XL CILAMCE
IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING
NOVEMBER 11-14, 2019
Praiamar Natal Hotel & Convention
Natal, RN-BRAZIL

COMPARATIVE STUDY OF CFD AND THE DMST APPLIED TO DARRIEUS H-ROTOR PERFORMANCE CALCULATIONS

Willian Minoru Okita
Kamal Abdel Radi Ismail
minoruokita@gmail.com
kamal@fem.unicamp.br
State University of Campinas, Faculty of Mechanical Engineering, Energy Department,
Mendeleiev street, 200, Cidade Universitária "Zeferino Vaz", 13083-860, Barão Geraldo, Campinas

Abstract: CFD and other vortex methods are used to predict the performance of horizontal and vertical axis wind turbines and investigate the wake effects with good precision. The main drawback of these methods that they usually consume a lot of computational time and consequently expensive for quick evaluation studies. There are other numerical methods that can be useful for this type of application needing less computational time and reasonably accurate. One of such numerical methods is the blade element momentum (BEM) for horizontal axis wind turbine and double multiple stream tube (DMST) for vertical axis wind turbine. This work reports the results of a comparative study between CFD, experimental measurements and the DMST to predict the performance of Darrieus H-rotor type vertical axis wind turbines (VAWTs). The DMST combines the multiple stream tube model with the double actuator disk theory. The results from the present study compared the CFD results with the present Matlab DMST code incorporating Xfoil. The DMST overestimated the power coefficient but presented similar behavior when compared with other numerical and experimental results. The overestimated values are mainly due to the fact that the wake is not accounted for in a simultaneous way as is the case in the experiments and CFD simulations.

Keywords: Double multiple stream tube, Vertical axis wind turbine, CFD, Aerodynamic performance

Introduction

The installed wind power capacity reached almost 540 GW worldwide, with Brazil contributing with more than 12.7 GW [1]. The decrease of the prices of wind turbines made the technology more competitive in several countries. However, most of the worldwide growth of wind technology is due large scale generating farms on and off shore. Small wind turbines on the other hand is limited in extension irrespective of the fact that small wind turbines have great potential with about 12% growth forecast between 2015 and 2020 [2]. The leading markets for this technology are in China, the United States and the United Kingdom, Germany, Canada, Japan, and Italy. Small-scale wind turbines are still an inexpressive market in most developing countries, although the technology has great potential in these locations in off-grid applications, such as in rural electrification and urban applications.

In recent years the possibilities of urban applications and the increasing demand in decentralized power plants renewed the interest in Vertical Axis Wind Turbines (VAWT) since it offers several advantages in comparison with Horizontal-Axis (HAWT) machines. The VAWT does not need yawing mechanism for keeping the wind turbine in the wind direction while the transmission and electrical generation equipment can be located at ground level which results in lighter structure. On the other hand, VAWT aerodynamics is inherently unsteady, complex and highly nonlinear.

A literature survey indicates that the most studied models can be classified into three categories (i) Momentum model, (ii) Vortex model and (iii) Cascade model. The momentum model is fast and provide reasonably accurate prediction of steady state average turbine output. Bhutta et al. [3] reviewed various configurations of VAWT along with their merits and demerits. Moreover, design techniques employed for VAWT design were reviewed along with their results. Tummala et al. [4] presented a review of different types of small scale horizontal axis and vertical axis wind turbines. The performance, blade design, control and manufacturing of horizontal axis wind turbines were reviewed. Vertical axis wind turbines were categorized based on experimental and numerical studies. Kumar et al. [5] reviewed details of horizontal and vertical axis machines, advantages and operational recommendations and projects and concluded that further research is critical in making VAWTs a viable, dependable, and affordable power generation technology for many low and decentralized power applications.

Many studies were devoted to investigate the aerodynamic performance of small VAWT using the double multiple stream tube (DSMT) model while varying the airfoil of the blades and solidity of the rotor as in Beri and Yao [6], Paraschivoiu et al. [7], Castelli et al. [8], Rogowsk et al. [9], Hasan et al. ([10] and Kumar et al. [11]. Sunny and Kumar [12] presented aerodynamic modeling, fabrication and the performance evaluation of vertical axis wind turbine (VAWT). The test results showed that the VAWT has a reliable and efficient performance. Li et al. [13] investigated the effect of rotor aspect ratio and solidity on the power performance in three-dimensional analysis by panel method. The results indicated that the peak of power coefficient increases with the increase of the ratio of the diameter and blade length H/D at the fixed solidity.

