DIMENSIONAL ANALYSIS AND EXPERIMENTAL DESIGN FOR PREDICTING THE CALCULATION OF THE VALUE OF THE TORQUE COEFFICIENT ON PROPELLER B-SERIES, CASE STUDY OF B3-50 AND B5-80

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ABSTRACT

Experimental design is a fairly old method of statistically analyzing an experimental prediction. This is used to replace a fairly old system as well, namely in the form of a trial and error method. Because with this method the response results approach from a study can be predicted statistically. In this study, we will calculate some torque values of a propeller on a displacement ship type. Where the ship's operational displacement ship runs on a Froude number below 0.25, for that the Wageningen B-series propeller type is very suitable for this ship. Furthermore, dimensional analysis is carried out with variables that affect propeller performance and uses multivariate combination calculations. The results of the study show the regression equation between the KQ values of the B-series propeller data and the regression formula with the equation Y = 0.9916x + 0.000835 with the value of R^2 being 0.9931. so we try to apply an experimental design method to be validated with the polynomial results of the B-series propeller on blades 3 to 6, so that the statistical method of this experimental design is up-to-date in propulsion design calculations.

Keyword: Dimensional Analysis, Experimental Design, Coefficient of Torque, B-Series, Regression Equation

Introduction

The biggest incentive to improve ship energy efficiency at the moment is the recent enactment of international laws for ship emissions and their phased implementation plan with even stricter limits in a few years. Significant goals have been attained from a hydrodynamic perspective, particularly with regard to advances in propulsive efficiency. The development of numerical and modelling tools has increased the popularity of optimization techniques for the construction of extremely efficient propellers and made it possible to reliably exploit the performance of typical propellers and the condensed loaded tip (CLT) [1], [2], [3], [4], and [5] and CLT [6, 7, 8] were also created employing numerically sophisticated methodologies [3, 4, 6], and optimization techniques to take full use of tip loading and their superior performance. In this study's solutions, we will determine several propeller torque values for a displacement ship type.

These solutions in this study, we will calculate some torque values on a propeller on a displacement ship type. Where the ship's operational displacement ship runs on a Froude number below 0.25, for that the Wageningen B-series propeller type is very suitable for open propellers supported by previous research, namely the B-series propeller is much better as an open propeller (both default and with PBCF), while the Kaplan series is excellent when fitted with ducted [9].

In general, experimental design is a series of experimental research conducted. Thus, a series of tests in which intentional changes are made to the input variables or factors of a system so that we can observe them and identify reasons for changes that might be observed in the output response.

In this experimental design, we use a factorial design raised to the power of 4 so that we have 16 variables for the response to the Y value (table.6). this is done to illustrate the use of factorial designs to develop simple models in the form of regression equations as a substitute for complex equations or time-consuming computer models.

Develop a simple equation model to estimate the torque coefficient value of the B-series propeller on blades 3 to 6. Where there are several variables that are considered influential, namely, Blade Element ratio, pitch ratio, camber to diameter ratio, and advance coefficient. Made a minimum limit (-) and Maximum Limit (-) (table 4).

Methodology

Methodology can be divided in two ways, namely dimensional analysis and experimental design on B-Series propeller performance.

Determination of dimensional analysis is carried out by carrying out several input variables that affect the propeller torque coefficient. so that in this study we tried to input 16 variables that might have the potential to change the output response in the form of the torque coefficient to be searched for. After that, an equation for the function of the torque coefficient is created which contains several variables that have been input.

- dimensional analysis is carried out; priority variables are selected based on the direction of our research objectives. The maximum and minimum assessment limits are carried out.
- Experimental design analysis was carried out with 24 multivariate combinations so that variations were obtained to get the response output value in the form of KQ. With 16 calculations, we can estimate 15 effects. Four main effects (A, B, C, and D), and ten two-factor interactions (CE, AB, BE, CD, AD, AC, BD, BC, AE, DE),
- Making a Pareto diagram by making the effect values of variables and the interactions between variables made absolute from the highest absolute value to the lowest, as well as calculating the coefficients on each variable and the interactions between variables.
- Create a regression equation from the coefficient values obtained for each variable and the interaction of variables
- As well as proving the calculation of the torque coefficient value by comparing the calculation results with regression and B-series propeller polynomials.

Result and Discussion

This paper has demonstrated the benefits of the developed on the calculation of the B-series propeller torque coefficient, can be seen in Table 1.

