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ORIGINAL ARTICLE

Optimum design of B-series marine propellers

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Abstract The choice of an optimum marine propeller is one of the most important problems in naval architecture. This problem can be handled using the propeller series diagrams or regression polynomials. This paper introduces a procedure to find out the optimum characteristics of B-series marine propellers. The propeller design process is performed as a single objective function subjected to constraints imposed by cavitation, material strength and required propeller thrust. Although optimization software of commercial type can be adopted to solve the problem, the computer program that has been specially developed for this task may be more useful for its flexibility and possibility to be incorporated, as a subroutine, with the complex ship design process.

1. Introduction

Naval architects can easily design an optimized propeller with the theoretical propeller design methods (lifting-line/surface theories) using a computer without the geometry constraints seen in series propellers [1]. However, series propellers are still valuable; they are still widely used in the preliminary design of light or moderately loaded propellers [2]. Moreover, for those who cannot afford lifting surface software, traditional series propellers are good choices. Among the propeller series, the B-series is one of the commonly used series.

In this study, a computer program has been specially developed to find the optimum characteristics of any B-series propeller. The propeller design process is handled as a single objective function subjected to several constraints such as cavitation, material strength and the required propeller thrust.

2. Optimization problem

The main difficulty in most optimization problems does not lie in the mathematics or methods involved. It lies in formulating the objective all the constraints.

The propeller design problem has been handled as a multi-objective constrained optimization problem [1–4]. There are two principal ways to handle ‘multi-objective’ problems, both leading to single objective optimization problems [5]:

- one objective is selected and the other objectives are formulated as constraints.

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Nomenclature

A_E	propeller expanded area, m^2
A_O	propeller disk area, m^2
$C_{0.75R}$	blade chord length at 0.75R, m
C_{mi}	regression coefficient of torque coefficient
C_{si}	regression coefficient of thrust coefficient
D	propeller diameter, m
H_{PAP}	height of propeller aperture, m
J	advance coefficient
K_Q	torque coefficient
K_T	thrust coefficient
N	propeller rotating speed, rpm $N = 60 * n$
N_P	number of propellers
n	propeller rotating speed, rps
M	number of the design variables
P	propeller blade pitch, m
P_{CL}	propeller immersion, m
P_D	developed power, kW
P_S	shaft power per blade, kW
P_O	static pressure at the centerline of the propeller shaft, Pa
P_V	vapor pressure, Pa
P	total number of constraints
q	number of inequality constraints
Rn	Reynolds number
R_T	ship total resistance, N
S_C	maximum allowable stress of the propeller material, MPa
si	exponent of (J) in K_T equation
si′	exponent of (J) in K_Q equation
T	propeller thrust, N
T_{Cal}	calculated propeller thrust, N
T_R	required propeller thrust, N
T	propeller blade thickness, m
t_d	thrust deduction
ti	exponent of (P/D) in K_T equation
ti′	exponent of (P/D)in K_Q equation
t_{min}	minimum thickness of propeller blade, m
ui	exponent of A_E/A_O in K_T equation
ui′	exponent of A_E/A_O in K_Q equation
V_A	speed of advance, m/sec
V_S	ship speed, m/sec
Vi	exponent of Z in K_T equation
Vi′	exponent of Z in K_Q equation
w	wake fraction
Z	number of propeller blades
ΔK_Q	correction of torque coefficient
ΔK_T	correction of thrust coefficient
η	propeller efficiency
η_{max}	maximum propeller efficiency
ρ	water density, kg_m/m^3
v	water kinematic viscosity, m^2/s

- a weighted sum of all objectives forms the optimization objective function.

The rather arbitrary choice of weight factors makes the optimization model obscure and the first option is mostly preferred [5]. In this study, the propeller design problem is handled as a constrained optimization problem according to the first option.

Any constrained optimization problem can be handled according to the optimization model shown in Fig. 1.

This optimization problem can be formulated as follows [6]:

$$Find\ X = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{Bmatrix} \quad (1)$$

which maximizes an objective function called $f(X)$ subjected to the following constraints:

$$\left.\begin{array}{l} g_j(X) \leqslant 0, \quad j = 1, 2, \ldots, q \\ \text{and} \\ \ell_j(X) = 0, \quad j = q+1,\ q+2, \ldots, p \end{array}\right\} \quad (2)$$

where, $g_j(X)$ and $\ell_j(X)$ are the inequality and the equality constraints, respectively.

