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COMPARISON BETWEEN TWO PERFORMANCE CALCULATION METHODS APPLIED FOR VAWT

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This paper presents a new model of 2D performance calculation applied to VAWT. The idea consist in considering only one blade to which a rotational oscillation motion is gave. Hence, the effect of the machine rotation and the influence of the rest of the machine on the focused blade are modelled. The study is purely numerical based upon the use of ANSYS- Fluent code to solve unsteady RANS equations, which follow from the new model. Several 2D geometry configurations of Darrieus machine were tested using the new approach and the results are compared to ones applied to the whole 2D rotor. A quasi concordance of the results is noticed for the overall predictions done from the two CFD methods. Although computational time is lower for the new model, tests reveal inadequate prediction of the peak's power coefficient and its Tip Speed Ratio value.

Keywords: wind turbine, NACA0015, aerodynamic coefficient, tandem turbine

1 INTRODUCTION

A wind turbine uses kinetic energy to rotate a shaft in order to get electrical power through a generator. In fact, the main aim of this study is how to maximize recoverable energy on the shaft.

Marco Castelli et al [1] led a numerical study with the aim of establishing a rotor optimised power curve regarding to the standard functioning parameters in straight bladed VAWT, as well as defining the aerodynamic forces acting on it. This model represents a tool for developing and optimising the configuration of the rotor architectures as newly set data.

In order to avoid divergence problems on the numerical model impacting the torque magnitude during the revolution, many techniques are set. Marco castelli et al [2] led an investigation in order to reduce torque variation during the revolution by increasing the blade number. Numerical analysis would offer a view on the behaviour of the straight bladed vertical axis wind turbine concerning much more the power coefficient.

Moreover, geometric parameters impact strongly on the wind turbine efficiency. Taher G.abu El-Yazid et al [3] led an investigation in which the effect of blade numbers and the chord on the performance of Darrieus wind turbine were revealed. Therefore, It was found that for a constant chord, the power coefficient goes higher in a three-bladed machine, and it does decrease for machines with more than three blades.

Marco castelli et al [4] performed simulation studies based on full RANS unsteady calculations for three-bladed machine aiming to set a comparison between aerodynamic and centrifugal forces acting on the blade for multiple tip speed ratio values. It was found that with the increase in tip speed ratio, the blade is less efficient in its upwind section than its rear, also the peak ratio between radial and inertial forces becomes smaller with the increase of the rotational speed for higher azimuthally positions. NormundJekabsons et al [5] led a study focusing on an experimental and numerical investigation of the aerodynamic performance of six and three bladed VAWT Darrieus type. Due to computation domain limitation Betz's limit of performance is passed over in some cases contrarily to the literature, and yet it's not a failing in concept. 2D domain study proved good agreement with experimental study, and it can be counted on in comparison between multiple VAWT performances configurations, though it can be an alternative to three-dimensional time consuming studies.

Airfoil geometry has a big influence on VAWT's performance and functioning. MD Farhad Ismail et al [6] conducted a study introducing a geometric change in the lower surface of NACA0015 airfoil using Gurney flap and a semi-circular dimple, the aim is to improve the performance and energy recovery within a VAWT. An optimised unique design can be obtained according to the results at an appropriate Reynolds number value with constant tip speed ratio. The combination between Gurney flap and semi-circle inward dimple has offered an increase by third in tangential force. Masoud Ghasemian et Al [7] led an investigation in order to study the installation of a wind turbine farm in urban areas; multiple parameters were to be discussed. Focusing on the aerodynamic configuration, results show that for a weak speed ratio, the more solidity increases the least the power coefficient goes. Also, for weak angular velocities, installing more blades on the rotor would pull up the power coefficient and vice versa. It has been found as well that the self-wind starting problem for weak wind could be overcome by introducing a guide vane working on speeding up the oncoming wind as well as correct automatically the flow angle to have better power coefficient.

Solidity and rotating speeds have undergone various studies among researchers' works. Song Jun Joo [8] investigated the aerodynamic performance of a double straight bladed H vertical axis wind turbine for multiple solidities and tip ratios. Results have revealed that the higher performance is gained out of a relatively bigger solidity. It has been found also that the flow configuration lies under the effect of both the blockage and the interaction between the two blades. Thus, both relative velocity and attack angle is changed due the effect of both precedent two factors.

Sajid Ali et al [9] presented a study aiming to deeply investigate and analyse the aerodynamic behaviour of an H Darrieus three bladed VAWT. Analysing instantaneous tangential velocity variation could lead indirectly to help predicting the performance of the wind turbine. Results show that for lower TSR values, the tangential velocity was set to be negative in a wider azimuthal position, this is due to the flow separation marked within the critical azimuthal angle. Thus, this failure led into a critical loss in power coefficient as well.

Both torque and power have been main characteristics investigated in many VAWT's conceptions. Young-Tae et al [10] set both numerical investigation and wind tunnel experiment on Darrieus VAWT's performance in function of different functioning parameters (helical angle, chord...etc). The study offers an improved airfoil shape with maximum power extraction. It was found that higher power coefficient is gained out of less drag and bigger solidity in small TSR domain, and vice versa. Weaker drag could be optimised by watching the rotational speed. Results show that the airfoil's thickness ratio has no influence on the power coefficient. In addition, pitch angle varying is not simple to predict its optimum but it set to be varying in accordance to the attack angle. Helical shaped airfoil does not give high performance, however higher performance is obtained from airfoil with zero-degree helical angle.

