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## A Practical Approach for Design of Marine Propellers with Systematic Propeller Series

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**Received (Primljeno):** 2011-01-31

**Accepted (Prihvaćeno):** 2011-03-29

**Open for discussion (Otvoreno za raspravu):** 2012-06-30

Original scientific paper

Although there have been important developments in marine propellers since their first use in 1850, the main concept has been conserved. Parallel to the developments in the computer technologies in the past 50 years, methods based on the circulation theory are often used for the design and analysis of propellers. Due to the ability to predict the propulsion performance with just a few design parameters, the use of systematic propeller series based on open water model experiments is still widespread. The design with standard propeller series is usually made with diagrams developed from model experiments. Reading errors during the use of these diagrams are inevitable. In the presented study a practical approach is developed for preventing reading errors and time loss during the design with standard propeller series. A practical approach based on empirical formulas for the design and performance prediction for four-bladed Wageningen B propeller series is presented, and design applications for three propellers with different loading conditions are realized. The results obtained from the presented method are compared with those of open water diagram data and a good agreement between the results is observed.

**Keywords:** *propeller design, propeller series, propeller performance, open water diagram*

### Praktični pristup projektiranju brodskih vijaka korištenjem sistematskih serija vijaka

Izvorni znanstveni rad

Iako je od začetaka korištenja brodskih vijaka 1850. godine došlo do njihovog značajnog razvoja, osnovni princip je istovjetan i danas. Usporedno s razvojem računalnih tehnologija zadnjih 50 godina, metode temeljene na cirkulacijskoj teoriji se često koriste za projekt i analizu vijaka. Uslijed mogućnosti da se propulzijska svojstva vijka predvide poznavajući samo nekoliko osnovnih projektnih parametara, korištenje sistematskih serija vijaka temeljeno na modelskim ispitivanjima slobodne vožnje je i dalje u širokoj uporabi. Projekt vijka prema standardnim serijama vijaka obično se provodi pomoću dijagrama koji su razvijeni temeljem modelskih ispitivanja. Greške pri očitavanjima vrijednosti iz dijagrama su neizbježne. U ovoj je studiji razvijen praktični pristup za sprečavanje grešaka očitavanja i gubitka vremena tijekom projektiranja uz pomoć standardnih serija vijaka. Praktični pristup temeljen na empirijskim formulama za projektiranje i prognozu propulzijskih svojstava za četverokriline vijke Wageningenske B serije je prikazan, te su prikazane primjene za tri vijka sa različitim stanjima opterećenja. Rezultati dobiveni primjenom ove metode uspoređeni su sa onima dobivenim iz dijagrama slobodne vožnje te je uočeno dobro poklapanje rezultata.

**Ključne riječi:** *projekt vijka, serija vijaka, propulzijska svojstva, dijagram slobodne vožnje*

## Nomenclature

$A_E/A_0$	Blade area ratio
$C_{TH}$	Trust loading coefficient
$D$	Propeller diameter (m)
$J$	Advance coefficient
$K_Q$	Torque coefficient
$K_T$	Thrust coefficient
$n$	Propeller rate of rotation per minute (RPM)
$P$	Propeller pitch (m)
$P_D$	Delivered power (kW)
$Q$	Propeller torque (kNm)
$T$	Thrust (kN)
$R_T$	Total resistance (kN)
$V_A$	Advance speed (m/s)
$V_{KN}$	Ship speed (knot)
$w$	Taylor wake fraction
$Z$	Number of propeller blades
$\eta_o$	Open water efficiency
$P/D$	Pitch ratio
$\rho$	Density of water ( $\text{kg/m}^3$ )
$k$	Constant number
a,b,c,d,e,f,g	Equation coefficients

## 1 Introduction

In ship hydrodynamics, fixed pitch propellers, also named screw propellers, have an important place among the propulsion systems to propel a ship. The screw propellers, which showed up in the 19th century, have still secured their position as the best suitable propulsion system since that time. Although there have been significant developments in both the propeller design and the propulsion systems in this long period of time, any changes in the main concept of screw propellers was observed. It is seen that these propellers will be used for longer periods of time due to their high efficiency and suitable use.

