COB-2021-0223 MODIFYING FACTOR AND PROPOSAL FOR A NEW CAVITATION FORECASTING DIAGRAM IN MARINE PROPELLERS

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Abstract. *The classic method of predicting cavitation in marine propellers through the Burrill diagram has been employed for almost 80 years, being considered by researchers as a highly reliable tool for the use in the development of impellers of fixed pitch. There are also methodologies that consider the influence of hydrofoil on the performance of the component, relative to cavitation. However, previous work has questioned the reliability of such techniques for detecting low percentage cavitation, such as 2.5%. It is considered that both the experimental and numerical methods that give rise to those results are inaccurate to predict exact values of cavitation in such a small region. Thus, the authors propose in this paper a new methodology, which takes into account an angular modifying factor, symbolized as* $f_{\alpha\beta}$*, which focuses on the cavitation index* σ_{07R} *used in the classical methods, relative to the resulting velocity in the section at 0.7R of the blades. This factor considers the dimensional characteristics of the impeller, the physical properties of the fluid where it is navigating and the pressure conditions on the component axis. It is plotted against rotational speed values, in diagrams that indicate the occurrence of cavitation directly from the reading on the graph, without the need for excessive calculations. Because of the unreliability of the various methods in detecting cavitation in a very small region of the back of the blade, the diagrams are only built for percentages from 10% onwards. The* $f_{\alpha\beta}$ *values can be raised numerically or experimentally in tests in cavitation tunnels. However, the values of the Burrill diagram itself were employed, since they are considered highly reliable for projects that support cavitation above 10%. The intention of the method is to advance the state of the art in the knowledge of the subject and offer a facilitating tool to the designer. The results of cavitation prediction achieved herein are compatible with those from the classic methods used in the marine rotor market.*

Keywords: *Cavitation, Burrill Diagram Method, Marine Propeller*

1. INTRODUCTION

Cavitation is a classic problem in hydraulic machine propellers in general. The damage caused by blade erosion has been a matter of interest to manufacturers and researchers since the invention of the component in a modern metallic model. In this way, the theme is always current and subject to verification to advance the state of the art in the subject.

The power of a motor machine is basically a function of torque and rotation, but the entry and exit angles of a propeller blades (if any) also influence the magnitude because they can modulate the resistance to the flow that passes through it. Sousa and Freire, 2018, studied the influence of the constructive angles of the blades of a turbine of a conventional turbojet-type aeronautical engine and concluded that its thrust is directly influenced by the increase in the blade entry angle, although the rotor efficiency drops a little bit with this angle variation. Bondan and Cunha, 2020, studied the influence of the main angles that define the blades, in a vessel measuring 78 m in length, with a beam of 20 m and an average draft of 6.3 m, which had two propellers with 5 blades each. They concluded that at the entrance, the constructive angle formed between the tangential and radial velocity vectors also increases thrust and decreases efficiency but ends up causing cavitation of the back of the blades when it assumes very large values.

The calculation of cavitation conditions in vessel propellers is commonly done using the Burrill diagram (Burrill, 1943, Burrill and Emerson, 1963, Breslin & Andersen, 1994), which is based on a large number of tests of components of varied geometries in cavitation tunnels. See Figure 1.

The diagram links the loading coefficient τ_c related to pressures present in the blades and determined by Eq. (1), to the cavitation index σ_{07R} relative to the resulting velocity in the section at 0.7R of the blades, given by Eq. (2), where P_{atm} is atmospheric pressure and ρ is water density. Both τ_c and σ_{07R} take into account V_R, given by Eq. (3). This velocity is the one at 0.7R, resulting from the tangential component measured at the diameter 0.7D, the rotation n of the shaft and the axial component V_A. In this case, V_A is the effective fluid velocity between the blades. The height h used in the calculation of σ_{07R} is that between the surface and the point where V_R is measured and P_v is the vapor pressure at that point. However, P_v on rotor shaft can be used without incurring relevant error.

