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A METHODOLOGY APPLIED TO MARINE PROPELLERS DESIGN BASED ON THE BEM METHOD

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Abstract. *This paper describes a mathematical model applied to the efficient design of marine propellers based on the Blade Element Momentum (BEM). The BEM method corresponds to a classic technique of one-dimensional analysis applied to marine propellers design, and shows good results when compared with practical data. Another advantage of the BEM method is the easy implementation and low computational cost. The proposed model optimizes the chord and twist angle distributions of the marine blade propeller using the BEM technique, considering the effects of viscous. To avoid cavitation is implemented the minimum pressure coefficient criterion as a limit for a without cavitation flow over the hydraulic profile along of the propellant. The proposed model promotes a change in the load coefficient of the propellant to be no considering the cavitation effect at the nominal operating point. The results are compared with other geometries in the literature, with good results.*

Keywords: *Mariner propeller, Glauert's model, Propellant blade optimization, Cavitation effect.*

1. INTRODUCTION

The search for methods for the design of marine propulsion systems have been the subject of interest of scientists and engineers for a long time. Some theories for the analysis and design of propellers have been develop, however, the complexity of building models of blades based on an operating point of a propulsion system is difficult, since it is necessary to consider the influence of the viscous flow around the helix, addition of the velocity field and pressure surfaces of the blades. The use of numerical techniques is becoming ever more significant, as they present solutions with good agreement compared with experimental results. However, theoretical techniques are more consistent as to the accuracy of propeller design, but are much more complicated to develop, the need for knowledge of the physical characteristics of the flow around the propeller.

Thus, this work present an analytical mathematical approach with the aim of seek the efficient design of propellers for naval vessels based in the Glauert's (1935) theory, considering the effects of viscous flow and loss at the tip of the blade through correction Prandtl's factor (Vaz, *et al*.,2011). The results are compare with the optimal efficiency obtained by Glauert (1935).

2. MATHEMATICAL MODEL

In this paper, consider the propeller able to transfer energy from shaft to the flow. The flow of water through the propeller takes place according to Fig. 1 where the speed V, upstream of the propeller is increased by propulsive due to the transfer of kinetic energy. Therefore, given the axial flow and applying the equations of conservation of mass, energy and momentum, for volume control of Fig. 1, relations are obtained for determining the thrust dT and torque dQ on an element annular volume control.

$$dT = \pi s r \rho \Omega \; 1 - a' \; \lambda_1 \sec\phi \, dr \qquad (1)$$

$$dQ = \pi s r \rho \Omega \; 1 - a' \lambda_2 \sec\phi \, dr \qquad (2)$$

where r is the radial position of the propeller, ρ is the density of water, Ω is the angular velocity of the propeller, *a'* is the rotational inflow factor interference about the rotational propellant flow, ϕ is the actual pitch angle and *s* is the strength of the blade element, and is defined by:

$$s = \frac{Nc}{2\pi r} \qquad (3)$$

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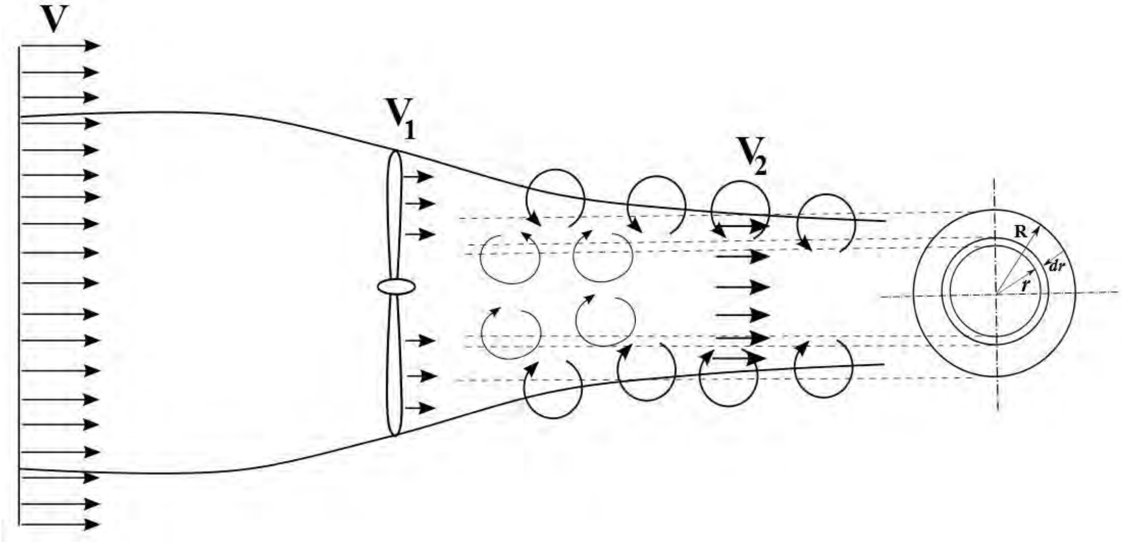

