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OPTIMIZATION PROCEDURE TO DETERMINE THE OPTIMUM PROPELLER OF TRADITIONAL PURSE SEINE BOAT

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ABSTRACT

Design of B-series propeller was made to improve the performance of traditional purse seine boat in Central Java Indonesia, [1]. The optimum B-series design should be determined from any kind design configurations of the B-series propeller. The aim of this article was to introduce the optimization procedure for determining the optimum design parameters of B-series propeller that would be applied for the improvement of thrust performance of traditional purse seine boat in Central Java Indonesia. The single objective function is adopted with the constraint parameters includes material strength, propeller cavitation and the propeller thrust requirement. Propeller Speed, Diameter and Pitch Ratio are selected as Independent Variables.

Key words: GFRP propeller, flexible model and propeller efficiency.

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1. INTRODUCTION

Almost 8000 boats can be found in the North Coast of Central Java to support the fishing activities. Majority of the boat types is the traditional purse seine boat that was made by wood as the primary material. The fishing boats commonly produced by the artisanal boat builder which is located in the local region of the fishery community. The boat builders have the building skill which is inherited from their predecessors as the tradition technique to build. Therefore the lack of practice to design propeller that considered the relation with hydrodynamic behavior of the boat dimension was observed. According to the condition the contemporary engineering method was adopted for improving the propulsion efficiency.

In the previous study, the standard propeller design of B-series was developed for the traditional purse seine boat in Central Java Indonesia, [1]. The performances of developed propeller design have been assessed using CFD technique that considered the hydrodynamic characteristics of the hull form of the traditional purse seine boat. During the design process of the developed propeller, the optimization method was adopted to determine the optimum parameters that were used for the propeller design. In this study, the optimization procedure was introduced to find the optimum parameters of the B-series propeller for the traditional purse seine boat.

2. LITERATURE REVIEW

The particle swarm optimization (PSO) for improving and evaluating the automated engineering optimization in the case of propeller design was presented by Vesting, [2]. The PSO algorithm are developed and applied to optimize the propeller design of the different ship types. The propeller design was compared with the design which is generated by the genetic algorithm to provide the benchmark procedures. The results shows that the developed PSO algorithm able to converge earlier and enhance the solution as the constraint violation.

Gaggero et. al., [3], developed a multi objective numerical optimization to design the propeller of high-speed craft. The combination of Boundary Element Method, Genetic Algorithm and Reynold Averaged Navier Stokes Equation (RANSE) viscous solver was applied to improve the propulsion efficiency and reduce the propeller cavitation. The results have generated the final geometry that was verified for the full scale measurement on the high speed craft. In the other study, Gaggero et. al., used RANSE based optimization to design the ducted propeller nozzle, [4], and developed the optimization algorithm and boundary element method to design the contracted and tip loaded propellers, [5].

Nouri et. al, [6], investigated the using of RANSE-based CFD, genetic algorithm and Kriging method to optimize a marine contra-rotating propellers (CRP). The CFD tool was used to evaluate the hydrodynamic performance of the CRP. The optimization was performed with Kriging method that is coupled with genetic algorithm. The results presented the improvement of the propeller efficiency through the application of the optimization algorithm. It is concluded that the developed algorithm was reliable for the optimization of marine propellers.

Mizzi et. al, [7], proposed a design optimization procedure for Propeller Boss Cap Fins (PBCF) as Energy Saving Devices. The PBCF optimization was conducted using Computational Fluid Dynamic (CFD) analysis. The influences of the PBCF have improved the net energy propeller efficiency of 1.3% to contribute the substantial way for minimizing the cost and energy consumption.

Liu et. al, [8], study on the dual mode propellers as both propulsion and turbine devices for sailing boats and yachts. The dual mode rotor series was evaluated and optimized in term of a balanced propulsion and energy generation. The results indicate that the optimization able to balance the efficiency of both modes for low speed ships. The balanced power productivity and propulsive performance were achievable for low speed vessel which is anchored in a current or a regular sail boat that propeller was used as a towed turbine.

3. MATERIAL AND METHODS

3.1. Optimization procedure for B-series propeller

Actually, the characteristics of the propeller design have multi objectives that should be formulated as objectives functions. Therefore the main problems of optimization work lies in the formulation the objective and all the constraint. To solve the problems, two principal methods can be applied and both convert the multi objectives become the single objectives with the following approach:

- Formulate one objective function and the other objectives were defined as the constraints variables.
- Define a weighted function for the all of objectives to create the optimization objective function.

