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Final Report

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University of Wyoming
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Investigation of Dynamic Aerodynamics and Control of Wind Turbine Sections under Relevant Inflow/Blade Attitude Conditions

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Period Covered by Report:
August 15, 2009 – August 14, 2013

Work performed in conjunction with the National Renewable Energy Laboratory

Abstract

The growth of wind turbines has led to highly variable loading on the blades. Coupled with the relative reduced stiffness of longer blades, the need to control loading on the blades has become important. One method of controlling loads and maximizing energy extraction is local control of the flow on the wind turbine blades. The goal of the present work was to better understand the sources of the unsteady loading and then to control them. This is accomplished through an experimental effort to characterize the unsteadiness and the effect of a Gurney flap on the flow, as well as an analytical effort to develop control approaches. It was planned to combine these two efforts to demonstrate control of a wind tunnel test model, but that final piece still remains to be accomplished.

Introduction

Over the past several years, an attempt has been made to demonstrate the viability of closed loop local flow control of wind turbine blade flows. An experimental effort for the aerodynamics was combined with a modeling effort for the control. Much of the experimental effort was spent on developing a relevant unsteady flow to control. A description of the hardware and experiments performed are provided below. Similarly, a brief description of the modeling effort undertaken to develop control approaches is provided.

Description of Work Accomplished

Development of a Pitch Oscillating Testing Capability

In this section, the components necessary for performing tests on pitch-oscillating airfoils rapidly and cost effectively are discussed.

Pitch Oscillating Mechanism

To drive the airfoil oscillation, a pitch mechanism utilizing a 3 HP, 24V DC motor controlled by a Labview based PID control and a four-bar linkage was developed as shown in Figure 1. The design, which also allowed for plunge movement, is described in detail in references 3 and 8. Adjustment of the mean pitch angle was accomplished through an adjustable rod in the pitch linkage. Pitch amplitude was determined by connection of the pitch linkage rod ends in holes located on the motor cam. Two pairs of angular contact bearings were used in the pitch housing that constrained the pitch axis. One pair was used to constrain the motion to the rotational axis and to provide a sliding surface, whereas the other pair allowed compliance springs to be implemented in the design between the driving members and the airfoil. The pitch drive shaft connecting the airfoil to the driving members was hollow to allow the pressure tubing to be routed to the ESP modules located below the test section.

Rapid-Prototyped Airfoils

Instrumenting an airfoil with conventional pressure tap and tubing systems is difficult in small airfoils and limits the placement of taps near the leading and trailing edges due to geometric constraints. To reduce cost and manufacturing time as well as to obtain high spatial resolution pressure measurements, a stereolithography (SLA) process was utilized. This process allowed embedding of internal passages to route pressure taps to a location where they could be connected to vinyl turbine that linked them to pressure transducers. Figure 2 shows a rendering of a model of the Delft University DU-97-W-300 airfoil with a 0.02m chord. For further details and the range of models produced in this manner, see references 2, 4, 5, 6, *10*, *13*.

Compensation for Unsteady Pressure Measurement

Obtaining time dependent pressure measurements is conventionally obtained via surface mount pressure transducers. ESP modules were used in this research primarily due to the prohibitive cost and fragility of surface mount pressure transducers operating in a dynamic environment as well as the difficulties of placing taps near the leading and trailing edges of small airfoils. Inherent in the tap-tubing configuration to measure dynamic pressures, however, are latency and attenuation in the measured signal due to the tubing system as well as electronic and system noise that cannot be low-passed due to the multiplexed signals of the ESP module. To correct the measured pressure signal for the attenuation and distortion and to reduce high frequency noise, a Weiner deconvolution filter was implemented in post-processing. Details of this process can be found in reference 1.

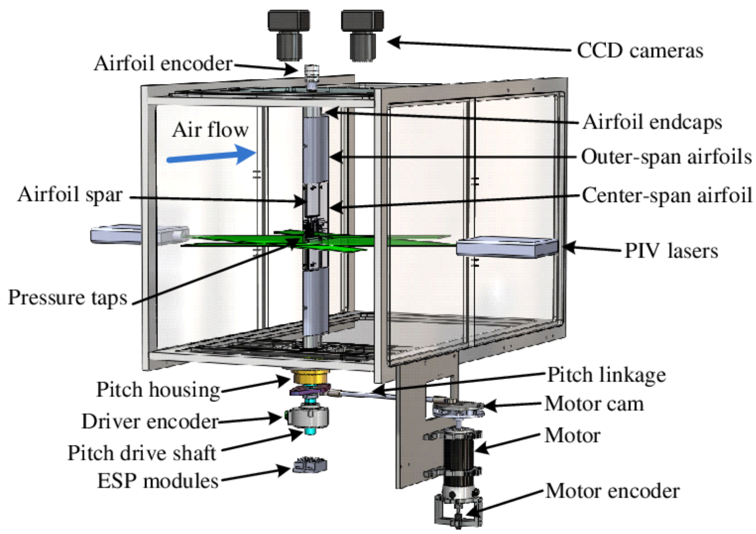

Figure 1 – Experimental setup for testing pitching blades.

