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Horizontal Axis Marine Turbine: Alternative Hydrodynamic Procedure to Obtain Rotor Blade Static Loads.

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ABSTRACT

Transforming the kinetic energy of the sea into renewable useful source electricity could be a relevant technologic development in the near future. In this field, marine horizontal axis turbines (HAT) are possibly, the most important devices. The current calculation techniques used to obtain the acting forces or loads in the marine current horizontal axis rotor blades: Actuator disc models, lifting lines and finite element method, have certain disadvantages which lead difficulties to obtain relatively quick results, in addition, these methods are not easy to understand and mastering, and furthermore, complex computing tools are required to obtain results. In the present work, the common physical and mathematic fundamentals will be studied and analyzed with the aim to create a new easier managing calculating tool. The proposed procedure of this document can be considered as a help towards to calculate preliminary solutions easier, and also a starting point to manage physical ideas which could be used with other calculation tools. And finally, the mathematic fundamentals will be explained and the implementation of the equations in a real case. Nevertheless, due to the real complexity of the problem, the assumed simplifications of this model must be taken into account, in order to know the possible calculating limitations of this procedure and consequently use it correctly.

1. Introduction

In the marine renewable energy realm, there are many devices that allow transforming the kinetic energy of the sea movement into electricity (López 2014). The horizontal axis turbine (HAT) with open rotor is probably one of the most important devices, because many of technologies developed in wind turbines, in the recent years, can be recycled in marine turbines due to the analogous functioning. In addition, the marine current turbines have an enormous potential in electricity generating, because, in certain geographical areas (Scotland's North, Gibraltar's Strait), it exist great extracting energy possibilities from tidal or inertial currents (López 2011). All these arguments provide, from a theoretical point of view, optimum electrical generating conditions, and thus, the marine HAT is the most suitable device for this activity.

Marine HAT functioning, as it was said above, is analogous with wind turbines, the basic principle is the loads or forces generated in its blades when a fluid current, which in this case is sea water (Bahaj 2007, Batten 2008), is passing through them. These forces or loads move the turbine rotor which also moves an electric generator. At the current time, there are various techniques used to calculate these hydrodynamic forces in a rotor blade. Depending on the nature and focus in each of them, the techniques could be classified among the following groups:

a) Actuator Disc Method.

b) Lifting Line Method.

c) Finite Elements Method.

Each one of these methods or techniques has advantages and disadvantages when they are used to obtain results of a certain rotor. Maybe the most important common inconvenience

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for all of them is the conceptual complexity, which leads in extremely hard to handle tools and great difficulty in understanding, in a relative few time, all the concepts and mastering the calculating steps.

From the state of the art analysis, it could be concluded that there is a great conceptual scattering and the lack of explanation the basic fundamentals ideas used in the articles and documents related with marine turbines (Nichols 2013). So that, at first moment, the idea of trying to extract the main mathematical fundamentals, in order to understand the principles, and then obtaining optimal geometric rotor blade designs encouraged the starting of this work.

Finally, the purpose has been achieved by creating a new tool, which can be used at first instance to estimate the static blade HAT (Kolelar 2013) loads and the power extracted in a rotor (Collier 2013), but, without using excessively complex fluid mechanics concepts. In this way, this alternative method or procedure will consist in a 3D rotor modeling which allows obtaining preliminary results and also could be used as a starting point to manage the most important mechanical fluid concepts concerned in marine turbines, in order to make an intermediate step before studying and mastering the advanced techniques written in the list above.

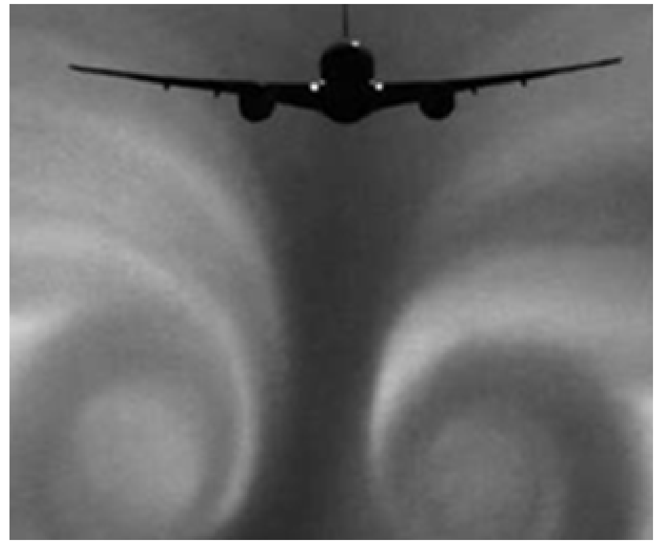
2. Mathematic Fundamentals

The main basic idea that inspire this new calculating procedure, is the wake created behind an airplane, which can be observed in many publications and photographies, such as the showed in Figure 1, extracted from the Reference 1 (Pijush, Cohen, Rowling 2011). The velocity field in the wake, are mainly formed by two vertexes which have the same vorticity, it means that the fluid around each vertex is rotating with the same circulation's intensity but with the opposite sense. This velocity field is described and studied in various documents related with the Fluid Mechanics, such as the showed in Reference 2 (Milne-Thompson 1968), with the corresponding equations.

