TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 8 Number 3 September 2014
DOI: 10.12716/1001.08.03.16

# Drag and Torque on Locked Screw Propeller

T. Tabaczek
*Wrocław University of Technology, Wrocław, Poland*

T. Bugalski
*Ship Design and Research Centre CTO S.A, Gdańsk, Poland*

ABSTRACT: Few data on drag and torque on locked propeller towed in water are available in literature. Those data refer to propellers of specific geometry (number of blades, blade area, pitch and skew of blades). The estimation of drag and torque of an arbitrary propeller considered in analysis of ship resistance or propulsion is laborious. The authors collected and reviewed test data available in the literature. Based on collected data there were developed the empirical formulae for estimation of hydrodynamic drag and torque acting on locked screw propeller. Supplementary CFD computations were carried out in order to prove the applicability of the formulae to modern moderately skewed screw propellers.

## 1 INTRODUCTION

In some modes of ship operation or maintenance the propeller shaft is immobilised and propeller becomes locked. The case of fast ships fitted with multiple-engine and multiple-propeller propulsion system with three or four propellers is discussed by Charchalis [1]. Such ships sometimes operate at high speed but often sail at reduced or cruising speed. Excessive engines are stopped and passive propellers are locked in order to prevent the gear and engine from wear or failure. Charchalis proposed the method for evaluating the drag and hydrodynamic torque on locked propeller. The method is based on thrust and torque coefficients from four-quadrant open water characteristics of considered screw propeller. In example calculations Charchalis refers to diagrams for three-bladed screw propellers presented in [2].

Propellers may also stay locked when ship is towed in emergency or in the course of delivery from shipyard to ship operator. Then the concern is to protect the gear and engine, and despite the additional drag during towing the propeller shaft may be intentionally immobilized.

All modern sailboats, with except for the smallest ones, are equipped with mechanical propulsion. When sailing - the engine is stopped and some sailors decide to lock the shaft and propeller, sometimes due to the mistaken belief that locked propeller is more favourable for low drag. (The question of whether the drag of the locked propeller is lower than the drag of the windmilling propeller was argued as late as in 2012.) Sometimes the manufacturers of small marine gearboxes specify that the shaft should be locked when the engine is stopped and the vessel is in motion, because some gearboxes receive adequate lubrication only when the engine is running.

Although some test results of hydrodynamic drag and torque acting on locked screw propeller are available in open literature and one may refer to them directly, it would be more convenient for ship designers and operators to have a simple formula ready to apply and provide the estimation of drag and torque instantly. The present authors have reviewed and compared the available test data. Based on a simple assumption of negligible effect of interaction between blades in the case of locked propeller they proposed the empirical formulae for estimation of drag and torque on locked screw propeller in open water.

The research was extended with CFD computations in order to confirm the applicability of developed formulae to modern moderately skewed propellers. The allowances to drag and torque were proposed in such cases.

## 2 NON-DIMENSIONAL COEFFICIENTS

The results of open water tests of marine screw propellers are presented in the form of non-dimensional coefficients of speed, thrust and torque. Usually, in standard range of ahead speed and ahead rotation, the advance coefficient $J$, thrust coefficient $K_T$ and torque coefficient $K_Q$ are defined as

$$J = V_A \,/\, (nD)$$

$$K_T = T \,/\, (\rho n^2 D^4) \tag{1}$$

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

where:

- $V_A$ –advance speed of propeller
- $n$ –rotational rate
- $D$ –propeller diameter
- $T$ –propeller thrust
- $Q$ –torque
- $\rho$ –density of water.

When screw propellers are tested in extended range of operating conditions, and when rotational sped equals zero or is close to zero, the values of conventional coefficients $K_T$ and $K_Q$ approach infinity, and non-dimensional coefficients must be defined otherwise in order to present the finite performance. Nordstrom [3] and Miniovich [2] applied the conventional coefficients (1) around bollard conditions and modified coefficients:

$$J' = nD \,/\, V_A = 1/J$$

$$K_T' = T \,/\, (\rho V_A^2 D^2) \tag{2}$$

$$K_Q' = Q \,/\, (\rho V_A^2 D^3)$$

around locked conditions ($n$=0). (Different symbols are used across the literature for modified coefficients.) The open water four-quadrant hydrodynamic characteristics of each screw propeller were presented in [2] and [3] using at the same time two systems of coefficients with overlapping ranges of advance coefficient far from bollard and locked conditions. The definition of advance coefficient $J$ implies that it does not define the operating conditions uniquely, and additional information is necessary do distinguish the ahead ($V_A$>0; $n$>0) and astern ($V_A$<0; $n$<0), as well as the crashback ($V_A$>0; $n$<0) and crashahead ($V_A$<0; $n$>0) conditions.