Table 1 presents the coefficients A and B in Eq. (1) that compose the curves that determine the percentages of cavitation in the back of the blades (suction region) of a generic impeller, obtained from the Burrill diagram.

$$\tau_C = A(\sigma_{0.7R})^B \quad (1)$$

$$\sigma_{0.7R} = \frac{P_O - P_V}{\frac{1}{2}\rho V_R^2} = \frac{P_{atm} + \rho g h - P_V}{\frac{1}{2}\rho V_R^2} \quad (2)$$

$$V_R = \sqrt{V_A^2 + (0.7\pi D n)^2} \quad (3)$$

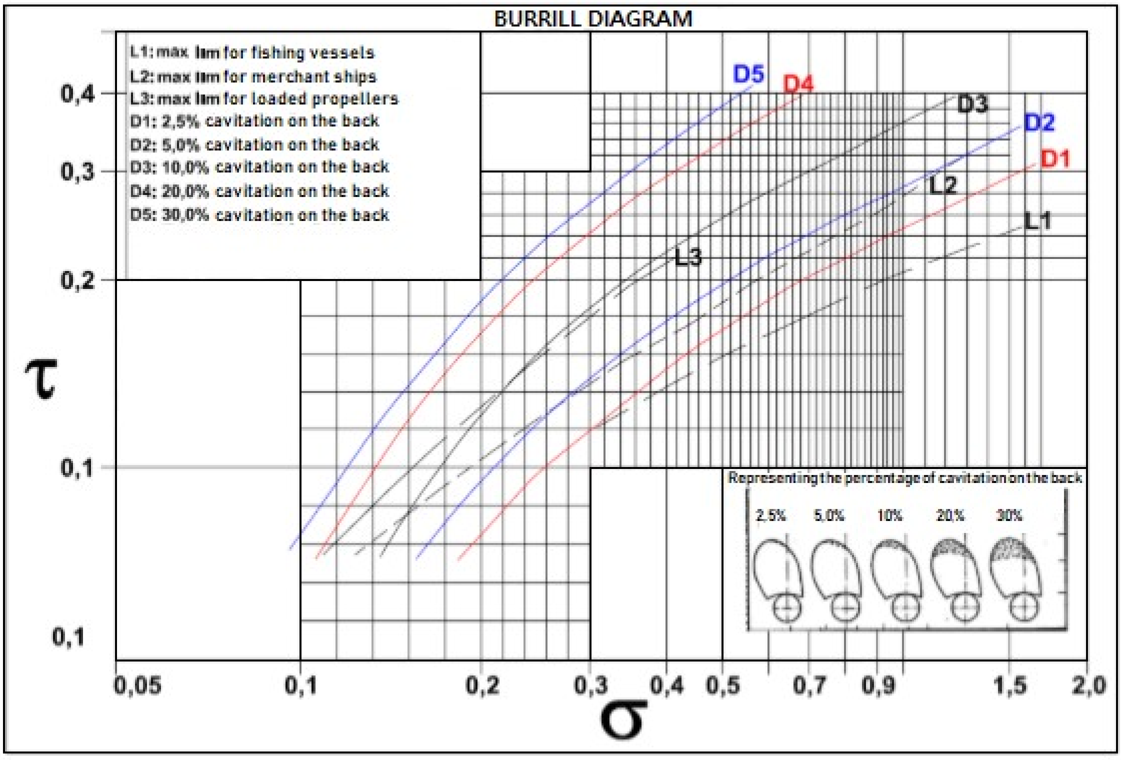

Figure 1. Burrill diagram, used to calculate cavitation on the back of marine propeller blades.

