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Experimental Study of Open Water Non-Series Marine Propeller Performance

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Abstract**—**Later marine propeller is the main component of ship propulsion system. For a non-series propeller, it is difficult to indicate the open water marine propeller performance without an experimental study to measure the marine propeller parameters.

In the present study, the open water performance of a non-series marine propeller has been carried out experimentally. The geometrical aspects of a commercial non-series marine propeller have been measured for a propeller blade area ratio of 0.3985. The measured propeller performance parameters were the thrust and torque coefficients for different propeller rotational speed and different water channel flow velocity, then the open water performance for the propeller has been plotted.

In addition, a direct comparison between the obtained experimental results and a theoretical study of a B-series marine propeller of the same blade area ratio has been carried out. A correction factor has been introduced to apply the operating conditions of the experimental results to that of the theoretical study for the studied marine propeller.

Keywords**—**Advance speed, marine propeller, open water performance, thrust coefficient, torque coefficient.

I. Introduction

MARINE propellers are designed to provide the maximum thrust and the minimum torque for the optimum propeller rotation speed and the required cruising ship speed which allows ships to efficiently travel at their design speed. However, it is important to know how the marine propeller performs during off-design situations as well as deign point by knowing its open water performance. This is important for all naval marine propellers whose missions require them to perform at a wide range of speeds.

Choosing the correct marine propeller is a vital design step to achieve the required performance, as the marine propeller is the principal ship component to provide the necessary propulsion. In real situations, assessment of marine propeller behind hull is still difficult since a highly disturbed wake field behind the hull exists. Consequently, a widely known approach to replace the behind hull performance is the open water performance one. In open water test, in which the propeller to be tested without the hull, the performance characteristics relate thrust and torque coefficients with the flow advance speed ratio.

Many researches have been studied marine propellers performance either by using experimental facilities or numerical schemes. From among these researches, the study of the open water marine propeller performance received high attention especially for the series propellers for its design and analysis simplicity. Martinez-Callewas *et al* [1] carried out an open water experimental model for a series marine propeller and made a comparison with a previous numerical study. A direct comparison showed a good agreement for both analysis procedures.

While Brandt *et al* [2] investigated performance tests for 79 propellers which nearly all fit in the range of 9 to 11 (in) diameter. Thrust and torque were measured over range of propeller advance ratios for discrete propeller rotational speeds. In addition, static thrust was measured over range of propeller speeds from nominally 1500 to 7500 rpm depending on the propeller diameter. They have concluded that significant Reynolds number effects with degradation in performance with lower rotational speeds.

While Benini [3] illustrates the implementation of a combined momentum-blade element theory, CMBET, for light and moderately loaded marine propellers. The obtained results using the theoretical model have been validated against experimental data concerning four Wageningen B-series propellers then these results are compared to those found using numerical calculations. The results revealed that the accuracy of such predictions are very sensitive to advance speed ratio, *J*, and when a three-dimensional model was carried out, it was found that the main reason for the discrepancies between the two approaches relies on the poor prediction, obtained from CMBET, of the incidence angles as functions of *J*.

Solomon Raj *et al* [4] studied the effect of advance velocity, V_a, rotational speed, n, and the stacking sequence, S, on the performance of a marine propeller using orthogonal array. A four bladed composite propeller made of glass-epoxy was used. The fluid analysis is carried out using commercial computational fluid dynamics program.

In the present paper, the open water marine propeller performance has been conducted experimentally to illustrate the thrust and torque coefficients of a non-series marine propeller. The non-series marine propeller geometrical parameters, such as diameter, blade area ratio, no. of blades, blade thickness distribution, pitch ratio and pitch angle, have been measured.

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The open water test has been carried out in a water channel equipped with different measuring facilities. The measured parameters such as the propeller thrust and torque for different advance speed ratios have been figured out. In addition, a direct comparison between the obtained experimental results and a theoretical study of a B-series marine propeller of the same blade area ratio has been carried out. A correction factor has been introduced to apply the operating conditions of the experimental results to that of the theoretical study for the studied marine propeller.

II. Experimental Test Rig

The experimental study for a commercial non-series marine propeller has been carried out in the water channel facility at the Department of Mechanical Power and Energy in Military Technical College; Cairo. The thrust, torque and rotation speed of the propeller have been measured using force transducer, strain gages and proximity switch while the channel flow speed has been estimated through the channel measuring facilities. The thrust and torque coefficients have been found at different advance speed ratios.

