32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

ANALYSIS AND CONTROL OF DYNAMIC STALL CHARACTERISTICS OF S809 AIRFOIL

Li-Shu Hao*, Yong-Wei Gao, Bin-Bin Wei, Bao Hu

National Key Laboratory of Science and Technology on Aerodynamic Design and Research,
Northwestern Polytechnical University, Xi'an 710072, China
*Corresponding author: haolishu@nwpu.edu.cn

Abstract

With the development of renewable energy, the utilization of wind power has made remarkable progress and the wind power become the main clean energy. In this work, the effects of different parameters on the dynamic stall of S809 airfoil were studied by using time-resolved pressure measurement technique, including mean angle of attack (AoA), reduced frequency and Reynolds number. In addition, the control effect of Gurney flap on the dynamic stall characteristics of S809 airfoil was also studied. The results showed that the reduced frequency had a significant effect on the dynamic stall characteristics of the airfoil. With the reduced frequency increasing, the hysteresis effect of aerodynamic characteristics increased gradually in the dynamic stall phase. Gurney flap had a significant control effect on the dynamic stall characteristics of the airfoil. With the increase of flap height, the normal force coefficient of airfoil moves up and the pitching moment coefficient moves down, which played a significant effect of lift increase.

Keywords: dynamic stall, airfoil, flow control, Gurney flap

1. Introduction

With the development of renewable energy, the utilization of wind power has made remarkable progress and the wind power become the main clean energy. Due to that the wind power generation is susceptible to the instability of airflow, how to improve the aerodynamic characteristics of airfoil, improve the wind-capturing ability of wind turbine blades, and control the local load of blades have always been hot issues for worldwide researchers.

Due to the gust, the local angle of attack (AoA) of the airfoil located on the tip of the wind turbine blade will change sharply, leading to prestall or stall, which requires good dynamic stall characteristics of the blade tip airfoil [1]. Early experiments [2] pointed out that the dynamic stall of airfoil strongly depended on the leading edge geometry, and the thinner the leading edge, the easier the dynamic stall. Shih et al. [3,4] used PIDV and PIV to study the pitching motion of NACA0012 airfoil in a water tunnel. They observed the vortex separation near the leading edge of the airfoil, and revealed the generation process of dynamic stall vortex near the leading edge. Chandrasekhara et al. [5] have done a lot of research on airfoil dynamic stall. It was found that at higher Reynolds number, the leading edge reverse pressure gradient and shock induced separation were two main mechanisms of compressible dynamic stall vortex (DSV) formation. Geissler et al. [6] found that the pulsation of the leading edge separation bubble caused a reverse vortex pair, and the mixing effect of this vortex pair with the main flow field could delay the occurrence of dynamic stall. McCroskey et al. [7,8] carried out an experimental study on the dynamic stall of airfoil, and pointed out that the dynamic stall was not entirely caused by the leading edge laminar separation bubble, but also may be caused by the forward movement of the fluid in the trailing edge recirculation zone. It can be seen that the airfoil dynamic stall is related to the airfoil leading edge geometry, airfoil thickness, airfoil oscillation parameters and incoming flow conditions. The dynamic stall may be induced by the leading edge stall vortex or by the development of the trailing edge separation vortex upstream.

Current research showed that the generation and development of the leading edge vortex

(LEV) and trailing edge vortex (TEV) dominate the flow pattern and aerodynamic characteristics of dynamic stall. For LEVs, some dynamic stall control methods had been proposed, such as dynamic deformation leading edge[9], leading edge synthetic jet [10], leading edge plasma [11], LEV generator [12]. For TEVs, dynamic stall control methods such as Gurney flap [13], Microtab [14], and multiple flaps [15] were proposed. These methods could improve the dynamic stall characteristics of airfoil.

In our previous researches, the transition/re-laminarization and flow separation/reattachment characteristics of S809 airfoil during pitching oscillation were studied in detail [16]. In this paper, the dynamic stall and its passive control of S809 airfoil are studied. Here, the Gurney flap, which is a traditional and effective method of control, was chosen to control the dynamic stall.