Table 1. Coefficients of Eq. (2)

Cavitation in the back	A	B
2.5%	0.302	0.763
10%	0.494	0.880
20%	0.661	0.880
Thrust drop	0.700	1.000

In this way, to check if there will be cavitation in the propeller, the value of σ_{07R} must be entered, thus obtaining a value of τ_c. With this value, the projected area A_P is calculated through Eq. '(4), which also uses the thrust T. Once the pitch-diameter ratio P/D is known, the A_P/A_E ratio is obtained by Eq. (5), where A_E is the expanded area of the blade. If A_P/A_E is less than the expanded area ratio A_E/Ao, the propeller will cavitate. In this case, Ao is the area of the circle that contains the outer diameter D given by Eq. (6):

$$\tau_C = \frac{T}{\frac{1}{2}\rho V_R^2 A_P} \quad (4)$$

$$A_P = \left(1.067 - 0.229\frac{P}{D}\right) A_E \quad (5)$$

$$A_o = \pi \frac{D^2}{4} \quad (6)$$

The use of the Burrill diagram only makes it possible to estimate the amount of cavitation in the blades and verify whether there is a risk of a drop in thrust and torque in the propeller, resulting from excessive cavitation. The diagram does not indicate the type of cavitation present or whether there is a possibility of erosion by cavitation in the blades.

Shinomiya et al, 2014, citing Sale et al, 2009, which in turn refer to Lecoffre, 1999, used a similar method. In this case, the condition required to avoid cavitation is given by Eq. (7), where σ is the dimensionless number of cavitation given by Eq. (8) and C_{pmin} is the minimum local pressure coefficient of the hydrofoil coupled to the helix, experimentally provided.

$$\sigma + C_{pmin} \geq 0 \quad (7)$$

If the condition is not met, then there will be cavitation.

In this approach, it is taken into account that cavitation depends on the pressure distribution of the moving fluid around the hydrofoil. The pressure at a point on the surface of the hydrofoil is defined by the pressure coefficient C_p. Pressure coefficient depends on the angle of attack, Reynolds Number, surface roughness and hydrofoil shape. C_p values are typically measured in tests in cavitation tunnels or can be calculated using numerical methods. The dimensionless cavitation number, defined by Eq. (8), takes into account the pressure changing due to the induced axial velocities V_A and tangential Ωr in the rotor plane.

The local velocity in the plane of the impeller V_{loc} is given by Eq. (9). The local velocity needed to induce cavitation, V_{cavit} , will be calculated by Eq. (10), using Eq. (8). To ensure that the rotor does not cavitate, the V_{loc} must never exceed or be equal V_{cavit} at any location along the blade..

$$\sigma = \frac{P_{atm} + \rho g h + \frac{1}{2}\rho V_A^2 a(2-a) - \frac{1}{2}\rho(\Omega r a')^2 - P_V}{\frac{1}{2}\rho V_{loc}} \quad (8)$$

$$V_{loc} = \sqrt{[V_A(1-a)]^2 + [\Omega r(1-a')]^2} \quad (9)$$

$$V_{cavit} = \sqrt{\frac{P_{atm} + \rho g h + \frac{1}{2}\rho V_A^2 a(2-a) - \frac{1}{2}\rho(\Omega r a')^2 - P_V}{-\frac{1}{2}\rho C_{Pmin}}} \quad (10)$$

In this case, a and a' are dimensionless velocity induction factors and are experimental data that must be provided, without which the calculation is not possible. Therefore, this methodology requires experimental surveys related to the hydrofoil.

1.1 Construction angles of entry and exit on the blades of a marine propeller

The triangle of velocities in a generic axial propeller blade of a generating machine is a classical matter and widely dominated in the literature. (Macintyre and Silveira, 1969, Macintyre, 1983). In Figure 2 we see the angles β, called constructive and the angles α, resulting from the tangential velocity vector u (equivalent to the multiplication of the angular velocity by the expression $0.7R$) and the vector w that rests on the blade. Indices 4 and 5 refer to the entrance and exit of fluid in the propeller.