The problem of two different systems of coefficients has been overcome by application of advance angle $\beta$ and non-dimensional coefficients based on speed of blade section at radius $r$=0.7$R$ across the water $V_r = [V_A^2 + (0.7\pi nD)^2]^{1/2}$ [4]:

$$\beta = \text{arc tan}(V_A \,/\, 0.7\pi nD)$$

$$C_T^* = T \,/\, \{0.5\rho\, [V_A^2 + (0.7\pi nD)^2]\, \pi/4 \quad D^2\} \tag{3}$$

$$C_Q^* = Q \,/\, \{0.5\rho\, [V_A^2 + (0.7\pi nD)^2]\, \pi/4 \quad D^3\}$$

(Similar idea by Lavrentiev, based on reference speed $(V_A^2 + n^2D^2)^{1/2}$, was noticed but not used in [2].) Performance characteristics $C_T^*(\beta)$ and $C_Q^*(\beta)$ are single-valued, continuous and periodical, and more suitable for theoretical investigation of ship manoeuvres.

In the following analysis only the thrust and torque at $n$=0 are considered and the authors use the coefficients $C_T^*$ and $C_Q^*$ at $\beta$=π/2. The modified thrust and torque coefficients $K_T'$ and $K_Q'$ needed conversion according to the following correspondence (valid only at $n$=0):

$$C_T^* = K_T' \,/\, (\pi/8)$$

$$C_Q^* = K_Q' \,/\, (\pi/8)$$

## 3 AVAILABLE TEST DATA

In 1948 Nordstrom [3] described model tests carried out in order to determine open water performance of screw propellers in all regimes of operation (in four quadrants of operating conditions). Tests were carried out with a series of four-bladed propellers of blade area ratio equal to 0.45. The only parameter differing propellers in the series was the pitch ratio that varied from zero to 1.6. Nordstrom presented the results in the form of non-dimensional coefficients plotted against advance ratio. He applied two systems of coefficients: the conventional one based on rotational speed $n$ (Eq. (1)) and the modified one based on advance speed $V_A$ (Eq. (2)). (Nordstrom applied different symbols but the same definitions as used in this paper.) Values of coefficients at $n$=0 were converted and shown in Fig. 1.

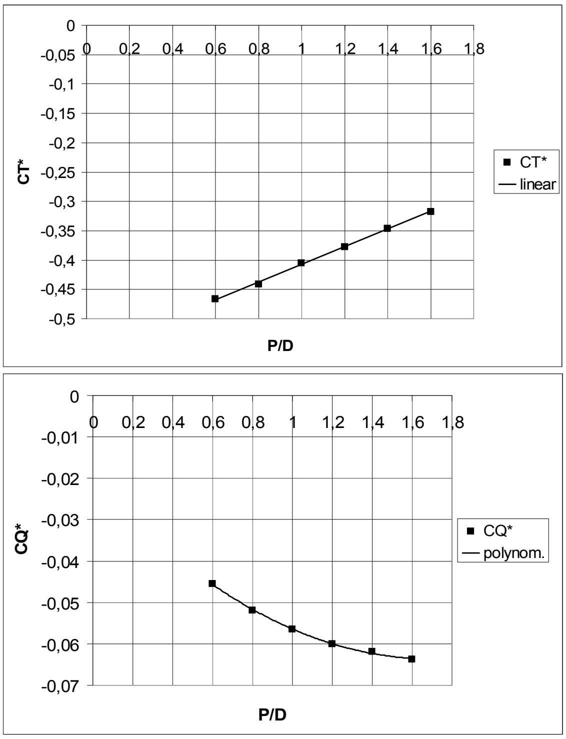



Figure 1. Thrust and torque coefficients of four-bladed propellers tested by Nordstrom [3], $n$=0

In 1954 through 1956 Miniovich [2] carried out model tests with a series of three-bladed screw propellers. The series included propellers with three values of blade area ratio $A_E/A_0$: 0.5, 0.8 and 1.1. For each value of $A_E/A_0$ the pitch ratio $P/D$ varied in the range 0.6≤ $P/D$ ≤1.6. In [2] the results were presented in diagrams, using two systems of coordinates defined by formulae (1) and (2). Values of coefficients at $n$=0 were converted and are shown in Fig. 2. The results for $A_E/A_0$=1.1 read out from the tangle of lines in the original diagrams [2] are highly irregular and were omitted in the following analysis.