In this work, the dynamic stall characteristics of the wind turbine blade airfoil S809 was experimentally studied using the time-resolved pressure measurement technique [16,17]. The effects of reduced frequency, mean angle of attack (AoA) and Reynolds number on the dynamic stall characteristics of the clean airfoil were discussed. In addition, the control effects of the Gurney flap on the airfoil were investigated. And the effects of the flap height and reduced frequency were discussed in detail.

2. Experimental setup

The experiment was performed in the NF-3 wind tunnel at Northwestern Polytechnical University, Xi'an, China. NF-3 wind tunnel has three interchangeable test sections for low speed testing, i.e. airfoil test section, three-dimensional testing section and propeller test section. The size of airfoil test section is 8.0m×1.6m×3.0m (length×height×width). The maximum wind speed is 130m/s and turbulence intensity is less than 0.05% in NF-3 wind tunnel.

The test model of airfoil S809 made of wood with steel skeleton inside was 500mm chord length, 1600mm span, and 21% relative thickness. The airfoil model pitch axis was located at 1/4–chord. The model was driven in a sinusoidal motion of $\alpha = \alpha 0 + A\sin(2\pi ft)$, where α0 is the mean angle of attack (AoA), A is the amplitude of AoA and f is the oscillation frequency.

Thirty-one XCQ-093 type of dynamic differential pressure transducers produced by Kulite, Inc, America were arranged on the upper and lower surface of the airfoil as displayed in Fig. 1. The diameter of the cylindrical probe of the sensor is 2.4 mm. These sensors were embedded in the test model. Agilent VXI system with 32 phases (Type E8401A) accomplished the dynamic data acquisition. The acquisition speed was 100 kHz/phase, acquisition frequency was 0~20 kHz, and the acquisition accuracy was 0.1%. In this study, the pressure data on the airfoil surface were collected for 20s with a sampling rate of 10 kHz.

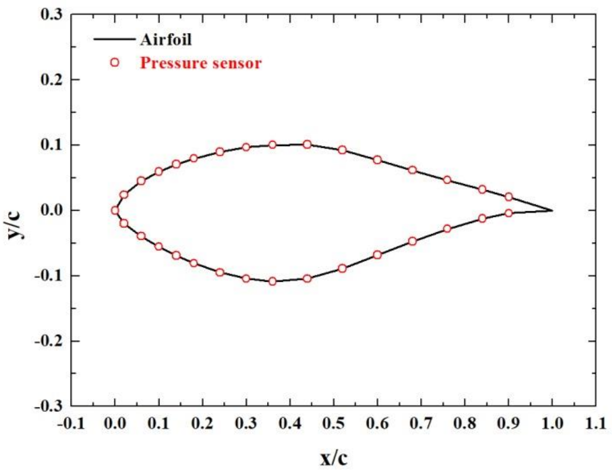


Fig.1 Airfoil and pressure sensor

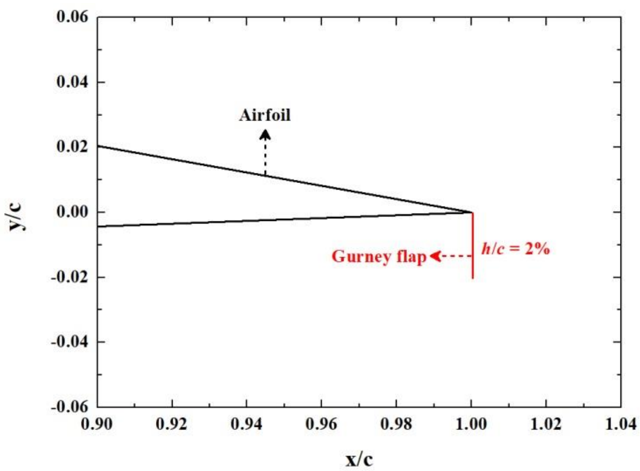


Fig.2 Installation of Gurney flap

In order to study the effect of flow parameters on the dynamic stall characteristics of the airfoil, the following experiments are arranged. In the experiment, the amplitudes of AoA were all A=10°. The reduced frequency k in Table 1 was calculated by $k = \pi fc / U$, where U was the inflow speed. And h was the height of the Gurney flap.

