96.

Thus, frictional torque in the shaft line is Q=1000 Nm torque coefficient:

$$K^t{}_Q = \frac{Q_t}{\rho n_p^2 D^5} = 0.64/vp2. \tag{12}$$

Advance coefficient J_o=f($K_Q{}'$) is determined on the grounds of hydrodynamic characteristics of a propeller for the whole range of the exploitational speed of a vessel. The estimated advance coefficient enables determining the rotational speed of a freewheeling propeller in first approximation:

$$n = \frac{J_o v_p}{D} . \tag{13}$$

In order to determine the resistance coefficient for a freewheeling propeller graph $K_T{}'$ J_o is used and approached with a calculated value of advance coefficient for the relevant pitch ratio H_1/D. The value of $K_T{}'$ is read off the axis of ordinates.

In calculating the resistance of freewheeling propellers the relation below is used

$$R_{so} - T - K_T \rho v_p^2 D^2 - 434.2 v_p^2 , \tag{14}$$

In the second approximation of calculating the resistance of a freewheeling propeller, it is assumed that frictional torque depends on the rotational speed of a shaft and the calculations use the rotational speed of the shaft determined in the first approximation. Frictional torque is determined with the use of relation (9).

Figure 5 illustrates the calculated resistance values of idle propellers, freewheeling and locked ones, depending of the speed of a vessel.

5. Conclusions

The presented results of the calculations were confirmed in the experiment on the real object.
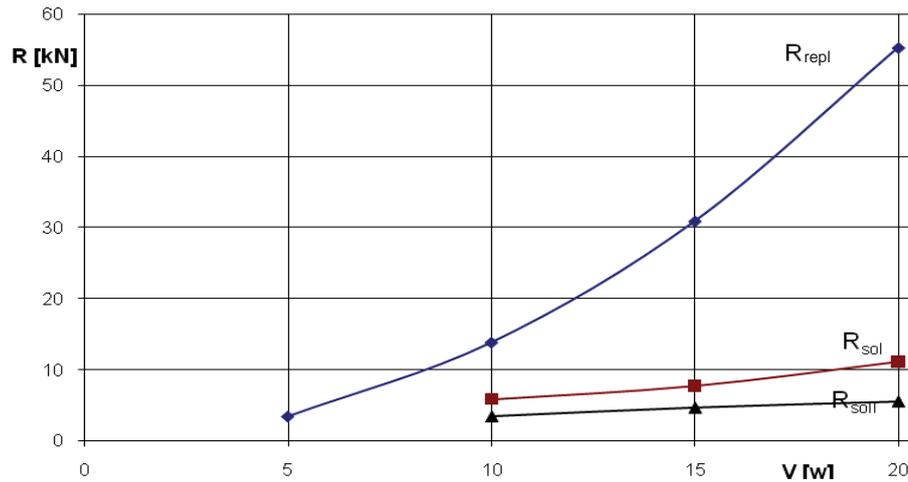
Fig. 5. Resistance of dragged propellers 1- locked, 2- freewheeling- I approximation, 3- freewheeling- II approximation

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