The aim in the propeller design is to obtain the optimum propeller which applies to minimum power requirements and against maximum efficiency conditions at an adequate revolution number. Usually two methods are used in the propeller design. The first is to use diagrams obtained from open water propeller experiments for systematic propeller series. The second is to use mathematical methods (lifting line, lifting surface, vortex-lattice, BEM (boundary element method)) based on circulation theory. After 1950, due to the developments in the computer technology, great improvements were seen in the second method, above mentioned, for the design and analysis of propellers [1-11]. In the past ten years, three new developments have appeared in the design and analysis of propellers. These are CFD methods (RANS solvers), high speed camera techniques, and PIV techniques [12-17].

In the first stage of propeller design, usually the open water experiment diagrams of systematic model propeller series are used. These series consist of propellers whose blade number ( $Z$ ), propeller blade area ratio ( $A_E/A_0$ ), pitch ratio ( $P/D$ ), blade section shape and blade section thickness are varied systematically. The most known and used propeller series is the Wageningen (Troost) series. Besides this series, the Gawn (Froude) series, Japanese AU series, KCA series, Lindgren series (Ma-series), Newton-Rader series, KCD series, Gutsche and Schroeder controllable pitch propeller series, Wageningen nozzle propeller series, JD-CPP propeller series are also mentioned in literature through various studies [18].

When examining the studies about propeller design for the past ten years, it is seen that advantage of the improvements in the computer technology has been utilized. Tanaka and Yoshida in [19] developed a computer program for propeller designers which transforms the dimensionless tables obtained from

propeller series experiments into numerical graphics with great accuracy. In a similar study a computer program has been developed by Koronowicz et.al. for the design calculations for a propeller which is analyzed in the real velocity environment [20]. In this study, calculations considered are the scale effects in the velocity field where the propeller is operating, corrections in the velocity field due to the rudder, maximization of the propeller efficiency, optimization of accurate blade geometry in terms of cavitation and strength, optimization of blade geometry depending on induced pressure forces and the blade numbers. A multipurpose optimization method is made by Benini in [21] for the Wageningen B propeller series using an algorithm for maximizing both; the thrust and torque coefficients under a constraint determined according to cavitation. Unlike the classical lifting line methods, Celik and Guner in [22] suggested an improved lifting line method by modelling the flow deformation behind the propeller with free vortex systems. In his study Olsen in [23] developed a method to calculate the propeller efficiency with the help of energy coefficients including the propeller loss. He compared his findings with the results obtained from vortex-lattice method. Hsin et.al. in [24] applied in their study a method derived from the adjoint equation of the finite element method to two propeller design problems. Matulja and Dejhalla in [25] realized the selection of the optimum screw propeller geometry with artificial neural networks. Roddy et.al. in [26] used the artificial neural network method for the prediction of thrust and torque values of the Wageningen B series propeller. Chen and Shih in [27] realized the propeller design by the use of the Wageningen B series propellers by considering the vibration and efficiency characteristics using genetic algorithm. A similar study was made by Suen and Kouh in [28].

In this study a practical design approach is presented by using the Wageningen B series propellers for a case where the delivered power ( $P_D$ ), the advance speed ( $V_A$ ) and the revolution number ( $n$ ) is known. A set of propellers suitable for a wide loading range is developed by the use of polynomials representing the open water diagrams of the Wageningen B propeller series. The set of propellers consists of four-bladed propellers and is developed in such a manner that the whole range of the blade area ratios ( $A_E/A_0$ ) and pitch ratios ( $P/D$ ) of the Wageningen B series are included. The effects of the Reynolds number are not included in the calculations. The propeller design and performance characteristics are presented by means of empirical formulas and diagrams to propeller designers as a practical tool for the use in the preliminary design stage. Besides the propeller design, the diagrams and empirical formulas can also be used for the propeller performance prediction.

