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A simple arithmetic mean to ensure the convergence of models based on Blade Element Momentum theory applied to Vertical Axis Wind Turbines simulations

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Abstract. The computer models based on the Blade Element Momentum (BEM) theory are able to predict the aerodynamic performance of wind turbines with good accuracy and efficiency; however, these methods may present some convergence difficulties. This work presents the development of a methodology adopting arithmetic mean in situations of flow instability to ensure the convergence of BEM models applied to Vertical Axis Wind Turbines (VAWT) simulations. This methodology was used in the creation of a program written in Fortran, called FASTEEVSIM. Tests were conducted in a Darrieus wind turbine using NACA0018 and DU06W200 airfoils as blade profiles. A comparison of the results using the FASTEEVSIM with experimental data from well-known literature sources has been done in order to validate the method. When comparing the power coefficients obtained for two types of blade profiles, one symmetrical (NACA0018) and another asymmetrical (DU06W200), the final validation results showed a mean square deviation of 3.62% and 6.09%, respectively. The results showed that the developed methodology can assist the convergence effectively and that the FASTEEVSIM program is able to predict the performance of VAWT, providing data close to experimental values in a simple and fast way.

Keywords: Vertical Axis Wind Turbine. Aerodynamic Profile Simulations. Power Coefficient Curve. Convergence Methodology. BEM Models.

1 Introduction

Factors such as the increasing demand for electricity, the concerns about CO_2 emissions in the atmosphere and the possible shortage of fossil fuels have led scientists to think about the use of renewable energy sources. Among these, the wind power has shown to be a promising market and has motivated the research and development of wind turbines (BONOW; PETRY, 2018). According to the Global Wind Energy Council (2020), the capacity for wind energy globally was over 837 GW in 2021, an increase of 12% compared to 2020.

Currently, the most efficient way to capture kinetic energy and transform it into electrical energy is to use wind turbines that use the winds to obtain rotary motion. The modern wind turbines can be classified into two basic types determined by which way the turbine spins: the horizontal axis wind turbines (HAWT) and the vertical axis wind turbines (VAWT). The VAWT can be classified into drag force type (Savonius turbine) and lift force type (Darrieus turbine). The HAWT are characterized by having high technological development and are currently installed even on the surface of the oceans. On the other hand, the VAWT, due to excessive vibration problems, had their development stopped in the mid-80. At that time, the HAWT market had a boost due to its greater efficiency at a high power range (approximately 500 kW at that time). However, it was never shown that HAWT are aerodynamically more efficient than VAWT. Furthermore, according to R.Howell et al. (2010), the VAWT have some advantages such as:

- The VAWT do not need a yaw system since their vertical rotors can face the wind from any direction, which results in less energy loss;
- Due to its blade with a constant profile shape along the length, the manufacturing cost of VAWT is lower when compared to the cost of a complex three-dimensional shape of the HAWT blades;
- The VAWT are quieter due to its lower tip speed ratio;
- While operating, the VAWT absorbs better the stall on the blades when subjected to stronger winds, providing an operational safety advantage during wind gusts.

The turbines capture the kinetic energy from the wind using rotors connected to blades with aerodynamic profiles (or airfoils) that transform this energy into rotational mechanical energy of a shaft. An electric generator can be adapted to transform the rotational energy into electric power (BRINCK; JEREMEJEFF, 2013). As a means to obtain efficient turbines and to find its best characteristics, several tests have to be taken. The existing computational models are able to accurately predict the VAWT efficiency. These methods allow numerical prediction of wind turbine performance, which can reduce the number of experimental tests required. Besides, computational studies are more economical than costly experiments (ZHANG et al., 2020).

The vertical axis wind turbine (VAWT) has a simple operation. However, a complete mathematical description of its behaviour is quite complex, requiring a number of simplifications. A good wind turbine model must have the ability to describe physical reality in a simple way, but with good predictive capacities (R.HOWELL et al., 2010).

This work presents the development of a computational program, called FASTEEVSIM, written in FORTRAN, for the performance analyses of Darrieus type wind turbines with straight blades. The program is based on the Double Multiple Streamtube model and uses the XFOIL, version 6.96 (DRELA, 1989), to obtain the profiles aerodynamic characteristics as the lift and drag coefficient.

The main objective of the work was to develop a methodology applied to a computer program that could converge in any situation, whether with flow instabilities or not. Thus, being able to contribute to the dimensioning of vertical axis wind turbines quickly and simply. The FASTEEVSIM program was validated using wind tunnel data from Claensens (CLAESSENS, 2006). The results showed that the program can be used to predict the VAWT performance with good accuracy. It is also presented a comparative analysis between two airfoils used on VAWT as blade profiles: the NACA0018 (symmetric) and the DU06W200 (asymmetric)[1].