Supposing that, these two vertexes are part of the same vertex line, and according with the First Helmholtz Theorem, which establishes that the circulation's intensity remains constant along a vertex line, thus, it is expected that the wake formed behind a marine turbine blade is analogous with the wing airplane; despite in this case, the movement of the blade is rotational. This is the main hypothesis, and all the following mathematical development is based on it.

At first, in order to start the analysis of the velocity field in marine horizontal-axis turbine blade, it is necessary to define a control volume that contains a blade, the geometry of the frontier surface is formed by six planes and eight corners named by the letters ABCDEFGH. The arrangement of these control surfaces is showed in Figure 2. The sea water fluid particles entries in the volume control, with the current velocity, named by the letter U, through the surface BCFG, and also the fluid particles are entering the control volume with the rotor rotational velocities ωr through the surface ABCD; where ω is the rotational angular velocity and r is the distance between the rotor's origin and a determined radial position in the blade. On the other side,

Figure 1: Wake produced behind an airplane.



Source: Authors

the water leaves the control volume trough the surfaces defined by the corners ADEH and EFGH. Finally, it can be considered approximately, that there is no fluid particle passing through the surfaces ABFE and CDGH. If a is the rotor hub radius, b is the blade radius, Z the number of blades and z the axis in the fluid current direction, the control volume is represented in Figure 2.

In the surface EFGH, owing to the main hypothesis made before, the blade wake is mainly formed by two vertexes, V_1 and V_2. If Γ is the intensity circulation of these vertexes, and v_r , v_z the velocity components in r and z directions respectively, the velocity field produced in this plane is defined by the following equations and represented in Figure 3.

$$v_r = \frac{\Gamma}{2\pi}\left[\frac{z}{(r-a)^2+z^2} - \frac{z}{(r-b)^2+z^2}\right] \tag{1}$$

$$v_r = \frac{\Gamma}{2\pi}\left[-\frac{r-a}{(r-a)^2+z^2} - \frac{r-b}{(r-b)^2+z^2}\right] \tag{2}$$

These equations above are deducted from expressions studied in the Reference 2 (Milne-Thompson 1968), in which the complex velocity potential produced by two vertexes is represented. The main changes made are: to transform the complex velocity into a two real variable function and a origin translation, in order to set up the velocity field in its correct spatial location.

The last consideration is about the perpendicular velocities to the planes EFGH and ACDH, as it was said before, by these planes the fluid leaves the control volume. These velocities will be treated as unknown variables named by U^* in the case of the plane ACDH, and $v^*_{\omega r}$ in the plane EFGH, as it is showed in Figure 4, and it is supposed that they only are r depending, thus $U^* = U^*(r)$ and $v^*_{\omega r} = v^*_{\omega r}(r)$.

The following mathematical development is based on the mass, momentum and energy volume control equations, combined with the two dimensional foil theory, which establish that

Table 1: Advantages and disadvantages of calculating methods used marine turbines.

	Actuator Disc Method	Lifting Line Method	Finite Element Method	Alternative proposed procedure
Advantages	Conceptually Intuitive	Most common used method. Very real approximated results can be obtained.	Great accurate results can be obtained 3D rotor detailed models can be carried out.	Based on basic fluid mechanics concepts. It could be an intermediate step in order to manage an advanced tool in the future. Can be programmed in a calculating sheet or other easy-using calculating tool.
Disadvantages	Not easy to implement a certain rotor geometry Non-rigorous Mathematic ideas are used trying to estimate the induced velocities.	The master of complex fluid mechanics ideas and formulation is required.	Great time and work consuming. Great calculating power machines and software are required.	The possible results must be checked. Complex fluid phenomena's are not taken into account.

Source: Authors

Figure 2: Blade's control volume layout.

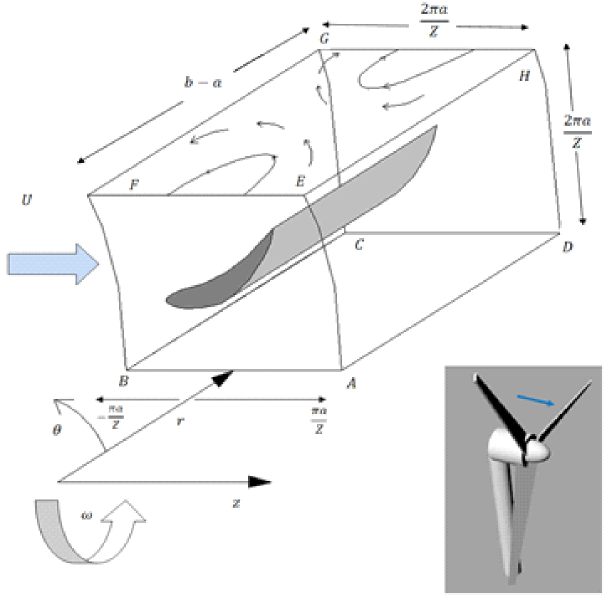


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Figure 3: Velocity field in the control surface EFGH.

