A review of Stall Delay Models and their Application on Hybrid Methods

Mohamed Nadjib Hamlaoui, Arezki Smaili, and Hachimi Fellouah

Abstract—This paper is a review on the stall delay phenomenon that Horizontal Axis Wind Turbines (HAWT) encounter under typical flow conditions and its numerical modelling. Aerodynamic performance predictions of HAWT have been often carried out through Computational Fluid Dynamics method with the combination of the concept of actuator disk i.e. hybrid method. For this purpose, the hybrid method is presented in details together with the numerical modelling of such stall delay phenomenon. Despite modern wind turbines are equipped with sophisticated control systems for avoiding stall, nevertheless, stall is still inevitable in the near root region of the rotor blade. This paper focuses on recent research development materials which have been undertaken on the stall delay phenomenon where the engineering models (stall delay models) of the literature being presented and criticized based on the predictions obtained from the NREL Phase VI wind turbine experiments.

***Keywords*—Actuator disk, Horizontal Axis Wind Turbine, Stall delay, Hybrid method**

NOMENCLATURE

HAWT	Horizontal Axis Wind Turbine.
CFD	Computational Fluid Dynamics.
ADM	Actuator Disk Method.
SDM	Stall Delay Models.
B	Number of blades.
c	Local chord.
r	Local radius.
α	Angle of attack.
β	Twist angle.
ϕ	Flow angle.
θ_p	Pitch angle.
Ω	Rotational speed.
U_∞	Free stream velocity (m/s).
a	Axial induction factor.
a'	Tangential induction factor.
Q	Mechanical torque (N.m).
T_h	Thrust force (N).
F	Tip loss correction factor.
C_l, C_d	The corrected lift and drag coefficients.
C_n, C_t	Normal and tangential force coefficients.

I. INTRODUCTION

The rapid drop of wind energy cost has provided motivation for manufacturers and researchers to conduct several research on Horizontal Axis Wind Turbines (HAWTs) optimization and performance predictions [1]. For HAWTs optimization and performance predictions, the actuator disk concept used for the first time by Rankine [2] and Froude [3] is one of the widely used approaches. It consists of permeable surface, instead of the real geometry, on which the rotor exerted forces act upon the incoming flow providing pressure jump and discontinuities on the flow field properties [4].

The computational application of the actuator disk concept has been used, at first, in its analytical approaches such as the Blade Element Momentum (BEM) method. It is the combination of the Blade Element (BE) and the momentum theories where it has been used for the first time by Glauert [5]. Many wind turbines design companies use codes to predict the aerodynamic performances of Horizontal Axis Wind Turbines (HAWT). These codes are usually based on the BEM method. For HAWTs design, Vaz et al. [6] proposed an extension of the BEM method to take into account the influence of the wake on the rotor plane in the general form. Dai et al. [7] coupled the BEM method with a modified Dynamic Stall (DS) model in which some influence factors such as wind shear, tower and blade vibration are considered in order to calculate the aerodynamic loads for large scale HAWT. Monteiro et al. [8] have conducted wind tunnel measurements for 1.2 m diameter HAWT and compared the experimental data with two well-known design codes of WT_Perf and Qblade which are based on the BEM method, a pretty encouraging predictions have been recorded. Yang et al. [9] have used the airfoil characteristics, extracted from full Computational Fluid Dynamics (CFD) calculation method, in the BEM method where good agreement have been found compared with the measured data. Sun et al. [10] proposed an improvement for the BEM method where both the influences from wake rotation and radial flow have been considered yielding new BEM relations for Glauert's and Shen's tip loss correction; also, the correction of Spera has been extended for the new BEM for large thrust coefficient where good agreement has been obtained against the MEXICO measurements. Dehouk et al. [11] used the BEM method to optimize the HAWT blade profile for specific initial condition of 7 m/s where new empirical relation for the chord distribution over the blade span has been proposed.

Manuscript received November 1, 2021; revised November 14, 2022.