Peng et al. [14] reported the results of experimental study on VAWT and indicated that the high-solidity straight-bladed VAWT has better self-starting performance and can achieve higher power coefficient at lower tip speed ratios, which enable VAWT to work at low rotational speed conditions.

Vertical axis wind turbines (VAWTs) have received growing interest for off-shore application and in the urban environments mainly due to their Omni-directional capability, scalability, robustness, low noise and costs. However, their aerodynamic performance is still not comparable with their horizontal axis counterparts. To enhance their performance, the impact of operational parameters such as tip speed ratio, Reynolds number and turbulence intensity on their power performance and aerodynamics needs to be deeply understood. Vertical Axis Wind Turbine is relatively simple to implement in urban areas on ground or/and building-roofs, the development of appropriate design of VAWT will open new opportunities for the large scale acceptance of these machines, Rezaeiha et al. [15] and Shah et al. [16].

This work reports the results of a comparative study between CFD, experimental measurements and the DMST to predict the performance of Darrieus H-rotor type vertical axis wind turbines (VAWTs). The DMST combines the multiple stream tube model with the double actuator disk theory. The results compared the CFD results with the present Matlab DMST code incorporating Xfoil and the experimental measurements to show how DMST predictions compare with CFD and experimental measurements.

1 Formulation and Computational Procedure

1.1 Multiple stream tube model

In the single stream tube model the blades react with the flow, decreasing the flow velocity for different azimuthal locations and therefore, the induction factor remain constant along the width of the blade. Figure 1 shows the multiple stream tube models using the momentum equations for many stream tubes separately to calculate the different inducted velocities.

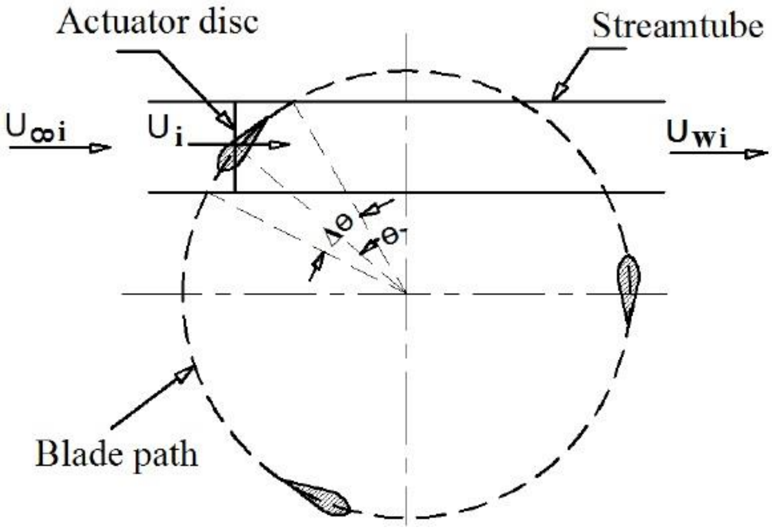

Fig. 1 Multiple stream tube model [17]

1.2 Double actuator disc

In the VAWT the velocity field is not linear throughout turbine and the blade passes twice by stream tube during one revolution, causing a different reaction between the blade and the fluid decreasing the fluid velocity from the first half to the second. In the double actuator disc theory two induction factors are calculated, the first for upstream half (a) and the second for the downstream half (a´), where each passage of the blade is considered as an individual disc.

The velocities through the turbine using the second induction factor are [17]:

$$u_i = u_\infty(1 - a) \quad (1)$$

$$u_e = u_\infty(1 - 2a) \quad (2)$$

$$u'_i = u_e(1 - a') \quad (3)$$

$$u'_w = u_e(1 - 2a') \quad (4)$$

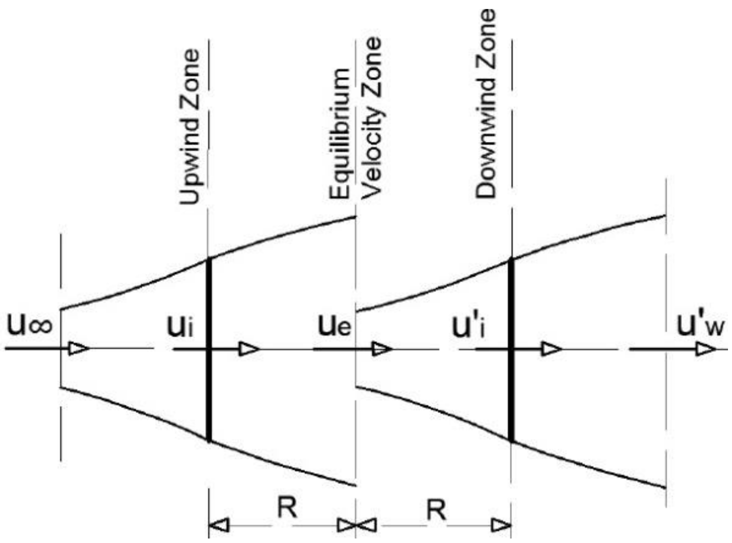

Fig. 2 Double actuator disc [17]

1.3 Double multiple stream tube model

The double multiple stream tube (DMST) model is the combination of the multiple stream tube and the double actuator disc theory. Therefore the two halves are considered aerodynamically independent, the method can model how the upstream half affects the downstream half of the turbine and admit variations perpendicular to the flow direction.

The assumptions and limitations of the model are:

- The flow is assumed to be steady, isothermal, inviscid, incompressible and rotation less
- The static pressure far upstream and far down stream of the rotor is equal to the undisturbed ambient static pressure
- The model does not account for the presence of shafts or struts.
- The model is unable to account for dynamic effects of dynamic stall and vortex shedding.

The blades movement is divided in two halves, the blade passes through only stream tube once per revolution. This leads to the fact that the relation between the time averaged force and the instantaneous force will be halved as the calculations will be doubled and more accurate.

For the upstream half:

$$w = \sqrt{u_\infty(1-a)\sin(\theta))^2 + (u_\infty(1-a)\cos(\theta) + \omega r)^2} \tag{5}$$

$$\alpha = tan^{-1}\left(\frac{u_\infty(1-a)\sin(\theta)}{u_\infty(1-a)\cos(\theta) + \omega r}\right) \tag{6}$$

$$a \leq \frac{1}{3} \qquad a_{new} = \frac{NT_i}{4\pi\rho rHsin(\theta)u_\infty^2} + a^2 \tag{7}$$

$$a > \frac{1}{3} \qquad a_{new} = \frac{NT_i}{4\pi\rho rHsin(\theta)u_\infty^2} + \frac{1}{4}(5-3a)a^2 \tag{8}$$

For the downstream half:

$$w = \sqrt{u_e(1-a')\sin(\theta))^2 + (u_e(1-a')\cos(\theta) + \omega R)^2} \tag{9}$$

$$\alpha = tan^{-1}\left(\frac{u_e(1-a')\sin(\theta)}{u_e(1-a')\cos(\theta)+\omega R}\right) \tag{10}$$

$$a' \leq \frac{1}{3} \qquad a' = \frac{NT_i}{4\pi\rho rHsin(\theta)u_e^2} + a'^2 \tag{11}$$

$$a' > \frac{1}{3} \qquad a' = \frac{NT_i}{4\pi\rho rHsin(\theta)u_e^2} + \frac{1}{4}(5-3a')a'^2 \tag{12}$$

Calculation of the average torque, power and dimensionless coefficients:

$$Q_{avg} = \sum F_t \frac{rNd\theta}{2\pi} \tag{13}$$

$$P = Q_{avg}\omega \qquad (13)$$

$$C_Q = \frac{Q_{avg}}{0.5\rho u_\infty^2 2rHr} \tag{14}$$

$$C_P = \frac{P}{0.5\rho u_\infty^3 2rH} \tag{15}$$

2 Numerical Treatment

This study presents comparisons between available CFD calculations, available experimental results and the present predictions from the double multiple stream tube (DMST) model.

The numerical code is based on Brinck and Jeremejeff [17]. The calculations were realized using the values of lift and drag coefficients for each Reynolds number obtained from the site airfoil tools [18]. For other values of Reynolds numbers that are not encountered, the values were obtained by linear interpolation of available values.

3 Results

Rezaeiha et al. [19] investigated a Darrius H-type VAWT in order to analyze the turbine performance, turbine wake and dynamic loads on the blades, using the Computational Fluid Dynamics (CFD) simulation. The nominal and geometric parameters used in their work are shown in Table 1.