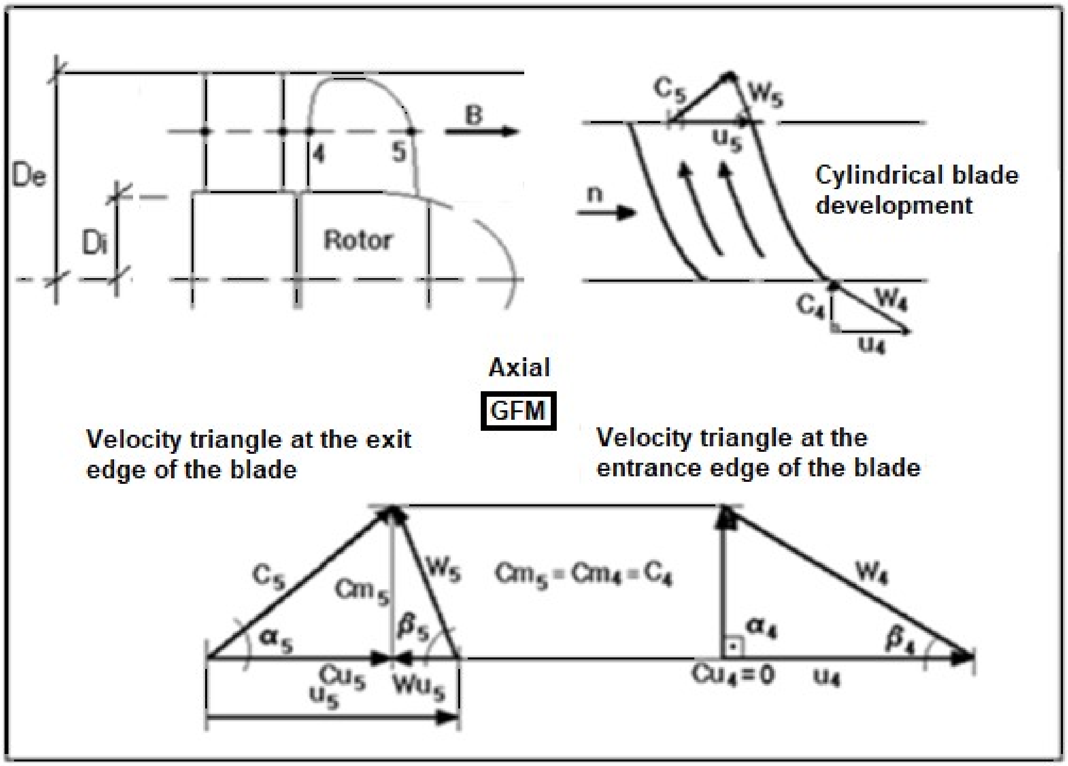

Figure 2. Generic velocity triangle of a generic propeller blade in a generating flow machine (GFM)

The vector *Cm* represents the meridional or effective velocity of the flow through the blades. This velocity can be expressed as a function of the angles β and α according to Eq. (11), deduced from simple trigonometric relations.

$$Cm = \frac{\pi n D}{60(\cot\beta + \cot\alpha)} \tag{11}$$

Equation (11) can be employed directly in Eq. (2), in place of V_A and in the consequent application of the Burrill diagram to predict the occurrence of cavitation. However, a more practical method based on the vessel design can be postulated, as we propose below.

2. MATERIALS AND METHODS

Taking as a starting point the physics of the cavitation prediction methods and the classical theory of velocity triangles of a propeller blade, it is reasonable to assume that an "angular modifier factor" $f_{\alpha\beta}$, that indicates the occurrence of cavitation, can be expressed as a function of physical properties of the fluid in which the vessel navigates, propeller dimensions and pressure conditions. Thus, after some mathematical iterations regarding the relevance of the variables that can influence cavitation, it was possible for the authors to conceive $f_{\alpha\beta}$, which will modify σ_{07R} taking into account the dimensional characteristics of the propeller, expressed in the constructive angles β and α, in the pitch P and the width L of each blade. Given the above, the proposal is to survey a diagram that relates Eq. (12) to the rotation of the vessel's engine shaft, composing curves below which cavitation does not occur.