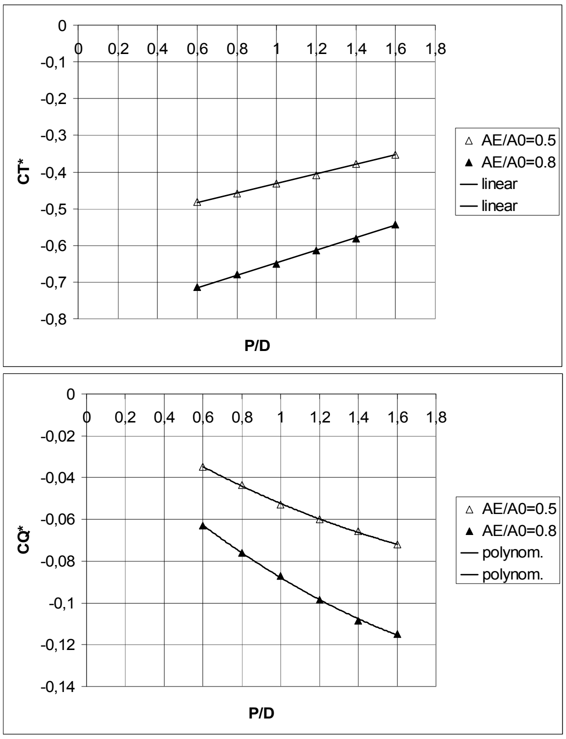
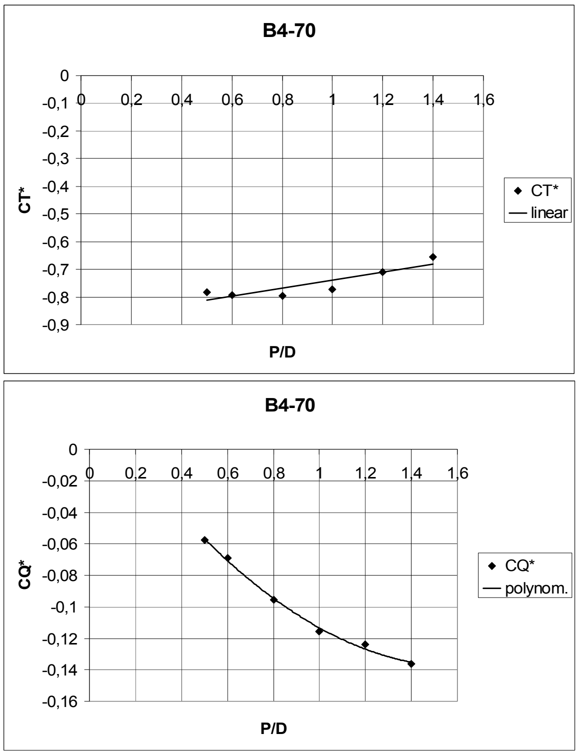



Figure 2. Thrust and torque coefficients of three-bladed propellers tested by Miniovich [2], $n$=0

In 1969 van Lammeren et al. [4] presented four-quadrant hydrodynamic characteristics of 14 screw propellers selected from the well-known B-series. The selection was made so that the effect of three basic parameters (namely $P/D$, $A_E/A_0$ and the number of blades $z$) on performance in all regimes of operation was revealed. Basic parameters of individual propellers are given in Table 1. The measured thrust and torque were converted into non-dimensional coefficients $C_T$* and $C_Q$* according to the definition (3) and presented in diagrams. Van Lammeren et al. [4] proposed also the approximation of characteristics with the Fourier series of 20 terms, convenient for ship manoeuvring study. However, some coefficients of Fourier series given in [4] do not allow reproducing the corresponding curves presented in diagrams. In order to determine the values of thrust and torque coefficients at $n$=0 ($\beta$=π/2) the present authors used the approximation of characteristics with Fourier series of 30 terms reprinted in report [5]. Calculated values of coefficients are listed in Table 1 and shown in Fig. 3.