M. N. Hamlaoui is with University of Ferhat Abbas, Setif 1, Algeria. (e-mail: mohammed_nadjib.hamlaoui@g.enp.edu.dz).
A. Smail is with the Mechanical Engineering Department, Ecole Nationale Polytechnique, Algiers, ALGERIA. (e-mail: arezki.smaili@g.enp.edu.dz).
H. Fellouah is with the Mechanical Engineering Department, University of Sherbrooke, Quebec, Canada. (e-mail: Hachimi.Fellouah@usherbrooke.ca).

Digital Object Identifier (DOI): 10.53907/enpesj.v2i2.65

With the development of CFD techniques and effective calculation hardwares, the Actuator Disk Method (ADM) has been used by combining the BE theory with 3D Navier-Stokes equations in a CFD solver where the forces have been inserted as sink in the momentum equation. Sørensen et al. [12–14] have been the first to use the actuator disk concept where the blade forces are computed through the blade element approach. Masson et al. [15, 16] used the ADM to investigate, at first, the tower-shadow impacts on HAWT and then studied the unsteady flow phenomena around the rotor operating on an Atmospheric Boundary Layer (ABL) flow. Based on the last approach, later, authors works on the nacelle anemometry of typical HAWT rotors have been reported [17–19]. Mainly, they tackled the impact of rotor aerodynamic key parameters upon the flow features within the nacelle region, especially, around the anemometer location. Alinot et al. [20] presented numerical method, based on the ADM, for predicting the ABL flow under stratified and neutral conditions where they proposed original expression for one of the closure coefficients related to the buoyancy production term of the k-ϵ turbulence model. Ameur et al. [21] used the 2D and 3D ADM computations in order to study the wind rotor/nacelle interaction in a neutral ABL flow, they found that for complex nacelle geometries the 3D ADM computations are required. Tata et al. [22] also performed a simulation study on nacelle anemometer using the ADM approach, with the emphasis on the effect of grid topology upon numerical predictions accuracy. Recently, Amini et al. [24] proposed modifications of Snel et al. [25] stall delay model empirical coefficients than studied the effect of the proposed modifications on the MEXICO rotor using the ADM implemented in OpenFOAM where a certain improvements has been noticed. Nevertheless, important discrepancies are still recorded for the loads prediction and no validation using another HAWT type has been carried out. Furthermore, notice that two different actuator approaches have been developed based on the ADM, Sørensen et al. [26] proposed the Actuator Line Method (ALM), while, Massouh et al. [27] proposed the Actuator Surface Method (ASM). Through comparison between the ALM and the ASM, Nathan [28] concluded that an ADM would be much better and less expensive approach for HAWT performance predictions; Because in the ADM, the computed forces are inserted directly in the mesh cell center unlike the ALM and the ASM approaches where the forces distribution projection is required providing different velocity distributions downstream from the rotor which could lead to unrealistic numerical solutions.

For specific flows corresponding to an attached flow regimes, the hybrid method provides reliable and consistent performance and wake predictions of HAWT rotors. Nevertheless, for high incoming wind speeds stall occurs (stall conditions) and such method breakdown due to the appearance of the effect of rotation (stall delay). It is, mainly, based on the airfoil characteristics extracted from wind tunnel measurements for a non-rotating blade along the calculation process. Nevertheless, in real flows and for typical incoming wind speeds stall occurs and the effect of rotation appears leading to the performances under-prediction. Himmelskamp [29] have been the first to record the aerodynamic loads increase through a qualitative analysis on a propeller blades, they postulated that this phenomenon is due to the centrifugal and Coriolis forces appearance. Banks and Gadd [30], Wood [31], Du and Selig [32] and Chaviaropoulos and Hansen [33] concluded that, for a rotating blade, the centrifugal and Coriolis forces appear causing an alleviation of the adverse pressure gradient acting on the boundary layer; as a results, delaying the separation point. McCroskey [34] and Madsen and Rasmussen [35] suggest that the centrifugal and Coriolis forces acting on the separated flow region, create radial pressure gradient which move the mass flow outboard comparing the process as a centrifugal pumping. Narramore and Vermeland [36] carried out a CFD analysis on a helicopter blade, they concluded that the angle of attack in which the separation point begins to stall is much higher in rotation compared to the stationary case. Through a CFD analysis of a rotating and a stationary blade, Shen et al. [37] showed that the effect of rotation causes a pressure change in the separated region with no influence on the separation point location. Snel et al. [25] and Lindenburg [38] proposed, later, correction models for the 2D lift coefficient where it has been shown that the dominant cause of the stall delay is the reduction of the adverse pressure due to centrifugal forces appearance. Through an experimental study of the turbulence effects on the stall delay phenomenon, Sicot et al. [39] concluded that the free stream turbulence is the primary cause of the delay of the boundary layer separation where the rotation have no influence. Dumitrescu and Cardoş [40] have been the first to call the phenomenon "stall delay" by suggesting that the Coriolis forces causes the movement of the separation point toward the trailing edge in rotation.