First approach was selected for the optimization procedure for B-series propeller because the weight factor made the optimization model obscure. Otherwise most study was preferred to adopt the first approach for the optimization in marine design, [9]. Therefore the optimization procedure was formulated as:

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

To have the maximum value of the propeller efficiency as an objective function, $f(x)$, with the defined constraints that was formulated as inequality, $p_i(X)$, and equality function, $q_i(X)$, that can be described mathematically, as:

$$p_i(X) \leq 0, \quad i = 1, 2, \dots, n \quad \text{and}$$
$$q_i(X) = 0, \quad i = 1, 2, \dots, n \qquad (2)$$

In the case of B-series propeller, the equality constraint comply with the thrust and the torque coefficients that was defined as the function of the number of propeller blade (Z), the ratio of blade area (A_E/A_0), pitch ratio (P/D) and advanced coefficient (J), that can be expressed as:

$$K_T = \sum_{n=1}^{39} C_{Tn}\ J^{Sn} \left(\frac{P}{D}\right)^{tn} \left(\frac{A_E}{A_0}\right)^{un} Z^{vn} \qquad (3)$$

$$K_Q = \sum_{n=1}^{47} C_{Qn}\ J^{Sn} \left(\frac{P}{D}\right)^{tn} \left(\frac{A_E}{A_0}\right)^{un} Z^{vn} \qquad (4)$$

where C_{Tn} is the thrust regression coefficient, C_{Qn} is the torque regression coefficient. If the Reynold number is greater than 2×10^6 - 2×10^9, the correction must be considered as follow:

$$\begin{Bmatrix} K_T(R_n) \\ K_Q(R_n) \end{Bmatrix} = \begin{Bmatrix} K_T(R_n = 2\times10^6) \\ K_Q(R_n = 2\times10^6) \end{Bmatrix} + \begin{Bmatrix} \Delta K_T(R_n) \\ \Delta K_Q(R_n) \end{Bmatrix} \qquad (5)$$

where ΔK_T and ΔK_Q is the thrust correction factor and the torque correction factor, respectively. The number of constant and detail equations can be found in Ref. [10].

3.2. Mathematical Formulation for Optimization Procedure

Optimization procedure is described where the mathematical formulations for the objective and constraints function is defined based on the iteration algorithm of the direct search optimization. Direct search methods do not require the gradient of the objective function. This method search a set of point on the domain, to find the value of objective function that might be lower (minimizing) or bigger (maximizing) than the value at the current point. Direct search also able to solve the problem which is the objective function is not differentiable and not continuous.

The definition of objective function for the optimum B-series propeller was commonly defined as the propeller efficiency (η). Therefore the objective function of the optimization can be formulated as follow:

$$Maximize, \qquad \eta = \frac{J}{2\pi}\frac{K_T}{K_Q} \tag{6}$$

where J is advanced coefficient, K_T is thrust coefficient, and K_Q is torque coefficient.

Since the optimization procedure is determined as a single objective function, therefor the other objectives should be defined as the constraint functions. The constraints for the B-series propeller optimization was suggested by Gaafary et. al., [11], as follow:

- Cavitation constraint, the minimum blade expanded area ratio, $(A_E/A_0)_{min}$, to avoid propeller cavitation should be follow, [10]:

$$\left[\frac{A_E}{A_0}\right]_{min} = \frac{(1.3 + 0.3Z)T}{(P_0 - P_V)D^2} + K \tag{7}$$

  where, Z is blade number of propeller, P_0 is static pressure on the centerline of propeller shaft, P_V is vapor pressure, D is propeller diameter and K is constant which can be put equal to 0.20 for single screw boat.

- Strength constraint, the minimum propeller blade thickness ratio on the $0.7R$ to propeller diameter, $[t_{min}/D]_{0.7R}$, should be follow, [12]:

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

  where, (P/D) is propeller pitch ratio, P_s is shaft power per blade, D is propeller diameter, n is propeller rotating speed in revolution per second, S_c is permissible stress of the propeller material in MPa.

- Thrust constraint, the generated propeller thrust (T_{CAL}) must be larger than the required boat thrust (T_R). Both thrust can be formulated as:

$$T_{CAL} = K_T\ \rho\ n^2\ D^4 \tag{9}$$

$$T_R = \frac{R_T}{N_P\ (1 - t_d)} \tag{10}$$

  where, K_T is thrust coefficient, ρ is seawater density, n is propeller rotating speed, D is propeller diameter, R_T is total resistance of the boat, N_p is number of propeller, and t_d is thrust deduction.