A. Propeller Particulars

The 0.198 (m) diameter, three bladed model propeller geometrical particulars were thoroughly lifted off. These included chord, thickness and pitch radial distribution. Blade area was found through numerical integration and verified by direct measurements using a Supeplanix B planimeter as shown in Fig. 1 and tabulated in Table I.

Fig. 1 Commercial marine propeller under investigation

TABLE I
PROPELLER GEOMETRICAL PARAMETERS

r/R	Propeller Geometrical Parameters			
	Chord distribution (c/R)	Pitch distribution (p/D)	Thickness distribution (t/D)	Pitch Angle (Φ)
0.4	0.536	1.192	0.028	43.506
0.5	0.689	1.090	0.024	34.76
0.6	0.726	1.039	0.021	28.869
0.7	0.717	0.99	0.0185	24.247
0.8	0.6709	0.847	0.0168	18.637
0.9	0.527	0.767	0.0152	15.19
0.95	0.388	0.747	0.0139	14.073
1.0	0.1476	0.533	0.0127	9.64

B. Experimental Water Channel Facility

The open water tests presented here were carried out in (0.3 m x 0.49 m x 12 m) Armfield S6MKII [5] water channel. The sides of the water channel have been extended by wooden plates to ensure sufficient water depth at the propeller test section and to avoid any aeration formation during the tests. The propeller was attached to an electrical motor, model 9CC31KQAF, of rated power of 340 (*Watt*) supplied from a 12 (*volt*) source and equipped with a speed control box to vary its rotational speed manually. The tested marine propeller has a rotational speed varying from 100 (*rpm*) to a maximum rotational speed of 1500 (*rpm*), as shown in Fig. 2:

Fig. 2 Experimental water channel facility

1. Water Channel Flow Rate Measurement

The water channel flow rate has been measured for different throttle valve position, namely four positions Q_1, Q_2, Q_3 and Q_4, using a rectangular weir measurement apparatus as shown in Fig. 3. The used equation for the given apparatus is as follows, [6]:

$$Q = 3.33(b - 0.2\ h)\ h^{3/2} \quad (1)$$

where Q is the water channel flow rate in (ft^3/s), h is the water head above the weir measured section in (ft), b is the weir width in (ft). The measured flow rates for different throttle valve positions have been tabulated in Table II.

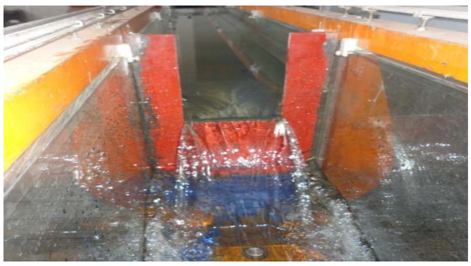

Fig. 3 Water channel Rectangular weir

TABLE II
WATER FLOW RATE VALUES

Throttle valve position	Water Channel flow rate (m^3/s)
Q_1	0.013178
Q_2	0.026151
Q_3	0.048585
Q_4	0.05355

From the measured flow rate, the averaged water channel cross-sectional velocity at the propeller test section for different throttle valve positions could be calculated as follows:

$$\bar{V} = \frac{Q}{H * \mathrm{W}} \quad (m/s) \tag{2}$$

where H is the water channel flow height in (m) and W is the water channel width in (m). In all measured cases, the water channel width is kept constant at 0.3 (m).

2. Propeller Rotational Speed Measurement

Propeller rotational speed has been measured by using a proximity switch LM8 inductance type, which has been calibrated and fixed on the marine propeller shaft motor. A second measuring technique has been used to confirm the previous method reading by use of photo-electric stropscope.

All measured signals have been stored and analyzed to a computer using a data acquisition card, NI BNC-2120 of a shielded connector for I/O connections, 12-Bit, 16 analog inputs and two 12-bit analog outputs through a graphical LABVIEW program.

3. Propeller Thrust Measurement

Propeller thrust has been measured using a calibrated digital force gauges and connected to the propeller motor stand by means of a steel wire.

The marine propeller motor carriage moves on a sliding rail on the water channel sides as shown in Fig. 4.