Table 1. Propellers from B-series tested in four quadrants [3]

| Propeller | z | $A_E/A_0$ | P/D | $C_T$* | $C_Q$* |
|---|---|---|---|---|---|
| B4-70 | 4 | 0.70 | 0.5 | -0.7818 | -0.0575 |
| B4-70 | 4 | 0.70 | 0.6 | -0.7935 | -0.0690 |
| B4-70 | 4 | 0.70 | 0.8 | -0.7958 | -0.0954 |
| B4-70 | 4 | 0.70 | 1.0 | -0.7719 | -0.1155 |
| B4-70 | 4 | 0.70 | 1.2 | -0.7092 | -0.1237 |
| B4-70 | 4 | 0.70 | 1.4 | -0.6545 | -0.1364 |
| B4-40 | 4 | 0.40 | 1.0 | -0.3550 | -0.0442 |
| B4-55 | 4 | 0.55 | 1.0 | -0.5795 | -0.0733 |
| B4-85 | 4 | 0.85 | 1.0 | -0.9626 | -0.1438 |
| B4-100 | 4 | 1.00 | 1.0 | -1.0363 | -0.1510 |
| B3-65 | 3 | 0.65 | 1.0 | -0.6660 | -0.0962 |
| B5-75 | 5 | 0.75 | 1.0 | -0.8539 | -0.1255 |
| B6-80 | 6 | 0.80 | 1.0 | -0.8903 | -0.1264 |
| B7-85 | 7 | 0.85 | 1.0 | -0.9234 | -0.1264 |



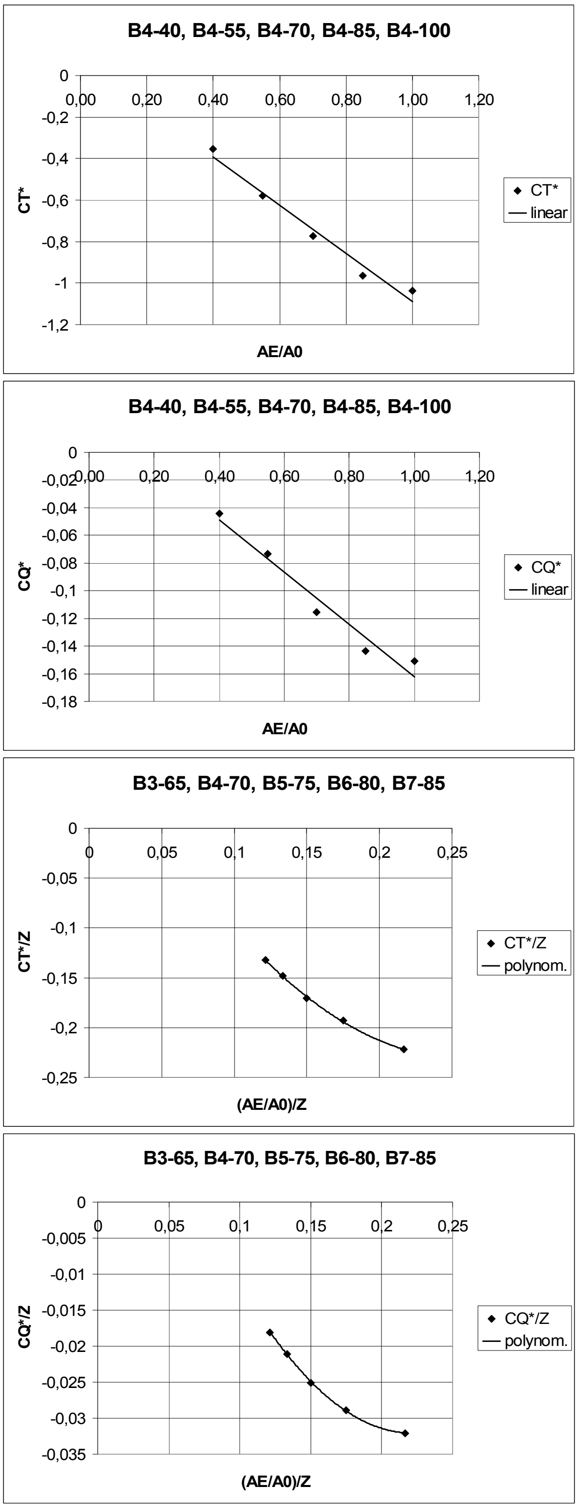



Figure 3. Thrust and torque coefficients of propellers from B-series [4], $n$=0

Lurie and Taylor [6] investigated performance characteristics of 2- and 3-bladed 13 inch commercially available propellers designed for use on small and medium size sailboats. Besides the non-conventional screw propellers (folding or feathering propellers) the four fixed-blade propellers were tested. The performance at forward speed was measured including propeller drag at $n$=0. Results were presented in the form of drag plotted against advance speed. Particulars of propellers along with values of thrust coefficient (torque was not reported in original paper) at speed $V_A$ above 3.0 m/s are summarized in Table 2.

