Numerical Simulation of Surface Roughness Effects on Dynamic Stall of Wind Turbine Blade*

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Abstract
Horizontal axis wind turbines can experience significant time varying aerodynamic loads, potentially causing adverse effects on structures, mechanical components, and power production. As designers attempt lighter and more flexible wind energy machines, greater accuracy and robustness will become even more critical in future aerodynamics models. Aerodynamics modeling advances, in turn, will rely on more thorough comprehension of the three dimensional, unsteady, vortical flows that dominate wind turbine blade aerodynamics under high load conditions. These variations may express the incidence angle and wind velocity changes over a 2-D S809 airfoil with the surface roughness effect. To numerically characterize these flows, the instantaneous speed and wind direction variations, represented by a peak function were used to characterize dynamic stall vortex kinematics and normal force amplification. For lack of experimental data in the pulsating motion case, the present numerical approach has been validated by comparing our results with an oscillating S809 airfoil experimental data. The results show the importance of taking into account the behaviour of the unsteady flow subject to abrupt variation of wind direction and velocity. As well as the influence of the surface roughness in the modelling of wind turbine flow. These results give an accurate estimation of aerodynamic loads which will subsequently improve the design of wind turbines.

Key words: HAWT, Dynamic Stall, Roughness, Pulsating Motion

Nomenclature

\[ C \quad \text{Chord line} \]
\[ C_D \quad \text{Drag coefficient } = D/q \]
\[ C_L \quad \text{Lift coefficient } = L/q \]
\[ C_P \quad \text{pressure coefficient } = (p-p_\infty)/q \]
\[ D \quad \text{Drag Force} \]
\[ L \quad \text{Lift Force} \]
\[ P \quad \text{pressure} \]
\[ P_\infty \quad \text{free stream reference pressure} \]
\[ q \quad \text{Dynamic pressure } = \rho U_\infty^2/2 \]
\[ U_\infty \quad \text{free stream velocity} \]
\[ W \quad \text{relative velocity} \]
1. Introduction

The study of horizontal axis wind turbines (HAWT) working in wind conditions remains a very complex problem. It was shown through the anemometry measurements that the wind speed and direction may change abruptly [1]. In less than a second, wind intensity can double and direction can change. In these conditions, the impact of the flow around the blade varies very rapidly for the values that exceed the static stall airfoil angle.

The intensity of this phenomenon leads to a sudden drop in lift coefficient of the turbine blades and hence the decrease in its aerodynamic performance [2]. The variations of instantaneous speed and direction of wind may cause the phenomenon of dynamic stall. Among the first theoretical study of unsteady separated flow around a profile, Johnson[3], modeled the airfoil in oscillating to showing that dynamic stall is related to the presence of moving vortex structures on the airfoil extrados. McCroskey and Fisher [4, 5] justified the approach of some of the unsteady effects of dynamic stall by approximating the oscillating profile.

Many studies [6] and [7] considered that dynamic stall came from the increase in the trailing edge turbulent separation. The study [8] showed that the point of transition from the boundary layer is strongly non stationary and that it is possible during the cycle of oscillation successively to see a laminar boundary layer then transitional and finally fully turbulent. McAlister [8] showed the impact of the maximum incidence angle for a constant frequency. Recently a very detailed report on the dynamic stall for an oscillating profile...
survey was presented by Wanget and al. [9]. In this work, the details of the complex flow development of the dynamic stall and the boundary layer transition using the DES approach were discussed.

A Work has been carried out by Guy Fortinet and al. [10] to determine the shape and size of the roughness from the accumulation of ice on wind turbine blades. Analytical formulations have been developed to characterize the state of surface of the blade.

Van Rooijet al. [11] studied experimentally the influence of roughness on the aerodynamic performance of a profile series with varying thickness. Among the results, it was noted that the roughness had a little effect on the profiles.

Ramsayet al.[12] studied experimentally a profile S809, from different angles. The authors showed that the roughness on the profile leading edge caused a loss of lift and an increase of drag.

Chakrounet and al. [13] designed for the experimental study of the position and roughness size effects on the aerodynamic characteristics of the flow around a profile. Their results showed that the drag varies proportionally with the roughness size.