Table 1 Experimental setup

Case	α_0 / °	k	Re / 10^6	h/c
Case1	8	0.0346	0.75	\
Case2	8	0.0691	0.75	\
Case3	8	0.1383	0.75	\
Case4	14	0.0691	0.75	\
Case5	8	0.0691	1.5	\
Case6	8	0.0346	0.75	1%
Case7	8	0.0346	0.75	2%
Case8	8	0.0691	0.75	2%
Case9	8	0.1383	0.75	2%

In this study, four parameters including the mean AoA, reduced frequency, Reynolds number and height of Gurney flap were studied. In the case of studying the effect of one parameter, ensure that the other three parameters were the same. Case 1, Case 2 and Case 3 were used to study the effect of the reduced frequency on the aerodynamic characteristics of the clean airfoil. Case 2 and Case 4 were used to study the effect of mean AoA on the aerodynamic performance of the airfoil. Case 2 and Case 5 were used to study the effect of Reynolds number on the aerodynamic performance of the airfoil. Case 1, Case 6 and Case 7 were used to study the control effect of the height of Gurney flap on the airfoil dynamic stall. Case 7, Case 8 and Case 9 were used to study the effect of reduced frequency on dynamic stall characteristics of airfoil under Gurney flap control. Gurney flap was installed on the trailing edge of the airfoil, which can be shown in Fig. 2.

3. Results and analysis

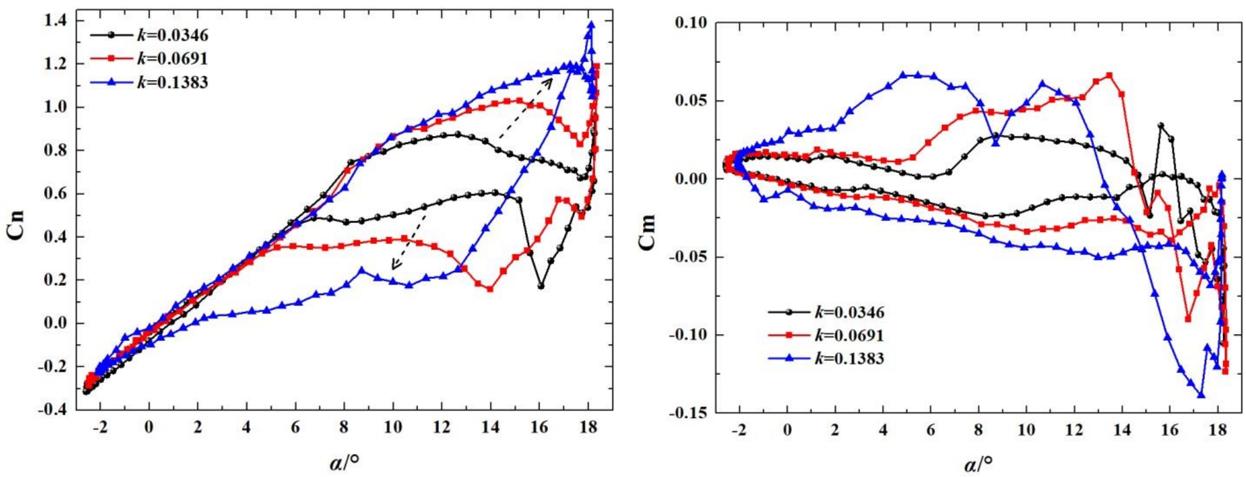
In this section, the dynamic stall characteristics of the clean airfoil and controlled airfoil by Gurney flap were presented in detail.

3.1 Aerodynamic performance of clean airfoil

The effects of reduced frequency, mean AoA and Re on the dynamic stall characteristics of the clean airfoil were studied in detail in this section.

3.1.1 Effects of reduced frequency

Case 1, Case 2 and Case 3 in Table 1 were used to study the dynamic stall characteristics of the airfoil at different reduced frequencies (Re=0.75×10^6), as shown in Fig. 3.