Table 2. Sailboat fixed-blade propellers tested by Lurie and Taylor [6]

| | Propeller | | | |
|---|---|---|---|---|
| | Campbell Sailer 2-bladed | Campbell Sailer 3-bladed | Michigan Wheel 2-bladed | Michigan Wheel 3-bladed |
| $z$ | 2 | 3 | 2 | 3 |
| $D$ [m] | 0.330 | 0.330 | 0.330 | 0.330 |
| $P/D$ | 0.769 | 0.769 | 0.769 | 0.769 |
| $A_E/A_0$ | - | 0.30 | 0.36 | 0.44 |
| $(A_E/A_0)/z$ | - | 0.10 | 0.18 | 0.147 |
| $C_T$* | -0.212 | -0.278 | -0.238 | -0.438 |

MacKenzie and Forrester [7] measured drag of another three 12-inch sailboat propellers. Results were presented in the form of drag plotted against speed. Particulars of propellers along with calculated values of thrust coefficient (torque was not reported in original paper) at speed $V_A$ of 3.09 m/s are summarized in Table 3.

Table 3. Sailboat fixed-blade propellers tested by MacKenzie and Forrester [7]

| | Propeller | | |
|---|---|---|---|
| | 'A' | 'B' | 'C' |
| $z$ | 3 | 3 | 2 |
| $D$ [m] | 0.305 | 0.305 | 0.305 |
| $P/D$ | 0.5 | 0.5 | 0.667 |
| $A_E/A_0$ | 0.54 | 0.52 | 0.40 |
| $(A_E/A_0)/z$ | 0,18 | 0.173 | 0.20 |
| $C_T$* | -0.512 | -0.463 | -0.322 |

In 2013 Dang et al. [8] presented the outcomes from open water model tests of 4-bladed controllable pitch propellers denoted C4-40, from the newly developed Wageningen C-series. There were 4 modern moderately skewed propellers designed according the best design practice. The propellers differed from each other with the design pitch ratio that was equal to 0.8, 1.0, 1.2 and 1.4. The performance of propellers was measured in two quadrants of operation including $n$=0. Test data were presented in the form of thrust and torque coefficients $C_T$* and $C_Q$* plotted in diagrams against advance angle $\beta$.

## 4 EMPIRICAL FORMULAE

For engineering applications the drag and torque of a locked propeller should be calculated using only basic parameters of propeller that are usually available, i.e. propeller diameter, number of blades, blade area ratio and pitch ratio. The available values of thrust and torque coefficients were used to determine the relationships between drag/torque and basic parameters of propeller. .

The relations between drag/torque and pitch ratio have been determined based on data from [2], [3] and [4]. The values of thrust and torque coefficients were normalised using the values for $P/D$ =1.0 (see Fig. 4). Using the least square approximation the relation between the normalised thrust coefficient $C_{Tn}$* and $P/D$ was fitted with linear function, and the relation between the normalised torque coefficient $C_{Qn}$* and $P/D$ with quadratic polynomial:

$C_{Tn}^{*} = -0{,}31\ P/D + 1{,}31$ (4)

$C_{Qn}^{*} = -0{,}30\ (P/D)^2 + 1{,}35\ P/D - 0{,}05$

The relations between coefficients $C_T^*$ and $C_Q^*$ and $P/D$ become as follows:

$C_T^* = C_T^*{}_{(P/D=1.0)}\ (-0{,}31\ P/D + 1{,}31)$ (5)