Table 1. Nominal and geometric parameters for Darrius H-type VAWT (Razaeiha et al. [19])

Parameters	Value
Number of blades	2
Diameter, d [m]	1
Swept area, A [m^2]	1
Airfoil	NACA0018
Airfoil chord, c [m]	0.06
Solidity, σ	0.12

Blade aspect ratio, h/c	16.67
Tip speed ratio, λ	4.5
Rotational speed, Ω [rad/s]	83.8
Freestream velocity, U∞ [m/s]	9.3

Figure 3 shows a comparison between [19] and the present predicted results showing the same behavior, but the predicted results overestimate the power coefficient over the tip speed ratio range from 1.5 to 4.5. This is due to the fact that the DMST does not calculate the wake and the way it interferes with the other rotating blades. The wake is generated by induced velocity that reduces the stream velocity at entry to the blades lying in the wake.

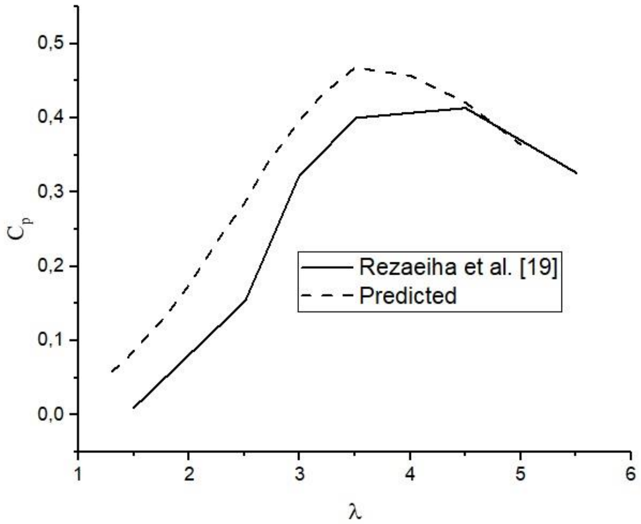

Fig. 3 Comparison between the predicted power coefficient and the results from [19].

Beri and Yao [6] studied a vertical axis wind turbine (VAWT) using double multiple stream tube (DMST) model and CFD, where the rotor is composed of three blades, NACA 0018, 0.2m chord length and 2m of radius subject to the flow conditions shown in Table 2.

Table 2 Nominal conditions for vertical axis wind turbine

TSR (*λ*)	Velocity (m/s)	Turbine ang.vel. (rad/s)
0.25	4	0.5
1	4	2
0.5	4	1
0.75	4	1.5
1.5	4	3
2	4	4
3	4	6
3.5	4	7
4	4	8
5	4	10

Figure 4 shows a comparison between the present predictions and the CFD results from [6]. As can be seen the agreement is good and this can be attributed to the fact that the velocity is low, hence the intensity of the wake is not too intense and the wake interference effects are not significantly strong.

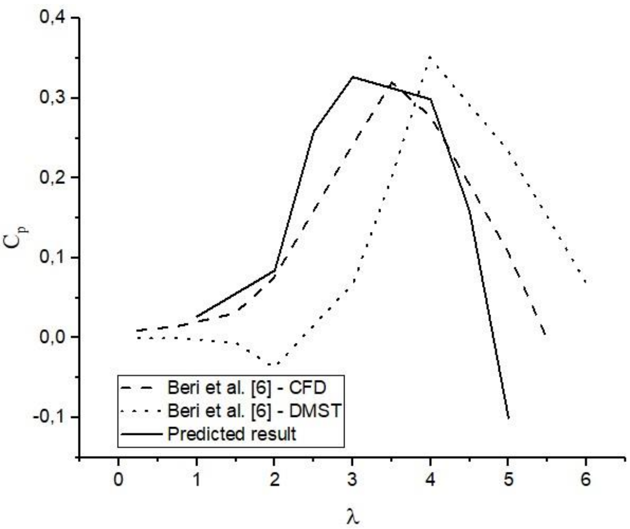

Fig. 4 Power coefficient along the tip speed ratio for predicted result, Beri CFD and Beri DMST.