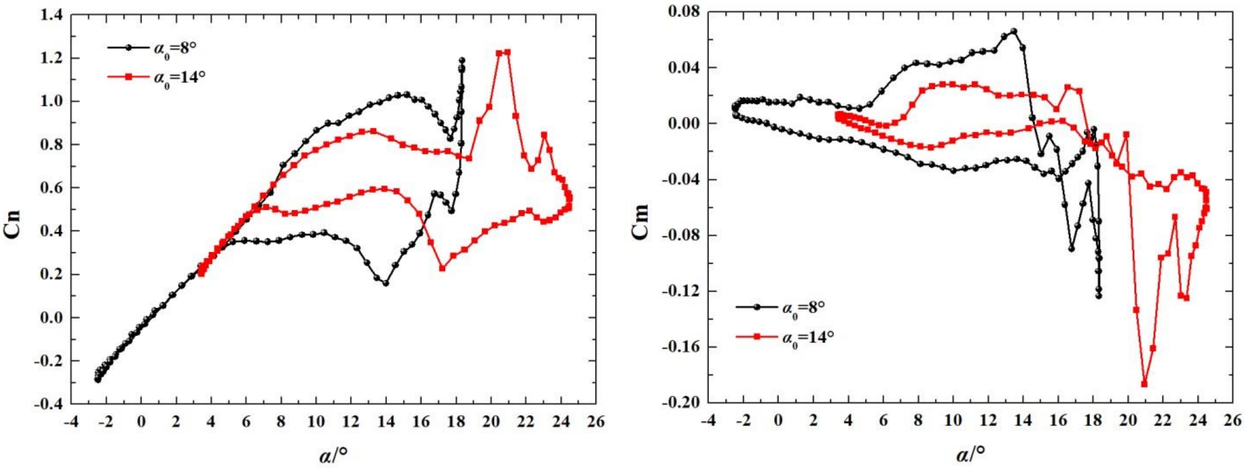
(a)Cn (b)Cm

Fig.3 Aerodynamic characteristics at different reduced frequencies (Re=0.75×10^6)

It can be seen from Fig. 3 that the reduced frequency had a significant effect on the dynamic stall characteristics of the airfoil. With the reduced frequency increasing, the occurrence of dynamic stall was delayed, and the hysteresis effect was enhanced. It also has a significant effect on the aerodynamic characteristics of the flow reattachment phase. With the increase of k, the flow reattachment ability gradually decreased. However, it had little effect on the upstroke stage. As a result, the hysteresis effect of airfoil aerodynamic performance increased with the reduced frequency.

3.1.2 Effects of mean AoA

Case2 and Case4 in Table 1 were used to study the dynamic stall characteristics of the airfoil at different mean AoAs (k=0.0691，Re=0.75×10^6), as shown in Fig. 4.



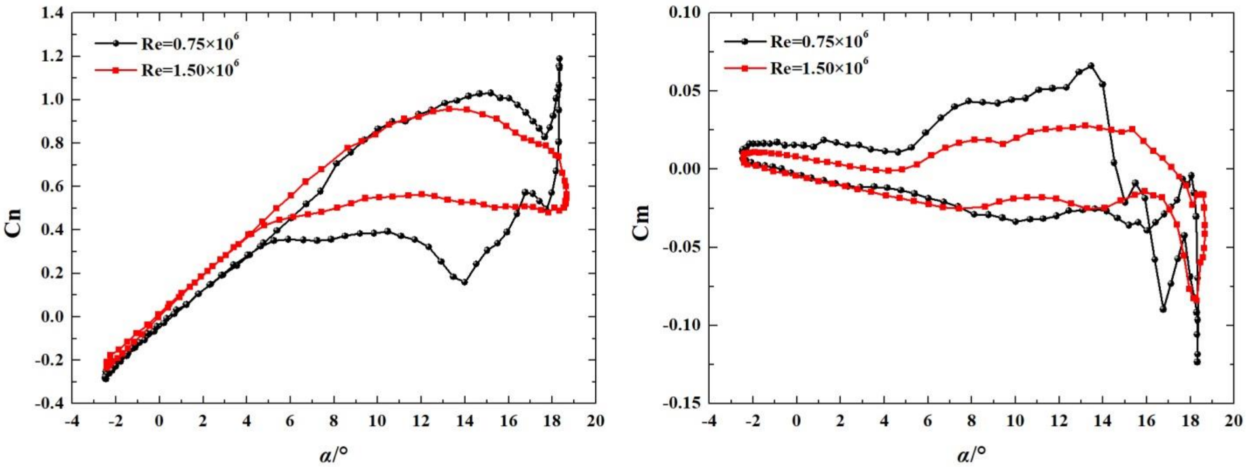
(a)Cn (b)Cm

Fig.4 Aerodynamic characteristics at different mean AoAs (k=0.0691, Re=0.75×10^6)