The roughness effect on the wind turbines performance has been studied experimentally by Khalfellah et al.[14]. They have shown that the power generated by a wind turbine decreased with increasing roughness induced by the dust on the blades.

A series of steady and unsteady states aerodynamic wind tunnel tests on a set of airfoils were performed by the NREL (National Renewable Energy Laboratory). The experiments concern the influence of roughness on the aerodynamic performance [15]. The purpose of these tests was to investigate the effect of pitch oscillations and leading edge grit roughness on airfoil performance.

This application simulates surface irregularities that occur in a wind turbine blades. For test cases involving roughness, a standard, repeatable pattern with grit as roughness elements was desired. A roughness pattern jointly developed by OSU/AARL and KENETECH Wind power personnel is used in a molded insect pattern.

![Figure 2: Roughness pattern](image)

The particle density was 5 particles per cm² in the middle of the pattern, and thinned to 1.25 particles per cm² at the edge of the pattern. Figure 2 shows the roughness pattern. To make a usable template the pattern was repeatedly cut into a steel sheet. Based on average particle size from the field specimen, standard 40 lapidary grit was chosen for the roughness elements, giving k/c=0.0019 for the model.

The results of steady state flow of the S809 showed that application of the edge grit
roughness reduced the maximum lift coefficient by approximately 16% and increased the minimum drag coefficient by more than 41%. In addition, the instantaneous changes analysis of direction and wind speed, such as those shown in Figure 1 [1], show that the changes in direction exceeds 20 degrees in a very short time.

Our contribution in this work is an analysis of the roughness effects on an airfoil undergoing dynamic stall when the wind speed changes rapidly. We study the influence of the abrupt variation of the direction and speed of wind flow and the influence of roughness of a wind turbine blade. A two-dimensional S809 is considered to model the wind turbine blade.

A numerical simulation of the flow around a S809 airfoil is performed to study the dynamic stall phenomenon induced by very fast variations of the wind velocity and direction. To this end, we analyze a very fast variation of the velocity amplitude of the wind which generates a very fast change of the blade incidence angle. Consequently all the rotor blades will be in dynamic stall situation and the phenomenon is perfectly known by some experimental measures which are made through the study of [9] on testing a sinusoidal movement of the airfoil. The intensity of this phenomenon leads to a sudden drop in lift coefficient of the wind turbine blades and hence the decrease of its aerodynamic performance [3].

To better model the changes in wind flow, the variations of the airfoil incidence angle and flow velocity are simulated as a pulse form. For this aim, three variation modes of the flow parameters were tested and adopted separately:

1. a pulsating variation (variation in two times) of the angle of incidence corresponding to an abrupt variation in the direction of the relative velocity.
2. a pulsating variation (variation in two times) of the velocity that corresponds to an abrupt variation of the module of the relative velocity.

The work of Mc Croskey and Fisher [4] justifies the 2D approach of the effects of unsteady part of dynamic stall by the approximation of the oscillating airfoil. This 2D approach will highlight the dynamic stall and its impact on the aerodynamic characteristics of the airfoil.

Due to lack of experimental data for this pulsating motion, the results predicted on the unsteady flow leads us to estimate the aerodynamic loads induced by the wind rotor in real wind flow conditions. In this study, the Fluent software [16] is used. Before simulating the pulsating airfoil, we validate the oscillating S809 airfoil by comparing the obtained results with experimental data of reference [15].

2. Numerical Modeling

All the numerical simulations are performed using Fluent [16]. The oscillating motion and the pulsating variations of the velocity direction and amplitude are modelled separately via UDFs (User's Defined Functions).

2.1 Computational domain grid

The grid of the computational domain is presented in figure 3. The boundaries of the computational domain are defined such as to have a height of 10 chords and a length of 20 chords. The rotation center of the oscillating motion is located at one quarter of the cord from the airfoil leading-edge.
The computational domain consists only one grid zone. The numerical study of steady and unsteady flows around the airfoil was carried on non-structured grid with triangular elements. The nature of this discretization does not present any limitation of topological nature.