The shape of the airfoil and its relationship with self-starting problem is widely well-known issue in VAWTs conception. A.R. Sengupta et al [11] established a comparison between symmetrical and non-symmetrical blades mounted on H-Darrieus rotors functioning under low streams, aiming to evaluate the optimum case parameters in terms of starting characteristics and performance along with flow parameters. Results show that all set of rotors acquires good self-starting ability as long as there is no negative torque, in addition both of them offer high torque on the rotor for a same given TSR range. Also it was found that lower wind speed and less TSR values make the unsymmetrical airfoil the best configuration to take under such conditions among others. Considering taken time to start, symmetrical airfoil takes minimum period to start from stagnation position in comparison to other configurations. The high solidity unsymmetrical airfoil gives higher values of static and dynamic torque in comparison to other airfoils considered in the investigation.

Marco Raciti Castelli et al [12] led an investigation to evaluate the contribution of both inertial and aerodynamic in accordance to the blade deformation in VAWT airfoil. An improved airfoil is generated by a specially structured code. CFD results show that relatively thick shell blade possesses higher inertial influence on the rotor, though; the aerodynamic displacement is related directly to the deformability of the rotor blade, reach higher values in respect with less thick shell blade.

Both inertial and aerodynamic influence are bigger on the blade's trailing edge to its leading edge. Start-up characteristics and their associated issues are widely handled in many investigations. Mahdi TorabiAsr et al [13] led an investigation aiming to study the behaviour of Darrieus H wind turbine while starting up, CFD 2D transient simulations were carried out for studying rotor geometry variation with the changing of airfoil every set of simulation. Results show many parameters to consider in order to reduce starting up time; although, start-up characteristics had been improved effectively by only using cambered airfoils with smaller pitch angles.

Numerical tools meshing acquisition and appropriate turbulent model choosen are common issues in modelling wind turbines. M.H. Mohamed et al. [14] led an investigation to study VAWT global performance, and established a comparison between two studied cases using ANSYS workbench and Gambit meshing tool. Results show ANSYS workbench meshing tool requires further mesh refinement near the walls while using SST K-ω turbulence model. Although, computational cost using this technique would go higher but it gives the chance to check viscous sub layer y+ with more confidential results. If Gambit is used to discretize the domain, K-ε proved advantage to use as turbulent model to achieve reliable results with less computing cost because it does not require greater mesh refinement.

An increasing interest is devoted these years to Darrieus machine equipped with blades in tandem or biplane configuration. These kind of wind turbine develop more power than the one of single blades, [16, 17]. Muhammad Alfian Mizar [18] led a study an analyze the influence of the cup diameter on the power performance of the HC vertical axis wind turbine (VAWT). Wind turbines used combination of H-type Darrieus wind turbine and C-type rotor VAWT. This result provides important information about the effect of the C rotor radius on the vertical axis performance of the HC rotor Darrieus wind turbine blade. Pierre-Luc Delafin et al [19] led a study for two-dimensional blade analytical unsteady Reynolds averaged Navier-Stokes (RANS) simulation was used to evaluate the performance improvement that the pitch blade can bring to the optimal performance of a three-blade vertical-axis tidal turbine. Defined and tested three pitching laws. Their goal is to reduce the angle of attack of the blades in the upstream half of the turbine. No pitch movement is used in the downstream half. The streamwise velocity, monitored at the center of the turbine, together with the measurement of the blades' angle of attack help show the effectiveness of the proposed pitching laws. Ahmed Gharib-Yosry et al [20] led a study focusing on an experimental and numerical investigation for to evaluate the operation of the Darrieus turbine rotor as a wind or hydraulic micro-generator, a series of wind tunnel and water flow trough tests were carried out. Obtain power and characteristic curves for all test conditions. In the wind test, all curves seem to be the same, which means that the turbine rotor works normally in open wind.

In the present paper, it is proposed a CFD method to predict the VAWT performances with a computational time less than the one of classical CFD methods which consume more time for the calculation. Indeed, the flow around a VAWT machine is strongly unsteady due to the fact that the blade rotation axis is perpendicular to the wind velocity. The unsteady RANS methods, which are based upon the sliding mesh, lead to a slowly convergence of calculations. To reduce computational time, an alternative in 2D computations, consist in focussing on any one blade in the VAWT machine and modelling the effect of the attack angle change on it by giving an oscillation motion to the blade as it's undergone by the VAWT blades.

Consequently, this method uses the very aerodynamic concept which explains overall how the flow around the wind turbine profile generates a torque. It is very instructive especially for predicting if or not a new design of machine produces mechanical energy. However, the real flow pattern of the VAWT machine could be slightly affected when using this approach since the effect of trajectory curvature while blade motion is not taken into account, Fig. 1

The calculations were performed using ANSYS Fluent 14.1 code at free stream wind with density ρ = 1.25 kg/m3 and speed U∞ = 9 m/s.