It can be seen from Fig. 4 that the mean AoA had a significant effect on the dynamic stall characteristics of the airfoil. With the increase of the mean AoA, the airfoil gradually entered deep stall. The dynamic characteristics of the airfoil under deep stall were significantly different from those under prestall. The main performance was that the hysteresis effect of the normal force coefficient and the torque coefficient gradually increased, and the unsteady characteristics of the airfoil under deep stall stage were more obvious.

3.1.3 Effects of Re

Case 1 and Case 5 in Table 1 are used to study the dynamic stall characteristics of the clean airfoil at different Reynolds numbers, as shown in Fig. 5.



(a)Cn (b)Cm

Fig.5 Aerodynamic characteristics at different Reynolds numbers (k=0.0691)

It can be seen from Fig. 5 that the Reynolds number had an effect on the dynamic stall characteristics of the airfoil. This effect was mainly featured in the dynamic stall in the upstroke at high AoA and the flow reattachment in the downstroke. With the increase of Reynolds number, the flow reattachment was advanced gradually, which indicated that the reattachment ability was enhanced gradually, which was contrary to the effect of reduced frequency.

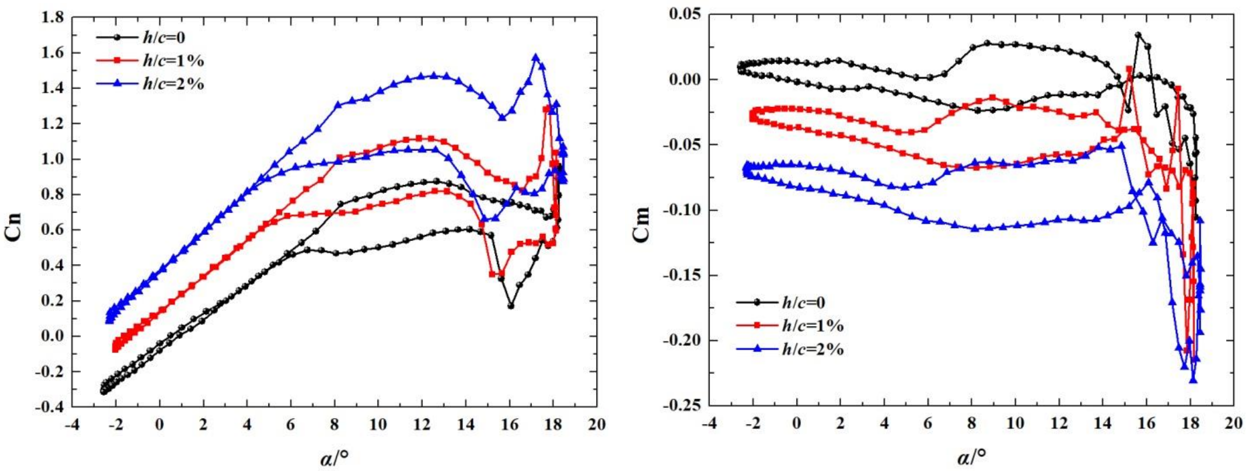
3.2 Aerodynamic performance of controlled airfoil

In this section, the control effect of Gurney flap on the dynamic stall characteristics of the airfoil was studied in detail. Specifically, the effect of flap height was deeply studied, and the effect of reduced frequency was studied in the case of that the flap height was fixed.

3.2.1 Effects of Gurney flap height

Case 1, Case 6 and Case 7 in Table 1 were used to study the control effect of flap height on airfoil aerodynamic characteristics, as shown in Fig. 6.