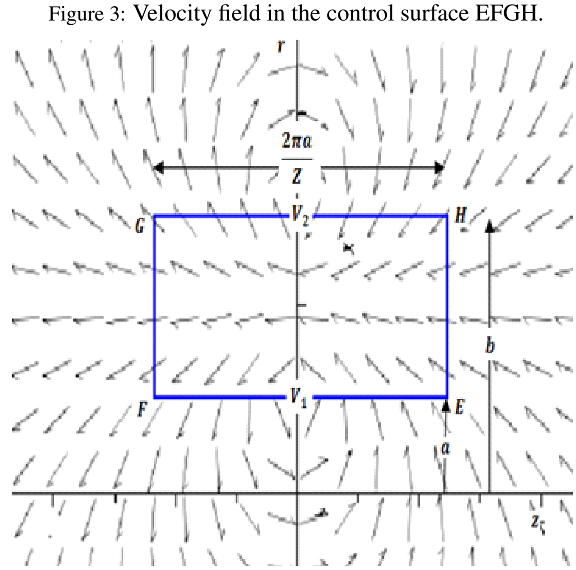

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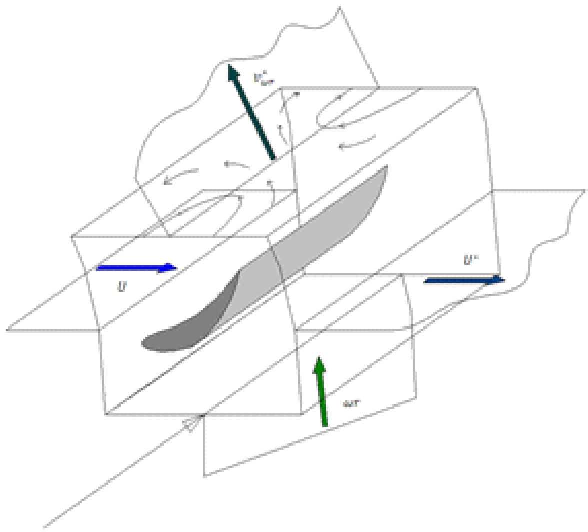
Figure 4: Representation of U^* and $v^*_{\omega r}$ schematically.



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when a foil is in a moving fluid of density ρ at velocity V, it produces two forces in the foil, one parallel to V, and the other one is perpendicular named by D and L respectively.

$$L = \frac{1}{2}\rho c_L c V^2 \tag{3}$$

$$D = \frac{1}{2}\rho c_D c V^2 \tag{4}$$

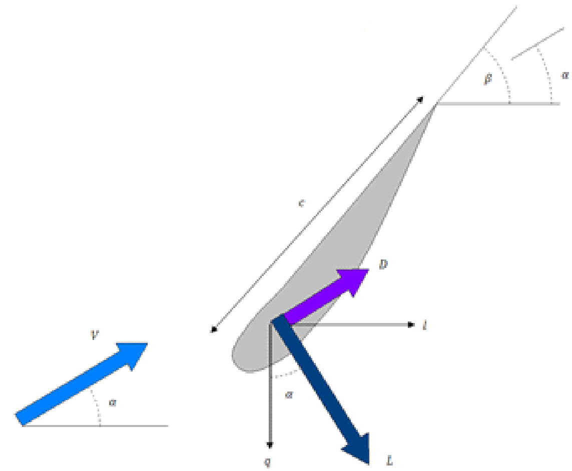
In the equations above, c represents the chord of the foil and it is the distance between the attack edge and the trailing edge. The lift coefficient is c_L and the drag coefficient is c_D, these two coefficients are depending mainly on the geometry of the foil and the angle which the foil forms with V (attack angle). Calling α and β to the angle which V and the foil forms with a horizontal reference respectively, then the attack angle γ , in which c_L and c_D functions are depending of ($c_L = c_L(\gamma)$ and $c_D = c_D(\gamma)$) , is related with α and β according to the following equation.

$$\alpha = \beta - \gamma \tag{5}$$

If the forces L and D are projected in the horizontal and vertical directions, as it is represented in Figure 5. The horizontal component l must be supported by the blade structure and thus it is a static load. The vertical component q is the force which produces the rotor movement, so that the expressions of l and q are:

$$\begin{aligned} q &= \frac{1}{2}\rho c_L c V^2 \cos\alpha - \frac{1}{2}\rho c_D c V^2 \sin\alpha \\ &= \frac{1}{2}\rho c V^2 (c_L \cos\alpha - c_D \sin\alpha) \end{aligned} \tag{6}$$

Figure 5: Forces applied in a blade section.