The effect of rotation causes the lift increase in the separated flow region of the rotor blade; however, its effect on the drag coefficient is still unknown where two different results have been presented in the literature. Du and Selig [32] suggested that the drag force decreases in the blade region when the effect of rotation is present. Corten [41] based his analysis on the Navier-Stokes equations for non-inertial boundary layer, he noted that the flow-separation point moves toward the trailing edge which reduces the blade wake and leads to a reduced sectional drag force. Nevertheless, Chaviaropoulos and Hansen and Sørensen [33, 42] suggested an increase of the drag force on a rotating blade. Based on full CFD study, Guntur [43] found that there is a slight increase of the drag coefficient between the 2D and the 3D cases; consequently, he assumed that there is no variation of the drag coefficient in a rotational case.

The aim of this paper consists on performing a review on the stall delay phenomenon where it has been discussed and detailed. Also, the proposed engineering models, presented in the literature, have been presented then criticized based on the predictions obtained from the mostly well-known NREL Phase VI wind turbine experiments.

II. The BEM method

The BEM is 1D analytical method as shown in Fig. 1, based on the combination of the BE and the momentum theories, used for HAWT performance predictions. For typical HAWT of B number of blades, local chord c, local radius r, twist angle β, pitch angle θ_p and rotational speed Ω subjected to a wind speed U_∞, the algorithm defining this method can be summarized as follows:

1. Initialize the axial and tangential induction factors a and a', typically $a=a'=0$.
2. Compute the flow angle ϕ using Eq. (1).

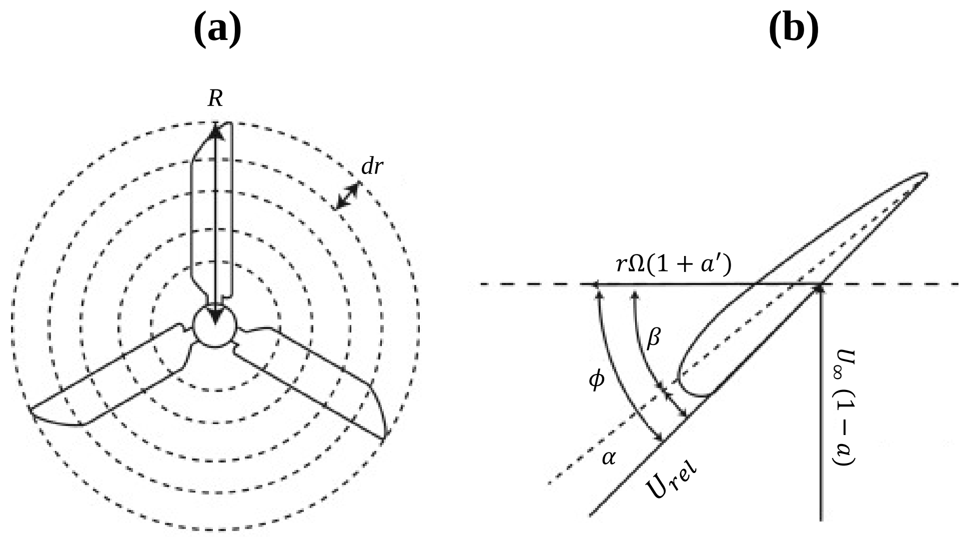

Fig. 1: BEM concept.

