Effect of oscillation frequency on wind turbine airfoil dynamic stall

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Abstract. At the same oscillation amplitude, Reynolds Number, mean angle of attack, the dynamic stall characteristics of the NREL S809 airfoil undergoing sinusoidal pitch oscillations of different oscillation frequencies were investigated with modified $k - \omega$ SST turbulence model of CFD solution for two-dimensional numerical simulation. The predicted lift, drag coefficients and moment coefficients were compared with the Ohio State University wind tunnel test results, which showed a good agreement. The birth, development and breaking off of eddies were analyzed through streamline distribution around airfoil and the influence of oscillation frequencies on dynamic stall characteristics was also described and analyzed in detail, which enrich the database of dynamic stall characteristics needed by the quantization of oscillation frequencies on dynamic characteristics and prove that sliding mesh method is reliable when dealing with dynamic stall problems.

1. Introduction
Dynamic stall is a term usually using for describing the phenomenon of dynamic stall delay undergoing unsteady motion of a airfoil and wing when the angle of attack exceeds the angle of attack of static stall [1]. Stall Delay has been a puzzled problem to pneumatic scientists for many years accompanying with great change of lift and pitching moment. According to the strength of viscous effects, dynamic stall could be divided into light stall and deep stall, both of which have a significant impact on forces and pitching moments of wing and blade [2]. In addition, the performance of the blade under dynamic stall would be greatly changed, resulting in the occurrence simultaneously of maximum loads and maximum output power, which may cause damages of overload or blades breaking off, so the effect of dynamic stall must be considered when designing a wind turbine.

Dynamic stall is a complex unsteady phenomenon, the lift and drag characteristics of dynamic and static motions exists great diversities. Experiments have shown that dynamic stall have a serious impact on aerodynamic loads of a wind turbine. The theoretical load was only 50% -70% that of the measured values excluding the effects of dynamic stall. The life of some mechanical parts of a wind turbine running under deep stall conditions would be reduced by 50% or more [3]. If the dynamic stall was not considered during designing a wind turbine, this may lead to the underevaluation of the aerodynamic characteristics of a wind turbine [4]. The trend of large-scale wind turbine requires much more for the structure design and accurate calculation of loads on rotor plays an important role on calculation of aerodynamic characteristics and structure design.

The characteristics of dynamic stall on a oscillation pitching NACA 0012 airfoil was numerically investigated by Lei Yansheng with a high calculation accuracy $k - \omega$ SST turbulence model [5]. The
dynamic stall characteristics of the NREL (National Renewable Energy Laboratory) S809 airfoil undergoing sinusoidal oscillation at different angles of attack, oscillation amplitudes and reduced frequencies were studied numerically by Yu Guohua [6]. The flow structures and aerodynamic characteristics of a NACA 0012 airfoil were investigated by Alex Zanlotti with experimental methods [7]. For a particular two-dimensional airfoil, the incoming flow velocity and the oscillation frequency of dynamic stall significantly influence the performance of dynamic stall, which would improve the design of airfoil, rich the aerodynamic database of a airfoil and improve aerodynamic efficiency of a wind turbine and the establishment of a turbulence model. The flow fields at the same angle of attack of three kinds of oscillation frequencies were compared in this paper. The effect of oscillation frequencies on dynamic stall was investigated by studies on flow fields.

2. Research method

2.1. Computational grid and boundary conditions
Abandoned the limitation of orthogonality, it’s easy to control grid cell size and geometry for unstructured grid which had a better adaptability to complex shapes. The computational grid used in the numerical simulation is shown in figure 1 and the unstructured grid that contained a block (not shown) close to the airfoil was set denser and another block away from it was set a little sparser was generated by Gambit 2.2.30. This led to less total amount of 123118 grids and declined the computation and saved the computing time. To accurately capture the flow characteristics of boundary layer, 500 nodes were arranged around of the airfoil, the first boundary layer thickness and the growth factor were respectively set as 0.0001m and 1.08. The value of y plus is less than 1. A sensitivity test has been done, which showed that the denser grid was meaningless.

The boundary conditions of computational domain are shown in figure 2, including velocity inlet, pressure outlet, the non-slip wall of airfoil and interface between the internal circular domain and the external one for data transmission. The size of domain whose length and width are 35 times and 30 times of the chord length respectively is large enough to completely describe the flow field.