Table 1. Variables that affect the propeller torque calculation

Symbol	Descriptions	Units	Dimension
Z	number of propeller blades	-	-
θ	skew propellers	deg	deg
D	diameter	m	L
n	rpm	rpm	T^{-1}
Va	speed advance	m/s	$L\ T^{-1}$
g	Speed gravity	m/s^2	$L\ T^{-2}$
ρ	density	kg/m^3	ML^{-3}
P	Picth propeller	m	L
Dh	Diameter Hubs	m	L
AE	Expanded Propeller Area	m^2	L^2
C	Camber	m	L
Ca	Chord Lenght	m	L
p	Fluid Pressure	$kg/m^2.s^2$	$ML^{-2}T^{-2}$
t	Foil thickness	m	L
μ	Dynamic viscosity	kg/m.s	$ML^{-1}T^{-1}$
Q	Torque	kN	ML^2T^{-2}

Table 2. Dimensional analysis of propeller torque

L	T	M	Variable
1	0	0	D
0	-1	0	n
-3	0	1	ρ
2	-2	1	Q
1	-1	0	Va
1	-2	0	g
1	0	0	P
1	0	0	Dh
2	0	0	A_o
2	0	0	A_E
1	0	0	C
1	0	0	C_A
-2	-2	1	p
1	0	0	t
-2	-1	1	μ

Table 3. Dimensional analysis of propeller torque after equation $C=A^{-1}xB$

D	n	ρ	Variable
1	0	0	D
0	-1	0	n
3	0	1	ρ
5	2	1	Q
1	1	0	Va
1	2	0	g
1	0	0	P
1	0	0	Dh
2	0	0	A_o
2	0	0	A_E
1	0	0	C
1	0	0	C_A
1	2	1	p
1	0	0	t
2	1	1	μ

So the dimensional analysis equation of the propeller torque can be written with the following equation:

$$\varphi\left[\frac{Q}{D^5N^2\rho},\frac{V_a}{D\,N},\frac{g}{D\,N^2},\frac{P}{D},\frac{D_h}{D},\frac{A_E}{D^2},\frac{C}{D},\frac{C_a}{D},\frac{P}{Dn^2\rho},\frac{t}{D},\frac{\mu}{D^2n\rho},\theta,Z\right]=0$$

$$\frac{Q}{D^5n^2\rho}=\varphi\left[,\frac{V_a}{D\,n},\frac{g}{D\,n^2},\frac{P}{D},\frac{D_h}{D},\frac{A_E}{D^2},\frac{C}{D},\frac{C_a}{D},\frac{P}{Dn^2\rho},\frac{t}{D},\frac{\mu}{D^2n\rho},\theta,Z\right]$$

So, it can be written:

$$\frac{Q}{\rho\,n^2D^5}=\varphi\left[,J,\frac{g}{D\,n^2},\frac{P}{D},\frac{D_h}{D},\frac{A_E}{A_O},\frac{C}{D},\frac{C_a}{D},\frac{P}{Dn^2\rho},\frac{t}{D},\frac{\mu}{D^2n\rho},\theta,Z\right]$$

Description:

$\frac{Q}{\rho n^2 D^5}$ = Propeller torque

$\frac{V_a}{Dn}$ = Advanced Coefficient (J)

$\frac{P}{D}$ = Pitch/diameter ratio

$\frac{A_E}{A_O}$ = Blade area ratio

$\frac{C_A}{D}$ = Chord length /diameter ratio

$\frac{C}{D}$ =Camber/diameter ratio

$\frac{D_H}{D}$ = hub ratio and propeller diameter

Some equation $\frac{g}{D\,n^2}$, $\frac{P}{Dn^2\rho}$, $\frac{\mu}{D^2n\rho}$ is a non-dimensional value that has a constant value. Several variable factors that greatly influence the calculation of the B-series propeller torque coefficient according to literature studies from [10] is J, P/D, Ae/Ao, Z. In this study, C/D was added as a factor that affects the value of the torque coefficient. thus, the equation used to do the analysis is:

$$\frac{Q}{\rho\,n^2D^5}=\varphi\left[,J,\frac{P}{D},,\frac{A_E}{A_O},\frac{C}{D},Z\right]$$

Table 4. Control Factors

	Parameter	Symbol	Low Level	High Level
A	Number of Blade	Z	-1	1
B	Expanded Bar	Ae/Ao	-1	1
C	Pitch Ratio	P/D	-1	1
D	Ratio Camber and Diameter	C/D	-1	1
E	Advanced Coefficient	J=(Va/n.D)	-1	1

Table 5. Control Factors and Ranges for Response Surface Design

	Parameter	Symbol	Low Level	High Level
A	Number of Blade	Z	3	6
B	Expanded Bar	Ae/Ao	0.5	0.8
C	Pitch Ratio	P/D	0.5	1.1
D	Ratio Camber and Diameter	C/D	0.002	0.004
E	Advanced Coefficient	J=(Va/n.D)	0.2	1.2

The data of propeller performance table in the Wageningen Propeller B-series book was used for determining KQ diagram and multivariate combinations can be made:

Table 6. Propeller Performance Table

Std Order	Run Order	A	B	C	D	E
1	1	-1	-1	-1	-1	1
2	2	1	-1	-1	-1	-1
3	3	-1	1	-1	-1	-1
4	4	1	1	-1	-1	1
5	5	-1	-1	1	-1	-1
6	6	1	-1	1	-1	1
7	7	-1	1	1	-1	1
8	8	1	1	1	-1	-1
9	9	-1	-1	-1	1	-1
10	10	1	-1	-1	1	1
11	11	-1	1	-1	1	1
12	12	1	1	-1	1	-1
13	13	-1	-1	1	1	1
14	14	1	-1	1	1	-1
15	15	-1	1	1	1	-1
16	16	1	1	1	1	1

The determination of the KQ value is obtained from the B-series propeller performance diagram with the types of number of leaves 3 and 5 and several control factor parameters described in table 5. The following is an example of a B-series propeller performance diagram [11].

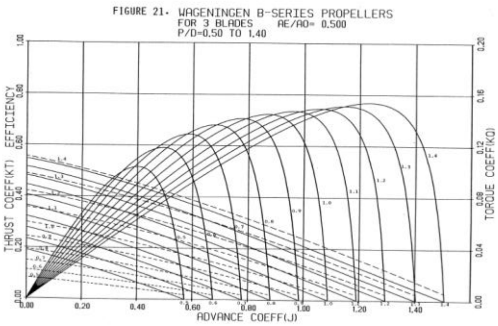

Figure. 1 B3-50 Propeller Performance Graph

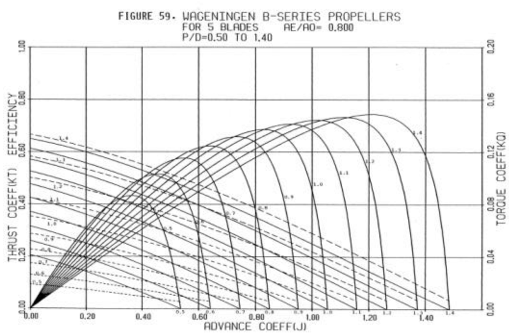

Figure. 2 B5-80 Propeller Performance Graph

Table 7. is a combination of 5 factorials based on the propeller KQ value obtained from the open water test propeller diagram.

Table 7. Combination Factors

Run Order	Z	Ae/Ao	P/D	C/D	J	KQ
1	3	0.5	0.5	0.002	1.2	0.0025
2	6	0.5	0.5	0.002	0.2	0.015
3	3	0.8	0.5	0.002	0.2	0.019
4	6	0.8	0.5	0.002	1.2	0.005
5	3	0.5	1.1	0.002	0.2	0.063
6	6	0.5	1.1	0.002	1.2	0.006
7	3	0.8	1.1	0.002	1.2	0.003
8	6	0.8	1.1	0.002	0.2	0.077
9	3	0.5	0.5	0.004	0.2	0.012
10	6	0.5	0.5	0.004	1.2	0.0035
11	3	0.8	0.5	0.004	1.2	0.0045
12	6	0.5	0.5	0.004	0.2	0.013
13	3	0.5	1.1	0.004	1.2	0.005
14	6	0.5	1.1	0.004	0.2	0.075
15	3	0.8	1.1	0.004	0.2	0.078
16	6	0.8	1.1	0.004	1.2	0.004

With the DOE analysis run in the multivariate program it can be seen, the 15 effect estimates shown in Table 4 are arranged in descending order by absolute effect sizes and plotted as a Pareto chart shown in Figure 3. By using a Pareto chart, one can determine visually several important effects.

Table 8. Estimated Effect (Based on Absolute Order)

Term	Effect	Coefficient
Constant	-	0.02409
E	-0.03981	-0.01991
C	0.02956	0.01478
C*E	-0.02894	-0.01447
A*B	-0.00281	-0.00141
B*E	-0.00281	-0.00141
B	0.00269	0.00134
C*D	0.00269	0.00134
A*D	-0.00244	-0.00122
A*C	0.00181	0.00091
B*D	-0.00169	-0.00084
A	0.00144	0.00072
D	0.00056	0.00028
B*C	0.00056	0.00028
A*E	-0.00056	-0.00028
D*E	-0.00044	-0.00022

From Table 4 and Figure 3, it is clear that the most important effects in order of absolute magnitude are: E (advance coefficient), C (Pitch Ratio), CE (interaction of pitch ratio with advance coefficient), AB (interaction of number of leaves with ratio of leaf area) propeller), BE (interaction of propeller blade area ratio with advance coefficient), and BC (interaction of propeller blade area ratio and Pith).