$C_Q^* = C_Q^*{}_{(P/D=1.0)}\ (-0{,}30\ (P/D)^2 + 1{,}35\ P/D - 0{,}05)$

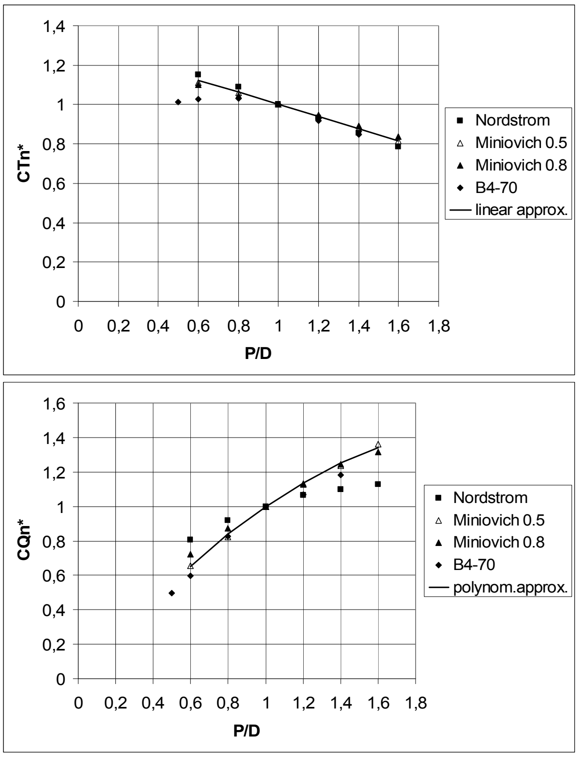



Figure 4. Variation of the normalized thrust and torque coefficients with pitch ratio

The assumption of negligible interaction between blades in the case of $n$=0 allowed to consider the force or torque on a single blade instead on entire propeller. Two basic parameters i.e. blade area ratio and number of blades were combined into a single parameter, namely the area ratio of a single blade $(A_E/A_0)/z$. The relationship was investigated using data for propellers with $P/D$ =1.0, an average value encountered in design of merchant ships. Much data were available directly without the need for extrapolation from other values of pitch ratio. Only the coefficients for sailboat propellers from [6] and [7] were extrapolated using the relationship (5). The values of thrust and torque coefficients per one blade were collected and presented in Fig. 5.

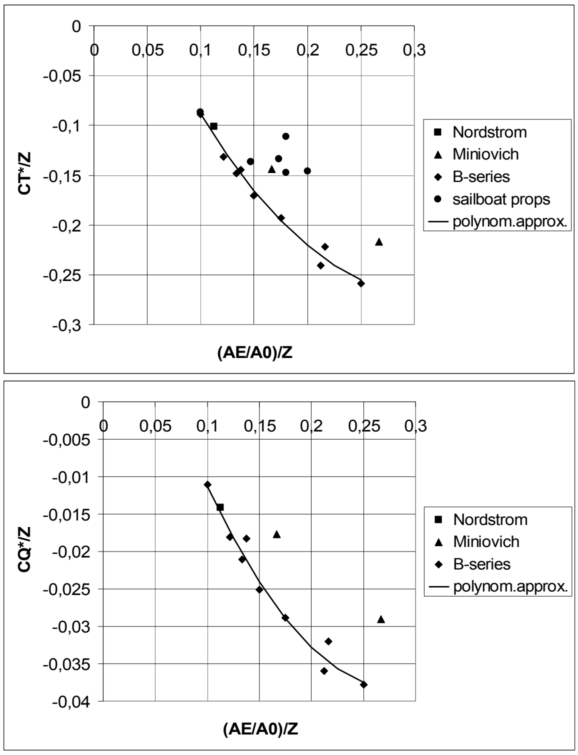



Figure 5. Relation between the thrust and torque coefficients per one blade ($C_T^*/z$ and $C_Q^*/z$) and unit blade area ratio $(A_E/A_0)/z$, at $P/D$ =1.0

Because the data for two- and three-bladed propellers from [2], [6] and [7] do not align with other data, the least square approximation was fitted using only data for B-series [4] and those given by Nordstrom [3]. For $P/D$ =1.0 the following formulae are proposed:

$C_T^*{}_{(P/D=1.0)}/z = 4{,}28\ [(A_E/A_0)/z]^2 - 2{,}61\ (A_E/A_0)/z + 0{,}13$ (6)

$C_Q^*{}_{(P/D=1.0)}/z = 0{,}796\ [(A_E/A_0)/z]^2 - 0{,}453\ (A_E/A_0)/z + 0{,}026$

Combining the approximations (6) and (5) the empirical formulae for 4- to 7-bladed propellers becomes as follows:

$C_T^* = z\ \{4{,}28\ [(A_E/A_0)/z]^2 - 2{,}61\ (A_E/A_0)/z + 0{,}13\}\ (-0{,}31\ P/D + 1{,}31)$ (7)

$C_Q^* = z\ \{0{,}796\ [(A_E/A_0)/z]^2 - 0{,}453\ (A_E/A_0)/z + 0{,}026\}\ (-0{,}30\ (P/D)^2 + 1{,}35\ P/D - 0{,}05)$

The fit of approximation (7) to empirical data is illustrated in Fig. 6.