2.2. Computational method
Compared to multiple reference frame model and hybrid surface model, the great advantage of sliding mesh is the ability to deal with the unsteady problems. Thus the sliding mesh was used in the simulation and the user-defined function (UDF) written with C language was used to control the airfoil oscillations. After the time step independent verification, the time step was set 0.001 s and all residual convergence criteria were $10^{-6}$. The SIMPLE method was used and the periodic steady flow fields were obtained after 4 continuous periods’ calculation.

2.3. Numerical simulation conditions
The aerodynamic stall of the representative S809 airfoil of a horizontal axis wind turbine [8] undergoing sinusoidal oscillation around 1/4 chord length of different frequencies were investigated numerically with $k-\omega$ SST turbulence model presented by Menter [9] of CFD software Fluent 14.0. The size of selected airfoil is kept the same with that of OSU (Ohio State University) wind tunnel experiment [10]. The related simulation conditions were the Reynolds number of $10^6$, the average angle of attack 14 degrees, the oscillation amplitude of 10 degrees, the flow fields were predicted with the oscillation frequencies of 0.6Hz, 1.2Hz, 1.8Hz respectively (denoted as case 1, 2, and 3), the corresponding reduced frequency 0.026, 0.052, 0.078. The sinusoidal oscillations are given by:

$$\alpha(t) = \alpha_0 + \alpha_1 \sin(2\pi ft)$$ (1)

Where $\alpha(t)$ is the instantaneous angle of attack, and $\alpha_0$ and $\alpha_1$ were average angle of attack and the oscillation amplitude respectively, $f$ is the oscillation frequency and $t$ is the recent time.

3. Results and analysis

3.1. Analysis of aerodynamic characteristic curves

The aerodynamic characteristics of case 1, case 2 and case 3 are shown in figure 3 to figure 5 respectively. The figures shows that two-dimensional CFD numerical simulations agreed well with the wind tunnel experiment OSU value [10]. The trends of two curves are consistent, which ensured the accuracy of subsequent analysis.

Contrasts of the lift coefficient curves under the three conditions were presented, there was a lift linear growth segment during the pitching up during the initial stage(saying case 1 of 4° ~ 10°, case 2 of 4° ~ 12°, case 3 of 4° ~ 15°). The greater linear growth segment corresponds to increasing oscillation frequency, the maximum lift coefficient and the corresponding angle of attack was growing. However the slope of the segment was almost equal to that of the static linear growth segment (about 0.09), indicating that the pitch up motion of airfoil had no effect on the slope of linear growth segment. The deep stall angle of attack of corresponds to case 1 to case 3 are 21.41°, 22.25° and 22.97° respectively and the maximum lift coefficients were 1.244, 1.537 and 1.740. It is obvious that the angle of attack corresponding to minimum lift coefficients were 19.89°, 18.64° and 17.89° during downward progress, which would be in decline with the increasing oscillation frequencies.

Seeing the drag coefficient curves, the flows around the airfoil remain attached at a small angles of attack. The friction influence most which made little variation on drag coefficient under both pitching up and downward. The flow gradually got into the state of separation with increasing angle of attack. The influence of pressure drag was enhancing. The full separation occurs in deep stall stage, which led to the maximum drag coefficient increasing with higher oscillation frequency. The corresponding drag coefficients were 0.582, 0.746 and 0.851. The drag coefficient played an important role in structure design of wind turbine. The safe operation of wind turbine requires consideration of drag coefficient of dynamic stall and a proper safety factor.
3.2. Airfoil flow field analysis

In order to better analyze the effect of oscillation frequency on the aerodynamic characteristics of airfoil dynamic stall, the streamline distributions at the same angle of attack during both pitching upward and downward were given by figure 6 and figure 7. The states of flow field of the three cases when the angle of attack is less than 10.56 ° were attached around the airfoil and the lift coefficient increases linearly, seeing figure 6. When the attack angle reaches 10.56 °, a trailing edge vortex appears in case 1. As the angle of attack pitched up to 12.00 °, a trailing edge vortex started to grow in case 2 and the training edge vortices continued to increase. When the angle of attack got 12.75 °, the trailing edge vortices appear in case 3 and the training edge vortices continued to increase in case 1 and case 2, the lift coefficients increased accordingly; when the angle of attack went to 16.00 °, the first lift coefficient peak occurred for the development of the primary dynamic stall vortex. Meanwhile, a reverse vortex was induced in case 1 and when the angle of attack increases to 20.80 °, the lift coefficient decreased slightly for the declined circulation around the airfoil. As the angle of attack reached 22.25 °, the primary vortex have been full developed, the secondary vortex at the leading edge also got promoted to a great extent, the combined effect of the two vortex led to the lift coefficient to be the maximum.