![Figure 3: Grid of the computational domain](image)

A dynamic mesh approach is used to model the airfoil motion. The update of the volume mesh is handled automatically at each time step based on the new position of the boundaries. The new position of boundaries is provided by a user defined function in which the kinematic of the airfoil motion is described. Concerning the meshing, 600 nodes are used on the airfoil with a growth ratio of 1.05 until the outer boundaries. This mesh refinement is performed such that to insure a dimensionless distance $y^+$ (depending to the ordinate of the first mesh) smaller than 30 which is most appropriate for complex flows involving recirculation and detachments in the flow.

### 2.2 Turbulence model

A statistical turbulence model was used within the framework of this numerical simulation. The SST (Shear Stress Transport) model was adopted. It uses a treatment close to the wall combining a correction for high and low Reynolds number in order to predict separation on smooth surfaces. This model gives a real estimation of the generation of the turbulent kinetic energy at the stagnation points. It is more accurate and more robust than or standard models [17].

The SST model performance has been studied in a large number of cases. In a NASA Technical Memorandum [18], SST model was rated the as most accurate model for aerodynamic applications.

### 2.3 Numerical model

The unsteady terms are implicit second-order discredited. A centered SIMPLE algorithm is used for the pressure-velocity coupling and a third-order MUSCL scheme discretization is used for the convection and diffusion terms. The conservation equations are solved using a segregated solver.
2.4 Governing parameters

The governing parameters of the steady state flow are taken from the wind tunnel data tests given by R. Reuss Ramsay et al [15]. Therefore, the calculations were made for a flow at Reynolds number of $10^6$ and an incidence angle varying from $-10^\circ$ to $20^\circ$. The value of surface roughness which has been adopted is 0.0019.

For the unsteady case, we are analysed three parameters of the oscillating airfoil, including the motion range, the average angle and the frequency that will define different regimes of the dynamic stall. The oscillations are done around the pitch axis as wind tunnel by R. Reuss Ramsay et al [15] for two average angles of $8^\circ$ and $14^\circ$, two frequencies 0.6 and 1.85 Hz and two amplitudes $\pm 5^\circ$ and $\pm 10^\circ$. For all cases of oscillation, the tested Reynolds numbers are $0.73\times10^6$ and $10^6$.

Martinat Guillaume et al [19] provides an exhaustive description of the various modes of dynamic stall. These modes are according to the amplitude of the incidence angle, the average incidence angle and finally of the motion frequency.

The criterion describing the unsteadiness of the oscillating airfoils is the non-dimensional reduced frequency defined by:

$$ k = \frac{n c}{V_\infty} $$

where $c$ is the airfoil chord length and $V_\infty$ the upstream velocity. In generally and according to Leishman [85], the unsteady effects are significant as $k$ exceeds 0.1.

The amplitude of the oscillation and the average angle of the incidence are interconnected through a sinusoidal law as follows:

$$ \alpha(t) = \alpha_m + A \sin(2nf t) $$

A combination of large maximum incidence angles and a large angular velocity, or through high amplitude of oscillation, either through a high oscillation frequency, is necessary to have a deep stall. Once these two conditions are met, the geometry of the airfoil and the Reynolds number will have little impact on the flow. In our study we have a deep stall ($k = 0.17$ and $0.24$).

3. Comparison with experiments

3.1 Steady state Case

3.1.1 Steady state Clean Case

In order to simulate the dynamic stall profile, it is important to know in advance the static stall and therefore the separation incidence and the value of the maximum lift coefficient. Modeling for static stall is performed on a wide range of fixed effects in order to establish the characteristics of the profile.

Figure 4 shows the lift coefficient calculated results versus incidence angle for a clean airfoil, compared with the experiments results for Reynolds number of $10^6$. For moderate values of incidence angles, the comparison shows a good agreement between numerical and experimental results.
Figure 4: Drag coefficient to incidence angle: calculations results compared with the experiments at Re =10⁶.

After reaching the angle of static stall predicted values are underestimated, this is due to the nature of the flow which becomes unsteady because of a separation on the suction side. Numerical results at Reynolds number of 10⁶ show a maximum lift of 0.92 for an incidence angle of 15.2°, which is the static stall angle, whereas the experimental data of R. Reuss Ramsay [15] for the same angle of incidence gives a maximum value of 1.03. The observed difference is about 10% between the two values.