The work is divided into four more sections. In section 2 a bibliographical review is presented, where some works that obtained problems of convergence in the results related to the performance of vertical axis wind turbines (VAWT) are mentioned. In section 3, the methodology developed in the study is presented, the equations used to calculate the performance of the turbines and the flowchart of the iterative procedure of the FASTEEVSIM program are presented. In section 4 the results obtained are detailed considering the simulations using FASTEEVSIM and the comparison with the experimental data obtained through the wind tunnel. Section 5 addresses the conclusion of the study in which the FASTEEVSIM program is able to predict power coefficient curves close to the curves constructed with experimental data.

2 Bibliographic review

Several works point out the problems in the convergence of results related to the performance of vertical axis wind turbines (VAWT). Mathematical models based on Blade Element Momentum (BEM) are able to efficiently predict VAWT performance. Streamtube models are based on the BEM theory and have evolved with time (PONTA; SEMINARA; OTERO, 2007).

The first of them is the single streamtube model proposed by Templin in 1974 (TEMPLIM, 1974). This model uses an actuator disk [13] to represent the rotor's interference, where the turbine rotor acts like a disc actuator and slows the fluid flow in the axis direction, spreading it over a larger transversal area and, consequently, reducing the flow velocity. The entire span of the rotor is covered for only one streambtube. It predicts a uniform flow for the entire cross section and doesn't consider the changes in the flow between the upwind

[1] The airfoil coordinates are available in: <http://airfoiltools.com/>. Access: 20 mar. 2015.

and downwind halves of the rotor. Therefore, a unique speed reduction factor (also called an interference factor) of flow is admitted for the entire turbine, regardless of the position of the blades. This model has little precision in evaluating the performance of VAWTs, resulting from the considerations made, offering values above the real values for high blade tip speed ratios (TSR).

In 1975, Strickland (1975) proposed the Multiple Streamtube model, an improved version of the Single Streamtube model. Instead of a single tube, it uses an array of adjacent streamtubes to cover the rotor's span. This model is more accurate due to its capacity to consider the flow variations on the rotor's cross-section. Despite its improvements, this model doesn't take into account the differences between the turbine's upwind and downwind halves and, like the Single Streamtube model proposed by Templin (TEMPLIM, 1974), it also presents performance values well above the real values when the TSRs are high (or at high loads). Besides, for these high loads, several authors reported convergence failures and erratic solutions related to the method's iterative procedure for obtaining local interference factors in each Streamtube (PARASCHIVOIU, 1983; KLIMAS; SHELDAHL, 1978; HEALEY, 1981; HEALEY, 1983; GUPTA; LEISHMAN, 2005).

Paraschivoiu (1983) introduced a more complex and sophisticated approach called the Double Multiple Streamtubes model. It uses two actuator disks in tandem. Despite the better ability to predict the performance of the rotor, the method still suffers from the same convergence difficulties previously identified in high loads, especially when the turbine blades are simulated with asymmetric profiles (BRINCK; JEREMEJEFF, 2013).

According to McIntosh, Babinsky e Bertényi (2009), the main cause of the failure can be identified as several inflection points very close to each other, with very different roots (or interference factors) between the model iterations. In such situations, it is usually the case that one of the solutions corresponds to a flow without separation of the boundary layer in the blades while the others are for various conditions of separation or stalling, implying in significant differences in the obtained force coefficients. The solution with the least interference factor represents a severe stall, the intermediate solution in a partial stall, which is probably more unstable, and higher solutions represent an attached flow. In the iterative scheme, the solutions identified under these conditions depend on the value chosen to start the iteration, and, depending on the hysteresis associated with the established stalling level, they should probably oscillate between one solution and another for the same azimuthal angle of the turbine blade. The existence of multiple solutions is probably the cause of the previously observed erratic solutions that occur in the BEM models. With due merit, the divergence was circumvented by McIntosh, Babinsky e Bertényi (2009) through the use of a graphical solution, where the iterative scheme was replaced by a root locator algorithm. It is based on the flow stall state (with or without flow separation) of the last solution obtained and, therefore, does not cause oscillations in the convergence. Despite the success of the method in modeling turbines with high TSR, the solution still presents a certain level of complexity and leaves doubts regarding the choice of the last obtained solution, because of the presence or not of a minor blade stall, however small, already causes considerable flow interference.