4. Propeller Torque Measurement

Due to the limited instrumentation of the propeller torque measurements under water while an indirect method was suggested. The propeller torque has been measured outside the water channel for different rotational speeds for the same propeller shaft.

Consequently, the torque rotational speed relation has been plotted and then propeller torque under water could be estimated as shown in Fig. 5.

(a)

(b)

Fig. 4 Digital force gauge used to measure the propeller thrust; (a) force gauge transducer (b) marine propeller motor carriage

Fig. 5 Propeller torque measurement test rig

III. RESULTS

The marine propeller open water performance has been plotted; the thrust and torque coefficient as a function of the speed of advance ratio for different operating conditions. The measured parameters, thrust, torque, flow speed and rotational speed could be related to these coefficients as follows [7]:

$$Advance\,coefficient = J = \frac{V_a}{nD} \tag{3}$$

$$Thrust\,coeffieint = K_T = \frac{T}{\rho n^2 D^4} \tag{4}$$

$$Torque\ coefficient = K_Q = \frac{Q}{\rho n^2 D^5} \quad (5)$$

$$Efficiency = \eta = \frac{K_T * J}{2\pi K_Q} \quad (6)$$

where J is the advanced coefficient, V_a is the water advanced velocity (m/s), n is the number of revolutions (RPS), D is the propeller diameter which equal 0.198 (m), K_T is the propeller thrust coefficient, T is the propeller thrust (N), ρ is the water density (1000 kg/m^3), K_Q is the propeller torque coefficient, Q is the propeller torque (N.m), η is the propeller efficiency.

A. Experimental Results

For a different measured advance speed ratios, the propeller rotational speed and water channel flow velocities could be varied. Herein, four different water channel flow velocity have been used by controlling the throttle valve while six positions have been used through the electric motor control box to vary the propeller rotational speed. For each measured position for either the water channel throttle valve or the motor control box setting, the corresponding propeller thrust and torque have been measured. Consequently, the thrust and torque coefficients could be calculated based on these measurement against the advance speed ratio, Equations (3-6).

In Fig. 6, the thrust coefficient as a function of the advanced speed ratios has been plotted. The propeller thrust coefficient decreases with the increasing of advanced ratios for the studied range of J from 0.09 to 0.24.

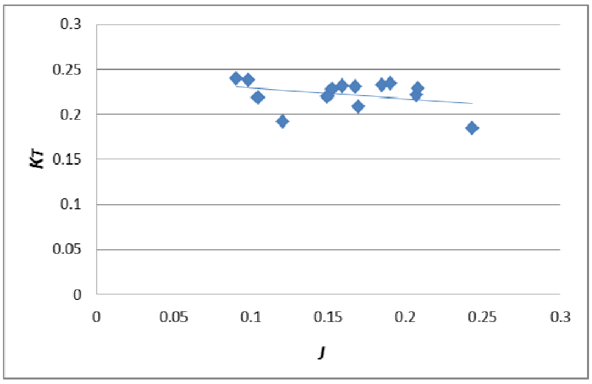

Fig. 6 Thrust coefficient, K_T, as a function of advanced speed coefficient, J

Fig. 7, displays the torque coefficient as a function of the advanced speed ratios has been plotted for the studied non-series propeller in open water test. The propeller torque coefficient, plotted as $10K_Q$, decreases with the increasing of advanced ratios for the studied range of J from 0.09 to 0.24. Noting that the slop of $10K_Q$ is steeper than that of thrust coefficient.

The studied commercial non-series marine propeller efficiency in open water channel has been calculated based on the measured data and plotted with the other coefficients in Fig. 8.