## 2 Propeller design with standard propeller series

In the initial ship design stage, it is necessary to predict the performance of the considered propeller. For this purpose the commonly preferred open water series with low cavitation risk is the Wageningen B screw propeller series. The experimental data of this series were firstly reported by Troost [29]. Later some corrections were made on the series by taking the scale effects into account. The results of the study are presented by van Lammeren et.al. [30]. A detailed regression analysis was made for the performance characteristics obtained from the Wageningen B propeller series by Oosterveld and van Oossanen [31]. They presented the open water propeller characteristics of the Wageningen B series for the Reynolds number at  $2 \times 10^6$  as polynomial functions as given in (1) and (2). Later this study was expanded by including viscous corrections for different Reynolds numbers [18]. Until the mid 1980s different reports about the Wageningen B propeller series were published. The variable parameters relating these series are the propeller blade number ( $Z$ ), the blade area ratio ( $A_E/A_0$ ), and the pitch ratio ( $P/D$ ).

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

$$K_T = \sum_{n=1}^{39} C_n (J)^{S_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \quad (2)$$

The dimensionless propeller characteristics are expressed as below:

$$\text{Thrust coefficient: } K_T = \frac{T}{\rho n^2 D^4} \quad (3)$$

$$\text{Torque coefficient: } K_Q = \frac{Q}{\rho n^2 D^5} \quad (4)$$

$$\text{Advance coefficient: } J = \frac{V_A}{nD} \quad (5)$$

$$\text{Open water propeller efficiency: } \eta_o = \frac{K_T J}{K_Q 2\pi} \quad (6)$$

$$\text{Propeller thrust loading coefficient: } C_{TH} = \frac{8 K_T}{\pi J^2} \quad (7)$$

The Wageningen B propeller series is a general purpose series. This series is expressed with open water diagrams obtained from model tests where the  $K_T$ - $K_Q$ - $J$  curves are showed for propellers with constant blade number ( $Z$ ) and constant blade area ratio ( $A_E/A_0$ ) but variable pitch ratios ( $P/D$ ). Because the open water experiments are made in fresh water, this must be considered in the design calculations. The Wageningen B series propellers are extensively used for the design and analysis of fixed pitch propellers.

### 3 A practical design approach to marine propellers for 4-bladed Wageningen B series

In this section empirical expressions and diagrams are presented for the practical design and performance analysis of four-bladed propellers by the use of the Wageningen B screw series. The delivered power ( $P_D$ ), the advance speed ( $V_A$ ), the number of propeller revolutions ( $n$ ), the blade number ( $Z$ ) and the blade area ratio ( $A_E/A_0$ ) are known and the pitch ratio ( $P/D$ ), the diameter ( $D$ ) and the performance characteristics ( $J$ ,  $K_T$ ,  $K_Q$ ,  $\eta_o$ ) are investigated among probable solutions. Namely, a set of propellers is generated designing the propellers by changing systematically the advance speed ( $V_A$ ) and the blade area ratio ( $A_E/A_0$ ) of the main propeller including all the four-bladed Wageningen B propellers ( $A_E/A_0$ : 0.4-1.0;  $P/D$ : 0.5-1.4). Then the  $P/D$ ,  $J$ ,  $K_T$ ,  $K_Q$ , and  $\eta_o$  curves and expressions for the design of new propellers are given for different blade area ratios in the order of  $P_D$ ,  $n$  and  $V_A$ . The set of propellers is generated by the design method given as below.

#### ***Propeller design method:***

Initial design variable requirements of the propeller are given below:

Delivered power,  $P_D$  in kW

Propeller rate of rotation,  $n$  in rps

Vehicle speed,  $V_S$  in m/s

Taylor wake fraction,  $w$

Number of blades,  $Z$

The necessary blade surface area required to minimize the risk of cavitation can be determined using an appropriate cavitation criteria, such as of Burrill in [32].