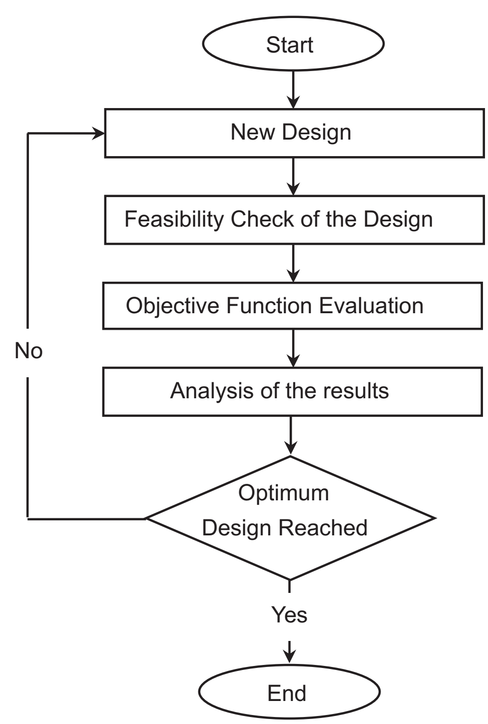

Figure 1 Optimization model for constrained problems.

3. B-series propeller

B-series propellers were developed in the Netherlands Ship Model Basin, and the section of the blade was improved later.

For any B-series propeller, the thrust and torque coefficients can be expressed as functions of the blade number (Z), blade area ratio (A_E/A_O), pitch ratio (P/D), and advance coefficient (J) as follows:

$$K_T = \sum_{i=1}^{39} C_{si}\, J^{si} \left(\frac{P}{D}\right)^{ti} \left(\frac{A_E}{A_O}\right)^{ui} Z^{vi} \tag{3}$$

and,

$$K_Q = \sum_{i=1}^{47} C_{mi}\, J^{si'} \left(\frac{P}{D}\right)^{ti'} \left(\frac{A_E}{A_O}\right)^{ui'} Z^{vi'} \tag{4}$$

where, C_{si} and C_{mi} are the regression coefficients of the thrust and torque coefficients, respectively. The values of the coefficients and exponents involved in Eqs. (3) and (4) are given in [7].

If Reynolds number of a propeller at $0.75R$ is greater than $2 * 10^6$, corrections to the thrust and torque coefficients must be taken into consideration [1].

$$(\mathrm{Rn})_{0.75R} = \frac{C_{0.75R} * \sqrt{[V_A^2 + (0.75\pi\ n\ D)^2]}}{\nu} \tag{5}$$

where, $C_{0.75R}$ is the blade chord length at $0.75R$ and V_A is the advance velocity (m/s).

3.1. Objective function

The most common objective function, for the optimum marine propellers, is the propeller maximum efficiency (η_{max}) [8]. The efficiency of marine propellers can be computed as follows:

$$\eta = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \tag{6}$$

3.2. Constraints

3.2.1. Cavitation constraint

Cavitation could affect a propeller's performance and needs to be considered in the propeller design process. A simple way to avoid cavitation is to increase blade area ratio. The minimum blade area ratio required to avoid cavitation was suggested by Keller [1] as follows:

$$\left[\frac{A_E}{A_O}\right]_{min} = \frac{(1.3 + 0.3Z)T}{(P_O - P_V)D^2} + K \tag{7}$$

where, $(A_E/A_O)_{min}$ is the minimum expanded area ratio. The coefficient K equals 0.1 for twin-screws ships, and 0.2 for single-screw ships.

3.2.2. Strength constraint

To achieve adequate blade thickness and thus ensure material strength, the following formula can be used to determine the minimum ratio of blade thickness at $0.7R$ to the diameter [4]:

$$\left[\frac{t_{min}}{D}\right]_{0.7R} = 0.0028 + 0.21\sqrt[3]{\frac{[3183.87 - 1508.15(P/D)]P_S}{1266652.04nD^3(S_C + 20.9D^2n^2)}} \tag{8}$$

where, $(t_{min}/D)_{0.7R}$ is the minimum propeller blade thickness ratio at 0.7R.

According to the B-series propeller geometry [7], the ratio of maximum thickness of propeller blade at each section to the propeller diameter is given as shown in Table 1.

