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SIMPLIFIED METHOD FOR DESIGN AND ANALYSIS OF NON-CAVITATING THRUSTERS: VALIDATION AND COMPARISON

Jonas Pedro Caumo
Department of Energy (DE), Course of Mechanical Engineering (FEM), Universidade Estadual de Campinas (UNICAMP), Brasil

Kamal Abdel Radi Ismail
Department of Energy (DE), Course of Mechanical Engineering (FEM), Universidade Estadual de Campinas (UNICAMP), Brasil

Abstract: The analysis of marine thruster designs can use several methods, each of which has a different degree of complexity and computational effort, empirical models, blade element theory, vortex theory, airfoil, airfoil, panel method and computational fluid dynamics are some examples. The present work evaluates and reviews thruster design methods related to Theodorsen and Goldstein's Vortex theory, proposing a simplified and fast method both for calculating a known thruster and for generating optimized geometry. The influence of the Reynolds number on the hydrodynamic parameters in terms of lift and drag was considered and the Levenberg-Marquardt method was applied to solve the set of equations. Despite these methods being relatively known, there are few works that present applications of the method and analyzing the results with comparisons.
Keywords: Propellant; numeric method; optimization; Levenberg-Marquardt.

INTRODUCTION

Based on the clarifications of the work of [1], which through an extensive and detailed review eliminated several doubts and obscure points, various information are correlated that culminate in the continuity and integration of several previous works. Among the main works evaluated for the formulation of this work consider [2], [3], [4] and [5]. Consequently, the objective and contribution of the present method was then to develop and validate a simplified and quick methodology for analyzing the efficiency of marine thrusters, since in previous works, validations and comparisons with numerical and empirical results were scarce and not detailed. Much focus is given to theory and formulation, but few studies have been carried out considering the application of the method and evaluation of the results.

The implementation of the theory of minimum induced drag losses for thruster design was then formulated, an algorithm was developed and numerically validated using the C# programming language. Two different approaches were elaborated, one of them considers the calculation of an existing thruster with known geometry and the other deals with the problem of generating geometric data from operating parameters, also considering in this methodology the implementation of an algorithm for optimizing hydrodynamic profiles taking into account viscous effects through the calculation of hydrodynamic properties considering the Reynolds number.

Validation was performed by comparing the results of the present method with numerical results available in [6] in addition to comparison with experimental results in [7], both demonstrating concordance and consistency.

Hydrodynamic characteristics of different hydrofoils were calculated using the XFoil program developed by [8], used and unusual hydrodynamic profiles, NACA 66 (modified considering a=0.8), NACA 4415, Joukowski (12%) and Clark Y, for the application of marine thrusters. The Levenberg-Marquardt method [9] was used to solve the system of equations. The influence of the number of blades was also evaluated. The results were satisfactory from the point of view of speed of response, thus making the present method a relevant tool for analysis and preliminary design of thrusters.

METHODOLOGY

VORTEX THEORY FOR THRUSTERS

To describe the vortex theories proposed by [2] and [3] it is first necessary to discuss the blade element theory that is used as the basis for the other two theories.

In the theory of the blade element, as simplifying hypotheses, an ideal geometry of the wake is adopted, which propagates according to the condition of [10], that is, as a propeller downstream of the rotor. It is also considered that the blades are extremely long and spaced as equal angular steps. Thus, we arrive at the condition that the induced velocity variation along the height of the blade can be neglected, so the drag and lift forces in the blade section can be considered very close to the values that would be obtained with a two-dimensional section of the blade. same profile under the same flow conditions and angle of attack.

A propeller is composed of a set of blades distributed radially around a hub and connected with a driving shaft, as [3] the blades can be considered rotating support surfaces.

In the absence of cavitation as a result, the flow and rotational speed of the propeller, as well as the velocity field around a blade element, which moves to the left, is shown in figure 1.

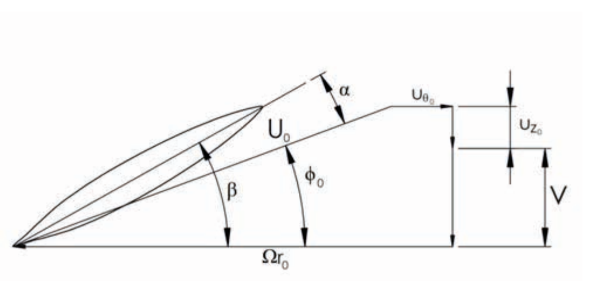

Figure 1. Velocity diagram for a blade section.