Figure 1. Illustration of the stream around propeller.

The parameters λ_1 and λ_2, shown in Eqs. (1) and (2) are obtained from the analysis of lift and drag forces acting on a section of the propeller blade, according coma Fig. 2, and correspond to the resulting forces in the x and y directions, normalized by the term $1/2\,\rho A W^2$.

$$\lambda_1 = C_L \cos\phi - C_D \sin\phi \qquad (4)$$

$$\lambda_2 = C_L \sin\phi + C_D \cos\phi \qquad (5)$$

where W is the relative velocity of the hydrodynamic flow on the profile, $C_D$and C_L is the drag and lift coefficients respectively, α is the incidence angle (or angle of attack), θ is the twist angle of the propeller blade (or angle geometric pitch) and$a$ is the axial interference factor paddle on the incident flow.

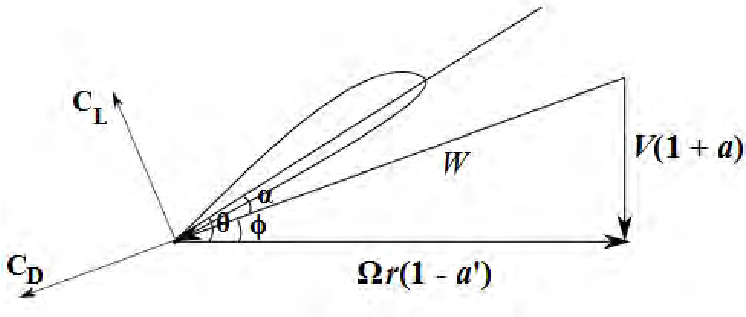

Figure 2.Forces and velocities acting on a section of the blade.

In the condition in which the cavitation effect is not considered, the geometric shape of the helix can be obtained by calculating the distribution of chord c and the blade twist angle is given by:

$$c = \frac{4\pi r}{N}\frac{aF}{1+a}\frac{1-\cos(2\phi)}{\lambda_1} \qquad (6)$$

$$\theta_{opt} = \tan^{-1}\left[\frac{1+a}{x(1-a')}\right] + \alpha \qquad (7)$$

where:

$$a_{opt} = \frac{(1+\varepsilon^2)(x\varepsilon-3)+\{\varepsilon[3x+\varepsilon(3-\varepsilon x)]-1\}\cos(4\phi)+\left[x-\varepsilon(\varepsilon^2-3+3x\varepsilon)\right]\sin(4\phi)}{4(1+\varepsilon^2)} \qquad (8)$$

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$$x = \frac{\Omega r}{V} \tag{9}$$

$$\varepsilon = \frac{C_D}{C_L} \tag{10}$$

Equation (8) carries information about the viscous flow effects between the propeller, caused by the drag of the screw. To determine a relationship between $a$and ϕ,consider the expressions described in the work of Glauert(1935)for the axial and rotational interference factors, given by Equations (11) and (12) respectively.