Some 2D VAWT machine models have been chosen to test them, in the present work, by using the two unsteady RANS methods; the new CFD approach and the classical one in which the machine rotation is taken account.

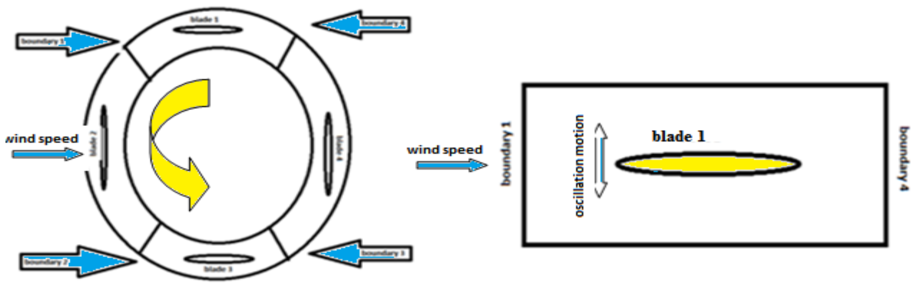

Fig. 1. Model of the new approach flow field of DARRIEUS wind turbine**.**

2 TURBINE PARAMETER

Vertical axis wind turbine of type Darrieus with its straight-bladed rotors has much simple conception regarding other wind turbines family, Fig. 2. Understanding the mechanism and the physic aspect of the wind turbine needs knowing the defined next parameters [17].

2.1 Tip speed ratio λ

Also referred as TSR, this non-dimensional parameter represents the ratio between the tangential velocity and the wind speed.

$$\lambda = \frac{\omega R}{U_\infty} \tag{1}$$

2.2 Incidence angle α

Darrieus wind turbine motion is assimilated to a cyclic incidence angle motion. The behaviour of rotor's blades is referred to an oscillating profile while revolution. During its rotating motion, incidence angle passes through both positive and negative values in function of azimuth angle θ. It is defined:

$$\alpha = \arctan\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) \tag{2}$$

2.3 Relative velocity

wind's relative velocity is function of θ too:

$$V_r = U_\infty\sqrt{(\lambda + \cos\theta)^2 + (\sin\theta)^2} \tag{3}$$

2.4 Aerodynamic coefficient

The lift and drag coefficient are essential to predicting wind's behaviour and to set its conception:

– Lift coefficient C_L:

$$C_L = \frac{F_L}{\frac{1}{2}\rho.S.U_\infty{}^2} \qquad (4)$$

– Dragcoefficient C_D:

$$C_D = \frac{F_D}{\frac{1}{2}\rho.S.U_\infty{}^2} \qquad (5)$$

– Momentum coefficient CM:

$$C_M = \frac{M}{\frac{1}{2}\rho.C.S.U_\infty{}^2} \qquad (6)$$

There's another formula available to obtain the momentum from.

2.5 Tangential force

The tangential force is written like so:

$$F_T = -F_D\cos(\alpha) - F_L\sin(\alpha) \qquad (7)$$

This formula is applicable in the second procedure, and from it the momentum can be obtained:

$$M= FT.R \qquad (8)$$

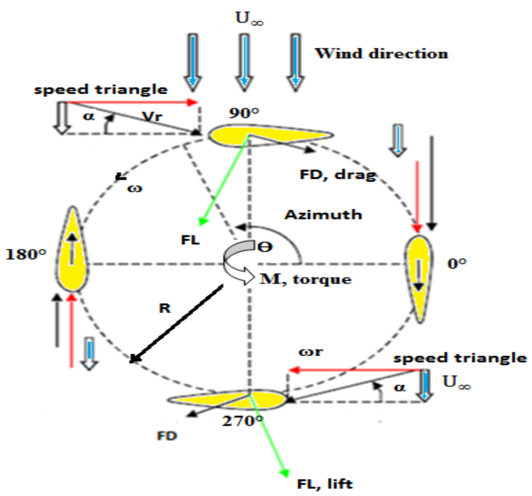

Fig. 2. Functional Diagram of Darrieus Rotor. [15]

Momentum's mean value: it is essential in defining power value:

$$\bar{M} = \int dM \qquad (9)$$

2.6 Power P

The power generated by the rotor, it's written:

$$P = \bar{M}.\omega \qquad (10)$$

2.7 Power coefficient Cp:

$$C_p = \frac{P}{\frac{1}{2}\rho.D.U_\infty{}^3} \qquad (11)$$

3 NUMERICAL MODELLING

The aerodynamic profile NACA 0015 is used in the current design of the tested rotors. It is symmetric with no camber airfoil widely used in wind turbine industry. Studies revealed that NACA 0015 profile is highly recommended for the Darrieus rotor thanks to its favourable stall characteristics [5]. All tested models are based on profile which has a chord C =85.8 mm and rotor diameter D = 1030 mm.

4 ROTOR DISCRETIZATION

4.1 First method:

In the first method, all complete rotor is considered for the numerical simulations. Several configurations are thus studied: Bi, tri, and four bladed with also different blade positioning.Fig.3.