The torque requirement of a propeller can be expressed as a function of the advance coefficient

$J = \frac{V_A}{nD}$  and extracting the diameter ( $D$ ) from this formula, substituting it in the expression

$K_Q = \frac{Q}{\rho n^2 D^5}$  and finally rearranging the equation the expression below can be obtained:

$$K_Q = \frac{P_D n^2}{2\pi\rho V_A^5} J^5 = k.J^5 \quad (8)$$

$$k = \frac{P_D n^2}{2\pi\rho V_A^5} = \text{constant} \quad (9)$$

For the cases where the design variables ( $P_D$ ,  $n$ ,  $V_A$ ), the “k” expression (9), are known, the propeller design is carried out as follows. Firstly, the torque requirement curve  $K_Q$ - $J$  obtained according to Equation (8) is drawn over the Wageningen B open water diagram. The intersection points of this curve which express the torque requirement of the propeller and the  $K_Q$  curves of different  $P/D$  values on the open water diagram describe the possible design solutions. The optimum efficiency curve is obtained by drawing vertical lines from the intersection points to the efficiency curves. And the maximum point of this curve, which represents the most efficient propeller among the different solutions satisfying the requirements, is read-off. Later the  $J$ ,  $P/D$ ,  $K_T$ ,  $K_Q$  and  $\eta_o$  values of the optimum propeller are read-off. A computer code based on polynomials of the Wageningen B series is used in the applications of the design method.

The main propeller data used for generating the set of propellers for each  $A_E/A_0$  (0.4, 0.55, 0.70, 0.85, 1.0) are given in Table 1. The set of propellers is generated by considering the  $P_D$  and  $n$  values of the main propeller constant and by changing the advance speed  $V_A$  (2.5-22.5 knots, with 0.5 step size, in total 39 values) to cover the whole  $P/D$  range (0.5-1.4) of the Wageningen B series. For this condition the propeller design is based only on the value of “k”, so the main propeller data are used to generate different values of “k” including all probable propeller cases of 4-bladed Wageningen B series. And,  $P/D$ ,  $J$ ,  $K_T$ ,  $K_Q$  and  $\eta_o$  values due to k are presented in relation to k in Figures 1-5.

Table 1 Main propeller design input data  
Tablica 1 Glavni ulazni podaci za projekt vijka

Delivered power, $P_D$ (kW)	648
Advance speed, $V_A$ (m/s)	4.372
Propeller rate of rotation per minute, RPM	380
Propeller diameter, $D$ (m)	2.12
Number of blades, $Z$	4
Blade area ratio, $A_E/A_0$	0.70

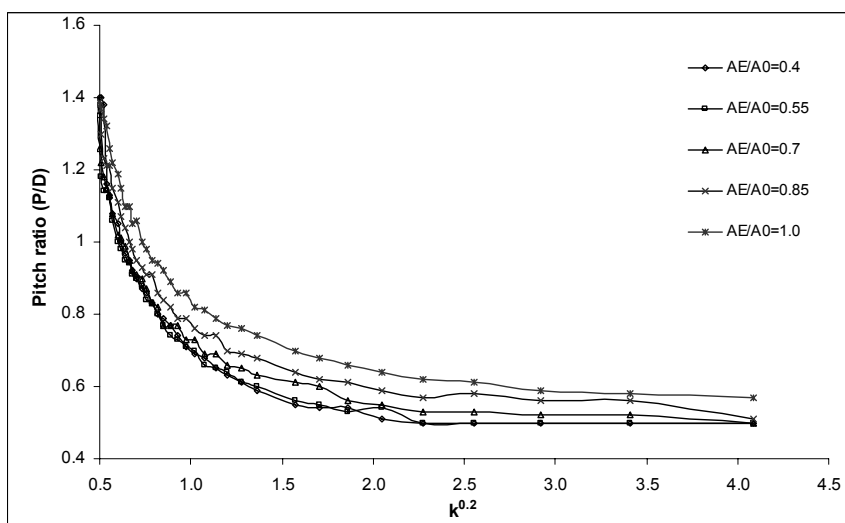


Figure 1 Variation of non dimensional pitch ratio ( $P/D$ ) in relation to  $k$   
Slika 1 Promjena bezdimenzionalnog omjera uspona i promjera vijka ( $P/D$ ) u odnosu na  $k$