It can be seen from Fig. 6 that the flap height had a significant effect on the overall aerodynamic characteristics of the airfoil. With the increase of flap height, the overall aerodynamic and torque characteristics of the airfoil shifted, which had a significant lift increase effect. Within the scope of this study, this effect was almost linear. In addition, the flap also had a certain effect on the aerodynamic characteristics of the dynamic stall stage. With the increase of the flap height, the hysteresis effect of the dynamic stall stage gradually increased, and the pulsation of the normal force and torque coefficient of the dynamic stall stage gradually increased, which indicates that the unsteadiness gradually increased.

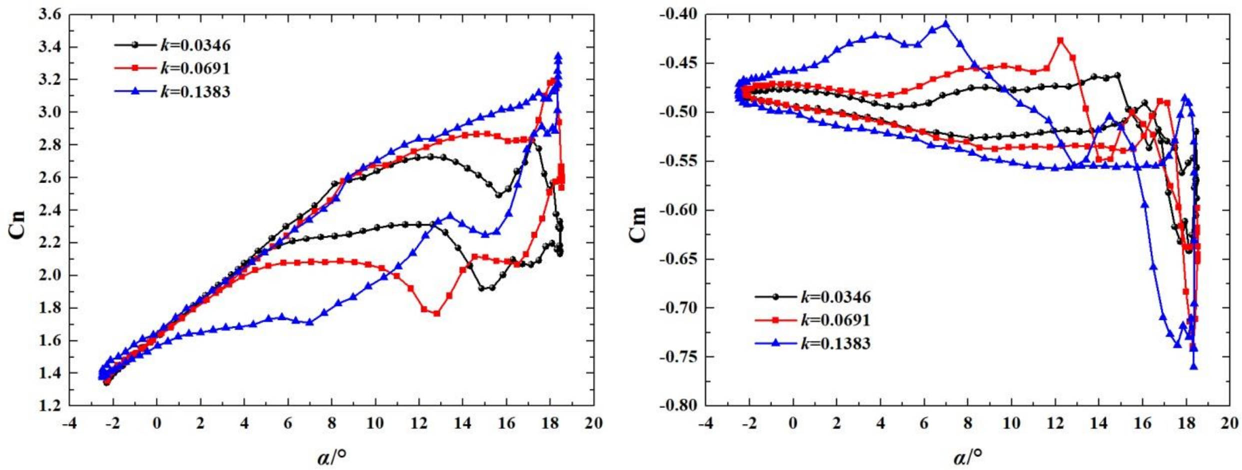


(a)Cn (b)Cm

Fig.6 Aerodynamic characteristics at different reduced frequencies (k=0.0346, Re=0.75×10^6)

3.2.2 Effects of reduced frequency on controlled airfoil

Case 7, Case 8 and Case 9 in Table 1 were used to study the dynamic stall characteristics of the airfoil at different reduced frequencies ((h/c = 2%, Re = 0.75×10^6), as shown in Fig. 7



(a)Cn (b)Cm

Fig.7 Aerodynamic characteristics at different reduced frequencies ((h/c = 2%, Re = 0.75×10^6)

It can be seen from Fig. 7 that when the airfoil was controlled by flap, the effect of reduced frequency on the dynamic stall characteristics of the airfoil was consistent with that of the clean airfoil. With the increase of the reduced frequency, the hysteresis effect in the dynamic stall phase increased gradually, and the flow reattachment ability decreased gradually, while the effect on the up stroke attachment flow phase was small.

4. Conclusions

In this paper, the dynamic stall characteristics of the clean S809 airfoil and Gurney flap controlled airfoil were studied by using the time resolved pressure measurement technique. The effects of reduced frequency, mean AoA and Reynolds number on the dynamic stall of the airfoil were studied. For the case controlled by Gurney flap, the effect of the flap height on the airfoil aerodynamic performance was studied. For the case of fixed flap height, the effect of reduced frequency was studied.

The results showed that the reduced frequency and Reynolds number had significant effects on the dynamic stall characteristics of the airfoil. With the reduced frequency increasing, the occurrence of dynamic stall was delayed and the flow reattachment ability was weakened. With the increase of Reynolds number, the flow reattachment was advanced gradually, which indicated that the reattachment ability was enhanced gradually, which was contrary to the effect of reduced frequency.