Figure 5: Drag coefficient calculations compared with the experiments.

The figure 5 shows a comparison of the drag coefficient of numerical and experimental results. The differences between experimental data and calculations are reflected in the coefficient of the drag. The accuracy of the drag to the angles between 0° and 5° is consistent with experimental data for other angles are more than accidental due to accurate modeling of the flow.
Figure 6: Pressure Coefficient at around 0° compared with experimental data of R. Reuss Ramsay [15]

Figure 6 shows a comparison between the airfoil pressure distribution of predicted and experimental data of [15] at incidence angle 0°. The pressure coefficients comparisons for an angle 0° show a reasonably agreement over the entire airfoil surface, except in the regions where x/c is less than 0.2, the flow is laminar.

Figure 7 shows a comparison of the pressure distribution around the airfoil for an incidence angle of 9.22°.

The pressure coefficients show a flow remaining attached to the wall. We can also notice an increase in the pressure coefficient on the pressure side of the airfoil as well as a decrease of the same pressure coefficient on the suction side, leading to an increase in the lift coefficient.

There is a difference between experimental and numerical results. The experimental data show that there is a small zone of separation on the suction side. This separation was not predicted by the simulation. In the same way the values of the pressure coefficient are underestimated on the suction side of the leading edge until x/c = 0.6.

The analysis of the steady flow through the velocity contour shows the behaviour of the boundary layer.
In figure 8.a, the flow near the wall remains laminar and does not show a separation for an angle of 5°. Experimental data shows that for positive incidence angles below 5°, the flow remains laminar and attached on the suction side of the airfoil. Figure 7.b shows a beginning of a flow separation on the airfoil suction side.

Figure 8.c shows a flow separation at the half-chord of the airfoil, which is validated by experimental data. When the angle of incidence is increased to 15°, the separation region moves forward until the middle of the suction side. This motion of the turbulent boundary layers separation will induce the airfoil dynamic stall phenomena. In opposition to that was supposed, the dynamic stall is induced by the bursting of the bubble of flow separation.

In Figure 8.d, with a further increase in the incidence angle 20°, almost the entire suction side boundary layer is detached, the separation is moving quickly forward to the leading edge.

### 3.1.2 steady state case with roughness

Figure 9 shows the lift coefficient of the rough airfoil compared to the incidence angle for a Reynolds number of 10^6. The value of surface roughness which has been adopted is 0.0019, the same as the one selected for wind tunnel tests of [15]. The numerical results of rough S809 are in good agreement with the experimental data for incidence angles between 0° and 10°.
However for more significant angles, the difference is observed when the angle of incidence is larger than the angle of static stall. This difference comes from the nature of the flow which becomes strongly unsteady. The fluctuations of the lift coefficient are observed for negatives angles. The maximum lift coefficient of the smooth model decreased of nearly 16%. One can say that the influence of surface roughness on the aerodynamic characteristics of the airfoil are validated.

The pressure distribution for a rough airfoil S809 is shown in Figure 10 at an incidence angle of 2°.

There is a correlation between experimental data and predicted values. From x/c = 0.6 to the trailing edge, there is a difference between the predicted values and the experimental values on the pressure side, the predicted values are over-estimated in this zone. On the other hand, predicted values are under estimated in the zone between x/c = 0.3 and X/c=0.5.)

As in the case of a smooth airfoil, the sharp increase of pressure experienced by the attachment of turbulent flow is not shown on these numerical results.
3.2 Unsteady Case

An analysis of oscillating motion of the airfoil is presented in this section. The oscillation is done around the pitch axis as wind tunnel of R. Reuss Ramsay[15]. By convention, we call the upswing phase of the oscillation motion concerning the growth of the angle of incidence and downswing phase for a decrease in the angle of incidence. Figure 11 shows a comparison of the lift coefficient of the oscillating smooth airfoil at a range of incidence angle ±5.5°, average incidence angle of 8°, frequency of 1.85 Hz and number of Reynolds 10^6. The hysteresis loops of numerical results are consistent with experimental data.

![Figure 11: Lift coefficient of the smooth airfoil to incidence angle: comparison with the experiments.](image)

For this case, the predicted values are overestimated for low incidence angles, but for a change of angle from 7° to 13°, the agreement is the best. The hysteresis loops are larger for higher frequencies and the oscillations of greater amplitude.