$$\frac{a}{1+a} = \frac{s\lambda_1}{2F\left[1-\cos\left(2\phi\right)\right]} \tag{11}$$

$$\frac{a'}{1-a'} = \frac{s\lambda_2}{2F\sin\left(2\phi\right)} \tag{12}$$

where F is the Prandtl'sFactor (Wald,2006), which conducted a study on the theory and design of propulsion with minimum induced loss, and suggests the Prandtl'sfactor as being good value for correcting the effect of loss energy at the tip of the blade. The Prandtl's factor, too, has been extensively used in the case of design of horizontal axis wind turbines and provides for the loss at the tip and at the root of a wind blade (Vaz*et al*, 2011). This factor is defined as the ratio between the ends of the blade movement and the movement for an infinite number of blades, and is given by:

$$F = \frac{2}{\pi}\cos^{-1}\left[\exp(-f)\right] \tag{13}$$

$$f = \frac{N}{2}\frac{R-r}{r\,\mathrm{sen}\,\phi} \tag{14}$$

$$J = \frac{V}{n\,D} = \pi\frac{r}{R}\frac{V}{r\Omega} = \pi\frac{r}{R}\frac{1-a'}{1+a}\tan\phi \tag{15}$$

$$\tan\phi = \frac{1+a}{x\left(1-a'\right)} \tag{16}$$

The Figure 3 shows the flow diagram of the procedure in order to obtain Chord and optimal twist angle for each blade station, no considering cavitation effect.