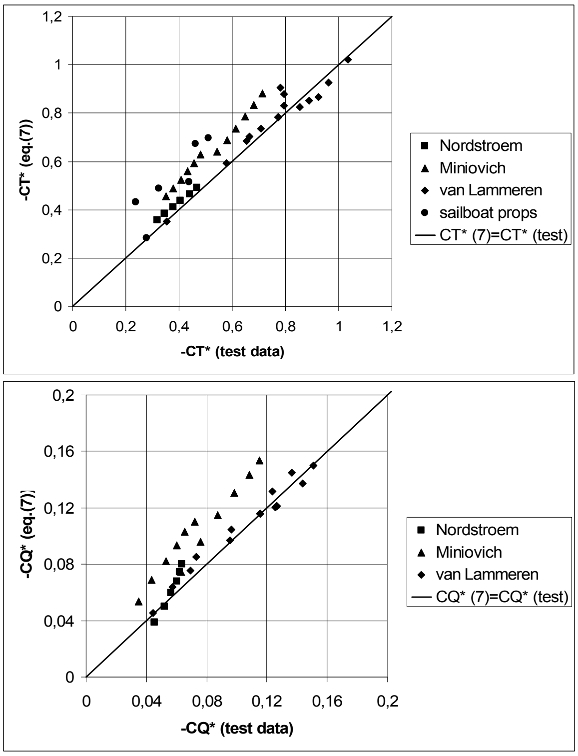



Figure 6. The fit of approximation (7) to empirical data

## 5 CFD COMPUTATIONS

In order to assess the applicability of empirical formulae to modern moderately skewed propellers a number of RANSE-CFD computations was carried out using ready geometries and grids previously used for computations of propeller flow in forward operating conditions [9], [10]. Main particulars of propellers are collected in Table 4.

Table 4. Propellers used in CFD computations

| | KP505 (KCS) | CP469 (Nawigator) | P0 | P2 | P9 |
|---|---|---|---|---|---|
| $z$ | 5 | 4 | 4 | 4 | 5 |
| $D$ [mm] | 250 | 226 | 233.33 | 247 | 3000 |
| $P_{0.7}/D$ | 0.997 | 0.942 | 1.0 | 0.920 | 0.973 |
| $A_E/A_0$ | 0.796 | 0.674 | 0.581 | 0.517 | 0.634 |
| rake [mm] | 0 | 0 | 5.83 | -27.64 | 0 |
| $(A_E/A_0)/z$ | 0.159 | 0.169 | 0.145 | 0.129 | 0.127 |
| skew-back ratio$s(R)/D$ | 0.224 | 0.229 | 0.120 | 0.248 | 0,133 |
| skew angle $\theta_S(R)$ [deg] | 24.9 | 25.7 | 13.2 | 27.6 | 14.7 |
| $C_T$* CFD | -1.042 | -0.842 | -0.572 | -0.598 | -0.766 |
| $C_T$* eq. (7) | -0.886 (-15 %) | -0.767 (-9 %) | -0.635 (+11 %) | -0.557 (-7 %) | -0.666 (-13 %) |
| $C_Q$* CFD | 0.152 | -0.112 | -0.077 | -0.076 | -0.106 |
| $C_Q$* eq. (7) | 0.129 (-15 %) | -0,106 (-5 %) | -0.092 (+19 %) | -0.072 (-5 %) | -0.091 (-14 %) |

Computations were carried out using the commercial CFD software CDadapco STAR CCM+. High accuracy of CFD computations using that software and appropriate grids has been proved for computations of flow around screw propellers operating in the conventional range of open water characteristics ($0 < J < J(K_T=0)$). The CFD computations have not been verified and validated at locked conditions (at $n$=0).

The results of computations in the form of non-dimensional coefficients are included in Table 4, in comparison to values calculated using the formulae (7). The fit of approximation is illustrated in Fig. 7 where approximated values are compared to results of CFD computations and to test data in the case of controllable pitch propellers C4-40 [8]. Approximated values are underestimated by approximately 5 to 15 per cent in relation to both CFD and test data.