Table 1 Maximum blade thickness % of D for B-series propellers.

r/R	Max. blade thickness (% of D)		
	$Z = 3$	$Z = 4$	$Z = 5$
0.2	4.06	3.66	3.26
0.3	3.59	3.24	2.89
0.4	3.12	2.82	2.52
0.5	2.65	2.40	2.15
0.6	2.18	1.98	1.78
0.7	1.71	1.56	1.41
0.8	1.24	1.14	1.04
0.9	0.77	0.72	0.67
1.0	0.30	0.30	0.30

As shown in table 1, the ratio of maximum thickness of propeller blade at $0.7R$ to the diameter is given as follows:

$$\left[\frac{t}{D}\right]_{0.7R} = \begin{cases} 0.0171 & \text{for} \quad Z = 3 \\ 0.0156 & \text{for} \quad Z = 4 \\ 0.0141 & \text{for} \quad Z = 5 \end{cases} \tag{9}$$

Using Eq. (8) and the geometry of B-series propellers, the required propeller blade thickness can be obtained as follows:

$$\left[\frac{t}{D}\right]_{0.7R} \geqslant \left[\frac{t_{min}}{D}\right]_{0.7R} \tag{10}$$

3.2.3. Thrust constraint

The calculated propeller thrust (T_{Cal}) must be equal to the required thrust (T_R). The propeller thrust can be calculated as follows:

$$T_{CAL} = K_T\ \rho\ n^2\ D^4 \tag{11}$$

$$T_R = \frac{R_T}{N_P * (1 - t_d)} \tag{12}$$

where, R_T is the ship total resistance, N_P is the number of propellers and t_d is the thrust deduction.

4. Developed computer program

A computer program has been specially developed to find the optimum characteristics of any B-series propellers. This program starts with an initial feasible point and proceeds towards the optimum point according to the steps shown in Fig. 1. The detailed procedure of this program is summarized in the flow chart shown in Fig. 2.

5. Case study

The problem is to find the optimum characteristics (D, A_E/A_O, P/D, J) of four bladed B-type propeller of a twin screw ship. The propeller diameter (D) is restricted at specified value to suit the ship lines and to provide acceptable hull clearances to avoid hull vibration. Ship speed (V_S) and corresponding resistance (R_T) are given for this design condition. Wake fraction (w) and thrust deduction (t_d) are given for this design condition. This problem can be formulated as follows:

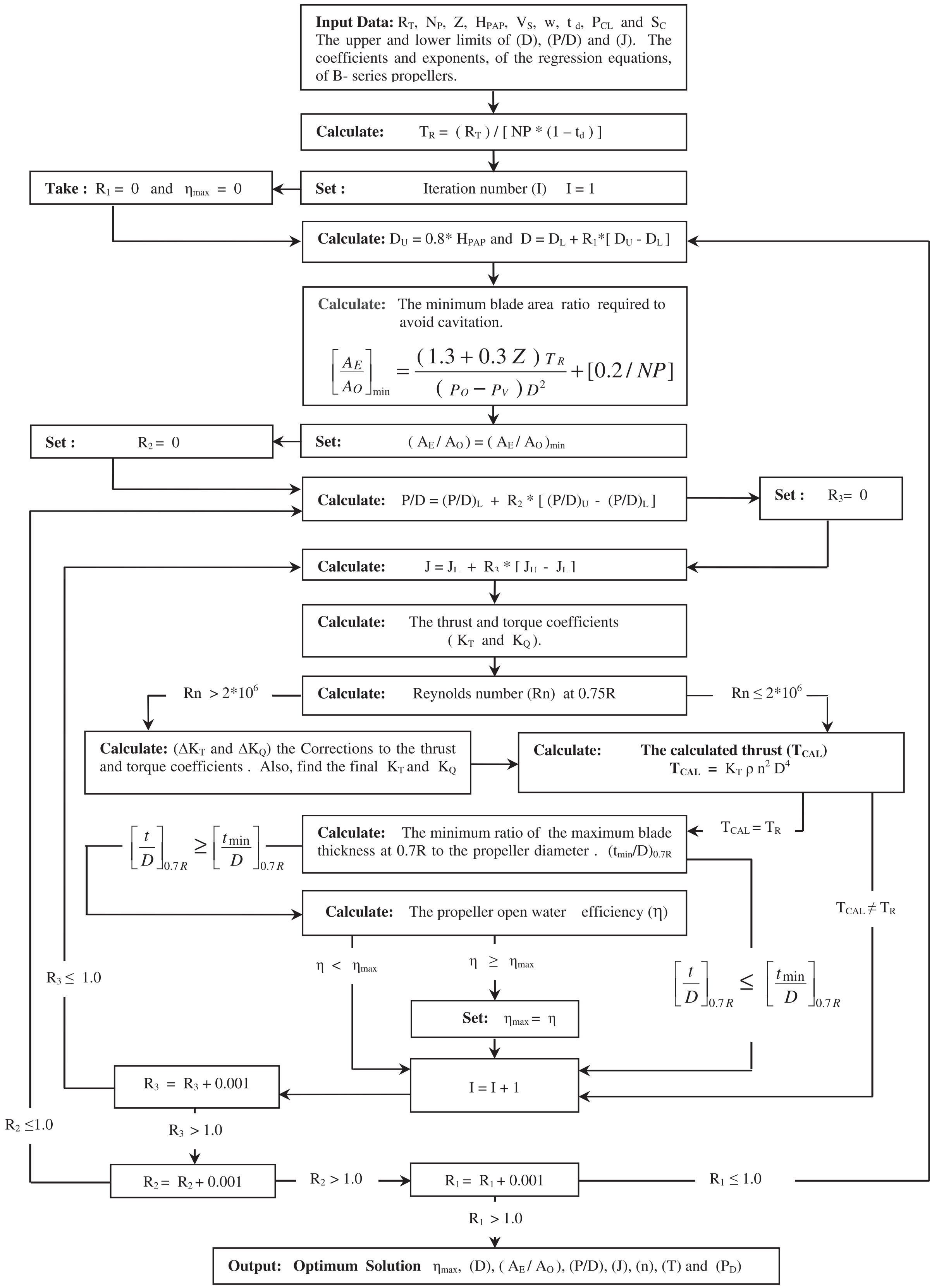

Figure 2 Flow chart for B-series marine propellers design process.

Table 2 Input data.

Ship total resistance (R_T)		35000.0
Ship speed (V_S)		10.289
Number of propellers (N_P)		2
Number of propeller blades (Z)		4
Height of propeller aperture (H_{PAP})		1.25
Propeller immersion (P_{CL})		2.0
Wake fraction (w)		0.20
Thrust deduction (t_d)		0.15
Max. allowable stress of propeller material (S_C)		260
Boundary constraint		
Design variable	Lower Limit	Upper Limit
Propeller diameter (D)	0.25	$0.8 * H_{PAP}$
Area ratio (A_E/A_O)	0.35	0.85
Pitch ratio (P/D)	0.7	1.5
Advance coeff. (J)	0.3	1.5

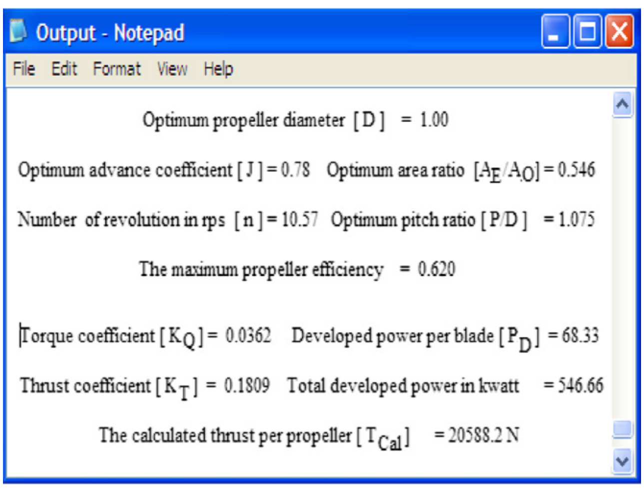

Figure 3 Output results of the developed computer program.

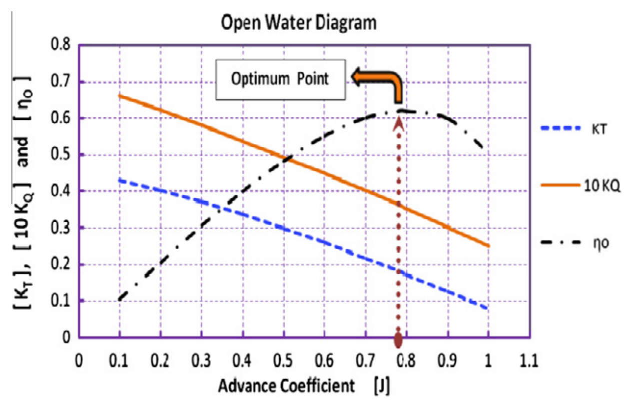

Figure 4 Open water diagram.

Use the input data which are shown in Table 2 to find (D, A_E/A_O, P/D, J) which maximize the propeller efficiency (η) when subjected to the following constraints:

- *Cavitation constraint:* the expanded area ratio should be larger than a minimum value in order to avoid cavitation, $(A_E/A_O) \geqslant (A_E/A_O)_{min}$ where $(A_E/A_O)_{min}$ can be calculated using Eq. (7).
- *Thrust constraint*: the calculated propeller thrust (T_{cal}) has to match the design requirement, as follows: $T_{cal} = T_{required}$.
- *Strength constraint:* to ensure adequate material strength, a minimum propeller blade thickness is required, as shown in Eq. (8).

$$\left[\frac{t}{D}\right]_{0.7R} > \left[\frac{t_{min}}{D}\right]_{0.7R}$$

- *Boundary constraint:* to obtain an optimum design point, the design variables must lie in an acceptable domain.