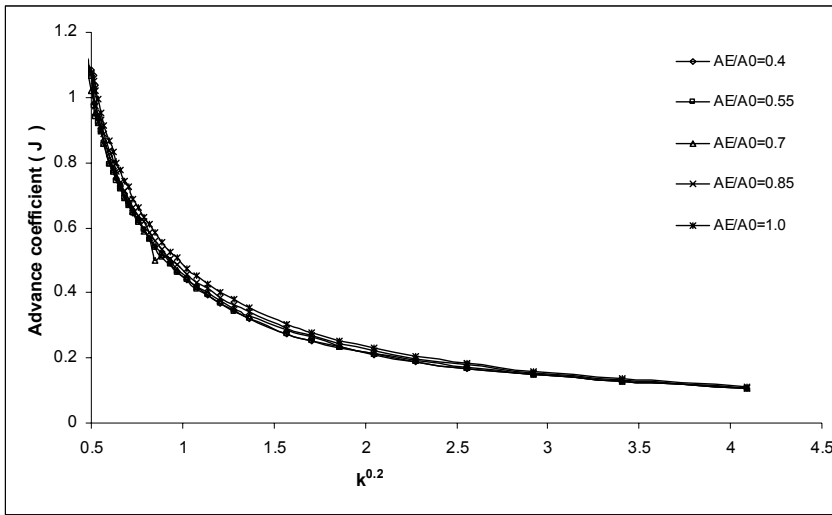


Figure 2 Variation of advance coefficient ( $J$ ) in relation to  $k$   
 Slika 2 Promjena koeficijenta napredovanja ( $J$ ) u odnosu na  $k$

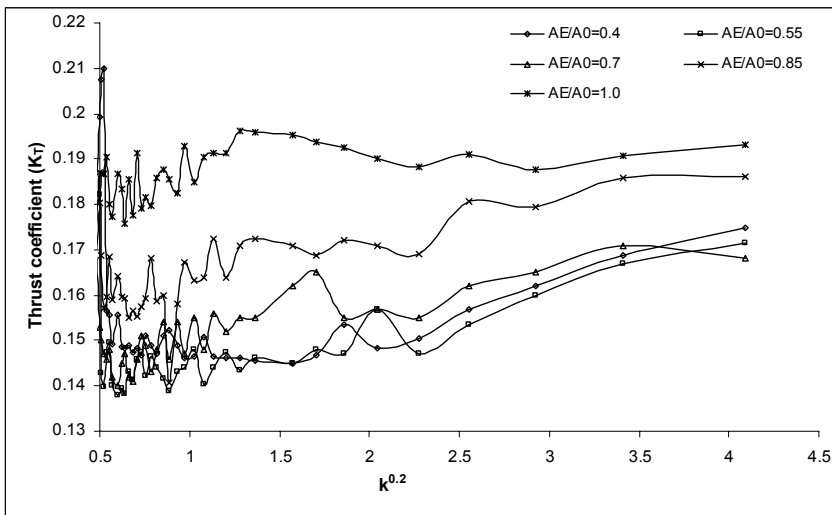


Figure 3 Variation of thrust coefficient ( $K_T$ ) in relation to  $k$   
 Slika 3 Promjena koeficijenta poriva ( $K_T$ ) u odnosu na  $k$