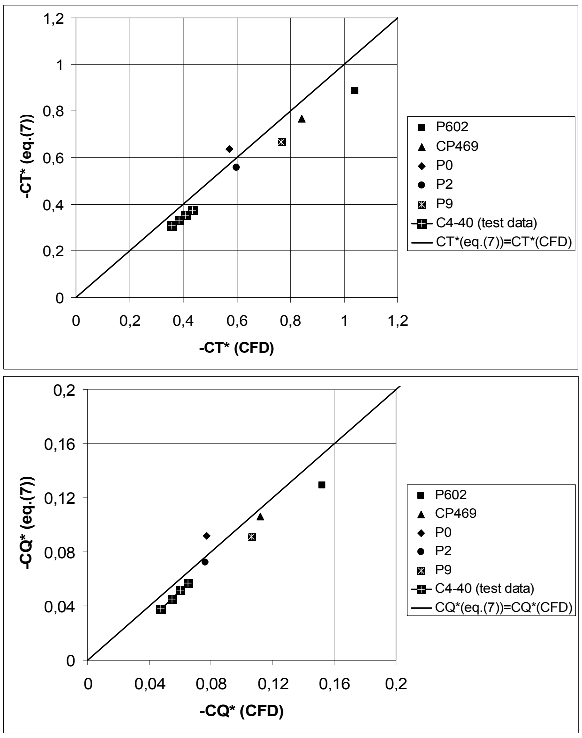



Figure 7. The fit of approximation (7) to CFD and test data

## 6 CONCLUSIONS

Using the available test data for locked screw propellers the formulae (7) for estimation of thrust and torque coefficients $C_T$* and $C_Q$* (defined by eq. (3)) are proposed. The coefficients are related to the basic parameters of propeller, namely to pitch ratio, blade area ratio and the number of blades.

The formulae are valid principally for non-skewed or low-skewed screw propellers, in the range of pitch ratio $P/D$ from 0.6 to 1.6 and in the range of single blade area ratio $(A_E/A_0)/z$ from 0.10 to 0.25.

In application to 2- or 3- bladed propellers the approximated values of drag and torque may be overestimated by up to 30% in relation to actual forces (Fig.6). In the case of moderately skewed propellers the approximated values may be underestimated. Based on the outcomes from CFD computations the authors propose the allowance of +16 %.

Known the drag and torque coefficients, the drag and torque on locked screw propeller are estimated according to the formulae:

$D = -T = -0.125\ C_T^*\ \rho V_A^2 \pi D^2$

$Q = 0.125\ C_Q^*\ \rho V_A^2 \pi D^3$

using the relevant advance speed. It is proposed to use the average velocity of flow in nominal wake of ship:

$V_A = V_S(1-w_n)$

where $V_S$ denotes ship speed, and $w_n$ - the nominal wake fraction.

## REFERENCES


[1] A. Charchalis: Resistance of idle propellers in marine multi-propeller propulsion systems, Journal of KONES Powertrain and Transport, Vol. 17, No. 4, 2010

[2] A.M. Basin, I.Ya. Miniovich: Theory and calculation of screw propellers, Sudostroienie, Leningrad, 1963 (in Russian)

[3] H.F. Nordström: Screw propeller characteristics, Publ. No.9, SSPA, 1948

[4] W.P.A. van Lammeren, J.D. van Manen, M.W.C. Oosterveld: The Wageningen B-screw series, Trans. SNAME, 1969

[5] R.F. Roddy, D.E. Hess, W. Faller: Neural network predictions of the 4-quadrant Wageningen propeller series, Naval Surface Warfare Center Carderock Division, Hydromechanics Department Report NSWCCD-50-TR-2006/004, April 2006

[6] B. Lurie, T. Taylor: Comparison of ten sailboat propellers, *Marine Technology*, 32, pp.209-215, 1995

[7] P.M. MacKenzie and M.A. Forrester: Sailboat propeller drag, Ocean Engineering, 35 (1), pp.28-40, 2008

[8] J. Dang, H. J. J. van den Boom, J. Th. Ligtelijn: The Wageningen C- and D-Series Propellers, 12th International Conference on Fast Sea Transportation FAST 2013, Amsterdam, 2-5 December 2013

[9] T. Bugalski, and P. Hoffmann: Numerical Simulation of the Interaction between Ship Hull and Rotating Propeller, Proceedings of Workshop on Numerical Ship Hydrodynamics Gothenburg 2010, Gothenburg, Sweden, 2010

[10] T. Bugalski, P. Hoffmann: Numerical Simulation of the Self-Propulsion Model Tests, Second International Symposium on Marine Propulsors smp'11, Hamburg, Germany, June 2011