Other problems have been observed in more recent days in the application of the Double Multiple Streamtube model, original by Paraschivoiu, Fraunie e Beguier (1985). As reported by Brinck e Jeremejeff (2013), whenever the turbine blades with asymmetric profiles pass to the region of the half downstream of the rotor, the method begins to estimate values for the interference factor very low or, as in the report, increasingly high induction factors are estimated, reaching values greater than 1 and, consequently, resulting in the divergence of the solution. In an attempt to find the cause of the problem, several proposed solutions were investigated in Brinck e Jeremejeff (2013), among them: how to interpolate the drag and lift coefficient values from the tabulated data for different Reynolds numbers; the number of Streamtubes that describe the rotor; a relaxation scheme to obtain the induction factor by the iterative procedure; and the maintenance of constant values for the lift coefficient. Only in the latter attempt, convergence was obtained, however, the option was discarded as it did not offer physical consistency. Because of the difficulty encountered in simulating the turbine with asymmetric profiles, the authors considered only the results obtained for half upstream of the rotor.

The graphic solution proposed by McIntosh, Babinsky e Bertényi (2009) has been used to obtain convergence until today, as seen in Saber, Afify e Elgamal (2018).This method is a root-finding algorithm, which locates crossing points occurring between the momentum and blade-element models. The streamwise force coefficient is calculated for interference factors in the range -1 to 1 at a resolution of 0.01 for both the blade-element and momentum models. The momentum model calculation is performed once at the start of the calculation. Next, the blade-element calculation is performed for each stream-tube. A numerical search is then made, for each stream-tube, locating crossing points occurring between the blade-element model and the momentum model trust coefficients. Once the location preceding a crossing point is identified, a double interpolation is performed with both force coefficients.

In order to reduce the convergence problems presented in the Double Multiple Streamtube mathematical model, this work presents a simplified methodology, such as arithmetic mean, used in software that was developed to perform the simulations without loss in the quality of the results, aiming to guarantee the convergence in symmetrical and asymmetrical blade profiles. The main difference between the method proposed here, concerning the previous literature (MCINTOSH; BABINSKY; BERTéNYI, 2009), is that we assumed the average between the two possible roots verified in situations of flow instability as a solution; that is, our answer is within the possible solutions found at the beginning of the stall condition.

Table 1 shows the summary with the main mathematical models used to obtain the performance of vertical axis wind turbines, presenting their methodologies, contributions, and limitations.

3 Methodology

3.1 Double Multiple Streamtube model

From the scheme presented by Paraschivoiu, Fraunie e Beguier (1985), the Double Multiple Streamtube model can be described by the following Eq. 1 for the interference factor u:

$$\begin{aligned}(1-u)\,u = &\frac{Nc}{4\pi R sin\theta} C_y\Big(\left(\frac{\lambda_0}{FC}\right)^2 + \\ &2u\left(\frac{\lambda_0}{FC}\right)cos(\theta) + u^2\Big)\end{aligned} \quad (1)$$

Where λ_0 is the initial tip speed ratio. The factor of compensation (FC) is expressed by $FC = 2u-1$ to the rotor's second half ($180° < \theta < 360°$), and $FC = 1$ to the rotor's first half ($0° \leq \theta \leq 180°$). N is the number of blades. C_y is the force coefficient in the airflow's direction. R and c are respectively the turbine's radius and the blade profile's chord.

The average torque ($Torque$) and the power (P) can be calculated using the Eq. 2 and 3.

$$Torque = \sum F_t \frac{NR\Delta\theta}{2\pi} \quad (2)$$

$$P = \omega \times Torque \quad (3)$$

The dimensionless coefficient for power (C_P) can now be calculated:

$$C_P = \frac{P}{\frac{1}{2}\rho A V_{inf}^3} \quad (4)$$

The power coefficient (C_P) is the measure to evaluate the turbine's performance. This coefficient allows you to chose the preferred design (BRINCK; JEREMEJEFF, 2013).

According to McIntosh, Babinsky e Bertényi (2009), the solution of the transcendental equation, Eq.1, by iterative procedures, can lead to divergence in situations of instability, such as those observed in the stall beginning, where the left side of Eq.1, coming from the momentum theory about actuating discs in each Streamtube (or Double Multiple Streamtube) is matched to the right side from the blade element theory. Therefore, multiple interference factors, u, are part of the roots of Eq.1 and fluctuate continuously at least between two well-established values during the iterative procedure. The procedure adopted here, unlike McIntosh, Babinsky e Bertényi (2009) (who chose the first root found as the basis for building the solution to the divergence), was to identify when this oscillation between two roots occurs and to propose a simple mean between them. The oscillation between two interference values in stall situations is quite common and was based on observations of several experimental results in the literature, such as those presented by Claessens (2006). Fig. 1 illustrates one of the experimental results of Claessens (2006) that presents a range of possible values for the lift coefficient when the stall begins. The wind tunnel data were obtained for Re = 300,000 and two different profiles, one of them is the symmetric profile NACA0018 and the other is the asymmetric profile DU-06-W-200. Therefore, the nature of the solution adopted here only proposes an intermediate value for the interference factor within a field of possible solutions at the beginning of stall situations. The regions indicated in Fig. 1 are the regions where the flow instabilities caused by the stall occur; that is, it is the beginning of the flow detachment over the blade (stall), where an adverse pressure gradient upstream is generated. The experimental results in this region are multiple; they show significant instability, varying between