- Model 1: is a simple symmetric three bladed rotor with constant radius for all the blades.
- Model 1.A is a simple symmetric four bladed rotor with constant radius rotor for all the blades.
- Model 1.B has the same geometric configuration as model 1.A but the diameters of the two opposite blades are different.
- Model 1.C is a simple two-bladed rotor with constant radius and the blades are opposites.
- Model 2 is a four-bladed rotor where the blades are arranged in two pairs or tandems.
- Model 3, is similar to Model 2 but the pair of blades have undergone a tangential shift of 0.5 C downstream.
- Model 4 is similar to Model 3 but with tangential upstream shift of 0.5 C.

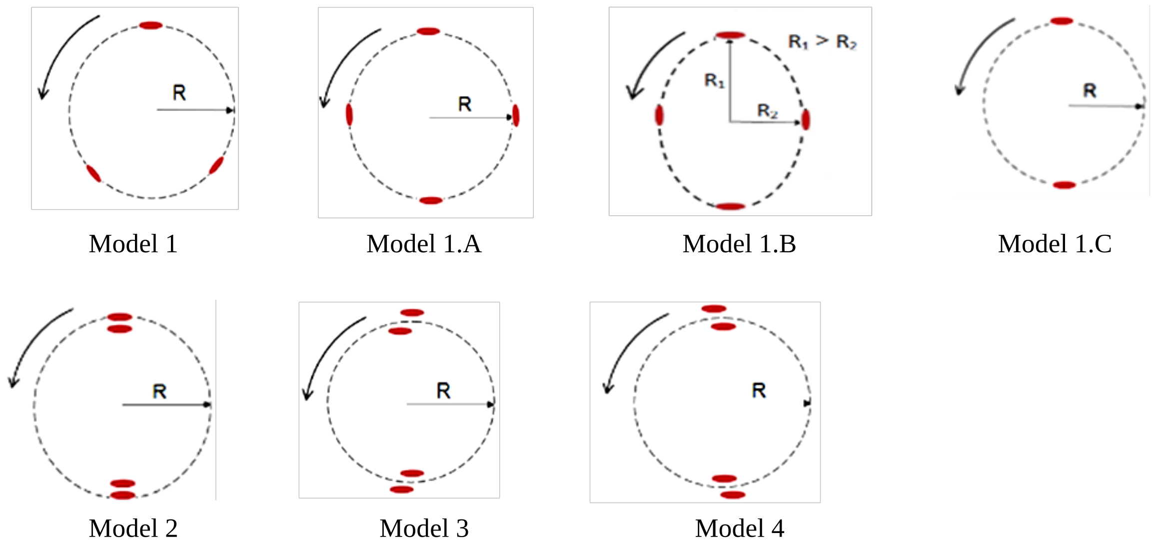

Fig. 3. Wind turbine configurations tested by the first procedure.

4.1.1 Meshing the rotor field:

The computational field is divided in two parts;

- rotating domain (rotor) which is a circle including the blades of the wind turbine and turning around its center,
- Static domain (stator) which is rectangular surrounding the VAWT machine.

The dimensions of the two domains, as it is recommended in the similar studies, [2], are indicated in the Fig. 4 as well as the boundary conditions.

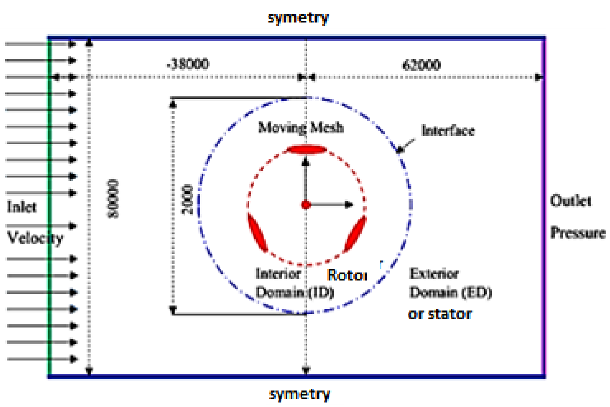

Fig. 4. Flow field dimensions and boundary conditions.

The grid generation for both stator and rotor domains, Fig. 5, was carried out using Gambit code and adopting the element sizes in the study [2]. Triangular element was chosen to the computational domain meshing for its good adaptation to the flow's direction sudden change that characterize Darrieus turbines. This method requires very divided computer fields. So the grid generated from the rotor assembly has 184000 nodes to perform the numerical simulation.

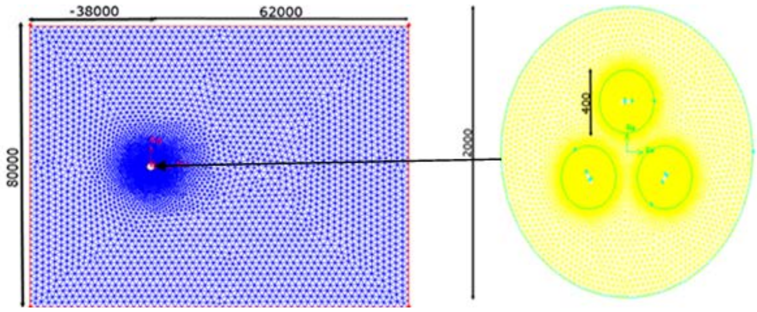

Fig. 5. Grids of static and rotating domains.