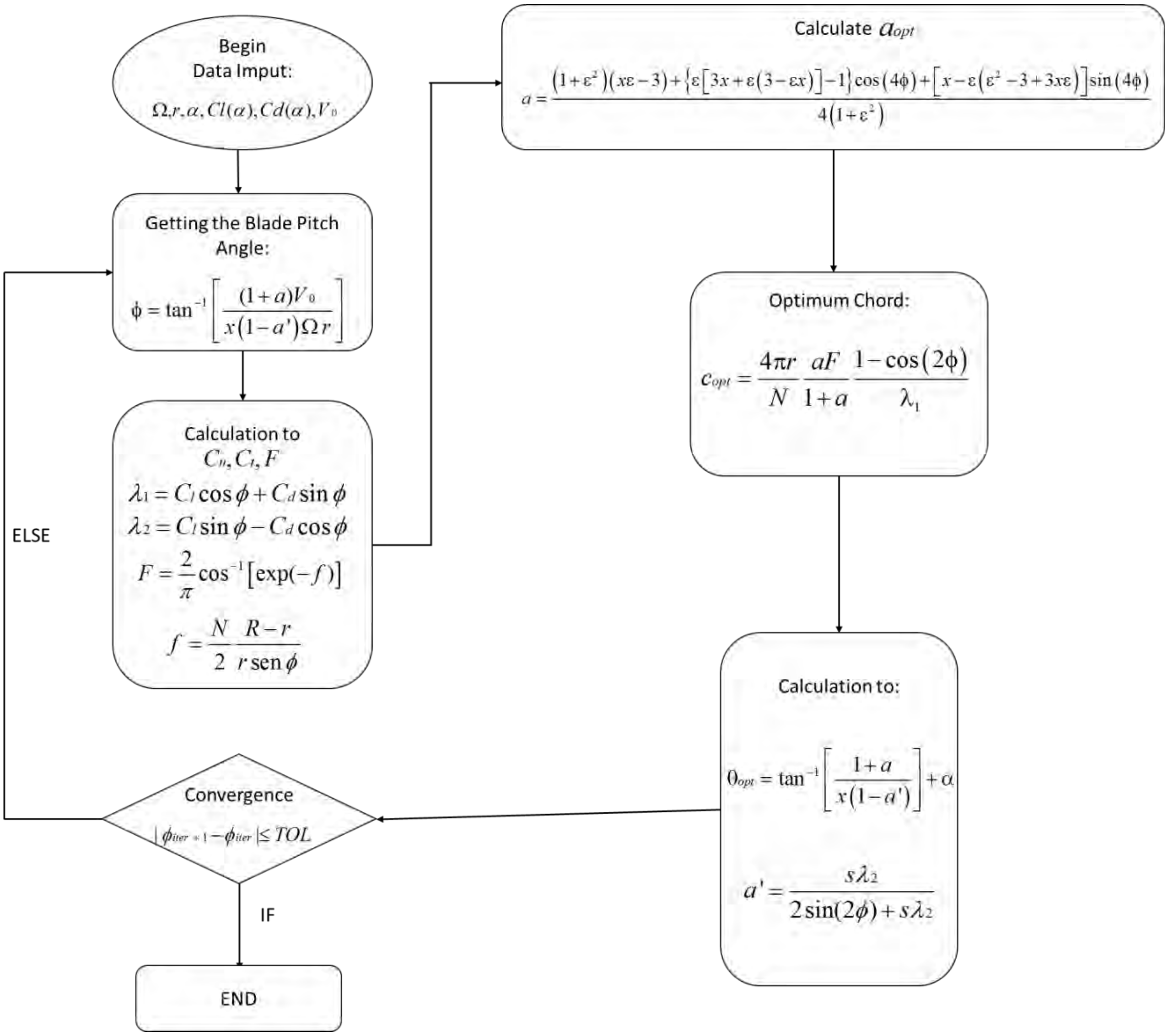

Figure 3. Routine to obtain Chord and Twist Angle, without considering cavitation effect.

3. RESULTS AND DISCUSSIONS

To evaluate the performance of the method and the influence of viscous dissipation of the flow around the propeller, we use the information shown in Table 1, which were obtained from Glauert (1935), at r/R = 0.7, s = 0.1 e $\theta = 24^0$.

Table 1. Parameters for a blade element according to Glauert(1935).

α (^{0})	ϕ (^{0})	λ_1	λ_2	a	a'	J
4	20	-0.012	0.036	-0.003	0.003	0.80
6	18	0.204	0.088	0.056	0.007	0.67
8	16	0.410	0.132	0.156	0.012	0.54
10	14	0.610	0.164	0.363	0.017	0.40
12	12	0.780	0.178	0.820	0.021	0.25
14	10	0.964	0.186	4.000	0.026	0.08
16	8	1.136	0.180	-3.13	0.032	-0.14

Figure 5 shows a comparison of proposed method and the results for optimum efficiency with a propellant described in Glauert (1935) in relation to the feed place coefficient J. It is observed that for zero drag ($\varepsilon = 0$), ie, without the influence of viscous dissipation, the model converges to the theoretical model Glauert. As the trawl becomes appreciable decrease the proposed model for calculating the local efficiency of the thruster, this effect was predicted by

Glauert, and occurs due to friction losses in the helix surface. Therefore, the proposed model physical consistency, compared to the classical model of Glauert.

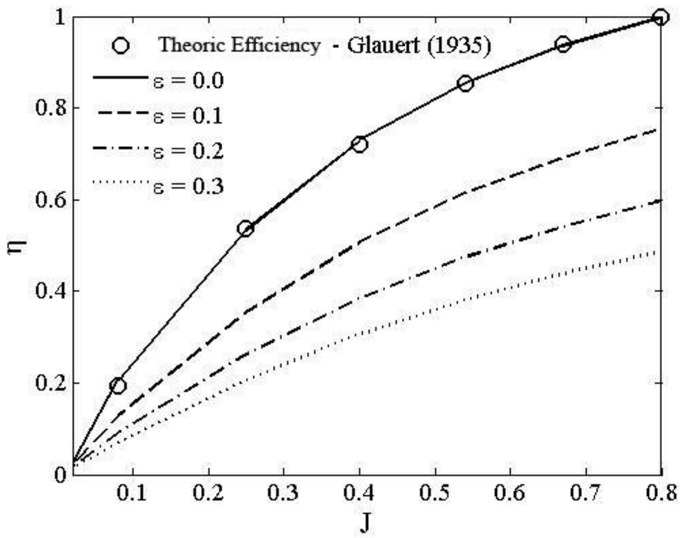

Figure 5. Efficiency location relative to the advance coefficient location.

To evaluate the effect of viscosity on screw geometry, it is considered in an analysis system of open water (without contribution imposed by the coupling of the vessel with propellant) to a propeller with blades 4, the water density of 997 kg/m3 , boss diameter of 0.3 m, 0.1 m, rotating shaft 1200 rpm, constant angle of attack of 10 and hydrodynamic aerofoil NACA 66206 (Abbot *et al*, 1959) for Reynolds number $5x10^5$. The hydrodynamic aerofoilis shown in Figure 6, and coefficients of lift and drag are shown in Figure 7. Table 2 shows the results obtained in this case, calculated from the hydrodynamic model proposed.