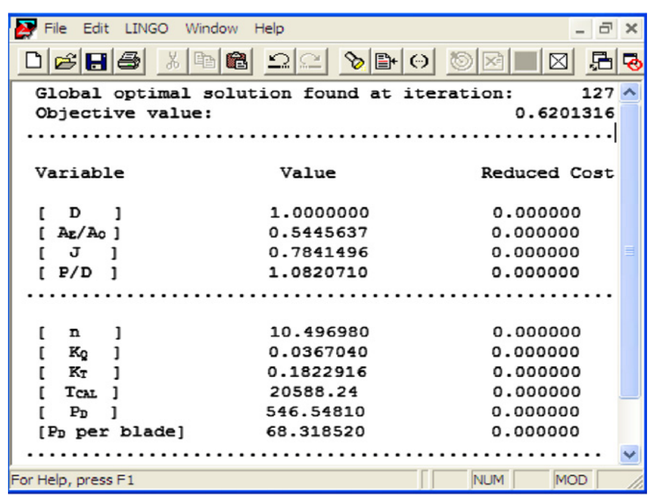

Figure 5 Output results of Lingo software.

In this part, the problem under consideration is carried out in details by using the following techniques:

- Using the developed computer program.
- Using a commercial software (Lingo).

Table 3 Output results.

Items	Developed program	Lingo
Objective: $\eta_{max.}$	0.620	0.62013
Design variables		
D	1.00	1.00
A_E/A_O	0.546	0.54456
P/D	1.075	1.082
J	0.78	0.784
[n] RPS	10.57	10.497
Coefficients		
K_T	0.1809	0.1823
K_Q	0.0362	0.0367
Power in kwatt		
P_D	546.66	546.548
P_D (Blade)	68.33	68.318

5.1. Using the developed computer program

The data which are shown in Table 2 are used to perform the problem under consideration by using the developed computer program. The output results of this program are shown in Fig. 3.

The obtained optimum point is plotted on the open water diagram for this design condition as shown in Fig. 4.

5.2. Using a commercial software (Lingo)

Lingo [9] is a comprehensive tool designed to make building and solving linear, nonlinear and integer optimization models. The problem under consideration is recalculated using LINGO software [9] and the output results are shown in Fig. 5.

5.3. Analysis of the results

The output results obtained by the presented solutions are shown in Table 3. It is clear that, the output results of Lingo software are found in a good agreement with those obtained by the developed program.

6. Conclusions

- The design process of a series propeller by traditional calculation or chart methods is a tedious job due to the multiple parameters and constraints involved.
- To handle the multi-objective constrained problem of the propeller design, one objective is selected and the other objectives are formulated as constraints.
- The developed computer program represents a tailored and simple tool to find the optimum characteristics of any B-series marine propeller. It is more flexible to use it as a subroutine in global ship design problems than to use commercial optimization software.

References

[1] C. Jeng-Horng, S. Yu-Shan, Basic design of a series propeller with vibration consideration by genetic algorithm, J. Mar. Sci. Technol. 12 (2007) 119–129.

[2] E. Benini, Multi-objective design optimization of B-screw series propellers using evolutionary algorithm design, J. Mar. Sci. Technol. 40 (2003) 229–238.

[3] J.-B. Suen, J.-S. Kouj, Genetic algorithm for optimal series propeller design, in: Proceeding of the Third International Conference on Marine Technology, ORDA 99, Poland, 1999.

[4] M.M. Karim, M. Ikehata, A genetic algorithm (GA)-based optimization technique for the design of marine propeller, in: Proceeding of the Propeller/Shafting Symposium, Virginia Beach, USA, 2000.

[5] H. Schneekluth, V. Bertram, Ship Design for Efficiency and Economy, Butterworth, Heinemann, 1998.

[6] S.S. Rao, Optimization Theory and Applications, second ed., Wiley Estern Limited, India, 1991.

[7] M.W.C. Oosterveld, V. Oossanen, Further Computer Analyzed Data of The Wageningen B-series, I.S.P., vol. 23, July 1975.

[8] M.M. Gaafary, Computerized method for propeller design of optimum diameter and rpm, in: 13th Congress of IMAM, Istanbul, Turkey, October 2009.

[9] Lindo Systems Inc., Lingo Software, Version (9), <http://www.lindo.com/>, April 2006.