3. Compute the Angle of Attack (AoA) α using Eq. (2).

4. Read $C_l(\alpha)$ and $C_d(\alpha)$ from table look-up.

5. Compute the normal and tangential coefficients C_n and C_t from Eq. (3) respectively.

6. Calculate a and a$^{'}$ from Eq. (4) and Eq (5).

7. If a and a$^{'}$ has changed more than a certain tolerance, go to step (2) or else finish.

8. Compute the local loads at each blade segment, torque Q and thrust T from Eq. (6).

$$\phi = \arctan(\frac{(1-a)U_\infty}{(1+a^{'})\Omega r}) \tag{1}$$

$$\alpha = \phi - (\beta + \theta_p) \tag{2}$$

$$\begin{cases} C_n = C_l\cos(\phi) + C_d\sin(\phi) \\ C_t = C_l\sin(\phi) - C_d\cos(\phi) \end{cases} \tag{3}$$

$$a = \begin{cases} \frac{\sigma C_n}{4F\sin^2(\phi)+\sigma C_n} & if \;\; a < a_c = 0.2 \\ \frac{1(2+K(1-2a_c) - \sqrt{(K(1-2a_c)+2)^2+4(Ka_c^2-1)})}{2} & otherwise \end{cases} \tag{4}$$

where $K = \frac{2F\sin^2(\phi)}{\sigma C_n}$

$$a^{'} = \frac{\sigma C_t}{4F\sin(\phi)\cos(\phi) - \sigma C_t} \tag{5}$$

$$\begin{cases} dF_n = \frac{1}{2}\rho B\frac{U_\infty^2(1-a)^2}{\sin^2(\phi)}C_n c dr \\ dF_t = \frac{1}{2}\rho B\frac{U_\infty(1-a)\Omega r(1+a^{'})}{\sin(\phi)\cos(\phi)}C_t c dr \\ T_h = \sum_1^n dF_n \\ Q = \sum_1^n dF_t \times r \end{cases} \tag{6}$$

A. *Stall delay models*

To obtain accurate sectional aerodynamic characteristics and loads predictions, the 2D airfoil data needs to be corrected to take into account the effect of rotation. Owing to the complexity of the rotational augmentation effects, several researchers tried to model and to explain this problem with different approaches by proposing several solutions based on different assumptions. Some models were based in theoretical analyses [32, 38] while the other models were developed empirically from experimental measurements [40, 44].

Snel et al. [25] have been the first to propose a simple model based on the ratio of the local chord to the local radius in order to correct the 2D airfoil data to take into account the 3D effect. Many stall delay models have been developed later where Du and Selig [32] proposed a model for the drag and the lift coefficients correction which include a modified tip speed ratio, the local chord, the local radial station and empirical factors. Chaviaropoulos and Hansen [33] proposed corrections for both the 2D lift and drag coefficients which depends on the local blade twist angle, the local chord, the local radial span wise position and several empirical coefficients. Dumitrescu and Cardoş [40] developed a stall delay model, having an exponential form, which depends on the local chord and the local radial position. Corrigan and Schillings [44] developed an empirical model rooted on experimental helicopter data and simplified boundary-layer equations. Lindenburg [38] proposed a model, for the lift coefficient correction, rooted on the centrifugal forces and the radial flow modeling; mainly, it depends on the local chord, local radial ratio and a modified tip speed ratio. To get (3D) airfoil characteristics, Bak et al. [45] corrected the pressure difference between a rotating and a non rotating blade at each radial station of the rotor blade. Eggers et al. [46] developed their model by relying the axial, angular induction factors and the tip speed ratio. Breton et al. [49] conducted deep study of six well-knowns stall delay models presented on literature through the NREL Phase VI HAWT measurements, they found that none of the presented approaches are able to reproduce correctly the rotational augmentation phenomenon due to the lack of generality. It means that the proposed solutions are still incomplete and unable to explain and model adequately the present phenomenon.

The rotational augmentation effect is still an unknown phenomenon, several researchers tried to model and to explain this problem with different approaches by proposing several solutions based on different assumptions. Some models were based on theoretical analyses [32, 38] while the other models were developed empirically from experimental measurements [40, 44]. The mostly used and well-known stall delay models have been used and expressed as follows:

$$C_l = C_{l,2d} + f_l \Delta C_l \tag{7}$$

$$C_d = C_{d,2d} + f_d \Delta C_d \tag{8}$$

where the specific functions f_l and f_d represent, respectively, the variation of the lift and the drag coefficients. $\Delta C_l = C_{l,inviscid} - C_{l,2d}$. The inviscid lift coefficient $C_{l,inviscid} = 2\pi(\alpha - \alpha_0)$, α_0 is the AoA at the zero lift coefficient and $C_{l,2d}$ is the 2D lift coefficient. $\Delta C_d = C_{d,2d} - C_{d,0}$ is the difference between the 2D drag coefficient and the drag coefficient at zero AoA.