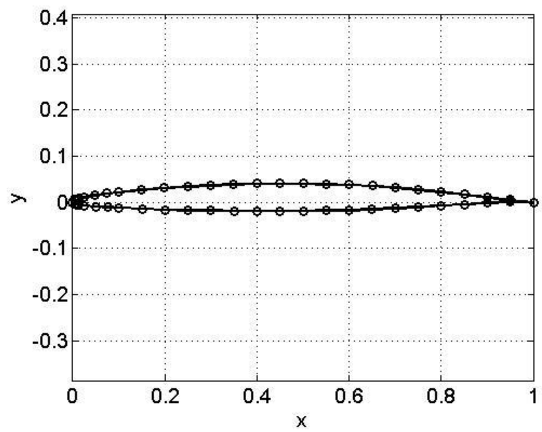

Figure 6. NACA 66206(Abbot *et al*, 1959).

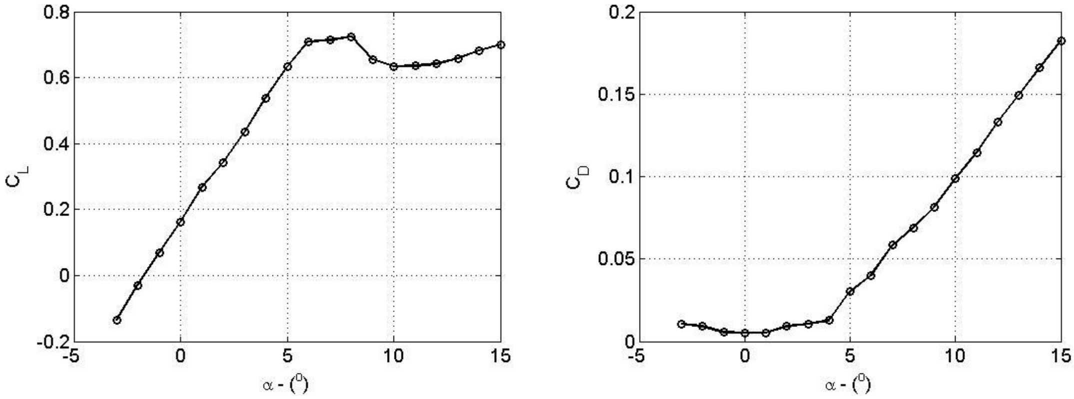

Figure 7. (a) Lift coefficient and (b) drag coefficient as a function of angle of attack for the hydrodynamic profile NACA 66206 (Abbot *et al*, 1959)- Reynolds $5x10^5$.

Table 2.Amounts effective pitch angle and the local coefficients of thrust and torque (no viscosity effect) to ten radial screw sections.

i	r/R	ϕ	k^*_{Ti}	k^*_{Qi}
1	0,333	0,278	0,01706	0,00092
2	0,407	0,278	0,05711	0,00363
3	0,481	0,278	0,12224	0,00898
4	0,556	0,278	0,21763	0,01813
5	0,630	0,278	0,34678	0,03231
6	0,704	0,278	0,50764	0,05232
7	0,778	0,278	0,68450	0,07732
8	0,852	0,278	0,83287	0,10232
9	0,926	0,278	0,84289	0,11190
10	1,000	0,278	0,07763	0,01108

where the index i corresponds to the radial position of the blade, and locations are the coefficients of thrust and torque without the viscous contribution as defined in O'Brien (1962) by:

$$k^*_{Ti} = \frac{R\frac{dT_i}{dr}}{\rho D^4 n^2}$$

$$k^*_{Qi} = \frac{r\tan\phi}{2R}k^*_{Ti}$$

The results in Figure 8 show that the viscosity effect resulting in a decrease in buoyancy of the propeller and an increase in torque. This result was also founded by O'Brien (1962), who developed a theoretical study of the effect of viscous dissipation on the coefficients of thrust and torque of marine propellers. The local coefficients of thrust and torque for the effect of viscosity are given by:

$$k^*_T = \left(1-\varepsilon\tan\phi\right)k^*_{Ti}$$

$$k^*_Q = \left(1+\frac{\varepsilon}{\tan\phi}\right)k^*_{Qi}$$

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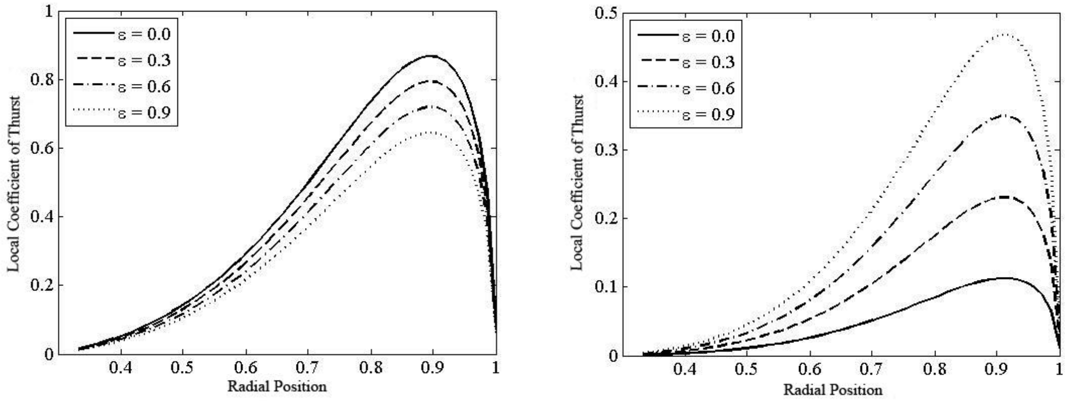

Figure 8. (a) Local thrust coefficient (k_T^*) and (b) Local torque coefficient (k_Q^*) as a function of radial position.

It is worth noting that the model does not consider the effect of cavitation. However, considering the effect of energy loss at the blade tip due to movement caused by the rotational movement of the propeller.This effect is quantified by Prandtl'sfactor (Wald, 2006). Moreover, the model presented in this paper has two important features for the efficient design of marine propellers: (1) consider the influence of viscous fluid on the engine and (2) be easy to implement.These characteristics represent important contributions to the advancement of efficient models for the design of marine propellers, since in the literature there is a big shortage of models based on BEM theory (Favacho *et al*, 2012), which in general are models that generate good results when compared with real data. Figure 21 shows the distribution of rope and twisting of the propeller according to the variation of the viscous effects. It is observed that as the viscosity is much more intense the distribution of rope, the torque distribution become greater. This occurs because, to overcome the viscous dissipation should be increased and the twist of the cord so that the propeller thrust and torque on the propeller also grow as described on Figure 9, so that the location of the propeller efficiency is not compromised as shown in Figure 10, where there are abrupt differences in the efficiency curves of the propellant when the effect of viscous increases, showing that the proposed model search mater good efficiency even in conditions of high viscous dissipation, by modifying the geometry of the helix.

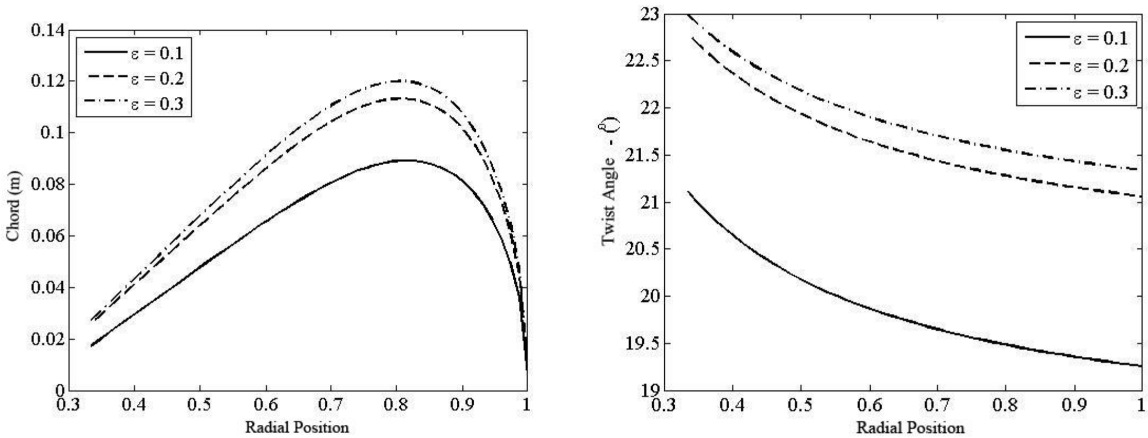

Figure 9. (a) Distribution of chord and (b) distribution of the blade twist angle on propeller.