At full speed U_0 in a blade section can then be decomposed vectorially resulting in V which is axial velocity as a function of the translational motion of the propeller, the rotational speed in the tangential direction. Due to the flow disturbance generated by the propeller, induced velocities are generated in tangential directions ($u_{\theta 0}$) and axial (u_{z0}). The angle of attack is represented by α and β, the pitch angle of the blade section and ϕ_0, the blade position angle in relation to the horizontal plane. Therefore, mathematically we arrive at:

$$U_0 = \sqrt{\left(V + u_{z_0}\right)^2 + \left(\Omega r - u_{\theta_0}\right)^2} \quad (1)$$

$$\phi_0 = tan^{-1}\frac{V + u_{z_0}}{\Omega r_0 - u_{\theta_0}} \quad (2)$$

From the Kutta-Joukowsky theorem and the two-dimensional theory of airfoils, the lift force on the section can be determined:

$$dL = \rho U_0 \times \Gamma dr = c_l \frac{\rho}{2} U_0{}^2 c dr \quad (3)$$

Applying the moment integral over all blade sections along the height, the torque (Q) and thrust (T) values can be obtained:

$$T = \rho B \int_{r_h}^{R} \Gamma\left(\Omega r - u_{\theta_0}\right) dr \quad (4)$$

$$Q = \rho B \int_{r_h}^{R} \Gamma\left(V + u_{z_0}\right) r dr \quad (5)$$

Combining the above equations:

$$dT = \rho[\Omega r - u_\theta(r)]\varepsilon\Delta\Gamma(r)dr \quad (9)$$

$$dQ = \rho[V + u_z(r)]\varepsilon\Delta\Gamma(r)rdr \quad (10)$$

Therefore, with the above equations, it is possible to obtain a relationship between the circulation and the geometry of the blade. The so-called vortex theories of [2] and [3] then use the above formulation, blade element theory, as a basis, but in these theories corrections are presented considering the induced velocity in the rotor plane as a function of the vortex wake.

During the development of the equations in the next chapters, it is necessary to introduce and consider the following index notation:

- 0, variable located in the thruster plane;
- 1, variable located in the helical vortex wake downstream of the propeller;
- 2, variable located in the helical vortex wake downstream of the propeller considering the effect of axial displacement of the vortex wake for a specific advance rate, this notation will be used as an auxiliary for some

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equations;

- h, variable located in the cube;
- (input) is a variable considered as supplied from the input data;
- (calc) is a variable that must be calculated throughout the calculation procedure, considering more complex calculations and not just input data.

GOLDSTEIN THEORY

It is necessary to develop Goldstein's theory before presenting Theodorsen's theory, as this second model is strongly based on the first.

The blade is assumed to be similar to a lift line, modeled by a vorticity line along the entire height of the blade with variable circulation distribution, which generates a wake of vortices continuously from the trailing edge of the blade.

As a simplifying hypothesis, Goldstein admits a low loading of the rotor blades, taking into account that the increment of velocity impressed on the fluid when passing through the propeller is negligible and much smaller than the velocity of the undisturbed flow. As a consequence of this simplification, the mat ends up propagating in a helical shape with constant pitch without suffering deformations on itself, such as contraction and winding. Mathematically this condition can be described by the equation below:

$$\frac{\Omega z}{V} = constante\ para\ r < R \tag{11}$$

Consider that r and z are two components of a cylindrical coordinate system, with the rotor axis as the reference axis.

Assuming the no-penetration boundary condition along the entire helical surface of the wake, Goldstein then found a potential velocity function that is associated with a circulation distribution that causes the wake to adopt a naturally helical shape.

The analytical solution developed by Goldstein is represented and expressed by the dimensionless circulation coefficient G and the functions of mass (κ) and axial kinetic energy (ε). These coefficients and functions were then extended and tabulated by [4], thus indicating in this work precise values obtained through great mathematical and computational effort.

The value of G can be calculated using the following equation:

$$G(r_1) = \frac{B\Gamma\Omega(r/R)}{2\pi V} \tag{12}$$

B is the number of rotor blades and R is the radius of the top of the propeller blades. This function allows obtaining the correction as a function of the speed induced by the wake on the propeller plane. Note that this function tends to zero at the top of the blade.

According to Goldstein's equations, it is then possible to find a circulation distribution that generates the lowest possible induced drag loss.