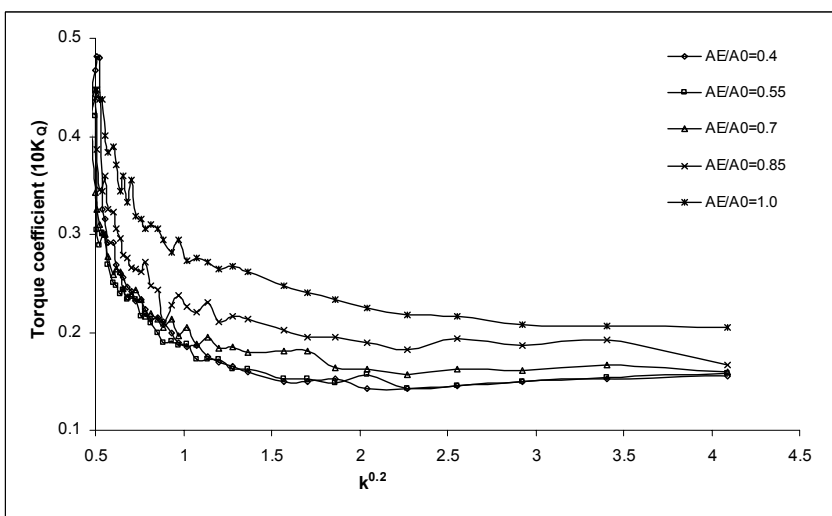


Figure 4 Variation of torque coefficient ( $K_Q$ ) in relation to  $k$   
 Slika 4 Promjena koeficijenta momenta uvijanja ( $K_Q$ ) u odnosu na  $k$

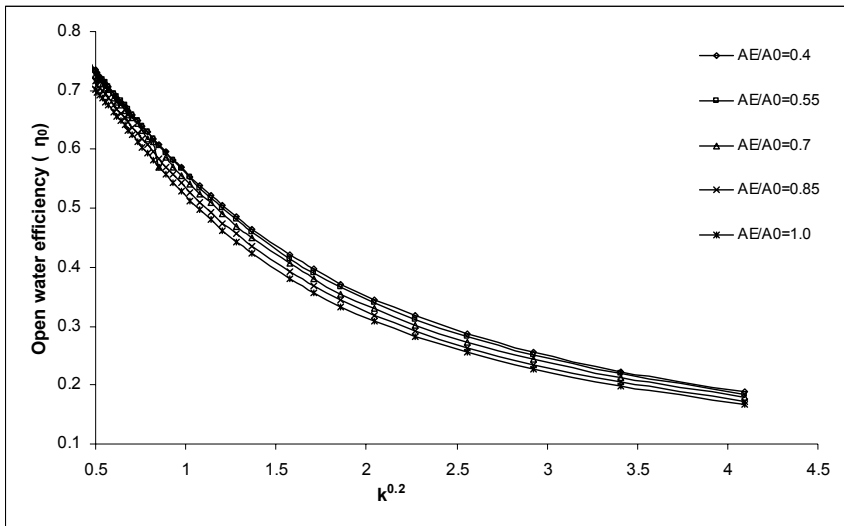


Figure 5 Variation of open water efficiency ( $\eta_0$ ) in relation to  $k$   
 Slika 5 Promjena korisnosti u slobodnoj vožnji ( $\eta_0$ ) u odnosu na  $k$

Since the pitch ratio ( $P/D$ ), advance coefficient ( $J$ ), thrust coefficient ( $K_T$ ), torque coefficient ( $K_Q$ ) and propeller efficiency ( $\eta_0$ ) are given as the function of “ $k$ ” in the graphics above, these can be also expressed in a general polynomial form (10). The expressions of the curves fitted to the points so as to ignore the effects of oscillations are determined by using the least square method (LSM). While the design of a propeller with the given  $P_D$ ,  $n$ ,  $V_A$  values of “ $k$ ” can be carried out with the graphics, it can also be executed by reducing the reading errors to a minimum with the use of (10). For the intermediate values of the blade area ratio the interpolation methods can be used. The other propeller parameters ( $D$ ,  $T$ ) can be obtained by ( $J$ ) and ( $K_T$ ) expressions given in (3),(5).