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$$\begin{aligned} l &= \frac{1}{2}\rho c_L c V^2 \sin\alpha - \frac{1}{2}\rho c_D c V^2 \cos\alpha \\ &= \frac{1}{2}\rho c V^2 (c_L \sin\alpha - c_D \cos\alpha) \end{aligned} \tag{7}$$

A important aspect to take into account is that actually the velocity V and the angle α are both unknown variables, nevertheless, on one side V can approximated to $V \approx \sqrt{U^2 + (\omega r)^2}$, and on the other side α is depending on β and the attack angle γ, according to equation (5). So that the expressions of l and d can be written depending only in the unknown attack angle γ.

$$q = \frac{1}{2}\rho c \left[U^2 + (\omega r)^2\right] \left[c_L \cos(\beta - \gamma) - c_D \sin(\beta - \gamma)\right] \tag{8}$$

$$l = \frac{1}{2}\rho c \left[U^2 + (\omega r)^2\right] \left[c_L \sin(\beta - \gamma) + c_D \cos(\beta - \gamma)\right] \tag{9}$$

To sum up, the unknown variables of the problem are: $v^*_{\omega r}$, U^*, Γ and the attack angle γ. The blade geometry is defined by the two dimensional foil selected with its chord c and the geometric pitch angle β, at every r section.

2.1. Equation Resolution

Due to the nature of the developed equations, a numerical solving method must be used, and it consists in divide the blade in a finite number of sections, being δr the radial length of these sections. Every section will be identified, in the calculating steps, by the sub-index k. In this way, k will be equal to 1 in the nearest hub blade section, and in the blade end section k will be n. Thus, it results obviously that summing all the length sections is equal to the blade length. The following equation represents this consideration.

$$\sum_{k=1}^{n} \delta r_k = b - a \tag{10}$$

Using this numerical method, despite the equations are fairly complicated, it is not very hard to implement them in an excel file or similar calculating tool, with the advantage of obtain results in real time.

The first step to made, with the aim of solving the deducted equation system is to define the number of sections (n) in which the blade will be divided and the section geometrical features. Each one of these, are named as was said before, by the sub-index k. Depending on the spatial position, a radial variable r_k is assigned to every section.

Since a is the rotor hub radius and b is the blade end radius, the auxiliary functions φ, λ and μ can be calculated. The mathematical expressions of these functions are showed in the scheme provided in Figure 6. It is important that φ, λ and μ , despite they are integral expressions, they are depending only in a , b, the number of rotor blades Z and the positional radius of every section r_k . So that, if the geometrical blade features; such as the section two dimensional profile, the chord section or the pitch angle; are changed these auxiliary functions will remain constant, which leads that they only have to be calculated only in the case when a, b, or Z were changed.

The solving procedure is based on estimating and error-test principle, at the first moment it will be useful starting by supposing zero attack angle γ_k distribution. With this blade attack angle distribution, as it is showed in Figure 6, the unknown velocities $v^*_{\omega r_k}$ and U^*_k can be obtained. Following the diagram, the next step will calculating the circulation's intensity Γ ,which as it can be observed the equation is relatively complex, thus when it was programmed, several revisions must be made to avoid calculating errors. The circulation Γ is the variable which links, in a mathematical way, all the blade sections, because every of them are represented in the equation. The final step is obtaining the $\psi(r_k)$ values of every section, if they are approximately zero, then the attack angle distribution γ_k supposed at first is a system solution, and with these the blade loads or forces can be obtained, and also the rotor power coefficient.

To sum up, having a defined rotor and blade geometry, the goal of this procedure is to obtain the attack angles γ_k of each blade section that made the auxiliary value $\psi(r_k) \approx 0$ or instead the nearest zero as it was possible. To achieve this, several iterations must be carried out, and for this reason, a calculating tool must be used (It is recommend to implement it on a calculating sheet, excel file or similar).

2.2. Betz Compatibility

It would possible that there were several rotor and blade geometries which were not compatible with the equations stated in this procedure, it means that attack angles which made $\psi(r_k) \approx 0$ does not exist, in this case the whole geometrical parameters must be revised.

Another problem that could happen when the equations are implemented in a real case is that there were certain blade and rotor geometries which could have the power coefficient higher than Betz's limit (0,592). In this case, the blade geometry must be modified. To avoid this problem, several restrictions must be applied into the pitch angles and/or chord blade distributions, and in that way, the blade and rotor geometry will become compatible with the Betz's Theorem.