THEODORSEN'S THEORY

Continuing Goldstein's work, Theodorsen then reworks the vortex theory for thruster, but now considers not only the low charge hypothesis.

Theodorsen evaluated that it is possible to use Betz's hypothesis also for rotors with a high load value, also resulting in this case that from the ideal circulation a helical geometry wake is generated, however a correction was made on the surface of the wake, following the condition below:

$$\frac{\Omega z}{V + w} = constant\ for\ r < R \tag{13}$$

Comparing the theory of Goldstein and Theodorsen, it is concluded that for a high load rotor to be modeled correctly, it is necessary to consider an increase in the axial component of velocity, therefore, w is the axial velocity of advancement of the helical vortex wake . As a consequence of this new formulation, the helix angle of the wake will be different when comparing the two methods.

The circulation function G can then be rewritten as:

$$G(r_1) = \frac{B\Gamma\Omega}{2\pi w(V+w)} = \frac{B\Gamma}{2\pi R_1 w\lambda_2} \quad (14)$$

Where λ is the advance rate and index 2 as described at the end of chapter 2.1.

Through then these developments, the equations that determine the buoyancy can be rewritten in terms of the functions of circulation, mass and axial kinetic energy:

$$T = \kappa\rho\pi R_1{}^2 V^2 \overline{w}\left[1+\overline{w}\left(\frac{1}{2}+\frac{\varepsilon}{\kappa}\right)\right] \quad (15)$$

Where:

$$\overline{w} = \frac{\lambda_2}{\lambda_1} - 1 \quad (16)$$

The energy expended by the propeller to generate the desired thrust in terms of these functions as well, can be calculated as follows:

$$E = \rho V(V+w)wS\left(\kappa + \frac{\varepsilon w}{V}\right) \quad (17)$$

The calculation procedure of the developed algorithm solves the set of equations above through an iterative method, considering the aid of some more equations that will be presented and identified in chapter 2.4. Before the calculation sequence, considerations related to cube modeling will be discussed.

CUBE MODELING

The model presented in this work considers the influence of the cube in the thruster calculation, the equations below are referenced and described in the works of [1] and [5].

By relating the propeller geometry to the helical conveyor through the following equation:

$$(V+u_{z_0})2\pi r_0 d_0 = (V+u_{z_1})2\pi r_1 dr_1 \quad (18)$$

And assuming that the difference between $(V+u_{z0})$ and $(V+u_{z1})$ is negligible and both values can then be equal and constant, they will be denoted by the variable m. By integrating the above equation, the result is the following equation:

$$m\int_{r_h}^{r_0} r_0 dr_0 = \int_0^{r_1} r_1 dr_1 \quad (19)$$

When applying the boundary conditions $x_0=x_1=1$, being:

$$x_0 = \frac{\mathrm{r}}{R_0} \quad (20)$$

$$x_1 = \frac{\mathrm{r}}{R_1} \quad (21)$$

$$x_h = \frac{R_h}{R_0} \quad (22)$$

As a result, we have the relationship between x_0, x_1 and x_h:

$$x_0{}^2 = x_h{}^2 + \frac{x_1{}^2\left(\frac{R_1}{R_0}\right)^2}{m} = x_h{}^2 + x_1{}^2(1 - x_h{}^2) \quad (23)$$

This relation will be used to correct the equations in order to consider the presence of the cube. The thrust can then be rewritten as follows:

$$T = \rho\pi R_0{}^2 V^2 \overline{w}(1+\overline{w})\left[\kappa(1 - x_h{}^2) - \frac{1}{2}\overline{w}(1-\overline{w})\lambda^2 I_1\right] \quad (24)$$

Where:

$$I_1 = \int_0^1 \frac{2G(x_1)x_1{}^3}{(x_1{}^2+\lambda_2{}^2)\left[x_1{}^2 + \frac{x_h{}^2}{(1-x_h{}^2)}\right]} dx_1 \quad (25)$$

Finally, the relationship between the propeller radius and the vortex wake radius can be calculated with the following equation:

$$\left(\frac{R_0}{R_1}\right)^2 = \frac{\left[1+\overline{w}\left(\frac{1}{2}+\frac{\varepsilon}{\kappa}\right)\right]/(1+\overline{w})}{\left[(1+x_h{}^2) - \frac{\frac{1}{2}\overline{w}(1+\overline{w})\lambda^2 I_1}{\kappa}\right]} \quad (26)$$

And the circulation equation can be rewritten as follows:

$$B\Gamma = 2\pi R_1 w \lambda_2 G(x) = 2\pi R \lambda w(1+\overline{w})G(x) \quad (27)$$