The flow around the calculation domain is considered 2D, unsteady, incompressible and turbulent. The one-equation of Spalart-Almaras was used as turbulence model. The governing equations are the Reynolds Averaged Navier-Stokes (RANS) equations which were solved by the numerical finite volumes method with standard pressure-based solver. The pressure-velocity coupling was treated using PISO scheme. Both momentum and modified turbulent viscosity were treated using first order upwind approach. The technique of Sliding Mesh was adopted for unsteady calculations.

4.2 Second method

This part of the work is set to introduce improvement in both single blade and tandem arrangement in order to predict the impact on the whole rotor behaviour. Due to the higher computational time relative to the simulation of the full rotor machine, this new technique is implemented so a single set of blades (one or two) in every machine undergoes the numerical simulation in isolation without rotation. The four configurations tested are:

Model 1 is a single blade; model 2 is a tandem blades without shift, model 3 is a tandem blades with 0.5C upstream shift, and model 4 is a tandem blades with 0.5C downstream shift Fig.6 .

Model **1** Model **2** Model **3** Model **4**

Fig. 6. Wind turbine configurations tested in second isolation procedure.

4.2.1 Isolated blade meshing

The second method requires meshing both surrounding rectangular fixed field which acts like wind tunnel and the inner circle in oscillating motion that holds the isolated blades. Regarding to the fixed grid's length, it is obtained by equation:

$$L = \frac{2\pi R}{N_p} \qquad (12)$$

Where R is the radius of the machine and N_p is the number of the blades.

The fixed grid's width is 4D, where D is the circle diameter and D is equal to 2.4 chords of the profile. In the fig. 7 all calculation field dimensions as well as the boundary conditions are indicated. It is noted that for the velocity at the inlet, the equation (3) is implemented in the Fluent code for a wind velocity U∞ = 9 m/s, while the oscillation motion of the rotor obeys to the equation (2).

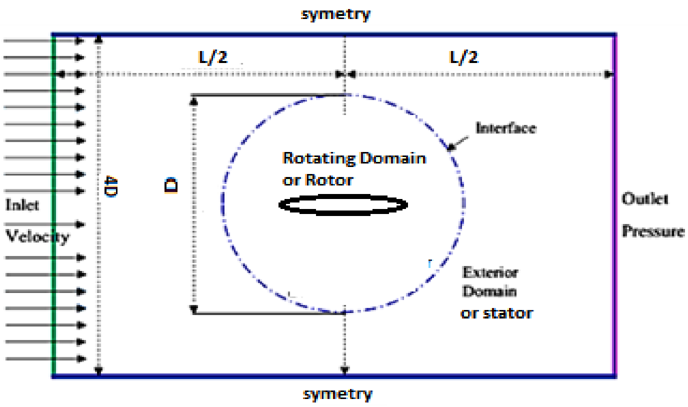

Fig. 7. Flow field dimensions and boundary conditions.

The meshing of the whole domain by Gambit has required only 52100 nodes since the second method depends on less resolution mesh grid, about fourth of the precedent mesh resolution Fig. 8. The numerical solution adopted for the second procedure has the same solving parameters except for the turbulence model where Kω-SST is used, and SIMPLE approach to treat the pressure-velocity coupling.

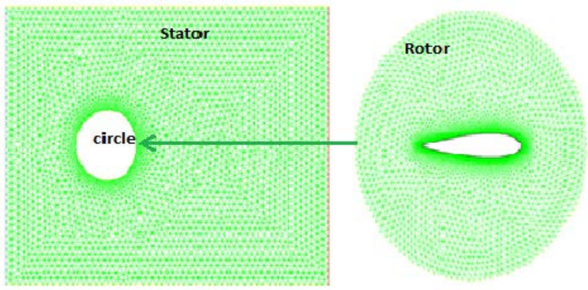

Fig. 8**.** Grids of static and rotating fields.

4.2.2 Time step defining for the two methods

Sliding mesh technique was used for the two approaches since the resolution method is unsteady. In the present work, numerical time step was calculated from the next formula, where m represents number of time steps taken in one turn or period and N is the rotation speed:

$$dt = \left(\frac{60}{N.m}\right) \tag{13}$$

For the two methods, a value of 360 was adopted for the parameter m when about of comparative calculation.

5 RESULTS AND DISCUSSION

The present numerical results were obtained from 2D simulation both to Darrieus full rotor in rotation and oscillating profile. The aim is to establish comparison with the results coming from the two approaches by using the main evaluation criteria that is the power coefficient Cp.

In both numerical procedures, a periodic solution is obtained due to unsteadiness nature of the problem. The sliding mesh technique provide, in the time, a real solution of behaviour VAWT machine's composed by a transient part and a periodic one. In order to reach solution's convergence the numerical solution is done for up to six revolutions Fig. 9a, Fig. 9b. The present study is putting the focus only on the periodic solution.

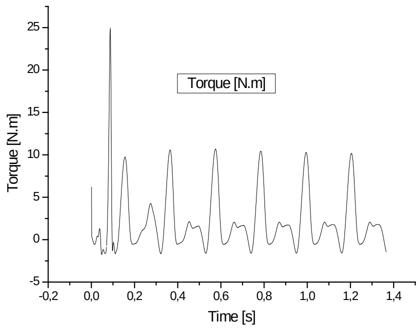

Fig. 9.a**.** Torque convergence in rotation for TSR=1.5.