Figure 12 shows the same comparison of the lift coefficient of an oscillating rough airfoil with the same conditions. The predicted values of lift coefficient are over-estimated for weak angles of incidence between 3.5° and 8°. This variation comes from the nature of the flow which is considered turbulent in calculation whereas it is actually laminar. In the ascending phase, for significant angles which exceeds 8°, the difference between the predicted and
experimental values increases when the angle of incidence increases. However for the same variation of the angle between 8° and 13.5° in the downward phase the agreement is better. The maximum value of lift coefficient is 0.9, it is smaller than the value reached for the same angle of incidence for a smooth airfoil. That is to say a difference of 28%.

4. Numerical simulation of pulsating velocity variations

The knowledge of the aerodynamics of rotor blades implies the understanding of the features of the isolated airfoil, particularly in dynamic phase of stall to obtain the best possible effectiveness over all velocity intervals. These intervals of velocity are very large if one refers to gusts of wind. The airfoil, by the variations of external conditions, sees its incidence constantly changing and consequently the flow is unsteady. This variation can strongly modify the aerodynamic behavior of the airfoil in the vicinity of stall. The rotor blades will thus be subjected to variable aerodynamic stresses. These stresses generate force constraints which will be transmitted to the remainder part of the HAWT.

The first objective of this work is the validation of the numerical approach before studying real flow conditions as abrupt changes on velocity’s amplitude and/or direction. This allows the simulation of unsteady flow around the airfoil with new conditions that are much closer to actual wind conditions to which the turbine is subjected. Recall that the gust wind changes direction and velocity very quickly [1]. This change of direction is far from being smooth, and he is not sinusoidal as well. To reproduce these variations in flow parameters, a very fast variation of the incidence angle following a pulsating motion is adopted. The velocity amplitude variation is simulated separately in the same way.

4.1 Amplitude velocity variations

There is a significant difference between the blades of wind turbine and the airfoil. Indeed the pressure created by the rotor decelerates the air passing through it. This deceleration of the air is very important. The theory of active disk of Froude-Rankine, [20], allows establishing the relationship between the fluid pressure variation passing through and downstream the rotor. This theory gives the possibility to use the airfoil characteristics and the detailed analysis of flow along the blade. The amplitude of wind velocity variation is translated by a real change in relative velocity direction and modulus. Recalling that the latter is related to the tangential velocity, the far-field velocity \( U \) and the induction factor \( \alpha \) by the following relation

\[
\vec{W} = r\vec{\Omega} + \vec{V}
\]  

(3)

In which:

\( r \) is the radius, \( \Omega \) is the rotational velocity and \( V = U (1-\alpha) \). \( \alpha = v_i / v_\infty \), where \( v_i \) is an axial inducted velocity [12] and [13]. The rotor angular velocity remains constant.

Figure 13 gives a schematic representation of the velocity triangle. When a variation of the relative velocity \( \Delta V \) occurs, it results in a very rapid variation of the incidence angle \( \alpha \) as the change in wind velocity.
the incidence angle \( \alpha \) is a function of the upstream wind velocity and the rotational velocity of rotor. A very fast variation of wind velocity upstream causes a very fast variation of the incidence angle. The rotational velocity of the rotor will have no influence on this variation due to the inertia of the rotor. This inertia does not allow a very fast variation of the rotational velocity in comparison to the wind velocity.

In the same way for the variation, the induced rotor velocity will not have influence and the angular velocity will not varying quickly, accordingly, the downstream wake conditions development from the rotor will not change.