Angle of attack increased from 22.97 ° to 23.96 °, the combined effect of the main vortex shedding and intense development of the reverse vortex in case 3 aroused the deep dynamic stall accompanying with the decreasing of lift coefficient and the increasing of drag coefficient. The results showed the decline in aerodynamic characteristics of airfoil. The streamline distributions at the same angle of attack of different oscillation frequencies during upstroke were shown in figure 6, it could be obtained that the vortex of oscillation frequency 0.6 Hz grew faster than that of 1.2 Hz, so did that of 1.2Hz with 1.8Hz. The higher oscillation frequency led to the slower development of vortex. Throughout the entire process, the oscillation frequency mainly influenced the time of birth, development and shedding of vortex.
Seeing figure 7, the angle of attack decreases to 19.89 °, the reverse vortex of suction has been fully developed and the secondary vortex started to shed in case 1, the corresponding lift coefficient reach the minimum value. As the angle of attack continued to decrease, the flow of the three cases gradually become attached from separation, the critical angles of attack of attached state were 8.26 °, 7.43 ° and 6.37 ° respectively with case 1, 2 and 3. From the comparison of streamline distributions at the same angle of attack of three oscillation frequencies during downward, a conclusion similar with
that of pitching upward was drawn that the higher oscillation frequency leads to the slower shedding of vortex and the flow attachment lags. Dynamic stall hysteresis loop reflected the conclusions.

4. Conclusions
The dynamic stall phenomena of sinusoidal oscillation S809 airfoil of different oscillation frequencies were numerically investigated by $k-\omega$ SST turbulence model in this paper. The related results were compared with the OSU experimental data, which showed a good consistency. On this basis, the aerodynamic characteristics were analysed and some useful conclusions are drawn as the following:

1. Oscillation frequency was closely relative to characteristics of dynamic stall. The higher oscillation frequency, the lift linear growth segment whose slope was almost equal to that of the static constant was longer. Meanwhile the higher oscillation frequency which played a lag and delay effect on development of vortex meant a greater maximum lift coefficient and drag coefficient.

2. The oscillation frequency of the airfoil influenced much on development of vortex. It was necessary to accurately predict the development of dynamic stall vortex at different angle of attack and change rate of angle of attack which would contribute to the understanding of vortex.

3. The relationship between dynamic stall and oscillation frequency of airfoil was discussed, which proved to be important for wind turbine design.

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References
[1] Carr L W 1988 Aircraft 25 6-17
[2] Qian W Q, Fu S and Cai J S 2001 Acta Aerodynamica Sinica 19 427-32
[3] Li C, Ye Z, Gao W and Jiang Z 2012 Prediction and Simulation of Modern Onshore and Offshore Wind Turbine (Shanghai: Shanghai Science and Technology Press)
[4] Chen X, Hao H, Tian J and Du Z H 2003 Acta Energiae Solaris Sinica 24 735-40
[5] Lei Y S and Zhou Z G 2010 Acta Energiae Solaris Sinica 31 367-72
[6] Yu G H, Zhu X C and Du Z H 2010 Proc IME J. Power Energ 224 657-77
[7] Alex Z and Giuseppe G 2012 Experimental investigation of the dynamic stall phenomenon on a NACA 23012 oscillating airfoil Proc IME J. Aerospace Engineering 0 1-14
[8] Walter P W and Stuart S O 1997 CFD Calculations of S809 aerodynamic charcateristics (Albuquerque, NM: Sandia National Labs)
[9] Menter F R 1994 Two-equation eddy viscosity turbulence models for engineering applications AIAA J. 32 1598-605
[10] Ramsay R R, Hoffman M J and Gregorek G M 1999 Effects of grit roughness and pitch oscillations on the S809 airfoil (Golden, Colorado: National Renewable Energy Laboratory) pp 1-165