Table 1: Resume of the mathematical models used to obtain the performance of VAWT's

Authors	Year	Model	Proposed Methodology	Main Contribution	Main Limitations
TEMPLIM, R.	1974	Single Streamtube	It uses an actuator disk representing an interference of the rotor, delaying the flow of air in the direction of the shaft and this way reduces the speed of the flow.	First model applied to measure the performance of vertical axis wind turbines.	The entire rotor span is covered by just one airflow tube; Does not consider flux changes between rotor halves; It presents low precision in the evaluation of the performance of VAWT's; A single turbine speed reduction factor is allowed.
STRICKLAND, J.H.	1975	Multiple Streamtube	It uses a series of adjacent tubes to cover the entire length of the rotor.	It has greater precision due to its ability to consider flow variations in the rotor cross section.	The model does not account for the differences between the upwind and downwind halves; Shows performance results above actual values when TSR's are high. At high loads, convergence failures and wrong solutions are reported.
PARASCHIVOIU, I. FRAUNIE, P. BEGUIER, C.	1985	Double Multiple Streamtube	It uses two actuator disks together.	It has greater ability to predict the performance of the wind turbine.	At high loads, the method cannot achieve convergence, especially when the turbine blades are simulated with asymmetric profiles.

Font: Author, 2022.

situations without a stall, intermediate, and completely stalled. Therefore, the solution adopted here for the interference factor, which leads to intermediate stall values, is within the possible experimental solutions, thus ensuring a physical nature also observed in the flow in blade profiles.

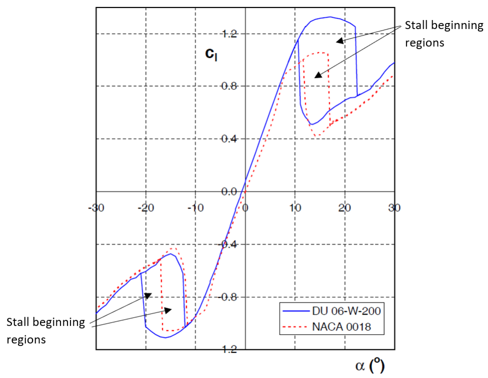

Figure 1: Wind tunnel measured data for NACA 0018 and DU 06-W-20 for Re=300,000 (CLAESSENS, 2006).

3.2 Program flowchart

Fig. 2 shows the program's iterative procedure flowchart.

First, the variables, parameters and initial values in which the simulation is going to be performed are defined. On this step, the number of streamtubes and the step ($\Delta\theta$) are also set. The interference factor is defined equal to one as an initial guess. Then the azimuthal angle (θ) in which the simulation begins is set.

Following, the local and relative velocities, angle of attack and Reynolds number (based in relative velocity) are calculated for the new blade location. Using the angle of attack and Reynolds number, run XFOIL to obtain the lift (C_L) and drag (C_D) coefficients, that will be used to calculate the normal (C_n) and tangential (C_t) coefficients in order to find C_y.

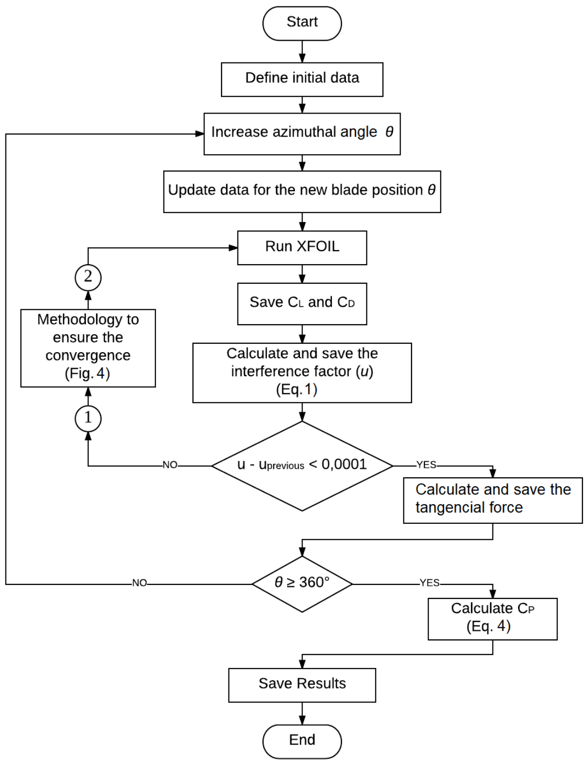

Figure 2: FASTEEVSIM's iterative procedure Flowchart.