To reproduce the best actual wind conditions, three modes of parameters flow variation were adopted separately, which will be detailed with the respective results in the following paragraphs:

### 4.2 Pulsating incidence angle variation

The abrupt variation of the velocity is imposed such as to be in the same conditions as a real gust where the infinite velocity changes very quickly. The variation of the incidence angle \( \alpha(t) \) is given by the following formulas:

For \( t_{\text{initial}} \leq t \leq t_{\text{pic}} \)

\[
\alpha(t) = \frac{\alpha_{\text{pic}} - \alpha_{\text{initial}}}{t_{\text{pic}} - t_{\text{initial}}} (t - t_{\text{initial}}) + \alpha_{\text{initial}}
\]  

(4)

And for \( t_{\text{pic}} \leq t \leq t_{\text{final}} \)

\[
\alpha(t) = \frac{\alpha_{\text{final}} - \alpha_{\text{pic}}}{t_{\text{final}} - t_{\text{pic}}} (t - t_{\text{pic}}) + \alpha_{\text{pic}}
\]  

(5)

With \( t_{\text{initial}} \) initial time, \( t_{\text{pic}} \) intermediate time where the variation is maximum and \( t_{\text{final}} \) the final time of the variation.
4.2.1 The incidence angle variations Results

The airfoil is tested for an incidence angle varying from -10° to +10°, with time-variation duration in wind velocity of 2 seconds, which represents the two pulsating phases motion. The initial incidence angle is 8° and two Reynolds numbers of 10^6 and 1.6x10^6. Figure 14 shows the lift coefficient variation against the angle of incidence. The hysteresis behavior can be observed for the unsteady simulations.

Notice that the general features of dynamic stall are evident and the results show a qualitative similarity and a good agreement compared with experimental data. This form of hysteresis loops is dependent on the adverse pressure gradient effects due to the angle of attack and the circulation induced by the angular velocity profile.

When the Reynolds number reaches 1.6x10^6, the flow is disrupted in the two phases. A large negative change in the descending phase is observed; it reached a negative value of -0.3. These disturbances provide high aerodynamic loads in a very short time.

4.3 Pulsating variation of the relative velocity modulus

The variation of velocity modulus is modeled by an abrupt pulse followed by stability. The initial static incidence angle is taken. The law of induced velocity variation is given by the following formulas:

For: \( t_{\text{initial}} \leq t \leq t_{\text{pic}} \)

\[ W = \frac{W_1 - W_0}{t_{\text{pic}} - t_{\text{initial}}} (t - t_{\text{initial}}) + W_0 \] \hspace{1cm} (6)

For: \( t_{\text{pic}} \leq t \leq t_{\text{final}} \)

\[ W = \frac{W_0 - W_1}{t_{\text{final}} - t_{\text{pic}}} (t - t_{\text{pic}}) + W_1 \] \hspace{1cm} (7)
4.3.1 Relative velocity modulus variations Results

The variation of velocity amplitude is modeled by an abrupt pulse. We assume that the static angle of incidence is constant with only the wind speed changing in direction over time. The initial static incidence angle is taken from 5° to 20°. The velocity varies during one second for each motion phase and the range of velocity variation is from 5 m/s to 25 m/s. Figure 15 shows the variation of the lift according to the wind velocity for various initial angles of incidence. A hysteresis behavior of the lift variation according to the incidence angle is observed. For an initial angle of incidence less than 5° and even 10° the lift curves of the two phases are similar. For these angles, the lift is weak because the incidence angle is very low in spite of the imposed variation of the wind velocity. On the other hand for an initial angle of incidence of 15°, one observes some fluctuations of the lift when the wind velocity increasing, this is due to the initial angle of incidence which is near the static stall angle.

Moreover, the variation of the lift is stable when the imposed wind velocity decreases in the second phase. For an initial angle of incidence of 20° the lift continue to increase until the angle of incidence reach the static stall. It appears a “soft” stall at the end of the ascending phase.

5. Conclusion

Many strides have been made in the understanding and modelling of wind turbine aerodynamics. Like all knowledge however, our understanding of aerodynamics is not absolute and can be viewed as tentative contribution. A two-dimensional unsteady flow analysis prediction is conducted over a NREL S809 airfoil, widely used in horizontal axis wind turbines, subject to abrupt changes of incidence angle and velocity of wind. The validation of the CFD model using an experimental data base is conducted. The results show a good agreement between prediction results and experiments. It was observed also that the surface roughness induces a decrease of aerodynamic performances of the airfoil. The results
of these tests will help in the development of new airfoil performance codes that account for unsteady behavior and will, also, improve the design process of new airfoils for wind turbines. Also, it was demonstrated that the dynamic stall was improved by the turbulent boundary layers separation of, and not by the bursting of the laminar bubble separation. The main contribution of this work concerns the analysis of the aerodynamic behavior of the S809 airfoil when it is subjected to a pulsating flow to simulate reel conditions.