As it was said in the before section, aiming to solve the equations, the blade is divided in a finite number of sections, and each of them contributes to the rotor movement. With this idea, the power coefficient (Fraenkel 2002, Ragheb 2010) can be written by the formula:

$$c_P = \frac{\frac{1}{2} Z\omega \sum_{k=1}^{n} r_k c_k V_k^2 \left(c_{L_k} \cos(\beta_k - \gamma_k) - c_{D_k} \sin(\beta_k - \gamma_k) \right) \delta r_k}{\frac{1}{2}\pi b^2 U^3} \tag{11}$$

The lower part of the division above represents the kinetic energy per time unit of the sea current. On the other side, in the upper part of the division, there is the power that the rotor has in its rotational movement. And between parentheses, in the upper part also, there is the difference of the lift and the drag actuating section forces. If in that difference, the drag force term is neglected, the equation 11 will transform into:

$$c_P \leq {c_P}^* = \frac{Z\omega \sum_{k=1}^{n} r_k c_k V_k^2 c_{L_k} \cos(\beta_k - \gamma_k) \delta r_k}{\pi b^2 U^3} \tag{12}$$

So that, if the rotor blade geometry satisfies the condition in which the theoretical maximum power coefficient ${c_P}^*$ is lower than the Betz's limit (0,592), then that geometry will be considered Betz's Theorem compatible.

Nevertheless, as it was explained in the precedent section, the attack angles γ_k will be determined by the equations deducted and showed in the calculation diagram of Figure 6, and they must satisfied the condition of the auxiliary values $\psi(r_k)$ have to be approximately zero. This consideration leads that, possibly at a first moment; rotor blade geometry could pass the ${c_P}^*$ restriction, but with estimated attack angles. It could happen that geometry configuration with the final calculated attack angles, do not pass the ${c_P}^*$ restriction. In this case, pitch angles and/or chord blade distributions must be modified, or even, changing the section two dimensional foil.

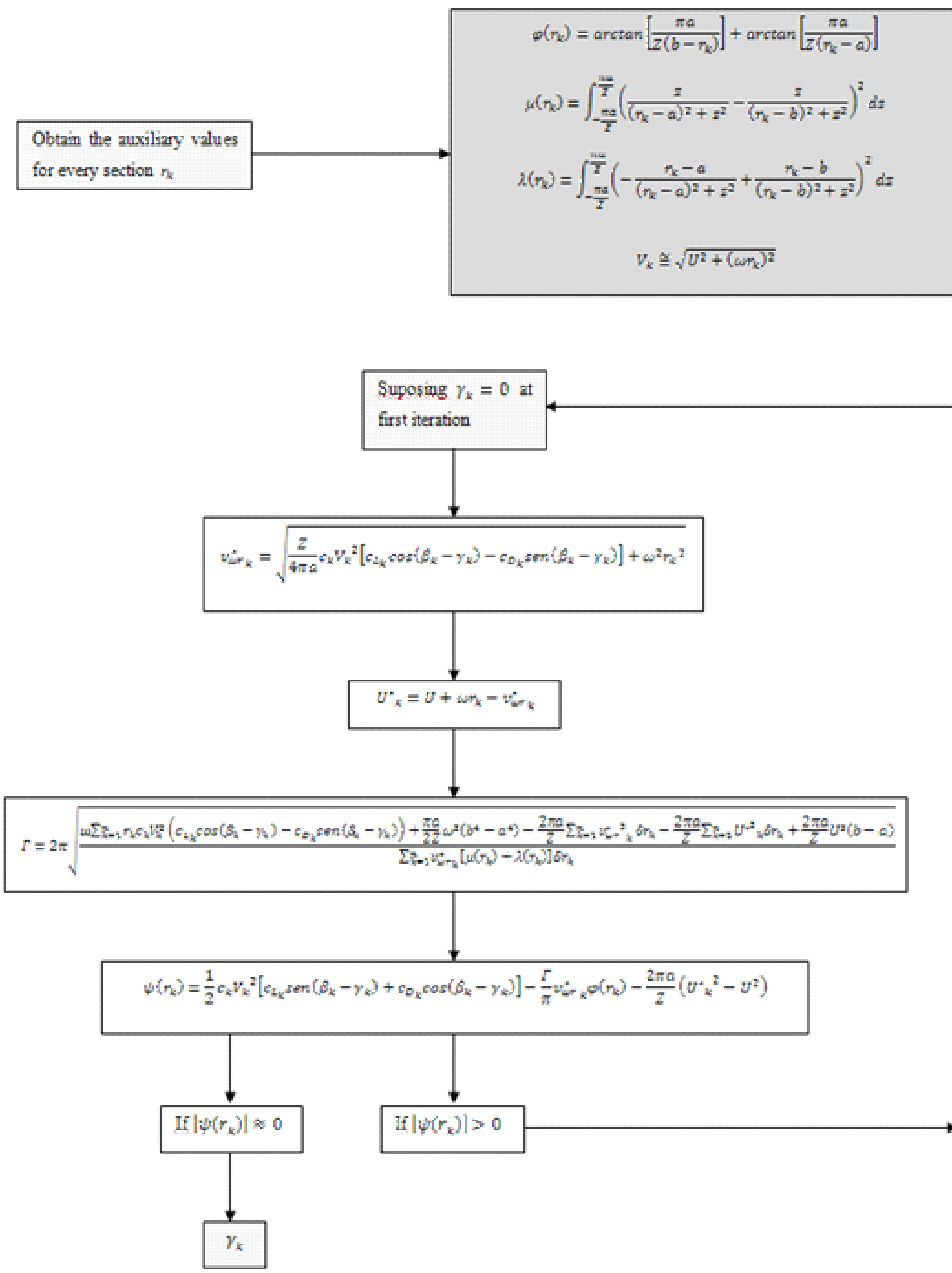
Finally, it is important to notice that the attack angle values will be only solutions when the following conditions are satisfied: The $\psi(r_k)$ are approximately zero values and the theoretical rotor power coefficient is lower than the Betz's limit.