So the product of the strength factor and the lift coefficient can be rewritten in terms of circulation as follows:

$$\sigma c_{l(Calc)} = \frac{2\lambda \overline{w}(1+\overline{w})G(x)}{\left(\frac{U_0}{V}\right)} \quad (28)$$

And in terms of input data (when they are provided, depending on whether the calculation is for the geometry definition or for a propeller with known geometry) through the equation:

$$\sigma c_{l(Input)} = \frac{Bc}{2\pi r} c_l \quad (29)$$

Where the solidity factor was defined for this case as:

$$\sigma = \frac{Bc}{2\pi r} \quad (30)$$

And the calculated helix pitch angle as defined in figure 1:

$$\beta(x) = \alpha + \phi_0 \quad (31)$$

Complementing the above formulations, it is necessary to add the force contributions from the drag force of the profiles. These increments can be calculated considering the equations below:

$$dT_p = -c_d \rho U_0{}^2 \sigma \pi R^2 \sin(\phi_0)\, dx \quad (32)$$

$$dQ_p = c_d \rho U_0{}^2 \sigma \pi R^3 \cos(\phi_0)\, x dx \quad (33)$$

Which in terms of coefficients of thrust and torque are as follows:

$$\Delta K_T = -2\int_0^1 c_d \sigma \left(\frac{U_0}{V}\right)^2 \sin(\phi_0)\, dx \quad (34)$$

$$\Delta K_Q = 2\int_0^1 c_d \sigma \left(\frac{U_0}{V}\right)^2 cos(\phi_0)\, x dx \quad (35)$$

At the end of the calculations, the thrust and torque coefficients need to be increased according to the equations above:

$$K_T = \frac{K_{T_1}}{\left(\frac{R}{R_1}\right)^2} + \Delta K_T \quad (36)$$

$$K_P = \frac{K_{P_1}}{\left(\frac{R}{R_1}\right)^2} + \Delta K_P \quad (37)$$

Where:

$$\Delta K_P = \frac{\Delta K_Q}{\lambda} \quad (38)$$

Below, dimensionless parameters will be presented that will help in the development of equations and in the evaluation of the characteristics of a propeller, starting with the thrust coefficient:

$$K_{T(Input)} = \frac{T}{(0.5\rho R_0{}^2 V^2)} \quad (39)$$

$$K_{T(Calc)} = \frac{2k\overline{w}\left[1+\overline{w}\left(\frac{1}{2}+\frac{\varepsilon}{\kappa}\right)\right]}{\left(\frac{R}{R_1}\right)^2} + \Delta K_T \quad (40)$$

The advance ratio is called:

$$\lambda_{(Input)} = \frac{V}{(\Omega R_0)} \quad (41)$$

$$\lambda_{(Calc)} = \frac{\lambda_1}{\left(\frac{R_0}{R_1}\right)} \quad (42)$$

It is determined as a coefficient of advance:

$$J = \frac{V}{nD} \quad (43)$$

Consider as power coefficient:

$$K_P = \frac{P}{\frac{1}{2}\rho \pi R^2 V^3} = \frac{2k\overline{w}\left[1+\overline{w}\left(1+\overline{w}\frac{\varepsilon}{V}\right)\right]}{\left(\frac{R}{R_1}\right)^2} + \Delta K_P \quad (44)$$

Torque coefficient can be calculated using the following formula:

$$K_Q = \frac{Q}{\rho n^2 D^5} = K_P \lambda \qquad (45)$$

Efficiency is defined as:

$$\eta = \frac{K_T J}{K_Q 2\pi} \qquad (46)$$

CHARACTERISTICS OF HYDROFOILS

Four different hydrofoils were used, the first one was a modified NACA 66 series profile considering a=0.8 since the validation and comparison made with experimental data considered the work [7], which used this hydrofoil.

Other airfoils that were investigated and used in this work were Joukowski (12%), Clark Y and NACA 4415. They were used for comparative studies, evaluating their influence on the dimensionless parameters of the propeller, including efficiency.