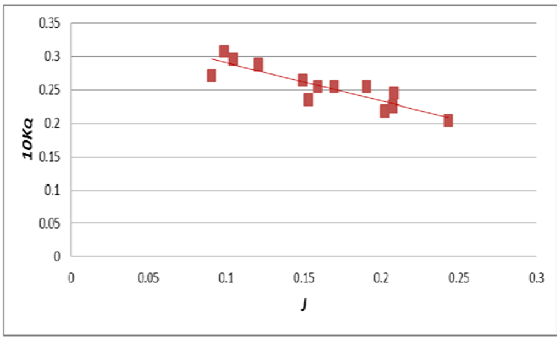

Fig. 7 Torque coefficient K_Q variation with advanced coefficient J

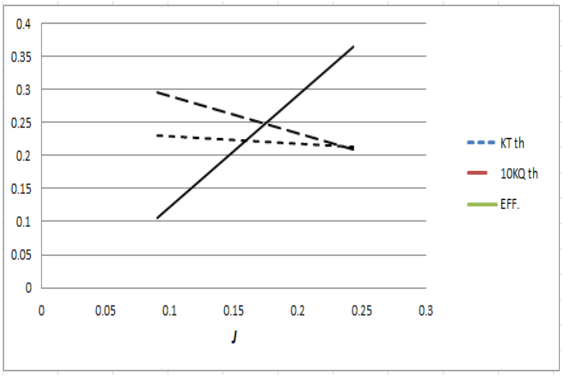

Fig. 8 Experimental open water marine propeller performance

B. Theoretical Results

Further, it was decided to check how to the measured results deviated from "equivalent" standard propellers with the same global parameters (i.e. no. of blades, blade area ratio and pitch diameter ratio). Wageningen propeller B-series has been selected to perform this task.

Empirical relations have been used to find the open water characteristics of the series at a Reynolds number 2×10^6 by an equation of the following form, [7]:

$$K_T = \sum_{n=1}^{n=39} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \quad (7)$$

$$K_Q = \sum_{n=1}^{n=47} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \quad (8)$$

where c_n , s_n , t_n , u_n and v_n are constants obtained from B-series tables for both calculation of K_T and K_Q coefficients [5]. P/D is the pitch ratio, A_E/A_0 is the blade area ratio, R_n is the Reynolds number and Z is the number of blades.

To estimate the propeller performance at a Reynolds number more than 2×10^6, a correction parameter could be added to the previous equations up to Reynolds number of 2×10^9 as shown:

$$\begin{Bmatrix} K_T(Rn) \\ K_Q(Rn) \end{Bmatrix} = \begin{Bmatrix} K_T(Rn = 2\,x10^6) \\ K_Q(Rn = 2x10^6) \end{Bmatrix} + \begin{Bmatrix} \Delta K_T(Rn) \\ \Delta K_Q(Rn) \end{Bmatrix} \quad (9)$$

where

$$\begin{aligned}\Delta K_T = {} & 0.000353485 \\ & - 0.00333758(A_E/A_0)J^2 \\ & - 0.00478125(A_E/A_0)(P/D)J \\ & + 0.000257792(Log\,R_n - 0.301)^2.\,(A_E/A_0)J^2 \\ & + 0.0000643192\,(Log\,R_n - 0.301).\,(P/D)^6J^2 \\ & - 0.0000110636(Log\,R_n - 0.301)^2.\,(P/D)^6J^2 \\ & - 0.0000276305(Log\,R_n - 0.301)^2.Z.\,(A_E/A_0)\,J^2 \\ & + 0.0000954(Log\,Rn - 0.301).Z.\,(A_E/A_0)\,(P/D)\,J \\ & + 0.0000032049(Log\,R_n - 0.301).Z^2.\,(A_E/A_0)\,(P/D)^3\,J\end{aligned}$$

$$\begin{aligned}\Delta K_Q = {} & - 0.000591412 \\ & + 0.00696898(P/D) \\ & - 0.0000666654.Z.(P/D)^6 \\ & + 0.0160818(A_E/A_0)^2 \\ & - 0.000938091(Log\,R_n - 0.301).\,(P/D) \\ & - 0.00059593(Log\,R_n - 0.301).\,(P/D)^2 \\ & + 0.0000782099(Log\,R_n - 0.301)^2.\,(P/D)^2 \\ & + 0.0000052199(Log\,R_n - 0.301)^2.Z.\,(A_E/A_0)\,J^2 \\ & - 0.00000088528(Log\,R_n - 0.301)^2.Z.\,(A_E/A_0)\,(P/D)J^2 \\ & + 0.0000230171(Log\,R_n - 0.301).Z.\,(P/D)^6 \\ & - 0.00000184341(Log\,R_n - 0.301)^2.Z.\,(P/D)^6 \\ & - 0.00400252\,(Log\,R_n - 0.301)\,(A_E/A_0)^2 \\ & + 0.000220915(Log\,R_n - 0.301)^2(A_E/A_0)^2\end{aligned}$$

A program has been written including these equations to get values of K_T and K_Q at different values of J with the same *BAR* of 0.3985, diameter of 0.198 (m), pitch ratio and no. of blades. The obtained theoretical results for the thrust and torque coefficients have been plotted in Fig. 9.