In addition to propeller design, these equations and graphics can also be interpreted as useful and timesaving tools for the prediction of the performance characteristics of an existing 4-bladed propeller. The values of the coefficients in (10) with the blade area ratio ( $A_E/A_0$ ) are given in Table 2.

$$F(k) = k^{0.2} (ak + bk^{4/5} + ck^{3/5} + dk^{2/5} + ek^{1/5} + f) + g \quad (10)$$

Here;  $k = \frac{P_D n^2}{2\pi\rho V_A^5}$ ;  $F(k)$ , function of pitch ratio ( $P/D$ ), advance coefficient ( $J$ ) etc.

Table 2 Coefficients of the  $F(k)$  equation with blade area ratio ( $A_E/A_0$ )  
 Tablica 2 Koeficijenti iz jednačbe  $F(k)$  sa određenom vrijednosti omjera površina krila ( $A_E/A_0$ )

$A_E/A_0=0.4$							
$F(k)$	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>f</b>	<b>g</b>
$P/D$	0.0469	-0.658	3.6709	-10.402	15.846	-12.53	4.7135
$J$	0.0182	-0.2659	1.5607	-4.7324	7.9103	-7.1721	3.166
$K_T$	0	0	0.0053	-0.0535	0.1875	-0.25914	0.2633
$10K_Q$	0.0236	-0.3287	1.818	-5.0795	7.556	-5.7157	1.9072
$\eta_0$	-0.003	0.0056	-0.0331	0.0794	0.0085	-0.4465	0.9475
$A_E/A_0=0.55$							
$F(k)$	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>f</b>	<b>g</b>
$P/D$	0.0437	-0.6128	3.4116	-9.636	14.614	-11.494	4.3615
$J$	0.0339	-0.4778	2.6798	-7.6654	11.878	-9.7354	3.7278
$K_T$	0	0	0.0036	-0.0345	0.1156	-0.1477	0.2038
$10K_Q$	0.0205	-0.284	1.5572	-4.3023	6.3058	-4.6823	1.5636
$\eta_0$	-0.0009	0.013	-0.0747	0.1959	-0.157	-0.3042	0.9246

$A_E/A_0=0.70$							
<b>F(k)</b>	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>f</b>	<b>g</b>
<b>P/D</b>	0.0428	-0.603	3.3695	-9.53597	14.462	-11.327	4.312
<b>J</b>	0.0323	-0.4573	2.5775	-7.4106	11.541	-9.5054	3.6688
<b>K<sub>T</sub></b>	0	0	0.002	-0.0192	0.0608	-0.0664	0.1719
<b>10K<sub>Q</sub></b>	0.0197	-0.2735	1.5028	-4.1506	6.0542	-4.4478	1.4905
<b>η<sub>0</sub></b>	-0.0011	0.0154	-0.0837	0.2046	-0.1394	-0.3806	0.9324
$A_E/A_0=0.85$							
<b>F(k)</b>	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>f</b>	<b>g</b>
<b>P/D</b>	0.029	-0.4161	2.3818	-6.9566	10.997	-9.1227	3.8503
<b>J</b>	0.0263	-0.3758	2.1437	-6.2669	9.9928	-8.5175	3.4603
<b>K<sub>T</sub></b>	0	0	-0.0005	0.0016	0.0022	-0.001	0.161
<b>10K<sub>Q</sub></b>	0.0089	-0.1301	0.7555	-2.2266	3.5196	-2.866	1.1633
<b>η<sub>0</sub></b>	-0.002	0.0283	-0.1537	0.3935	-0.3993	-0.2119	0.8802
$A_E/A_0=1.0$							
<b>F(k)</b>	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>f</b>	<b>g</b>
<b>P/D</b>	0.0112	-0.1747	1.1005	-3.5816	6.3924	-6.0879	3.175
<b>J</b>	0.0182	-0.2659	1.5607	-4.7324	7.9103	-7.1721	3.166
<b>K<sub>T</sub></b>	0	0	-0.0029	0.0296	-0.1054	0.1517	0.1183
<b>10K<sub>Q</sub></b>	-0.006	0.0723	-0.3214	0.6202	-0.3805	-0.2892	0.5878
<b>η<sub>0</sub></b>	-0.0042	0.0574	-0.3057	0.7859	-0.9192	0.1208	0.7864

The practical design approach presented in this work allows the design of a four-bladed Wageningen B screw series propeller or the performance prediction of an existing propeller based on just only the “k” value given as in (9) and the blade area ratio. The present approach is considered as a practical tool for propeller designers for use during the preliminary design stage as diagrams and empirical formulas.