$$f_{\alpha\beta} = \left|\frac{P}{(\cot\beta + \cot\alpha)L}(\sigma_{0.7R})\right| \tag{12}$$

The $f_{\alpha\beta}$ values must be collected from experimental measurements in cavitation tunnels or in computer simulation, but they can be known even through the Burrill diagram, identifying the σ_{07R} value corresponding to the rotation from which cavitation occurs in 10 and 20% of the back of the blade, shown in Figure 1. The value of 2.5% of cavitation will be neglected, as indicated in the references Bondan et al, 2021, and Moraes and Carvalho, 2021, which shows that this percentage in the Burrill diagram only works for the range of constructive angles that goes from 60 to 67 degrees, paired with 45 degrees. Values of 30% will also be ignored, however, due to the lack of coefficients A and B, shown in Table 1.

The factor is dimensionless. Eq. (12) appears between bars because obtuse angles will result in negative results, but of the same magnitude as its acute symmetric.

The Burrill diagram method takes into account the dimensions of the propeller when calculating the ratio A_P/A_E, however, this computation is time-consuming, as it is necessary to perform previous calculations in three steps before finding the effective ratio A_P/A_E. The use of a shape coefficient incident on σ_{07R} is faster and can indicate the cavitation condition directly from the diagram reading.

3. RESULTS AN DISCUSSION

The diagrams raised with the angular modifier factor $f_{\alpha\beta}$ values, linked to rotation, for the conditions of 10 and 20% of cavitation on the back of the blades, can be seen respectively in Figures 3 and 4, for diameters ranging from 0.251 m to 10 m. The smallest value corresponds to a little commercial rotor, easily found in the specialized market, and the largest corresponds to the propeller of a king-sized tanker. Intermediate values were postulated to fill the gap between the two extremes.