The measured K_T and K_Q results were compared to the "equivalent" B-series propellers in Fig. 10 and Fig. 11 respectively. It was noticed that the "equivalent" propeller results are higher than the present measured data. (The difference is around 25%)

As a first explanation, the reason for such discrepancy was attributed to different operating Reynolds's number. The B-series results were obtained at 2×10^6 while the present measurements were carried out at lower Reynolds's number values 2×10^5.

While Ref. [5] provided corrections for $R_n > 10^6$, no modifications were available for lower Reynolds's numbers.

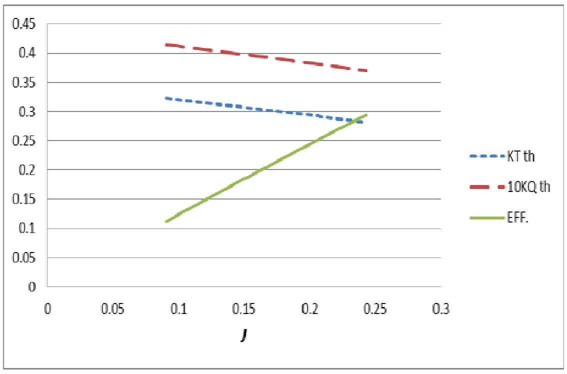

Fig. 9 Theoretical results for open water marine propeller performance of the same geometrical parameters of B-series

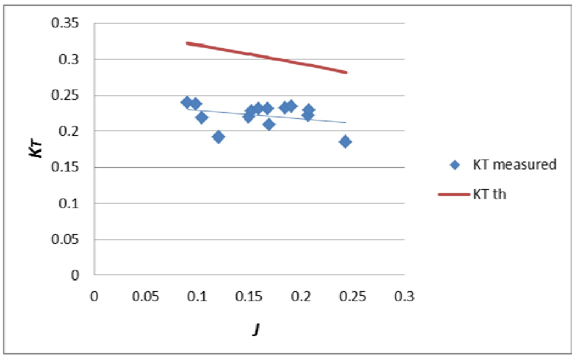

Fig. 10 Experimental and theoretical results of thrust coefficient for open water marine propeller performance

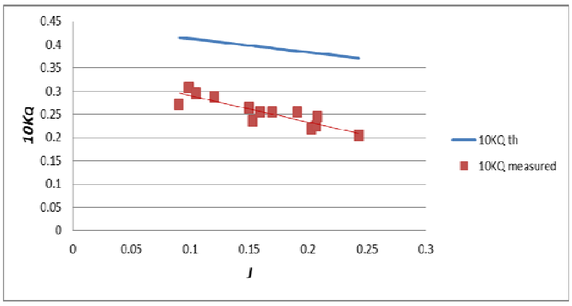

Fig. 11 Experimental and theoretical results of torque coefficient for open water marine propeller performance

C. Series Corrected Results

As the working Reynolds number for the studied propeller is 2×10^5 and below the theoretical empirical equations working Reynolds number of 2×10^6 or above. Then to bridge the gap between the "equivalent" sences propeller results and the present measurements for both thrust and torque, the difference was assumed as previously stated due to different operating Reynolds's number.

The difference between the "equivalent" and measured thrust and torque δK_T and δK_Q was plotted against tested Reynolds's numbers as shown in Fig. 12-13.

Such defenses were presented by simple relations 10 and 12. These are used to make the necessary corrections on measurements carried out at lower Reynolds's number values. Hence, the actual thrust and torque values at any Reynolds's numbers particularly at $R_n < 2\times10^6$ can be found from relations 11 and 13 respectively.