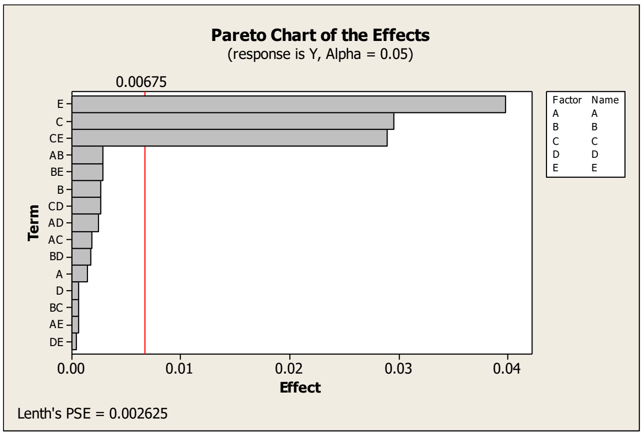

Figure. 3 Pareto effect chart

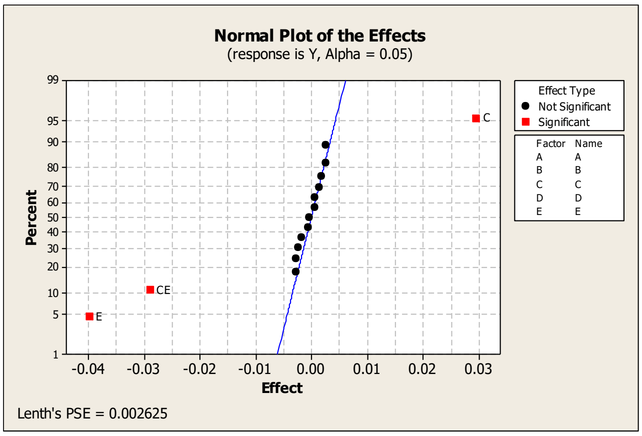

Figure. 4 Normal Graph Effect Plots

By using significant effects, one can develop a regression equation.

$$\sqrt{(K\_Q)} = 0.02409-0.01991(J)+0.01487(P/D)-0.01447(P/D.J)-0.00141(Z.BAR)-0.00141(BAR.J)+0.00134(BAR)+0.00134(P/D.C/D)-0.00112(Z.C/D)+0.00091(Z.P/D)-0.00084(BAR.C/D)+0.00072(Z)+0.00028(C/D)+0.00028(BAR.P/D)-0.00028(Z.J)-0.00022(C/D.J)\}$$

So that data comparison can be made between the Q value from the open water diagram and the Ks value from the results of the above formula. The following is a comparison table.

From figure. 5 show a regression equation between the KQ values of the B-series propeller data and the regression formula with the equation Y = 0.9916x + 0.000835 with the value of R2 being 0.9931.

Table 9. Comparison of KQ data between Propeller B-series graphs and KQ regression formula

Run Order	KQ Data B-Series	KQ Regression Formula Data
1	0.0025	0.00349
2	0.0150	0.01519
3	0.0190	0.01412
4	0.0050	0.00467
5	0.0630	0.05948
6	0.0060	0.00929
7	0.0030	0.00764
8	0.0770	0.08059
9	0.0120	0.01459
10	0.0035	0.00366
11	0.0045	0.00561
12	0.0130	0.01518
13	0.0050	0.00415
14	0.0750	0.07645
15	0.0780	0.07752
16	0.0040	0.00399

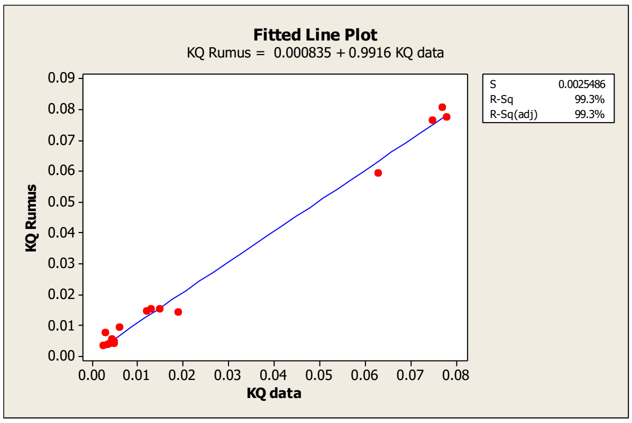

Figure. 5 The regression equation between the KQ values of the B-series propeller data and the regression formula

Conclusion

The present work discusses dimensional analysis and experimental design on propeller performance. In this case, the types of well-known series of propellers are used, namely the B-series. Overall results The study shows a regression equation between the KQ values of the B-series propeller data and the regression formula with the equation Y = 0.9916x + 0.000835 with the value of R^2 being 0.9931.

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