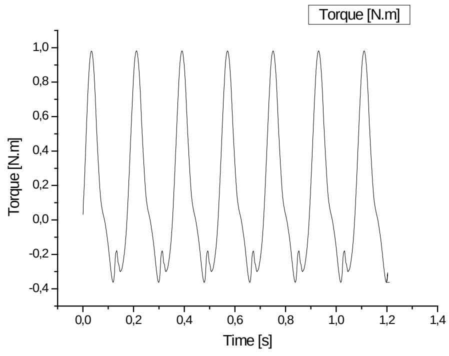

Fig. 9.b**.**Torque convergencewithout rotation for TSR=1.5**.**

First procedure: This procedure is known of its high computing time given that one calculation test can takes up to 72 hours of computing to get converged. The explored range of TSR was between 1.5 and 4.5 for the most tested rotors.

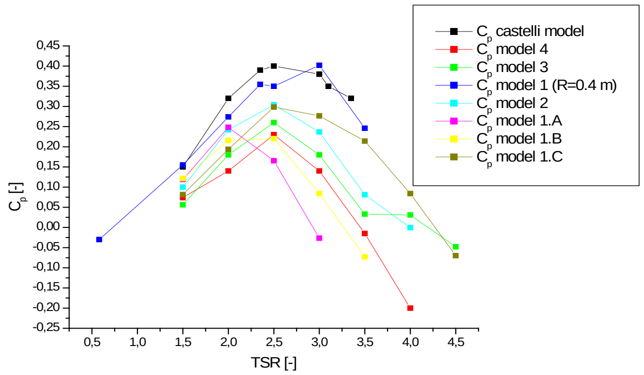

Fig. 10. Power coefficients as a function of tip speed ratio in the first procedure.

5.1 First procedure's

Rotors in rotation results were compared to the three bladed rotor treated in Castelli's work [2] since the same meshing was adopted also for the present configurations. Results show clearly a same maximal peak power coefficient but at slightly different TSR for the three bladed rotor obtained both by Castelli's curve and the configuration of model 1 one, among all simulated rotors Fig.10. Results of the present procedure have never exceeded the Betz limit value, 0.59, all along the simulation. It is noticed that the configurations in tandem among the high number of blades behaves less efficiently. This result is surprising by comparison with the one of the other study [16] which, on the contrary, confirms the superiority of the tandem for urban applications.

5.2 Second procedure

In the calculation, convergence is reached when every blade's wake is corresponding to the next blade. Otherwise, when the speed profile at the inlet is repeated at the outlet of the calculation field this validates the periodicity condition between the different blades of the rotor.

This is confirmed by the velocity distribution which is showing perfect superposition between both inlet of outlet of the physical domain Fig.11.

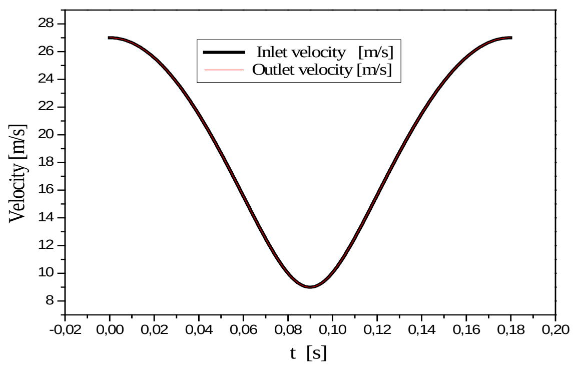

Fig. 11. Wake distribution, TSR=2.

Fig. 12. shows, for a given TSR value, the evolution of the tangential force during a period for the two, three and four single blade rotor configurations. It is noted that, for a given rotor radius, the length of the calculation field is proportional to the number of the machine's blade in accordance to the equation (12). It can be seen that three bladed VAWT gives much more of positive tangential force during one turn and hence more power in comparison to the other rotor configurations. This confirm the superiority of this type of machine and verifies Castelli's results [2].

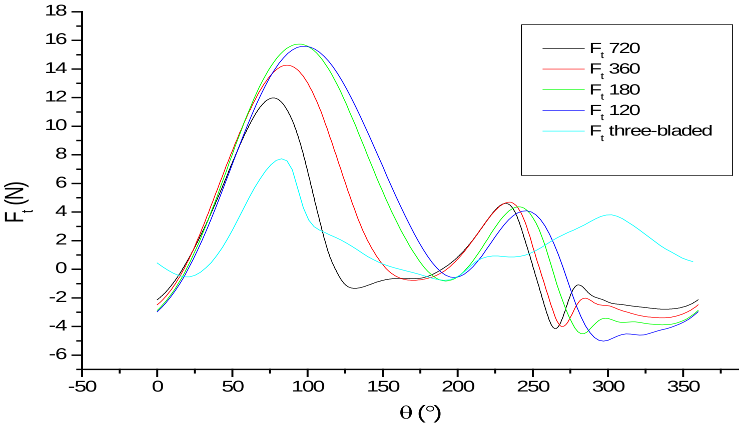

Fig. 12. Tangential forces in (2-3-4) bladed machine in term of azimuthal angle, TSR=2.