Rogowski et al. [9] analyzed the performance of vertical wind turbine type Darrius with the large solidity ratio. They used an experimental vertical wind turbine based on Bravo et al. [20] to realize their two-dimensional numerical simulation by CFD. The geometric and nominal parameters are presented in Table 3

Table 3. Operational and geometric parameters

Parameters	Values
Diameter	2.5 m
Height	3.0 m
Chord	0.4 m
Airfoil	NACA 0015
Wind velocity	10 m/s
TSR	1.75
Rotational speed	14 rad/s

Figure 5 shows good agreement between the CFD and the experimental results. The present predicted results even though they present the same tendency, the predicted results are overestimated. This noticeable difference is due to the fact the DMST does not consider the wake generation, resulting in high values of torque and consequently high power coefficients as presented in Fig. 5.

Castelli, et al. [8] developed a study to determinate the performance of vertical wind turbine type Darrieus using a numerical CFD code and the BEM method. The geometrical parameters for the rotor are presented in Table 4.

Table 4 Operational and geometric parameters [8]

Parameters	Values
Diameter [mm]	1030
Height [mm]	1456.4
Number of blades	3
Blade section	NACA 0021
Chord [mm]	85.5
Spoke-blade connection	0.5 c
Standard deviation	0.25
Wind speed [m/s]	9

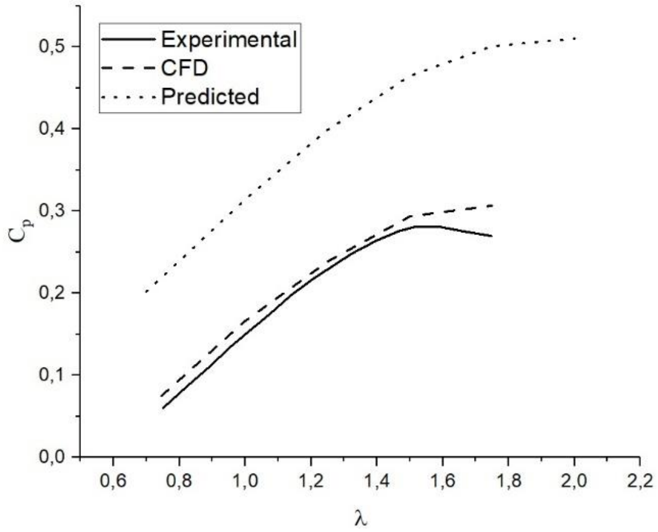

Fig. 5 Comparative result between CFD, experimental measurements of [9] and the DMST numerical predictions.

The CFD simulation and BEM method presented the same behavior in relation to the experimental result but showed overestimated values. The predicted results agreed well with the BEM and the CFD results for tip speed ratio range 1.25 to 2.25, as can be seen in Fig. 6.

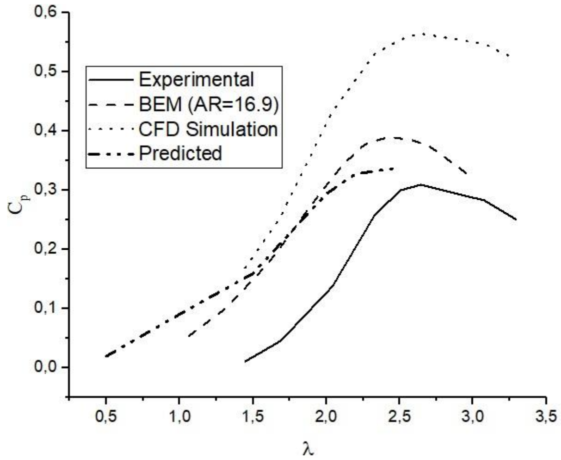

Fig. 6 Comparative result between CFD, BEM, experimental measurements of [8] and the DMST numerical predictions.

4 Conclusion

This work has the objective to analyze the accuracy between the DMST model and CFD and experimental results for Darrius H-type vertical axis wind turbine. For this were used four result of different authors in order to compare the power coefficient along the tip speed ratio.

The results show high values of power coefficient for DMST but presented the same behavior this happen because the present code not calculate the induced velocity for the wake generation. As it is a simultaneous process the wake affect each blade decreasing the performance of the rotor. However, for low wind speed the results were similar it is due to low influence of the wake for the other blades.

Acknowledgements

The first author wishes to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), while the second author wishes to thank the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) for the PQ Research Grant 304372/2016-1.