Whereas the objective and the constraints functions have been defined, the next step is to develop the optimization algorithm. The optimization algorithm was made through the modification of the optimization algorithm proposed by Gaafary et. al., [11]. In this optimization algorithm the propeller rotating speed, (n), is determined as the independent variables instead of the advanced coefficient (J). However the propeller rotating speed should be comply with the required advanced coefficient. The flowchart of the optimization procedure is presented in Fig. 1.

4. THE CASE STUDY AND NUMERICAL TEST

Confirming the developed optimization algorithm performs properly for any B-series propeller design configuration, it is important to determine the optimization parameters for the optimum solution is obtained.

The developed optimization procedure was applied on the propeller design for traditional purse seine boat. All design data of the boat hull form was defined from the geometry measurement and evaluation of the sample boat as a representation of the boat characteristics in the population. The sample boat is selected from the population with the criteria that have been discussed with the boat owners and communities. The four examples are executed which is consist of 3-bladed, 4-bladed, 5 bladed and 6 bladed propeller. The data of boat hull specification, input parameter and propeller clearance data for the optimization are presented in the Table 1, Table 2 and Table 3 respectively.

Table 1. The traditional purse seine boat data

Design parameters	Dimension
Length of Perpendicular (Lpp)	13.1 m
Breadth (B)	4.15 m
Draft (T)	1.56 m
Height (H)	1.97 m
Block Coefficient (C_b)	0.53
Service speed (V_s)	9 knot
Total Resistance (R_T)	15.18 kN
Wake Fraction (w)	0.15
Thrust deduction (t_d)	0.12

Table 2. Input parameters and boundary constraint

Design variable	Variable interval
Propeller Diameter (D)	$0.25 \leq D \leq 0.90$
Propeller Rotating Speed (n)	$5 \leq n \leq 33$
Expanded Area Ratio (A_E/A_0)	$(A_E/A_0)_{min} \leq (A_E/A_0) \leq 0.80$
Pitch Ratio (P/D)	$0.25 \leq (P/D) \leq 1.4$
Advance coefficient (J)	$J(Va, n_{min}, D_{min}) \leq (J) \leq 0.90$