In the present study, the mostly well-knowns correction models of Snel et al. [25] and Du and Selig [32] have been used.

Recently, Hamlaoui et al. [48] have proposed a new model for the lift coefficient correction based on the shift parameter expressed as follows

$$Cl = C_{l,2d}(1 + f_s) \tag{9a}$$

$$f_s = a \exp(-(\frac{\alpha - \alpha_s}{d})^2) \tag{9b}$$

Where a, α_s and d are constants which represent the amplitude, the specific AoA that corresponds to the peak (delayed stall angle) and the controlling peak width respectively. The constants a, α_s and d appropriate to the model are equal, respectively, to 1.45, 0.575 (33°), 0.28 (16°) for radial positions $r/R \leq 0.30$ and 0.55, 0.38 (22°), 0.12 (6.88°) for radial positions $r/R > 0.30$.

III. Application of Stall Delay models to the NREL Phase VI wind turbine

Fig. 2 shows the predicted results, extracted from the work of Hamlaoui et al. [48], of the stall delay models of Snel et al. [25], Du and Selig [32] and Hamlaoui et al. [48] compared with those

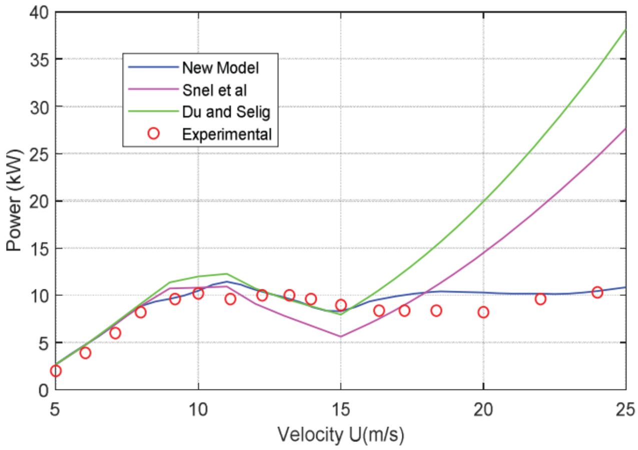

Fig. 2: Power curve: Comparison of the stall delay model predictions with the experimental data [48].

of data fields. It can be seen that the predicted power, using the new proposed model, agree well with the measured data in contrary to those of both Du and Selig [32] and Snel et al. [25] models where it can be noticed that for free stream velocities lower than 16 m/s, all the models provide good predictions. However, for free stream velocities higher than 16 m/s, significant over-estimations have been provided using the models of both Du and Selig [32] and Snel et al. [25] in contrary to the new proposed model of Hamlaoui et al. [48] which provides good predictions.

IV. Conclusion

The purpose of the present work is a review of the stall delay phenomenon, mostly encountered during HAWT operations, and its modeling using hybrid methods i.e. ADM. Firstly, the hybrid methods have been introduced where mainly their limitations have been tackled. Secondly, the stall delay phenomenon has been detailed and the mostly well-known engineering models (stall delay models) presented in the literature have been presented then criticized based on the predictions obtained from the NREL Phase VI wind turbine experiments. It has been found, from the work of Hamlaoui et al. [48], that the existing stall delay models fail to predict the aerodynamic performances of the NREL Phase VI wind turbine, for high incoming wind speeds, due to their lack of generality; the new model of Hamlaoui et al. [48] has shown good predictions and more realistic modeling of the stall delay phenomenon compared to the existing models.

References

[1] M. Hansen, Aerodynamics of Wind Turbines: Second edition, Earthscan, 2008.

[2] W. J. M. Rankine, On the mechanical principles of the action of propellers, Transactions of the Institution of Naval Architects, 1865, pp. 6.