Thereafter, the interference factor (u) is calculated and compared with its previous value. If the difference between the current and the prior interference is less than an admitted error (0.0001), the value of u is accepted for the streamtube. If this difference is greater than the admitted error, then it goes to the methodology that ensure convergence.

In the development phase of this methodology, many tests were carried out. In most of these tests, the FASTEEVSIM was able to simulate without problems. However, for some simulation conditions, the program presented convergence difficulties. In order to find a solution for such problems, the failed data was observed. Fig. 3 shows a graph of the interference factor versus blade position angle from a non convergence occurrence.

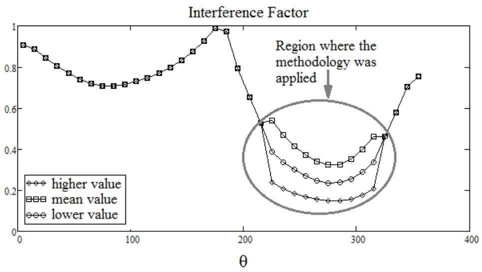

Figure 3: Graph of the interference factor.

As we can see, there is a region where more than one result is found for u. The program converged into two results, the higher and lower values shown in Fig. 3. The fact that two solutions may be found is due to the interference factor's second order equation. Therefore, the admitted error is never going to be reached since one interaction results in a lower value of u and the following in a higher value, causing a function discontinuity along θ.

In order to ensure that a solution will be found in every simulation, whenever the the program converge to two u values, the average between these values is chosen. In the Fig. 3, the values of interference factors chosen by the methodology to ensure the convergence is represented by the mean values line.

The Fig. 4 shows the flowchart of the methodology to ensure convergence. Note that the average is calculated only when the double solution problem occurs. Otherwise, the program iterates until convergence, with the error value decreasing until it reaches the admitted value.

Once the minimum error admitted is achieved, the interference factor is accepted and the tangential force (F_t) is calculated and saved. Then the process of iteration is repeated for every chosen θ until the blade completes a 360° turn. Finally, the torque ($Torque$) (Eq. 2) and the power (P) (Eq. 3) can be found and the power coefficient (C_P) is calculated (Eq. 4).

In order to validate the FASTEEVSIM program, a comparison with its simulated values and experimental data from reliable literature sources (CLAESSENS, 2006) was done. The results are shown in the next section. These were obtained for a 3-blade turbine, 2 m in

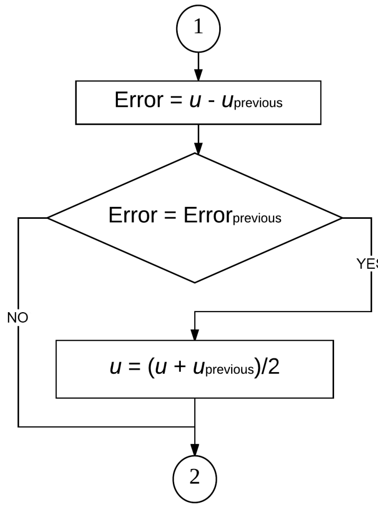

Figure 4: Flowchart of the methodology to ensure convergence.

diameter, 3 m in height, and a wind speed of 10 m/s. In addition, to verify the extent of applicability of FASTEEVSIM, other simulations were performed with wind speeds of 5.0, 7.5, and 12.5 m/s in the same turbine.

4 Results and discussion

The power coefficient (C_P) computed using FASTEEVSIM and measured experimentally is shown in Fig. 5. C_P of FASTEEVSIM is found by the program using the iterative procedure shown in Fig. 2. The experimental C_P was measured in wind tunnel tests by Claessens (2006).

As can be seen, both FASTEEVSIM and experimental C_P curves show close values at lower tip speed ratios, but FASTEEVSIM predicts higher maximum C_P value which is 0.44 at a tip speed ratio of around 4. The program presents an overprediction of C_P values at higher tip speed ratios.

As it is also verified in the current literature (PARASCHIVOIU; FRAUNIE; BEGUIER, 1985), this difference is explained due to limitations of the "BEM"models to obtain interference higher values. The higher the blade tip velocity, the greater spreading of the fluid flow upon reaching the turbine. As a consequence, the greater blockage, with high interference values (u). Among the "BEM"s based models, the Double Multiple Streamtube is the most complete and capable of estimating the interference values with the best accuracy for this λ's range. However, the model still presents limitations, which causes the difference between the values