The hydrodynamic characteristics, lift and drag, were calculated using the XFoil program for different Reynolds numbers: 50,000, 100,000, 200,000, 500,000 and 1,000,000. Considering that the Reynolds number uses the string as characteristic geometry, that is:

$$\mathrm{Re} = \frac{Vc}{\nu} \qquad (47)$$

The results will be presented below in the form of graphs:

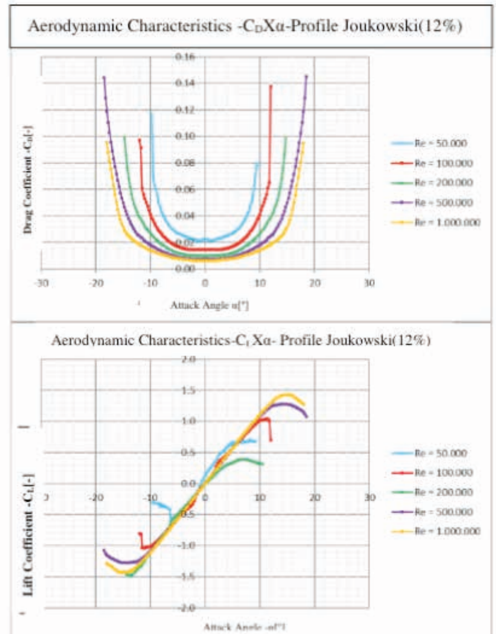

Figure 2. Lift and drag values of the Joukowski hydrofoil (12%) for various Reynolds values.

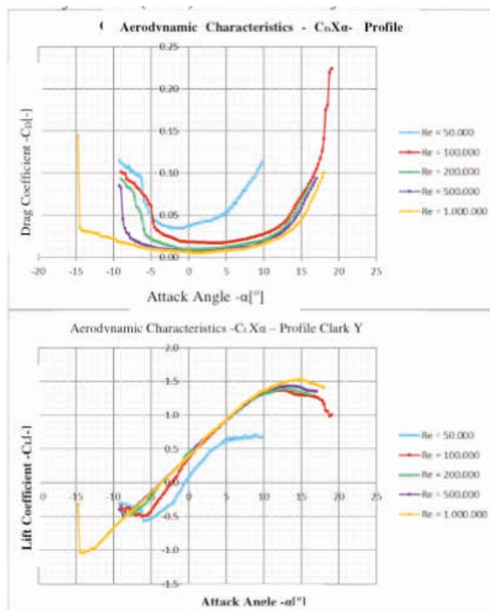

Figure 3. Clark Y hydrofoil lift and drag values for various Reynolds values.

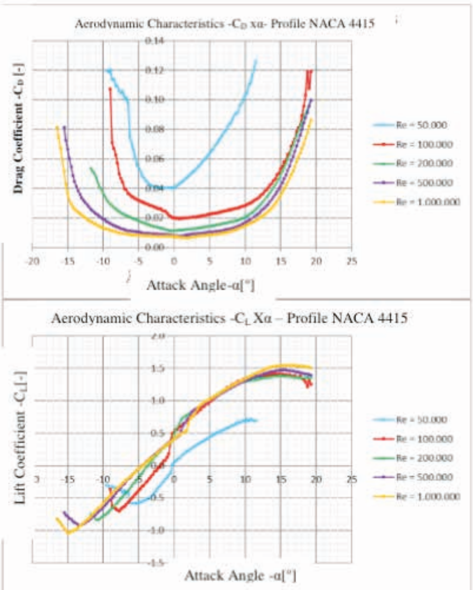

Figure 4. NACA 4415 hydrofoil lift and drag values for various Reynolds values.

CALCULATION PROCEDURE

For the calculation of a thruster, called optimization, the position angle and the chord will be calculated (*c*) of the hydrofoils and having with input data: B, R_h, n, T, R_0, ρ e V. Where n is the rotation.

With these values it is possible to calculate the values of $\lambda_{(Input)}$ through the equation (37) and the value of $K_{T\,(Input)}$ through the equation (35).

The values of λ_1, λ_2 and c are arbitrated and with the value of the number of blades B, as input data, it is possible to determine the values of κ and ε using the tables of [4] also present in the work of [1].

It is calculated $\bar{w}$ according to equation (17) and then the other parameters are calculated until the following differences between the variable values are made:

$$K_{T\,(Calculated)} - K_{T\,(Input)} \leq A \qquad (48)$$

$$\lambda_{(Calculated)} - \lambda_{(Input)} \leq A \qquad (49)$$

$$\sigma C_{l(Calculated)} - \sigma C_{l(Input)} \leq A \qquad (50)$$

Consider that A is a convergence criterion, for example,10^{-6}. The equations are solved considering the Levernberg-Marquardt method, more details about the method and algorithm used can be found in reference [9].