[3] R.E. Froude, On the part played in propulsion by differences of fluid pressure, *Transactions of the Institution of Naval Architects 30*, pp. 390, 1889.

[4] J.H. Horlock, Actuator disk theory-discontinuities in thermo-fluid dynamics, McGraw-Hill International Book Co, NewYork, 1978, pp. 256.

[5] H. Glauert, Airplane propellers, *Aerodynamic theory. Springer*, 1935, pp. 169–360.

[6] J.R.P. Vaz, J.T. Pinho & A.L.A. Mesquita. An extension of bem method applied to horizontal-axis wind turbine design. "*Renewable Energy*", vol. 36, pp. 1734 – 1740, 2010, doi:https://doi.org/10.1016/j.renene.2010.11.018.

[7] J. Dai, Y. P. Hu, D. S. Liu & X. Long, Aerodynamic loads calculation and analysis for large scale wind turbine based on combining bem modified theory with dynamic stall model, "*Renewable Energy*", vol. 36, pp. 1095 – 1104, 2011, doi:https://doi.org/10.1016/j.renene.2010.08.024.

[8] J.P. Monteiro, M. R. Silvestre, H. Piggott & J. C. Andre, Wind tunnel testing of a horizontal axis wind turbine rotor and comparison with simulations from two blade element momentum codes, "*Journal of Wind Engineering and Industrial Aerodynamics*", vol. 123, pp. 99 – 106, 2013, doi:https://doi.org/10.1016/j.jweia.2013.09.008.

[9] H. Yang, W. Shen, H. Xu, Z. Hong & C. Liu, Prediction of the wind turbine performance by using bem with airfoil data extracted from cfd. "*Renewable Energy*", vol. 70, pp. 107 – 115, 2016, doi:https://doi.org/10.1016/j.renene.2014.05.002.

[10] Z. Sun, J. Chen, W. Z. Shen & W. J. Zhu, Improved blade element momentum theory for wind turbine aerodynamic computations, "*Renewable Energy*", vol. 96, pp. 824 – 831, 2016, doi:https://doi.org/10.1016/j.renene.2016.05.035.

[11] V. Dehouck, M. Lateb, J. Sacheau & H. Fellouah, Application of the blade element momentum theory to design horizontal axis wind turbine blades, "*Journal of Solar Energy Engineering*", vol. 140, 2018.

[12] J.N. Sørensen & A. Myken, Unsteady actuator disc model for horizontal axis wind turbines. "*Journal of Wind Engineering and Industrial Aerodynamics*", vol. 39, pp. 139–149, 1992.

[13] J.N. Sørensen & C. W. Kock, A model for unsteady rotor aerodynamics. "*Journal of Wind Engineering and Industrial Aerodynamics*", vol. 58, pp. 259–275, 1995.

[14] J.N. Sørensen, W.Z. Shen & X. Munduate, analysis of wake states by a full-field actuator disc model. "*Wind Engergy*", vol. 1, pp. 73–88, 1998.

[15] C. Masson, A. Smaili, I. Ammara & C. Leclerc, Aerodynamic investigations on tower-shadow impacts for hawts, "*Proceedings of the ASME Wind Energy Symposium, AIAA*", 2000, doi:10.2514/6.2000-41.

[16] C. Masson, A. Smaili & C. Leclerc, Aerodynamic analysis of hawts operating in unsteady conditions, "*Wind Energy*", vol. 4, pp. 1–22,2001.

[17] A. Smaili, C. Masson, Numerical Investigations of Nacelle Anemometry for Horizontal Axis Wind Turbines, "*Wind Energy Symposium*", pp. 389–398, 2003, doi:10.1115/WIND2003-1185.

[18] A. Smaili, C. Masson, On the rotor effects upon nacelle anemometry for windturbines, "*Wind Engineering*", vol. 28, pp. 695–713, 2004, doi:10.1260/0309524043729958.

[19] C. Masson, A. Smaili, Numerical study of turbulent flow around a wind turbine nacelle, "*Wind Energy*", vol. 9, pp. 281–298, 2006, doi:10.1002/we.171.

[20] C. Alinot & C. Masson, k-epsilon model for the atmospheric boundary layer under various thermal stratifications, "*Journal of Solar Energy Engineering*", vol. 127, pp. 438–443, 2005, doi:10.1115/1.2035704.