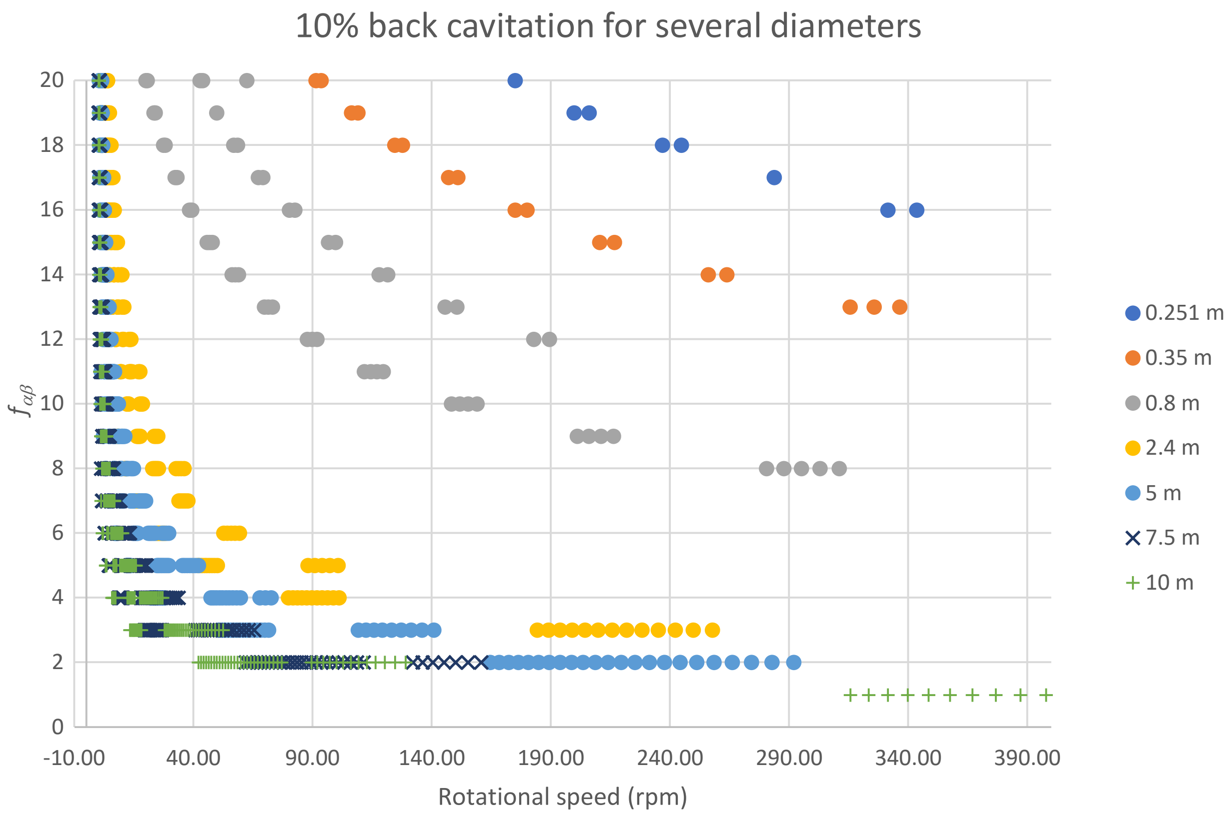

Figure 3. Diagram showing $f_{\alpha\beta}$ x propeller rotation for various diameters. Above each curve cavitation occurs in 10% of the back of the blades.

As initially informed, the factor was conceived by trial and error, testing variables that affect cavitation. For a given propeller diameter, $f_{\alpha\beta}$ is such that if you vary the dimensional quantities P, L, h, α and β, the environmental quantities Po, Pv and g, as well as the operational quantities h and n, it will only change its position along of the curve of that given diameter. There is no transfer of the factor to another curve belonging to another diameter within the diagram of the respective percentage of cavitation.

Reading the graphics is simple and straightforward. The designer shall calculate the value of $f_{\alpha\beta}$ following Eq. (11), (3) (2) and (12). For the vessel's pilot, this factor will be part of the design information and he shall have it within reach. With this in hand and the speed of rotation of the vessel's propeller, as well as its diameter, it is possible to see directly in the diagram if there is cavitation for the given navigation condition. For example, if the rotor diameter is 0.8 m and the factor is 12, the pilot will know that there will be cavitation in 10% of the back of the propeller blades from the 90 rpm rotation. If this is tolerable, by reading the graph in Figure 4, he will be able to see that he can go up to a rotation of about 170 rpm without cavitation reaching 20% of the back of the blade.

A closer look at the diagrams will lead to the conclusion that lower $f_{\alpha\beta}$ values will promote less cavitation at any given impeller diameter. Additionally, the larger the diameter of the vessel's impeller, the lower the rotation speed at which cavitation does not appear. On the other hand, smaller impellers can rotate at higher speed because cavitation will take longer to appear.