When chord and heading angle values are input, for example: with a propeller of known geometry, the above equations are simpler to solve by simplifying equation (50).

The values of the drag and lift coefficients were calculated and obtained through the XFoil program.

The developed program, when it does not have the value of the string as input data, finds the value of C_l optimized considering the highest ratio of C_l/ C_d, which is linked to an angle of attack value and which varies according to the Reynolds number for each blade section. Therefore, for the optimization calculation, the position angle and chord of the hydrofoil is defined according to the criteria described above, thus optimizing the lift value for an optimized relationship between lift and drag.

After the end of the iteration, the other thruster parameters are calculated.

RESULTS

Considering the method described above, two case studies were designed to validate and compare the methodology. The first case compares the calculated values with experimental data available in [7] and the other case compares results obtained with the methodology of the present work with another methodology developed by [6], noting that for these cases the chord values of the profile for each blade section have already been entered as input data.

From these results, the optimization methodology was applied, obtaining the chord value as a result.

CASE STUDY 1: DTRC 4119 THRUSTER

The first case study contemplates the calculation of an existing thruster with known geometry and available experimental results.

The propeller in question is known as DTRC 4119 and its data can be found in [7] such as diameter of 0.305 m, number of blades equal to 3 and ratio between hub diameter and top diameter of 0.2. Chord, thickness and curvature values along the height of the blade are presented in the table below:

Coda, thickness and curvature values: DTRC 4119			
r/R	*c/D*	t_m/c	f_m/c
0,20	0,3200	0,2055	0,01429
0,30	0,3625	0,1553	0,02318
0,40	0,4048	0,1180	0,02303
0,50	0,4392	0,09016	0,02182
0,60	0,4610	0,06960	0,02072
0,70	0,4622	0,05418	0,02003
0,80	0,4347	0,04206	0,01967
0,90	0,3613	0,03321	0,01817
0,95	0,2775	0,03228	0,01631
1,00	0,0000	0,03160	0,01175

Table 1. Geometric data from DTRC 4119.

Source: Data extracted from [7].

The hydrofoil used in this work was NACA series 66 modified with a=0.8 for all propeller blade sections. The design point of this thruster uses a value of 0.833 for the advance coefficient (J) and 0.150 for the thrust coefficient (K_T) as a reference. In addition to the design point, the thruster's dimensionless parameters were measured at other points with advance coefficients of 0.5; 0.7; 0.9 and 1.1. This detail is relevant, as it allows the assumptions adopted by Theodorsen to be evaluated, that is, with different loading values.

Below graphs indicating the results of the present work in comparison with the experimental data of [7]. First, dimensionless parameters such as feed coefficient, torque coefficient and efficiency are compared.

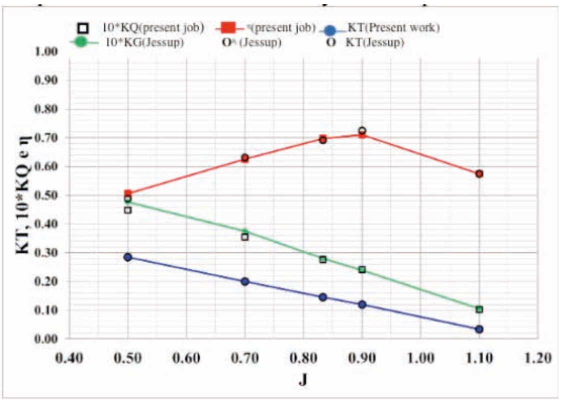

Figure 5. Dimensionless parameters calculated with the present method and experimentally measured for the DTRC 4119 thruster.

When carrying out a detailed analysis of figure 5, there is a maximum difference between calculated and experimentally measured values of 5.99% for K_Q and 3.43% in terms of efficiency both for values of advance coefficient of 0.5. The results demonstrate acceptable consistency between calculated and measured values.

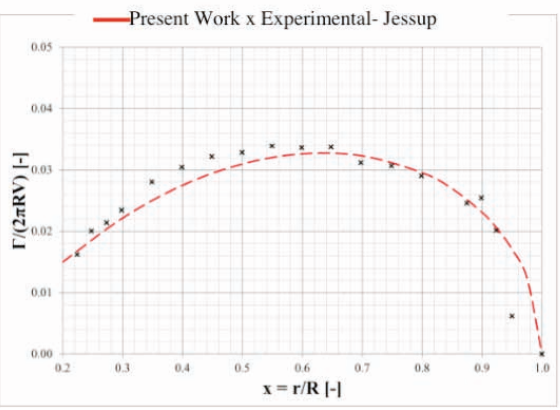

Figure 6. Circulation distribution calculated with the present method and experimentally measured for the DTRC 4119 propellant.