[21] K. Ameur, C. Masson & P. J. Eecen, 2d and 3d numerical simulation of the wind-rotor/nacelle interaction in an atmospheric boundary layer, "*Journal of Wind Engineering and Industrial Aerodynamics*", vol. 99, pp. 833 – 844, 2011, doi:https://doi.org/10.1016/j.jweia.2011.06.002.

[22] M. Tata, A. Smaili & C. Masson, Effect of grid topology on numerical simulations of flow fields around wind turbine nacelle anemometer, "*Journal of Applied Fluid Mechanics*" vol. 11, pp. 1569–1578,2018.

[23] J.N. Sørensen, K. Nilsson, S. Ivanell, H. Asmuth & R. F. Mikkelsen, Analytical body forces in numerical actuator disc model of wind turbines, "*Renewable Energy*", vol. 147, pp. 2259 – 2271, 2020, doi:https://doi.org/10.1016/j.renene.2019.09.134.

[24] S. Amini, M. R. Golzarian, E. Mahmoodi, A. Jeromin & M.H. Abbaspour-Fard, Numerical simulation of the mexico wind turbine using the actuator disk model along with the 3d correction of aerodynamic coefficients in openfoam, "*Renewable Energy*", vol. 163, pp. 2029 – 2036, 2020, doi:https://doi.org/10.1016/j.renene.2020.10.120.

[25] H. Snel, R. Houwink, & J. Bosschers, Sectional prediction of lift coefficients on rotating wind turbine blades in stall, "*Netherlands Energy Research Foundation Petten*", Netherlands, 1995.

[26] J.N. Sørensen & W. Z. Shen, Numerical modeling of wind turbine wakes, "*J. Fluids Eng*", vol. 124, pp.393–399, 2002.

[27] F. Massouh, I. Dobrev & M. Rapin, Numerical simulation of wind turbine performance using a hybrid model, "*44th AIAA Aerospace Sciences Meeting and Exhibit*", p. 782, 2006.

[28] J. Nathan (Ph.D. Dissertation), Application of actuator surface concept in LES simulations of the near wake of wind turbines, École de technologie supérieure, Quebec, Canada, 2018.

[29] H. Himmelskamp, Profile Investigations on a Rotating Airscrew, MAP, 1947, URL:https://books.google.dz/books?id=VlK3tgAACAAJ.

[30] W. Banks & G. Gadd, Delaying effect of rotation on laminar separation, "*AIAA journal*", vol. 1, pp. 941–941, 1963.

[31] D. Wood, A three-dimensional analysis of stall-delay on a horizontal-axis wind turbine, "*Journal of wind engineering and Industrial aerodynamics*", vol. 37, pp. 1–14, 1991.

[32] Z. Du & M. Selig, A 3-d stall-delay model for horizontal axis wind turbine performance prediction, "*ASME Wind Energy Symposium*", pp. 21, 1998.

[33] P. Chaviaropoulos & M.O. Hansen, Investigating three-dimensional and rotational effects on wind turbine blades by means of a quasi 3d navier-stokes solver. "*Journal of Fluids Engineering*", vol. 122, pp. 330–336,2000.

[34] W.J. McCroskey, Measurements of boundary layer transition, separation and streamline direction on rotating blades, pp. 6321, 1971.

[35] H.A. Madsen & F. Rasmussen, Derivation of three-dimensional airfoil data on the basis of experiment and theory, "*Proceedings Wind power*", pp. 166–174, 1988.

[36] J. Narramore & R. Vermeland, Navier-stokes calculations of inboard stall delay dueto rotation, "*Journal of Aircraft*", vol. 29, pp. 73–78, 1992.

[37] W.Z. Shen & J.N. Sørensen, Quasi-3d navier–stokes model for a rotating airfoil, "*Journal of Computational Physics*", vol. 150, pp. 518–548, 1999.

[38] C. Lindenburg, Modelling of rotational augmentation based on engineering considerations and measurements, "*European Wind Energy Conference*", London, pp.22–25, 2004.