Gurney flap had significant control effect on airfoil aerodynamic performance. With the increase of flap height, the overall aerodynamic and torque characteristics of the airfoil shifted, which had a significant lift increase effect. With the increase of flap height, the hysteresis effect in dynamic stall phase became more and more obvious, and the unsteady fluctuation of aerodynamic force / torque increased gradually.

5. Acknowledgement

Thanks to all the experimental staff of NF-3 wind tunnel for their hard work. The present work is supported by the Fundamental Research Funds for the Central Universities (D5000200685).

6. Copyright Statement

References

[1] F. Grasso. Usage of numerical optimization in wind turbine airfoil design[J]. Journal of Aircraft, 48(1): 248-255

[2] Mccroskey, W,J. The Phenomenon of Dynamic Stall[R].NASA TM-81264,1981.

[3] Shih, C., Lourenco, L., Van Dommelen, L.et al. Unsteady Flow Past an Airfoil Pitching at Constant Rate[J]. AIAA Journal,1992,30(6):1153～1161.

[4] Shih, C., Lourenco, L.M, Kothapalli, A. Investigation of Flow at Leading and Tailing Edge of Pitching up Airfoil[J]. AIAAJournal, 1995,33(8):1369～1376.

[5] Chandrasekhara, M.S., Wilder, M.C. Carr, L.W. On the Competing Mechanisms of Compressible Dynamic Stall[R]. AIAA Journal, 1998,36(3):387～393.

[6] Geissler, W., Haselmeyer, H. Investigation of Dynamic Stall Onset[J]. Aerospace Science and Technology, 2006, Vol.10:590～600.

[7] Mccroskey, W,J., Carr, L.W., Mcalister, K.W. Dynamic Stall Experiments on Oscillating Airfoils[J]. AIAA Journal, 1976,14(1):57～63.

[8] Mcalister, K.W., Carr, L.W., Mccroskey, W.J. Dynamic Stall Experiments on the NACA0012 Airfoil[R]. NASA TP-1100, 1978.

[9] Jeremy, J.B., Lakshmi, N.S., Prasad, J.V.R., et al. Computational Modeling of Variable-Droop Leading Edge in Forward Flight[J]. Journal of Aircraft,2009,46(2):617～626.

[10]Steven, A. T., Onkar, S., Dave, C. Synthetic Jet Based Active Flow Control of Dynamic Stall Phenomenon on Wind Turbines Under Yaw Misalignment[R]. AIAA Paper 2014-0871, 2014.

[11]David, G., Amos, B, H., Tanns, M, V., Dynamic Stall Control on a Vertical-Axis Wind Turbine Using Plasma Actuators[R]. AIAA Journal,2014,52(2):456～462.

[12]Costes, M., Richez, F., Joubert, G., et al. Dynamic Stall Control Using Deployable Leading-Edge Vortex Generators[R]. Journal of Aircraft,2012,50(10):2135～2145.

[13]Wang Yuanyuan, Zhang Binqian. Investigation of Gurney flap on improving dynamic stall aerodynamic characteristics of an airfoil[J]. Flight Dynamics, 2010,28(4):5～8.

[14]Raymond Chow, C.P. van Dam. Computational Investigations of Deploying Load Control Microtabs on a Wind Turbine Airfoil[R]. AIAA Paper 2007-1018, 2007.

[15]Wang Rong, Xia Pinqi. Control of Helicopter Rotor Blade Dynamic Stall and Hub Vibration Load by Multiple Trailing Edge Flaps[J]. Chinese Journal of Aeronautics, 2013,34(5):1083～1091.

[16]Wei B , Gao Y , Wang L , et al. Analysis of flow transition and separation on oscillating airfoil by pressure signature[J]. Journal of Mechanical Science & Techniques, 2019, 33(1):279-288. DOI：10.1007/s12206-018-1227-0

[17]Gao Y, Zhu Q, Wang L. Measurement of unsteady transition on a pitching airfoil using dynamic pressure sensors[J]. Journal of Mechanical Science & Technology, 2016, 30(10):4571-4578.