In addition to evaluating these parameters, circulation was also evaluated, considering the value of Γ/((2πRV)). Figure 6 shows the comparison of calculated data and those available in the literature.

Analyzing Figure 6, agreement can be seen between the measured and calculated values, in particular, it is observed that both in the cube (r/R = 0.2) and in the top of the blade, the values are very close, indicating that the methodology for considering the cube in the calculations is valid.

CASE STUDY 2: COMPARISON WITH RESULTS OBTAINED BY THE MVPL CALCULATION PROGRAM FROM [6]

The second case deals with the comparison of results between two different calculation programs. This comparison will allow to extract relevant information for the evaluation of the developed method and thus analyze if the present development is valid for a quick and preliminary evaluation, however with a certain richness of geometric details of a thruster.

The calculation program of [6] has the designation MVPL and is a program based on the theory of the support line and does not use Theodorsen's theory in its formulation. It is also important to mention that this program used in the example that can be found in the work of [6] a value of constant and equal to 0.008, without considering its variation according to the Reynolds number and the angle of attack. Soon the present method was adapted to use this assumption during the calculations.

Below is the rope distribution along the height of the blade in table form:

Life values along the height of the blade	
r/R	*c/D*
0,20	0,160
0,25	0,171
0,30	0,182
0,40	0,202
0,50	0,220
0,60	0,230
0,70	0,231
0,80	0,217
0,90	0,181
0,95	0,139
1,00	0,001

Table 2. Geometric data of the thruster used by [6] for calculation using the MVPL program.

Source: Data extracted from [6].

Below are indicated more relevant data of this propellant used in the analysis:

1. Aerodynamic profile used was NACA 65A010 as a=0.8;
2. Propeller diameter = 3.00 m;
3. Cube diameter = 0.60 m;
4. Quantity of blades = 6;
5. Rotation = 120 RPM;
6. Specific mass of the fluid (water) = 1.025 kg/m³;
7. Kinematic viscosity of the fluid (water) = 1.6438 x 10^{-6} m²/s;
8. V = 4,5 m/s;
9. J = 0,750;
10. T = 45.000 N;
11. K_T = 0,1355.

Just below, figure 7 presents the circulation distribution along the height of the blade, considering the value of $\Gamma/(2\pi RV)$.

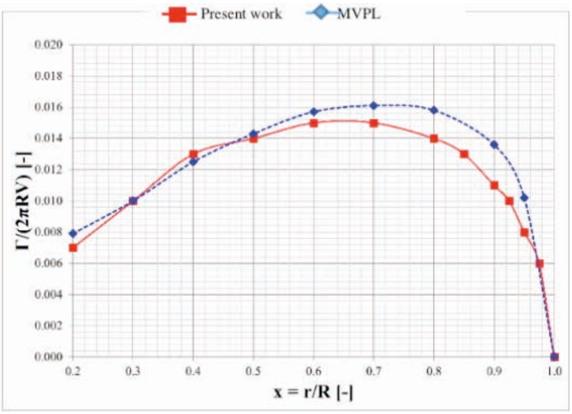

Figure 7. Circulation distribution calculated according to the present method and according to the MVPL program from [6].

There is consistency between the values of the two methods, especially highlighted in the cube ($r/R = 0.2$), the values are very close, also indicating for the second case study that the methodology to consider the cube in the calculations can be used. The largest deviation of 0.003 was found at the value of $r/R = 0.9$.

The comparative results also indicated that the efficiency values for the two methods were close, with the present method resulting in an efficiency value of 71.91% and the result of the MVPL program was 70.94% for the same variable.

CASE STUDY OPTIMIZATION 1

In this section of the work, a parametric and comparative study was carried out considering as initial data the validation values for case 1. This study consisted of applying other hydrofoils to the propeller blade sections, considering the same number of blades as the reference propeller., that is, with 3 blades, see the table below indicating the efficiency values for each case.

Hydrofoils and efficiency values	
hydrofoil	Efficiency (%)
NACA 66 (a=0,8)	71,291
Clark Y	70,270
Joukowski (12%)	71,141
NACA 4415	70,150

Table 3. Parametric optimization study of a propeller considering different hydrofoils for the propeller blade sections.

Source: Own elaboration.