[39] C. Sicot, P. Devinant, S. Loyer & J. Hureau, Rotational and turbulence effects on a wind turbine blade, investigation of the stall mechanisms, "*Journal of Wind Engineering and Industrial Aerodynamics*", vol. 96, pp. 1320–1331, 2008.

[40] H. Dumitrescu, V. Cardoş & A. Dumitrache, Modelling of inboard stall delay dueto rotation, "*Journal of Physics: Conference Series, IOP Publishing*", pp. 012022, 2007.

[41] G.P. Corten (Ph.D. Dissertation), Flow separation on wind turbines blades, University of Utrecht, Rotterdam, Netherlands, 2001.

[42] N. Sørensen, Evaluation of 3d effects from 3d cfd computations, "*IEA JointAction Committee on Aerodynamics Annex IV Aero Experts meeting*", 2000.

[43] S. Guntur (Ph.D. Dissertation), A detailed study of the rotational augmentation and dynamic stall phenomena for wind turbines, DTU Wind Energy, Denmark, 2013.

[44] J.J. Corrigan & J. Schillings, Empirical model for stall delay due to rotation, "*American Helicopter Society Aero-mechanics Specialists Conference*", San Francisco, CA, 1994.

[45] C. Bak, J. Johansen & P. B. Andersen, Three-dimensional corrections of airfoil characteristics based on pressure distributions, "*Proceedings of the European Wind Energy Conference*", pp. 1–10, 2006.

[46] A. Eggers, K. Chaney & R. Digumarthi, An assessment of approximate modeling of aerodynamic loads on the uae rotor, "*ASME Wind Energy Symposium*", American Society of Mechanical Engineers, pp. 283–292, 2003.

[47] S.P. Breton, F. N. Coton & G. Moe, A study on rotational effects and different stall delay models using a prescribed wake vortex scheme and NREL Phase VI experiment data. "*Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*", vol. 11, pp. 459–482, 2003.

[48] M.N. Hamlaoui, A. Smaili & H. Fellouah, Improved bem method for hawt performance predictions, "*International Conference on Wind Energy and Applications in Algeria (ICWEAA), IEEE*", pp. 1–6, 2018.

[49] S.P. Breton, F.N. Coton & G. Moe, A study on rotational effects and different stall delay models using a prescribed wake vortex scheme and nrel phase vi experiment data. "*Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*", vol. 11, pp. 459–482, 2003.

Mohamed Nadjib Hamlaoui is an assistant professor of Mechanical Engineering at University of Ferhat Abbas, Setif 1. He received his M.S. in Energy Mechanics from the Ecole Nationale Polytechnique of Algiers in 2016, and his PhD in Mechanical Engineering (major in: Clean and Renewable Energies-Mechanical Systems) in 2021. He joined, recently, the University of Ferhat Abbas, Setif 1 in 2021. His research field deals with the different methodologies applied for the aerodynamic performance predictions of horizontal axis wind turbines and wind farms optimization.

Arezki Smaili is a Professor of Mechanical Engineering and Director of Research Laboratory of Mechanical Engineering (Laboratoire de ‘’Génie Mécanique et Développement-LGMD”, at Ecole Nationale Polytechnique (ENP), Algiers. He received his engineer diploma in Mechanical Engineering from University of Sciences and Technologies Houari Boumediene (USTHB), Algiers in 1988, M.S. in Mechanical Engineering from Laval University, Québec (Canada) in 1991, and his PhD in Energy Sciences from University of Québec (Canada) in 1998. He joined the ENP in 2006. He was formerly research scientist at “Ecole de Technologie Supérieure”, Montreal (Canada). He has been involved with wide range of energy conversion applications, particularly in the area of thermal analysis of clean and renewable energy systems and aerodynamics of wind turbines since the 1992.

Hachimi Fellouah is with University of Sherbrooke, Quebec, Canada as full professor since 2021. In 2005, he defended his PhD thesis at University of Nantes, France. He has been a postdoctoral fellow with Queen’s University at Kingston. Canada, from 2007 to 2010. He has been an associate professor from 2015 to 2021 and an assistant professor from 2010 to 2015 at University of Sherbrooke, Quebec, Canada. His research interests are in are fluid mechanics, wind and solar energy, clean technologies and Heat transfer.