References

[1] Global Wind Energy Council. Global Wind Report: Annual Market Update 2017. GWEC, 2018.
[2] World Wind Energy Association. Summary - 2017 Small Wind World Report. WWEA, 2017.
[3] M. M. A. Bhutta, N. H. Ahmed, U. F. Z. Ali, S. R. Jamail and Z. Hussain. Vertical axis wind turbine – A review of various configurations and design techniques. Renewable and Sustainable Energy Reviews, vol. 16 pp. 1926-1936, 2012.
[4] A. Tummala, R.K. Velamati, D. K. Sinha, V. Indraja and V. H. Krishna. A review on small scale wind turbines. Renewable and Sustainable Energy Reviews, vol. 56, pp. 1351-1371, 2016.
[5] R. Kumar, K. Raahemifarb and A. S. Fung. A critical review of vertical axis wind turbines for urban applications. Renewable and Sustainable Energy Reviews, vol. 89, pp. 281-291, 2018.
[6] H. Beri, Y. Yao. Double Multiple Stream Tube Model and Numerical Analysis of Vertical Axis Wind Turbine. Energy and Power Engineering, vol. 3, pp. 262-270, 2011.
[7] I. Paraschivoiu, O. Trifu, and F. Saeed. H-DarrieusWind Turbine with Blade Pitch Control. International Journal of Rotating Machinery, 2009.
[8] M. R. Castelli, G. Ardizzon, L. Battisti, E. Benini and G. Pavesi. Modeling strategy and numerical validation for Darrius vertical axis micro-wind turbine. Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition, vol. 7, pp. 12-18, 2010.
[9] K. Rogowski, R. Marońskimaron and J. Piechnajpie. Numerical Analysis of a Small-Size Vertical-Axis Wind Turbine Performance and Averaged Flow Parameters Around the Rotor. Archive of Mechanical Engineering, vol. 64, n. 2, pp. 205-2018, 2017.
[10] M. R. Hasan, R. Islam, G.M. H. Shahariar and M. Mashud. Numerical Analysis of Vertical Axis Wind Turbine. The 9th International Forum on Strategic Technology, pp. 21-23, 2014.
[11] P. M. Kumar, S. R. Rashmitha, N. Srikanth, T. Lim. Wind Tunnel Validation of Double Multiple Streamtube Model for Vertical Axis Wind Turbine. Smart Grid and Renewable Energy, vol. 8, pp. 412-424, 2017.
[12] K. A. Sunny and N. M. kumar. Vertical axis wind turbine: Aerodynamic modelling and its testing in wind tunnel. Procedia Computer Science, vol. 93, pp. 1017-1023, 2016.
[13] Q. Li, T. Maeda, Y. Kamada, K. Shimizu, T. Ogasawara, A. Nakai and T. Kasuya. Effect of rotor aspect ratio and solidity on a straight-bladed vertical axis wind turbine in three-dimensional analysis by the panel method. Energy, vol. 121, pp. 1-9, 2017.
[14] Y. Peng, Y. Xu, S. Zhan and K. Shum. High-solidity straight-bladed vertical axis wind turbine: Aerodynamic force measurements. Journal of Wind Engineering & Industrial Aerodynamics, vol. 184 pp. 34-48, 2019.
[15] A. Rezaeiha, H. Montazeria and B. Blocken. Characterization of aerodynamic performance of vertical axis wind turbines: Impact of operational parameters. Energy Conversion and Management, vol. 169, pp. 45-77, 2018.
[16] S. R. Shah, R. Kumar, K. Raahemifar and A. S. Fung.] Design, modeling and economic performance of a vertical axis wind turbine. Energy Reports, vol. 4 pp. pp. 619-623, 2018.
[17] D. Brinck and N. Jeremejeff. The development of vertical axis tidal current turbine. KTH Shool of Industrial Engineering and Management, Master of Science Thesis, 2013.
[18] Air foil tools. < http://airfoiltools.com>, 2019.
[19] A. Rezaeiha, H. Montazeri, B. Blocken. Towards accurate CFD simulations of vertical axis wind turbines at different tip speed ratios and solidities: Guidelines for azimuthal increment, domain size and convergence. Energy Conversion and Management, vol. 156, pp. 301-316, 2018.
[20] R. Bravo, S. Tullis, and S. Ziada. Performance testing of a small vertical-axis wind turbine. In Proceedings of the 21st Canadian Congress of Applied Mechanics CANCAM, vol. 7-9, 2007.