3. Results

In this section the equations of the procedure are to be implemented in a case of a real turbine rotor. The relevant technical information is extracted from the publication of the Reference 14 (López 2011), and it corresponds with the rotor of GESMEY generator GSY-A6.5 prototype. This rotor has 20 meters diameter and three blades, which leads in b=10 m and Z=3, using the present article notation. This rotor is intended to generate 600 kW with a rotational speed of 12 RPM and with a marine current speed of 2 m/s. The rotor hub radius is no specified, but it can be estimated in approximately 1 meter (a=1 m).

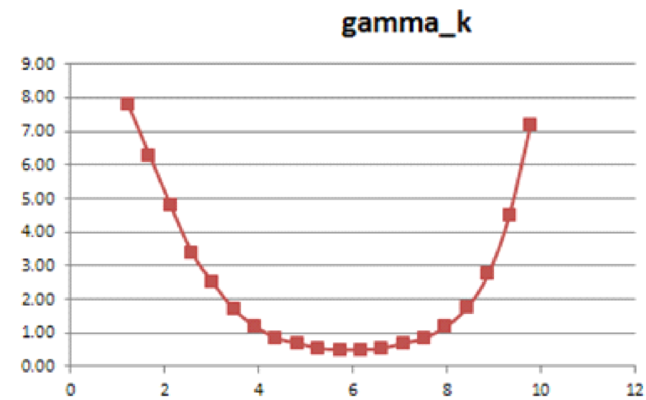
The blade geometry details are not specified neither, but a commonly used configuration will be implemented. In one side,

Figure 6: Calculation steps diagram.



Source: Authors

Figure 7: Graphic attack angle representation.



Source: Authors

the chord distribution will be linear decreasing from the hub section to the blade end, and on the other side, the geometry sections will be defined by the two dimensional foil NACA 63-212. Finally, the pitch angle distribution has increasing values, in the sections near to the rotor hub and fairly decreasing values at the blade end.

In Table 2, it can be observed that the blade has been divided in 20 sections of $\delta r = 0,45m$, the pitch angle and chords distributions are showed in the fourth and fifth columns starting by the left. In the last column there are the $\psi(r_k)$ values, and it can be checked that all of them are near zero values.

The attack angle distribution is located in the second column starting by the right, and in Figure 7, the graphic evolution of attack angles has been plotted.

As it was stated in previous section, the first step to made, in order to use this hydrodynamic method is to obtain the auxiliary variables which are φ_k, $\mu(r_k)$ and $\lambda(r_k)$, and they values are in located the third, fourth and fifth columns of Table 2 starting again by the right. And finally, in the central columns there are the values of lift and drag coefficients corresponding to a NACA 63-212 two dimensional profile.

By solving the equations with the help of a calculating sheet, the attack angles are obtained, with these values, the power coefficient obtained is $c_P = 0,45$, and the rotor power is 580 kW, which is a very approximated to the 600 kW expected in the initial considerations. The maximum theoretical power coefficient is $c_P{}^* = 0,47$, and that implies that the geometry selected is compatible with the Betz's limit. Finally, the circulation intensity reaches the value $\Gamma = 5,76m^2/s$.

Other important aspect, are the values of U^* and $v^*_{\omega r}$ velocities. In Table 3, it can be noticed that the value of U^* is a little lower than the 2 m/s current speed. It is seemed logical, because when the fluid pass through the rotor it results affected and so that the fluid particles reduce its speed.