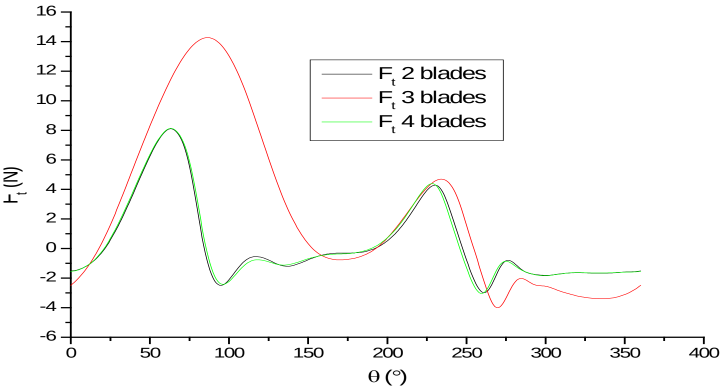

Fig. 13. Tangential force in different steps time number, TSR=2.

Fig. 13. depicts the evolution of instantaneous tangential force for three bladed configuration and for different time steps. The value of TSR was fixed at 2 and time refinement was operated by modifying the value of m in the equation (2). Thus, m takes four values; 120,180, 360 and 720. It is observed that despite the use of time steps very fine, the solution is not really stable. Indeed the comparison of the curves corresponding to the respectively cases; 360 and 720 show it. In the figure, it can be seen also that all curves have the same trend, though; the curve of 720 time steps nears closely to the one classic methods.

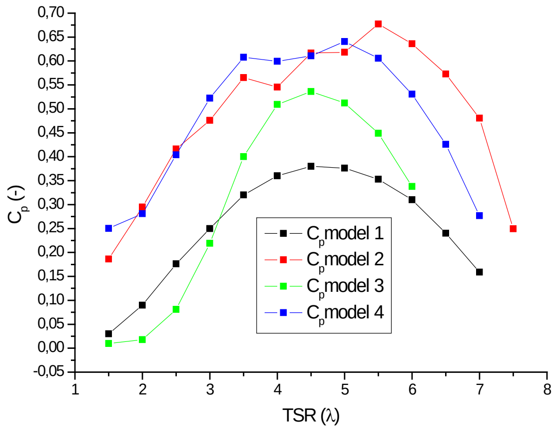

Fig. 14. Power coefficients as a function of tip speed ratio in the second procedure.

Fig. 14. shows the evolution of power coefficient versus TSR for model 1, model 2, model 3 and model 4. It is remarked that model 2, which corresponds to six bladed rotor in tandem configuration without shift, gives the best power coefficient peak relative to TSR equal to 5.5.

As a comparison between the two procedures, Fig. 15. shows the power coefficient evolution for model 1 resulting from both procedures. Power coefficient peak in rotation can be reached in smaller TSR range going up to 5 which conforms to experimental taken TSR field. Second method, with non-rotating isolated blade, reaches peak power coefficient, in wider TSR range, a bit larger, this can be blade interaction and rotation absence related.

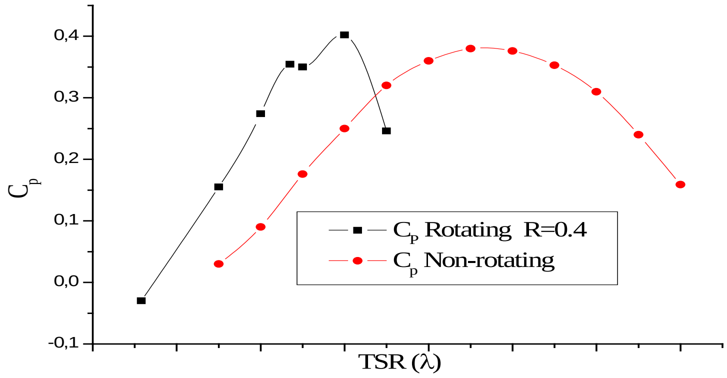

Fig. 15. Comparison between two procedures.

6 CONCLUSION

A numerical investigation was leaded on the Darrieus VAWT with different geometric configurations. The purpose is to test the reliability in predicting rotor's performances of a new technique based upon the isolation of one blade among the rest of the machine and studying the flow during its rotational oscillation. This technique proved superiority with its lower both computational time and resolution mesh by comparison with the classical method which takes account the whole rotor. Furthermore, the oscillating profile technique reaches the same conclusion regarding to the dominance of the three bladed wind turbine among VAWT with single blades. Moreover, its predictions about the blades in tandem configuration applied to Darrieus machine are more consistent than the classical method. Indeed, this type of configurations are known in practice for their higher efficiency.

However, power coefficient's curve peak, obtained by the new technique, show an offset regarding to the TSR value due probably to the absence of rotation motion. Moreover, this method could give unrealistic maximum Cp exceeding the Betz limit.

Further investigations would point on how to improve accordance in power coefficient for the new method.