Once the dynamic stall occurred, the airfoil does not find these characteristics of lift with a lower incidence in the static stall angle along a hysteresis curve. These results were never presented before and may be considered as a first digital database of real conditions wind turbines modeling. With this study we expect to improve the design of horizontal axis wind turbines by taking into account the abrupt variation of incidence and intensity in the computation of aerodynamic loads.

References

[1] The wind turbine. Theory, design and practical calculation D.Gourieres Publishing millcadieu2008.
[2] Julien Szydlowsky ‘Numerical simulation around a profile in configuration of dynamic stall’ thesis University of Orleans French 2006.
[3] W. Johnson, The effect of dynamic stall loading on a two-dimensional airfoil during stall, AIAA Journal, vol. 3, No; 3 pp.218-224, 1966
[4] W. J. Mc Croskey et R.K. Fisher, Dynamic stall of airfoils and helicopter rotors, AGARD R595, pp.2.1-2.7,1972.
[5] W.J. McCroskey, L.W. McAlister, Dynamic stall experiments on oscillating airfoils, AIAA Journal, vol. 14,No 1, 1976.
[6] SarunBenjanirat Computational studies of horizontal axis wind turbines in high wind speed condition using advanced turbulence models. Thesis by the Academic Faculty Georgia Institute of Technology December2006
[7] Felli M., Di Florio D, Comparison between PIV and LDV techniques in the analysis of a propeller wake, Journal of Visualization, Vol. 5-2002.
[8] K.W. McAlister, L.W. Carr, and W.J. McCroskey. Dynamic stall experiments on the NACA0012 airfoil. Technical Paper TP 1100, NASA, 1978.
[9] Wang, et al., "Turbulence modeling of deep dynamic stall at relatively low Reynolds number", Journal of Fluids and Structures, Vol. 33, pp. 191-209. 2012.
[10] G. Fortin, A. Ilinca, J.L. Laforte and V. Brandi, ‘A New Roughness Computation Method and Geometric Accretion Model for Airfoil Icing’, Journal of Aircraft, Vol. 41, N°5, pp. 1 – 14,2004.
[11] R.P.J.O.M. van Rooij and W.A. Timmer, ‘Roughness Sensitivity Considerations for Thick Rotor Blade Airfoils’, Technical Report, N°350, Delft University, 2003.
[12] R.R. Ramsay, M.J. Hoffman and G.M. Gregorek, ‘Effects of Grit Roughness and Pitch Oscillations on the S809 Airfoil’, Technical Report, NREL/TP-442-7817, 1995.
[13] W. Chakroun, I. Al-Mesri and S. Al-Fahad, ‘Effect of Surface Roughness on the Aerodynamic Characteristics of a Symmetrical Airfoil’, Journal of Wind Engineering, Vol. 28, N°5, pp. 547–564, 2004.
[14] M.G. Khalfallah and A.M. Koliub, ‘Effect of Dust on the Performance of Wind Turbine’, Journal of Desalination, Vol. 209, N°1-3, pp. 209 – 220, 2007.
[15] R. Reuss Ramsay M. J. Hoffmann G.M. Gregorek the Ohio State University Columbus, Ohio Effects of Grit Roughness and Pitch Oscillations on the S809

[16] FLUENT, Fluent, Inc., 2003.

[17] Menter, F.R, “Zonal Two Equation k-ω Turbulence Models for Aerodynamic Flows”, AIAA Paper 93-2906. 1993

[18] Bardina, J.E., Huang, P.G. and Coakley, T.J., “Turbulence Modeling, Validation, Testing and Development,” NASA Technical Memorandum 110446. 1997.

[19] Martinat Guillaume ‘ Physical analysis and modeling of turbulent unsteady flows around oscillating profiles and wind turbine’ Thesis IN P of Toulouse French 2007.

[20] IvanDobrev “Hybrid modelactive surfacefor analyasisof the aerodynamicbehavior ofwindrotorswith rigid ordeformableblades”.ENSA thesisfor the degree of DoctorFrench2009.