#### 4 Design applications

For verification and to show usability of the presented approach, three propeller designs for medium, low and high thrust loading cases were realized. Various loading conditions were provided by changing only the revolution number of the propeller to data as given in Table 3. From the design variables of these three propellers, with the use of the open water curves of the Wageningen B screw series and the above presented empirical formulas, the propeller designs were realized. The obtained propeller design and performance results ( $P/D$ ,  $K_T$ ,  $K_Q$ ,  $J$  and  $\eta_0$ ) are presented in Table 4. The design results of the three propellers with different loading conditions are compared with those of  $K_T$  and  $K_Q$  polynomials for the 4-bladed Wageningen B screw series developed in [31], and it is seen that the order of the error values is in an acceptable range.

Table 3 Design variables of the propellers  
Tablica 3 Projektne varijable vijaka

	Propeller 1	Propeller 2	Propeller 3
Propeller rate of rotation per minute (RPM)	100	200	300
Delivered power (kW)	6090	6090	6090
Ship speed (knot)	17.5	17.5	17.5
Taylor wake fraction	0.15	0.15	0.15
Number of propeller blades (Z)	4	4	4
Blade area ratio ( $A_E/A_0$ )	0.7	0.7	0.7

Table 4 Comparison of the propellers design results  
 Tablica 4 Usporedba rezultata za projektirane vijke

	Propeller 1			Propeller 2			Propeller 3		
	k=0.10025 $C_{TH}$ =0.6396			k=0.4010 $C_{TH}$ =1.210			k=0.90223 $C_{TH}$ =1.7355		
	Open Water Diagram	Present Method	% Error	Open Water Diagram	Present Method	% Error	Open Water Diagram	Present Method	% Error
$P/D$	1.0000	1.0032	0.3183	0.8100	0.7946	1.9049	0.7300	0.7265	0.4727
$D$	6.0000	5.971	0.483	4.1129	4.21875	2.573	3.28326	3.36263	2.41
$J$	0.7650	0.7687	0.4854	0.5580	0.5440	2.5099	0.4660	0.4555	2.2519
$K_T$	0.1470	0.1497	1.8367	0.1480	0.1486	0.4338	0.1480	0.1490	0.6703
$10K_Q$	0.2630	0.2637	0.2616	0.2170	0.2078	4.2392	0.1980	0.1960	1.0227
$\eta_0$	0.6780	0.6762	0.2602	0.6050	0.6024	0.4281	0.5550	0.5540	0.1883

## 5 Results

Although the propeller designs can be made with computer programs based on circulation theory, the conventional design method using propeller series based on model experiments remains the most applied method. The primary advantage of this method is the practice of the design with a few design variables and the availability of the performance prediction.

In this study a practical design approach is presented for the four-bladed Wageningen B series propellers for the cases where the delivered power ( $P_D$ ), the advance coefficient ( $V_A$ ) and the propeller revolution number ( $n$ ) are known. Further, this method can be applied in a rapid and accurate manner by the use of the given diagrams and empirical formulas as an alternative method to design with Bp-delta diagrams. Additionally, the prediction of the performance characteristics that is not possible with Bp-delta diagrams for an existing propeller can also be available by the present approach.

In this study the design applications for three propellers with different thrust loading conditions are taken into account for the presented method. The results obtained from this method are compared with those of the open water diagrams, and a good agreement has been found.

The presented method can be expanded to the remaining Wageningen B series (propellers other than the 4-bladed ones) or to other propeller series. A further aim is to present in the future similar diagrams and empirical expressions for practical propeller design approaches for different propeller conditions for various given design variables.

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