In the figure below it is possible to evaluate the chord distribution along the height of the blade for several optimized results in comparison with the propeller of [7].

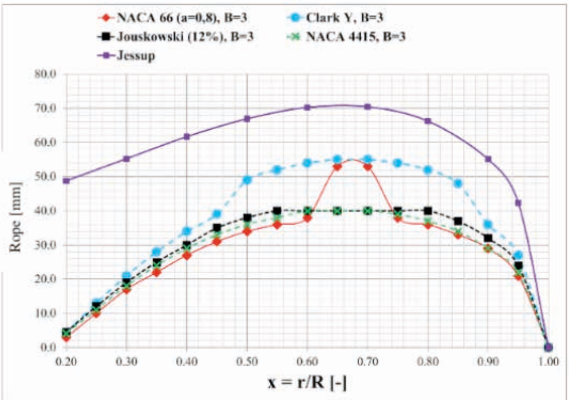

Figure 9. Distribution of chord values when comparing thrusters designed with different types of profiles and considering the reference of [7].

Note that the optimization methodology allows reaching smaller chord values than the case before being optimized, thus allowing to improve the ratio between weight and power of a propeller, a relevant design parameter.

The chord distribution considering the Clark Y hydrofoil and the NACA 66 (a=0.8) showed reliefs in regions between r/R = 0,5 e 0,9. This characteristic is a result of the optimization made considering the values of lift, drag and Reynolds number related to the chord at the same time. In these regions, a better relationship was sought between all these parameters that would culminate in the highest value of lift by drag for a given Reynolds number.

CASE STUDY OPTIMIZATION 2

Starting from the initial data of case 2, a table is prepared with the result in terms of calculation efficiency using the MVPL program, considering the present methodology for validation and optimization, arriving at the following results:

Hydrofoils, efficiency values and method description		
hydrofoil	Efficiency (%)	Description
NACA 65A010 (a=0,8)	70,94	MVPL
NACA 65A010 (a=0,8)	71,91	Validation
NACA 4415	72,80	Otimização

Table 4. Comparative study for case 2.

Source: Own elaboration.

When observing the results above, we notice an increase in efficiency in the case of the optimized propeller by 0.89%.

By applying the optimization methodology, the following result in terms of chord distribution along the blade height was achieved:

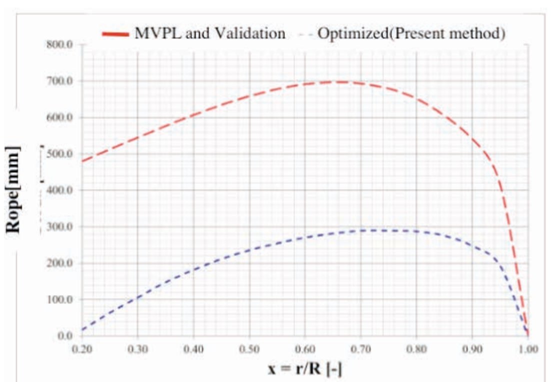

Figure 10. Distribution of string values when comparing the thruster of the reference [6] and the optimization of this case.

Through Figure 10 it is possible to identify a significant reduction in terms of rope and consequently weight of the propeller. Therefore, when we consider the optimizations of the lift and drag values taking into account the viscous effects through the Reynolds number, it is possible to notice a great significance in terms of results based on this premise.

CONCLUSIONS

The calculation program developed from the above methods proved to be a relevant tool for predicting dimensionless parameters of a propeller such as efficiency, power coefficient, torque and thrust, as well as for defining the position angle of the hydrofoils and chord distribution along the height of the shovel.

The Levenberg-Marquardt method and the sequence of calculations applied to solve the equations in this work, differing in parts from other literature, indicated to be a viable procedure and a different option for solving the problem.

Comparisons made with experimental data and results from another calculation program showed acceptable agreement in the results, thus validating the method employed.

Regarding the optimization method, it offers the possibility to study new rotor geometries with optimized chord distribution and in some cases with greater efficiency, thus being one of the important tools if the objective is to achieve, for example, a lighter thruster design.

All calculations in this article took no more than fifteen seconds to be performed considering the use of a computer with 2.60 Gigahertz processors, 16.0 Gigabyte of RAM and a 64-bit operating system.

For future projects, it is recommended to explore applications more and more and implement methodologies such as, for example, computational fluid dynamics. The methodology presented here therefore represents an option for generating preliminary designs before more complex calculations, which take a significant amount of time and effort.

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