7 REFERENCES

[1] Castelli, M R., Englaro, A., Benini, E. (2011). The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD. Energy, vol. 36, 4919-4934, Doi:10.1016/j.energy.2011.05.036

[2] Castelli, M R., De Betta S,. Benini, E. (2012). Effect of Blade Number on a Straight-Bladed Vertical-Axis Darreius Wind Turbine. International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, vol. 6, no. 1, 68-74

[3] Abu-El-Yazied, T G., Ali, A M., Al-Ajmi, M S., Hassan, I. M. (2015). Effect of Number of Blades and Blade Chord Length on the Performance of Darrieus Wind Turbine. American Journal of Mechanical Engineering and Automation, vol. 2, no. 1, 16-25

[4] Castelli, M R., De Betta S., Benini, E. (2013). Numerical evaluation of the contribution of inertial and aerodynamic forces on VAWT blade loading. World Academy of Science: Engineering and Technology, vol. 7, no. 6, 373-378

[5] Jekabsons, N., Upnere, S., Kleperis, J. (2016). Numerical and experimental investigation of H-Darrieus vertical axis wind turbine. Engineering for rural development, vol. 25, no. 15, 1238-1243

[6] Farhad Ismail, M., Vijayaraghavan, K. (2015). The effects of aerofoil profile modification on a vertical axis wind turbine performance. Energy, vol. 80, no. 01, 20-31, DOI:org/10.1016/j.energy.2014.11.034

[7] Ghasemian, M., Ashrafi, Z N., Sedaghat, A. (2017). A review on computational fluid dynamic simulation techniques for Darrieus vertical axis wind turbines. Energy Conversion and Management, vol. 149, 87-100, DOI: 10.1016/j.enconman.2017.07.016

[8] Joo, S., Choi, H., Lee, J. (2015). Aerodynamic characteristics of two-bladed H-Darrieus at various solidities and rotating speed. Energy, vol. 90, part 01,439-451

[9] Ali, A., Lee, S M., Jang, C M. (2018). Effects of instantaneous tangential velocity on the aerodynamic performance of an H-Darrieus wind turbine. Energy Conversion and Management, vol. 171, part 01, 1322–1338, DOI: 10.1016/j.enconman.2018.06.075

[10] Lee, Y T., Lim, H C. (2015). Numerical study of the aerodynamic performance of a 500 W Darrieus-type vertical-axis wind turbine. Renewable Energy, vol. 83(C), 407-415, DOI:10.1016/.renene.2015.04.043

[11] Sengupta, A R., Biswas, A., Gupta, R. (2016). Studies of some high solidity symmetrical and unsymmetrical blade H-Darrieus rotors with respect to starting characteristics, dynamicperformances and flow physics in low wind streams. Renewable Energy, vol. 93, 536-547, DOI: 10.1016/j.renene.2016.03.029

[12] Castelli, M R., Dal Monte, A., Quaresimin, M., Benini, E. (2013). Numerical evaluation of aerodynamic and inertial contributions to Darrieus wind turbine blade deformation. Renewable Energy, vol. 51, 101-112, DOI: 10.1016/j.renene.2012.07.025

[13] Torabi Asr, M., Zal Nezhad, E., Mustapha, F., Wiriadidjaja, S. (2016). Study on start-up characteristics of H-Darrieus vertical axis wind turbines comprising NACA 4-digit series blade airfoils. Energy, vol. 112, 528-537, DOI: 10.1016/j.energy.2016.06.059

[14] Mohamed, M H., Ali, A M., Hafiz, A A. (2014). CFD analysis for H-rotor Darrieus turbine as a low speed wind energy converter. Engineering Science and Technology, an International Journal, vol. 18, no. 01, 1-13, DOI: 10.1016/j.jestch.2014.08.002

[15] Beri, H., Yao, Y. (2011). Effect of Camber Airfoil on Self Starting of Vertical Axis Wind Turbine. Journal of Environmental Science and Technology, vol. 4, no. 03, 302-312, DOI : 10.3923/j.jest.2011.302.312

[16] Cismilianu, A M., Boros, A., Oncescu, I C., Frunzulica, F. (2015). New Urban Vertical Axis Wind Turbine Design. Incas Bulletin, vol. 7, no. 4, 67 – 76

[17] Oulhaci, Z S., Imine, O., Ladjedel, O., Yahiaoui, T., Adjlout, L., Sikula, O. (2017). Experimental Performance Analysis of Biplane VAWT Configurations. Journal of Applied Engineering Science, vol. 15, no. 475, 480 – 488, DOI: 10.5937/jaes15-13690

[18] Mizar, M A., Puspitasari, P., Taufiq, A., Trifiananto, M. (2020). An experimental test of the effect of cup diameter on the power performance of novel design HC-type VAWT. Journal of Applied Engineering Science, vol. 15, no. 738, 631 – 636, DOI: 10.5937/jaes0-25010

[19] Delafin, P L., Deniset, F., Astolfi, J A., Hauville, F. (2021). Performance improvement of a darrieus tidal turbine with active variable pitch. Energies, vol. 14, no. 667, 631 – 636, DOI: 10.3390/en14030667

[20] Gharib-Yosry, A., Blanco-Marigorta, E., Fernández-Jiménez, A., Espina-Valdés, R., Álvarez-Álvarez, E. (2021). Wind–water experimental analysis of small sc-darrieus turbine: an approach for energy production in urban systems. Sustainability, vol.13, no.5256, 1-15, DOI:10.3390/su13095256

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