The rotor blade structure must support the static loads l_k . The values of l_k located on each section are increasing along the blade, in the hub section the static load is equal to 1294,85 N and 14678,73 N in the blade end section. This distribution generates, in the hub-blade connection, a static reaction force

Table 3: U^* and $v^*_{\omega r}$ distributions.

SECTION nº	r_k	V_k	$v^*_{\omega r\,k}$	U^*
1	1.225	2.524	1.76672	1.77237
2	1.675	2.903	2.25904	1.84543
3	2.125	3.336	2.78330	1.88655
4	2.575	3.804	3.31719	1.91804
5	3.025	4.295	3.86654	1.93407
6	3.475	4.802	4.41732	1.94867
7	3.925	5.322	4.97449	1.95688
8	4.375	5.849	5.53364	1.96311
9	4.825	6.384	6.09605	1.96608
10	5.275	6.923	6.65814	1.96937
11	5.725	7.466	7.22188	1.97101
12	6.175	8.012	7.78636	1.97191
13	6.625	8.561	8.35155	1.97210
14	7.075	9.111	8.91830	1.97073
15	7.525	9.664	9.48676	1.96765
16	7.975	10.217	10.06106	1.95873
17	8.425	10.772	10.63960	1.94557
18	8.875	11.328	11.23105	1.91950
19	9.325	11.885	11.85138	1.86455
20	9.775	12.443	12.55029	1.73102

Source: Authors

which reaches 80063,15 N and total momentum of 585576,30 Nm. In Figure 8 these distributions are plotted, and with the purpose of enhance the graphic, scale factors are applied to l_k and the shear force distributions. Figure 9 shows the blade's surface in a 3D model.

4. Conclusions

The alternative hydrodynamic procedure proposed in this article, has important conceptual differences compared with other calculating techniques used in marine turbines. In one hand, in the lifting line and actuator disc methods, one of the basics ideas is the generating of induced velocities in the fluid when it passes through the rotor. The use of induced velocities has the inconvenience that it is no easy to understand, and in many occasions, authors use complicated formulas and considerations, in order to obtain its values and how it affects to the attack angle in each blade section. In this alternative procedure, on the other hand, the induced velocities concept is not used, and the attack angles are treated as unknown variables which will be determined by the control volume equations.

Despite the equations of the method are not simple, it is not a very complicated task to implement them in a calculating sheet or other similar tool, and the results are almost in real time, so there is not a time computing lapse.

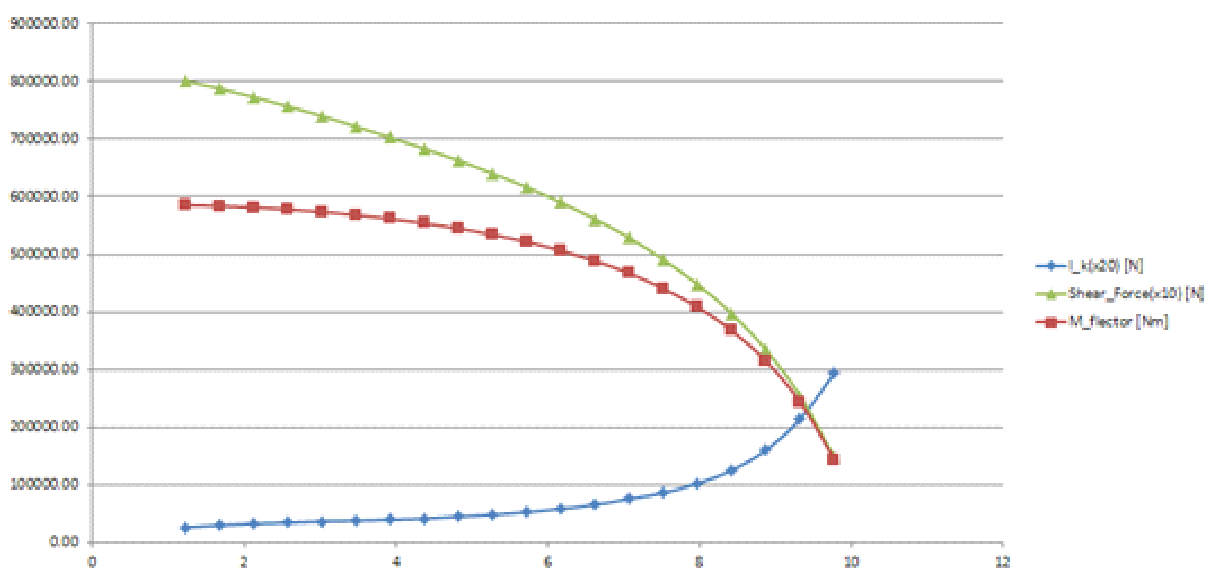
Other advantage of the method is that it can be very useful for students who are starting in the hydrodynamic related to marine turbines. The concepts and mathematical fundamentals are not extreme complex and also are analogous to other techniques and ideas.