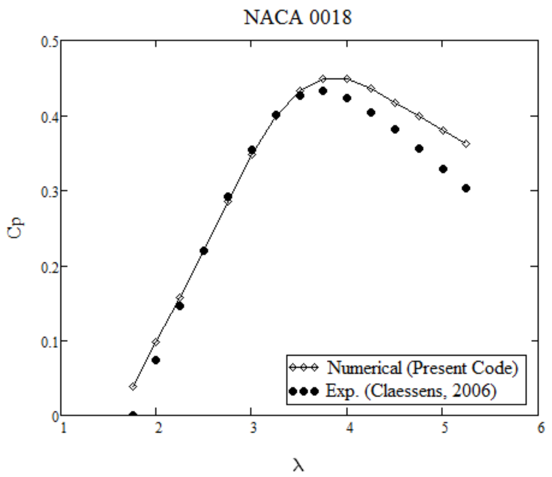

Figure 5: Power coefficient results from FASTEEVSIM and Claessens (CLAESSENS, 2006) for a VAWT using NACA0018 as blade profile.

presented in Fig. 5 to occur.

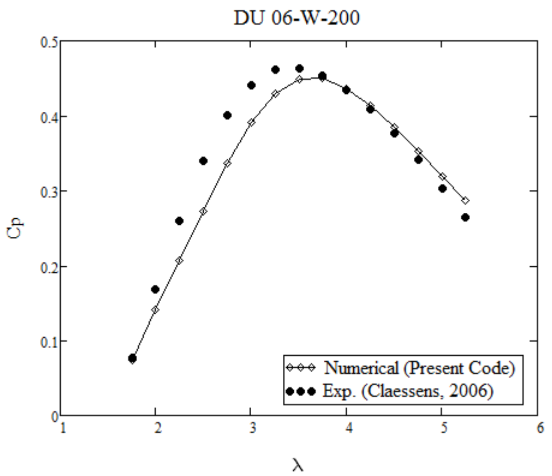

Figure 6: Power coefficient results from FASTEEVSIM and Claessens (CLAESSENS, 2006) for a VAWT using DU06W200 as blade profile.

The opposite occurs on the comparison of FASTEEVSIM with experimental C_P curve for a VAWT using DU06W200 as blade profile (see Fig. 6). FASTEEVSIM and experimental C_P curves show close values at higher tip speed ratios, but FASTEEVSIM underestimates the C_P value at lower tip speed ratios.

This phenomenon is observed with lower tip speed ratios ($\lambda < 3.5$), when blades are subjected to higher angle of attack (above 10º), and more wide recirculation regions of airfoil's exit can occur. Such a recirculation region causes great instability in the blade's lift coefficient, as it is also seen in the experimental results of Claessens (CLAESSENS, 2006). Consequently, these instabilities also present difficulties in the non-linear response of the BEM-based models, where the interference values oscillate between ups and downs. The methodology proposed here circumvents this numerical oscillation through the proposition of an average interference value, which can also overestimate or underestimate such interference values when its compared with experimental results. In the case of the DU06W200 profile, there was an overestimation of the interference values due to a greater application of the methodology, around 20% higher than the NACA0018 profile.

In order to compare VAWT using NACA0018 and DU06W200 as blade profiles, both were tested for different wind velocities (V_{inf}). The Figures 7 and 8 show C_P values obtained using FASTEEVSIM program for NACA0018 and DU06W200 blades.

As can be seen, for both profiles, the C_P increase as the value of the wind speed increases. The percentage increase from $V_{inf} = 5\ m/s$ to $V_{inf} = 7.5\ m/s$ and from $V_{inf} = 7.5\ m/s$ to $V_{inf} = 10\ m/s$ are higher than from $V_{inf} = 10\ m/s$ to $V_{inf} = 12.5\ m/s$. Thus, it appears that the C_P for $V_{inf} = 10\ m/s$ and $V_{inf} = 12.5\ m/s$ are close.

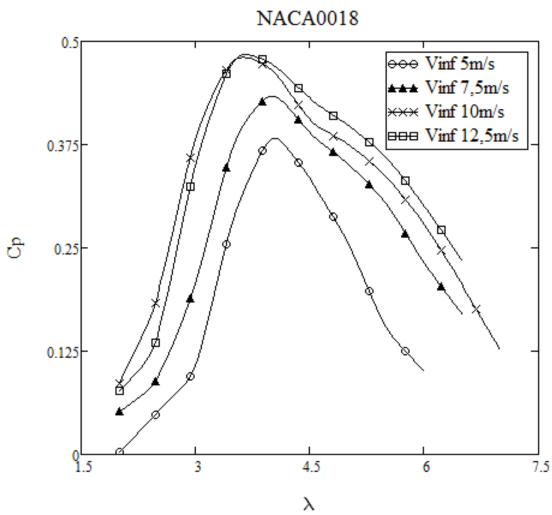

Figure 7: Power coefficient for a VAWT using NACA0018 blade profile with different wind velocities.