The correction factor for the thrust coefficient as a function of Reynolds number has been shown as follows:

$$\delta K_T = -(0.00000006 * R_n) + 0.1014 \qquad (10)$$

$$K_{T\,actual} = K_{T\,series} - \delta K_T \qquad (11)$$

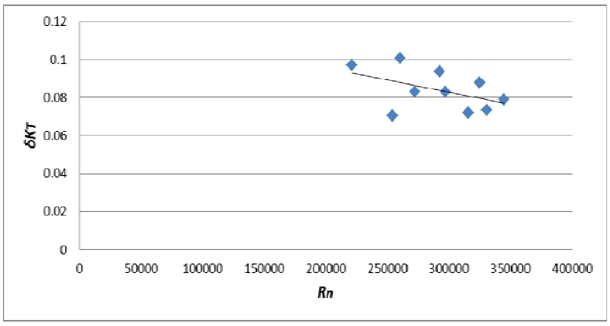

Fig. 12 Thrust coefficient correction factor for different Reynolds number

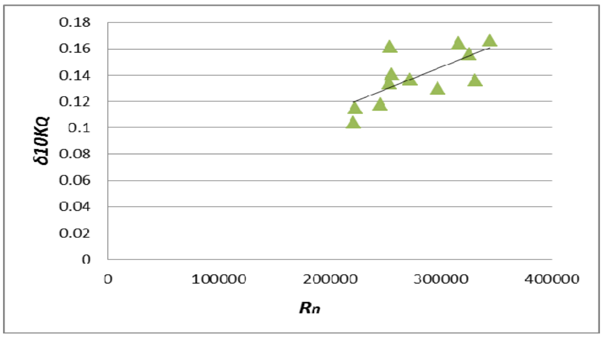

Fig. 13 Torque coefficient correction factor for different Reynolds number

Thrust coefficient correction factor for different Reynolds number has been plotted in Fig. 12 and the corrected theoretical performance for the thrust coefficient has been plotted in Fig. 14. The different between the corrected and experimental results may be explained due to the wall effects and uncontrolled measuring errors.

The correction factor for the torque coefficient as a function of Reynolds number has been shown as follows:

$$\delta 10K_Q = (0.0000002 * R_n) + 0.0764 \qquad (12)$$

$$10K_{Q\,actual} = 10K_{Q\,th} - \delta 10K_Q \qquad (13)$$

Torque coefficient correction factor for different Reynolds number has been plotted in Fig. 13 and the corrected theoretical performance for the torque coefficient has been plotted in Fig. 15. The different between the corrected and experimental results may be explained due to the wall effects and uncontrolled measuring errors.

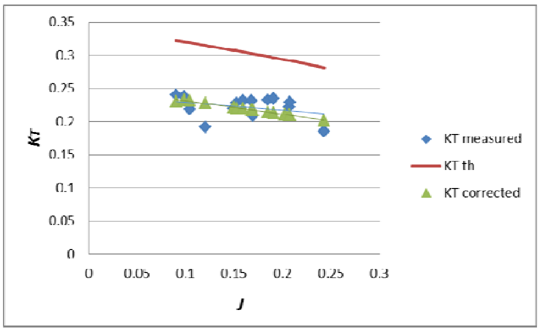

Fig. 14 Corrected thrust coefficient for different advanced coefficients

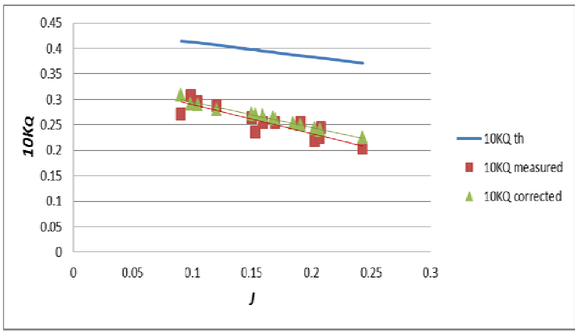

Fig. 15 Corrected torque coefficient for different advanced coefficients

IV. Conclusions

An experimental study of a non-series marine propeller has been conducted to figure out the propeller open water performance. Geometrical parameters of the non-series marine propeller have been measured. The thrust and torque have been measure of the studied propeller for different operating conditions in a water channel facility. A direct comparison of the experimental results with a theoretical one of the same propeller parameters has been carried out for a Wageningen B-series propeller. Due to the working Reynolds number for the studied propeller is 2×10^5 and below the theoretical empirical equations working Reynolds number of 2×10^6 or above, a correction factor could be introduced to adapt the theoretical empirical equations to the studied range of Reynolds number.

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