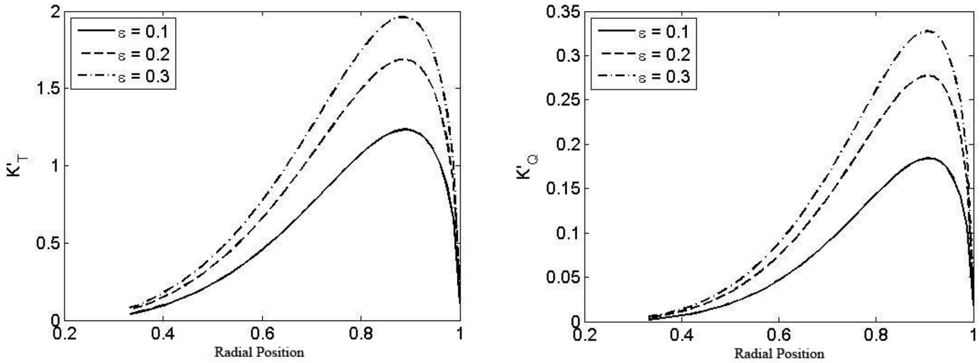

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Figure 10. (a) Local thrust coefficient (k_Q^*) and (b) Local torque coefficient (k_T^*) as a function of radial position.

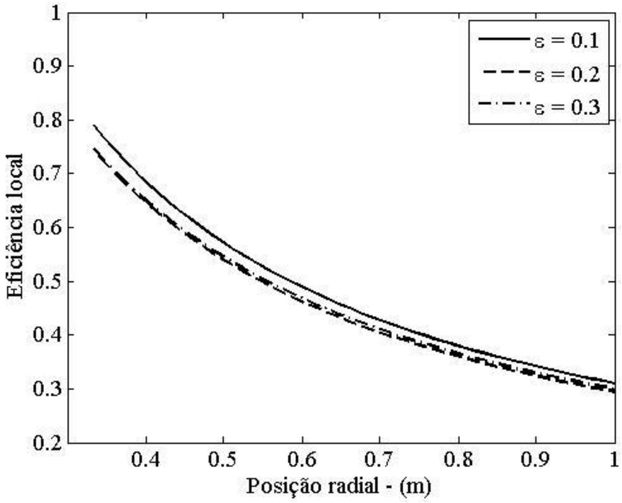

Figure 11.Local propeller efficiency as a function of radial position for each blade element.

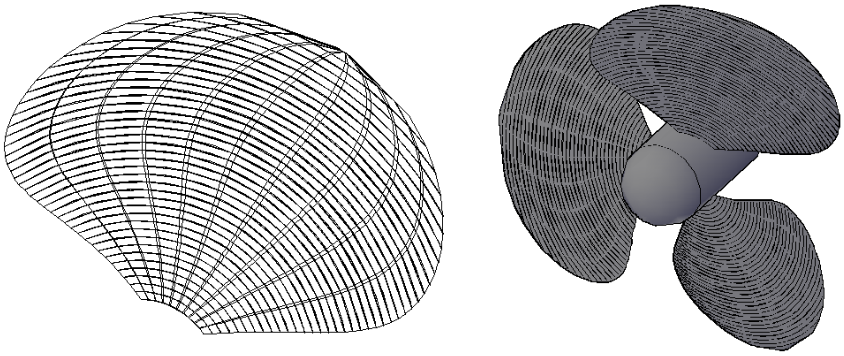

Figure 12.(a) Details of the blade designed. (b) Propeller 3 blade designed in 3D.

4. CONCLUSIONS

The model of the hydrodynamic design of marine propellers presented in this work represents an alternative toolin which an extension is used Glauert model (Glauert, 1935), the effects of rotation of the conveyor and the viscous influence on the propeller. The proposed method features easy computational implementation, low processing time and considers the viscous effects on the propeller. The results show that the mathematical model, given open water system

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converges to the theoretical Glauert model (Glauert, 1935), with physical consistency. The propellant designed with the methodology described in this study has good efficiency. It is emphasized that optimization models hydrodynamic propellers are scarce, highlighting the difficulties in developing more accurate comparisons, especially for small boats, which are present in greater numbers in the Amazon region.

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