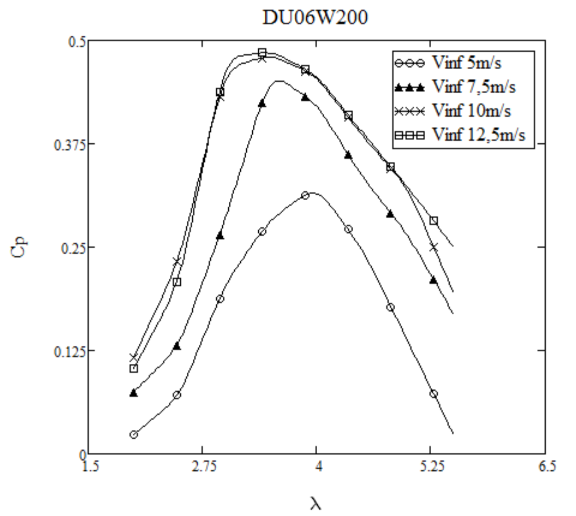

Figure 8: Power coefficient for a VAWT using DU06W200 blade profile with different wind velocities.

Figures 9 to 12 show C_P values obtained for NACA0018 and DU06W200 blades. Each of them shows the C_P values for a different wind velocity individually.

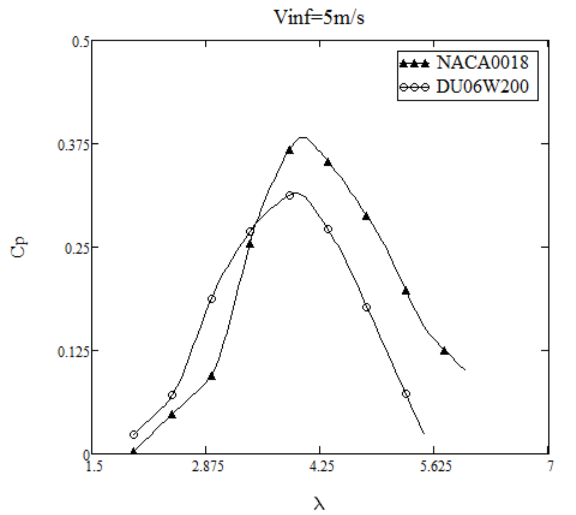

Figure 9: Power coefficient for a VAWT using DU06W200 and NACA blade profile with 5 m/s wind velocity.

In Fig. 9 it can be seen that the predicted C_P maximum at $V_{inf} = 5\ m/s$ the NACA0018 is equal to 0.38, while the DU06W200 profile has a C_P maximum equal to 0.31, thus the NACA 0018 profile has a maximum power coefficient 21.24% higher than the DU06W200.

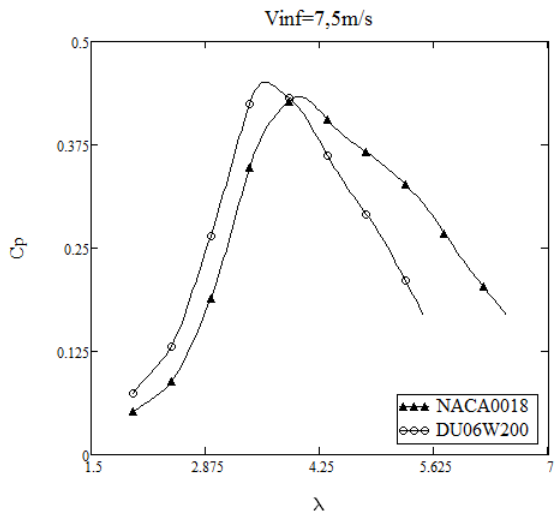

Figure 10: Power coefficient for a VAWT using DU06W200 and NACA blade profile with 7.5 m/s wind velocity.

For $V_{inf} = 7.5\ m/s$ Fig.10, the DU06W200 blade profile overcomes the NACA0018 at lower tip speed ratios. Furthermore, the DU06W200 blade profile has a C_P maximum equal to 0.45 and the NACA0018 blade profile has a C_P maximum equal to 0.43, thus the power coefficient of the DU06W200 blade profile is 4.03% higher to NACA0018.

The Fig.11 shows the results for $V_{inf} = 10\ m/s$. The C_P maximum for both blade profiles (NACA0018 and DU06W200) are equal to the value of 0.48. For this wind speed, the DU06W200 slightly outperforms the NACA0018 at lower peak speed rates. At higher tip speed ratios, the NACA0018 shows better results regarding the power coefficient.

At $V_{inf} = 12.5\ m/s$ (Fig. 12) the same phenomena are presented as at $V_{inf} = 10\ m/s$. In this case the maximum power coefficient is also equal to 0.48 for both blade profiles. For both $V_{inf} = 10\ m/s$ and $V_{inf} = 12.5\ m/s$, the difference between the maximum power coefficient is less than 0.6% for both blade profiles.