Table 2: Blade geometry distributions.

SECTION nº	r_k	δr_k	β_k	c_k	perfil	c_{L_k}	c_{D_k}	φ_k	$\mu(r_k)$	$\lambda(r_k)$	γ_k	ψ_k
1	1.225	0.45	68	1.085	NACA 63-212	0.9017	0.0075	1.4779315	5.09	7.5992	7.8	-0.0850
2	1.675	0.45	72	1.055	NACA 63-212	0.7857	0.0059	1.1233743	0.78302	2.6613	6.3	-0.0987
3	2.125	0.45	74	1.025	NACA 63-212	0.6527	0.0048	0.8817974	0.21016	1.5219	4.8	-0.0418
4	2.575	0.45	76	0.995	NACA 63-212	0.5360	0.0041	0.7268818	0.07124	1.017	3.4	-0.0287
5	3.025	0.45	77	0.965	NACA 63-212	0.4600	0.0041	0.6262835	0.027957	0.75136	2.5	0.0236
6	3.475	0.45	78	0.935	NACA 63-212	0.3879	0.0044	0.5594014	0.01191	0.59847	1.7	-0.0169
7	3.925	0.45	78.5	0.905	NACA 63-212	0.3389	0.0048	0.5144986	0.005154	0.50593	1.2	-0.0409
8	4.375	0.45	79	0.875	NACA 63-212	0.3022	0.0052	0.4849227	0.00208	0.44931	0.85	-0.0794
9	4.825	0.45	79.5	0.845	NACA 63-212	0.2858	0.0054	0.4668895	0.00065	0.41645	0.7	-0.0446
10	5.275	0.45	80	0.815	NACA 63-212	0.2688	0.0057	0.4583314	0.00011	0.40133	0.55	-0.0750
11	5.725	0.45	80.5	0.785	NACA 63-212	0.2630	0.0058	0.4583314	0.00011	0.40133	0.5	-0.0659
12	6.175	0.45	81	0.755	NACA 63-212	0.2630	0.0058	0.4668895	0.00065	0.41645	0.5	-0.0587
13	6.625	0.45	81.5	0.725	NACA 63-212	0.2688	0.0057	0.4849227	0.00208	0.44931	0.55	-0.0572
14	7.075	0.45	82	0.695	NACA 63-212	0.2858	0.0054	0.5144986	0.005154	0.50593	0.7	-0.0036
15	7.525	0.45	82	0.665	NACA 63-212	0.3022	0.0052	0.5594014	0.01191	0.59847	0.85	-0.0794
16	7.975	0.45	81.5	0.635	NACA 63-212	0.3389	0.0048	0.6262835	0.027957	0.75136	1.2	-0.0563
17	8.425	0.45	81	0.605	NACA 63-212	0.3926	0.0044	0.7268818	0.07124	1.1017	1.75	-0.0809
18	8.875	0.45	80	0.575	NACA 63-212	0.4815	0.0041	0.8817974	0.21016	1.5219	2.75	-0.0722
19	9.325	0.45	78	0.545	NACA 63-212	0.6273	0.0046	1.1233743	0.78302	2.6613	4.5	-0.0632
20	9.775	0.45	73	0.515	NACA 63-212	0.8718	0.0068	1.4779315	5.09	7.5992	7.2	-0.0617

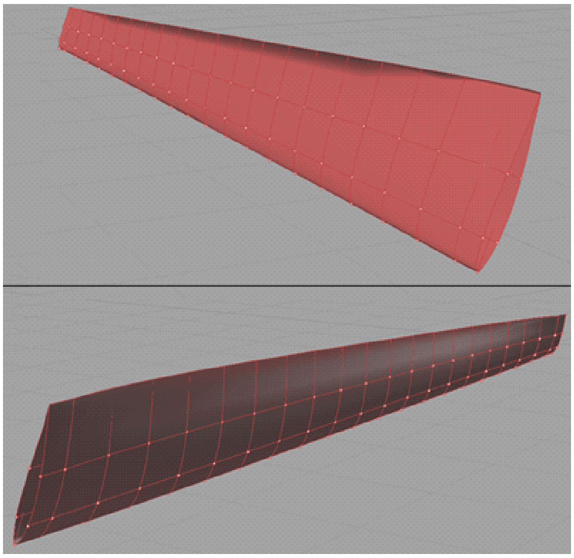
Source: Authors

Figure 8: l_k Shear force and bending momentum distributions.



Source: Authors

Figure 9: 3D blade model.



Source: Authors

The creation of a new 3D method that allows estimating the static and dynamic loads produced in a horizontal axis marine turbine, without using complex calculating tools or method, was the goal of this work at first, and it has been achieved. The obtained results are not very far of the reality, nevertheless it must be tested much more in the future, and other readers must be critic the fundamentals, and so, possible corrections and enhancements could be introduced.

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