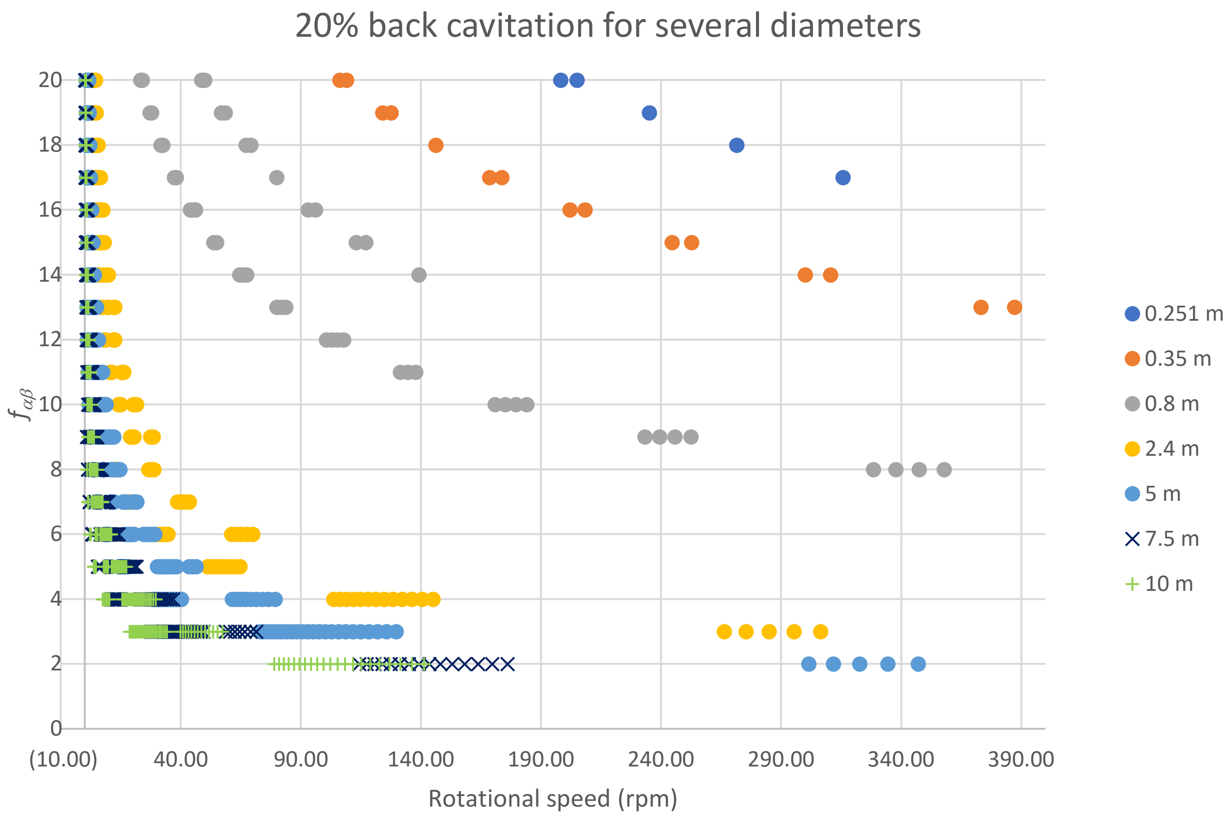

Figure 4. Diagram showing $f_{\alpha\beta}$ x propeller rotation for various diameters. Above each curve cavitation occurs in 20% of the back of the blades.

4. CONCLUSION

The classic method for detecting cavitation in marine propellers using the Burrill diagram was presented, as well as an alternative method that takes into account the existence of the hydrofoil next to the rotor. Despite the wide acceptance of such techniques in marine propeller designs, the present authors consider them likely to present unreliable results for small percentages of cavitation, due to the fact that experimental results and even computer simulations are imprecise.

Given the above, the present work proposes an angular modifier factor $f_{\alpha\beta}$, incident on the cavitation index σ_{07R}. This factor takes into account the physical properties of the fluid where the vessel navigates, dimensional characteristics of the propeller and operating pressure conditions. This variable is plotted against rotation values, in diagrams for 10% and 20% of cavitation, and may be developed in the future for higher percentages, where the designer or even the pilot of the vessel can see directly from the graph if such a navigation condition is liable to cavitation or not.

The designer shall look for a propeller that has the smallest possible angular modifier factor, so that cavitation is avoided at any level of rotation.

5. ACKNOWLEDGEMENTS

The authors acknowledge “Programa Pesquisa Produtividade - Universidade Estácio de Sá” and “Fundação Coordenação de Aperfeiçoamento de Pessoal de Nivel Superior – CAPES” for funding the research.

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