The FASTEEVSIM predicted different power coefficient curves for different wind velocities. These results are in agreement with Li et al. (2016). For the tested wind velocity values, the DU06W200 presents

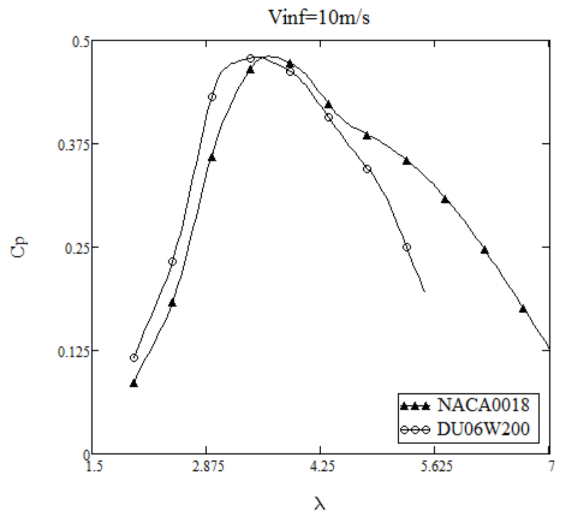

Figure 11: Power coefficient for a VAWT using DU06W200 and NACA blade profile with 10 m/s wind velocity.

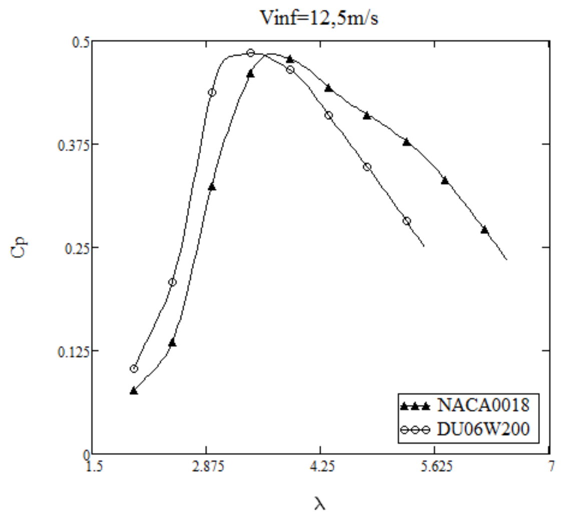

Figure 12: Power coefficient for a VAWT using DU06W200 and NACA blade profile with 12.5 m/s wind velocity.

higher C_P values than the NACA0018 at lower tip speed ratios and the NACA0018 profile overcomes the DU06W200 at higher tip speed ratios which is in agreement with Claessens (2006)

5 Conclusion

In this paper, it was presented the development of a methodology to guarantee the convergence of the Double Multiple Streamtube model, which is based on the blade element moment theory (BEM) applied to the analysis of VAWT. The method was implemented in a program called FASTEEVSIM. The methodology to guarantee the convergence of the simulations proposes to circumvent the numerical oscillations or instabilities caused by regions of the beginning of stall in the blades. This methodology uses an average value of interference and therefore, it selects an average flow as a solution among the possible flows that occur at the beginning of the stall. An investigation of performance of Darrieus type straight blade VAWT was done using NACA0018 and DU06W200 as a blade profiles.

After the FASTEEVSIM's validation, it was concluded that the program is capable to predict power coefficient curves close to experimental data. To extend the use of the methodology beyond validation, both blade profiles were tested, one symmetrical (NACA0018) and the other asymmetric (DU06W200), as well as in low and in high TSR, as in different wind conditions. As seen in the results achieved, the method proposed here did not present problems of convergence or erratic solutions in all cases.

When comparing the power coefficients with experimental data, the validation results showed a root mean square deviation of 3.62% for symmetrical profile and 6.09% for asymmetrical one. The developed methodology to ensure convergence showed to be useful and effectively assisted the program, making sure a solution was found for every simulation.

We proved that the program managed to reach reliable results through comparative analysis with experimental data, besides accelerating the simulation process. However, in the current state of development, the program can still receive improvements. For future work, we listed the following suggestions:

- Conduct simulations for a wider variety of airfoil profiles to verify the possibility of improving the accuracy and reliability of FASTEEVSIM results;
- To compare the results obtained from CFD since CFD simulations allow predicting the performance of the complete TEEV in three dimensions. It is also possible to quantify the interference from the upstream side on the downstream side of the turbine, as well as to capture the blade tip effects and to introduce them into our model;

- Carry out tests in a wind tunnel to obtain more reliable results, as there are still little experimental data on airfoil profiles used in TEEVs available in the literature.

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