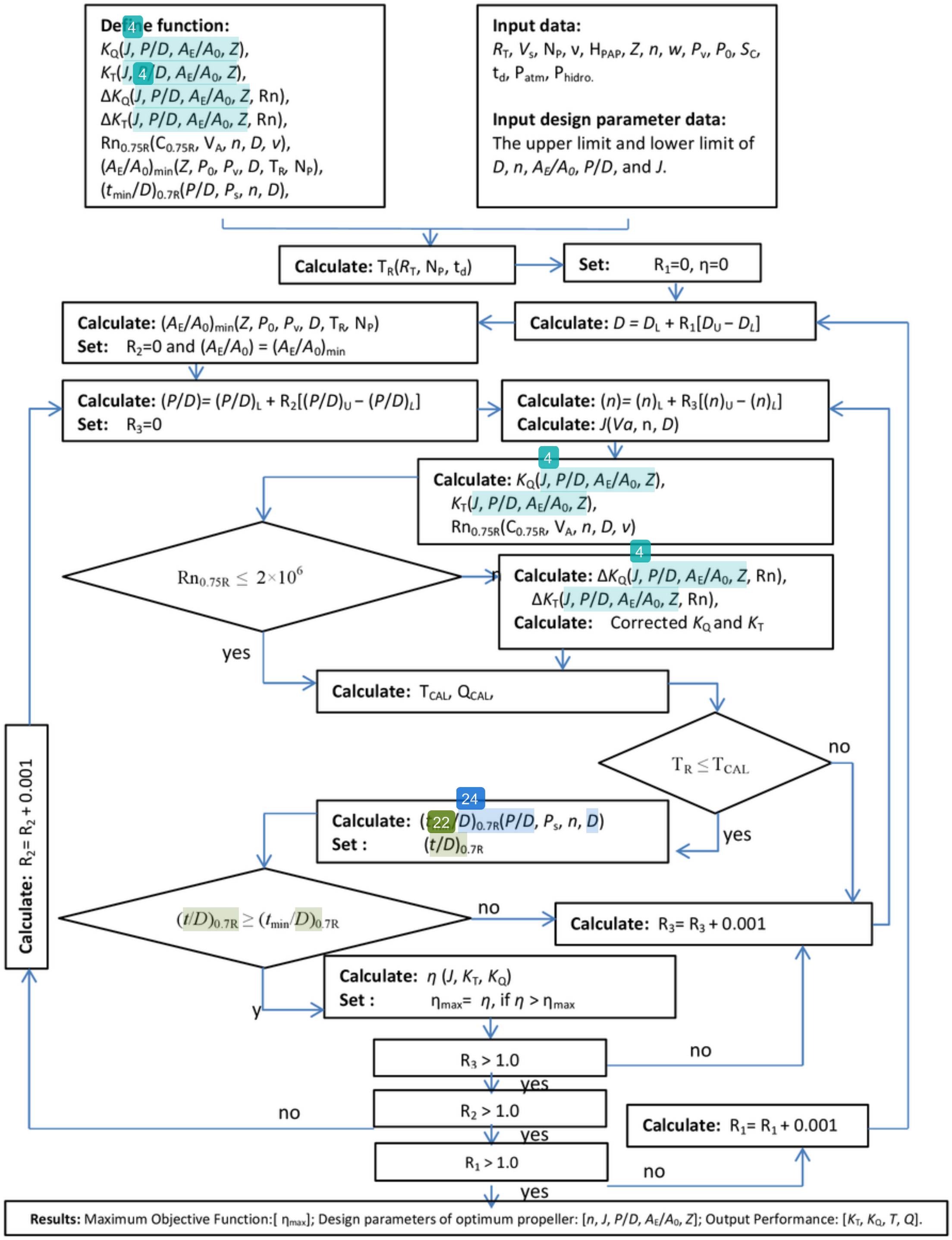

Figure 1 The flowchart of optimization procedure.

Table 3. Propeller clearance dan material data

Number of propeller (N_p)	Single Screw
Height of propeller aperture (H_{PAP})	1.20 m
Number of propeller blade (Z)	3, 4, 5 and 6 blade
Propeller immersion (P_{CL})	0.80 m
Permissible stress of propeller material (S_C)	260 MPa

The numerical examples was used to test the capability and functionality of the developed optimization procedure to achieve the optimum objective function which is generate the optimum propeller efficiency for the traditional purse seine boat in Central Java Indonesia. The calculations were carried out with the different number of blades which is included 3-bladed, 4-bladed, 5-bladed and 6-bladed B-series propeller. The results of the optimization process can be seen in Table 4.

Table 4. The optimization output results

Item	3-Bladed	4-Bladed	5-Bladed	6-Bladed
Objective Function:				
Prop. Efficiency(η_{max})	0.706	0.662	0.567	0.474
Optimum design parameter:				
Prop. Diameter (D)	0.894	0.881	0.764	0.582
Prop. Rotating Speed (n)	6.42	6.42	9.82	18.03
Exp. Area Ratio (A_E/A_0)	0.298	0.315	0.371	0.527
Pitch Ratio (P/D)	0.917	0.917	0.676	0.526
Advance coefficient (J)	0.686	0.697	0.525	0.375
Output performance:				
Thrust Coefficient (K_T)	0.140	0.150	0.114	0.102
Torque Coefficient (K_Q)	0.022	0.025	0.017	0.013
Propeller Thrust (T)	3766	3802	3823	3872
Propeller Torque (Q)	583.02	636.73	563.67	487.98

According to the optimization output results, it is indicated that the optimization result have a good agreement with the theory of propeller performance which explained that smaller blade number might provide better efficiency than the larger one. Furthermore the larger blade number could generate larger propeller thrust also can be found in the tendency of optimization output results. It can be concluded that the developed optimization procedure is reliable to be applied to find the optimum propeller design parameters for the traditional purse seine boat in Central Java Indonesia.

5. CONCLUSIONS

The simple and efficient optimization procedure was presented in this work constitutes an alternative technique to improve the performance of traditional purse seine boat in Central Java Indonesia through the application of optimum B-series propeller. Additionally, the optimization procedure showed an easy numerical algorithm and low computational cost.

The optimization procedure presents good agreement with the theoretical characteristics of Wageningen B-Series propeller which is the propeller efficiency usually can be performed by the propeller with the lower blade number. However in the case of thrust performance, the optimization results also presented that the largest thrust force was generated by the larger blade number propeller. Therefore it can be concluded that the optimization procedure able to help to find the optimum design parameters of B-series propeller to improve the performance of the traditional purse seine boat in Central Java Indonesia

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