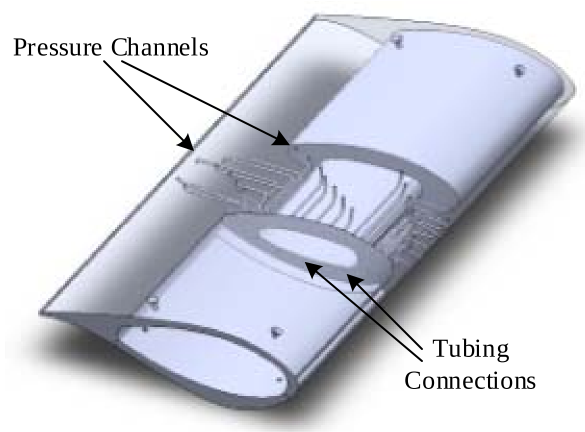

Figure 2 – Rapid prototyped model of a DU-97-W-300 Airfoil

Compliance

Compliance was added between the driving motor and the airfoil in order to simulate aero-elastic response. Details of the compliance mechanism design shown in Figure 3 can be found in reference 6. Two concentric circular components with spring mounted in between provide the compliance required.

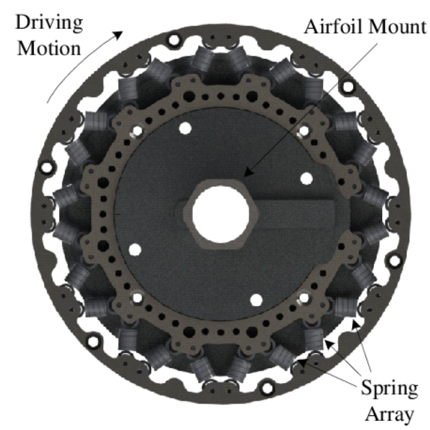

Figure 3- Compliance Mechanism

Flow Field Structure

In order to visualize the flow-field structure, Particle Image Velocimetry (PIV) was used to measure the flow field. The setup shown in Figure 1 consisted of two lasers and two cameras so that both sides of the airfoil could be imaged simultaneously. The data were analyzed as two sets of two-dimensional data and the results were then combined. For details of the setup and processing, see reference 3. Acquisition of the data was repeated at specific phases in the oscillation cycle such that the phase-averaged velocity field could be determined. To reveal flow structure, these phase-averaged velocity fields were integrated to determine phase-averaged streamlines.

Blade Characterization Work

To characterize the nature of the flow for different airfoils under different oscillation conditions, the lift coefficient, moment coefficient, pressure distribution, and flow field were all considered. An example case is presented here, but a detailed discussion of the different results can be found in references 2, 4, 5, 6, *10*, *13*.

The response of an airfoil to its loading can be characterized by the lift, moment, and drag behavior. The unsteady pressures measured above were used to calculate the phased averaged values of the lift and moment coefficients. Drag was not considered due to the large uncertainty that would be incurred in determining it from the pressure measurements. An example phase-averaged lift curve is shown in Figure 4 for a DU-97-W-300 airfoil. As can be seen, the oscillating airfoil far exceeds the static separation point delaying stall until ~21°. The airfoil then stalls, exhibits some complex behavior near its peak angle of attack, and then remains stalled until it returns to the minimum angle of attack. Interpretation of such data is somewhat difficult, and as a result, the pressure distribution is considered.

The pressure distribution for the same case is plotted in Figure 5 where a complex pressure field is observed. The suction surface is shown on the left, and the pressure surface is shown on the right. The cycle proceed from minimum angle of attack at the bottom of the figures and proceeds upward to maximum angle of attack halfway up. The airfoil then descends for the remainder of the cycle reaching the minimum angle of attack again at the top of the figures. The horizontal coordinate in both figures represents the non-dimensional distance along the chord. In this figure, the pressure near the leading edge decreases and the stagnation point moves aft as the airfoils starts to rise. At approximately 20 degrees, stall is observed as the development of a region of constant pressure (color) in the horizontal direction on the suction surface. Such patterns are characteristic of trailing edge stall. The stall moves forward until it reaches the leading edge at approximately 24 degrees. At this point the pressure rapidly increases on the suction surface, followed by a decrease in pressure starting at about the peak angle of attack and completing at approximately 23 degrees falling. It is this second low-pressure region that is responsible for the cusp observed in the lift curve just after peak angle of attack. For the remainder of the cycle, the stall region decreases in size with the flow attaching near the leading edge and gradually moves backward. Despite the value of such pressure distributions, it is not clear what exactly happening during the stall process, and thus the flow-field must be considered.

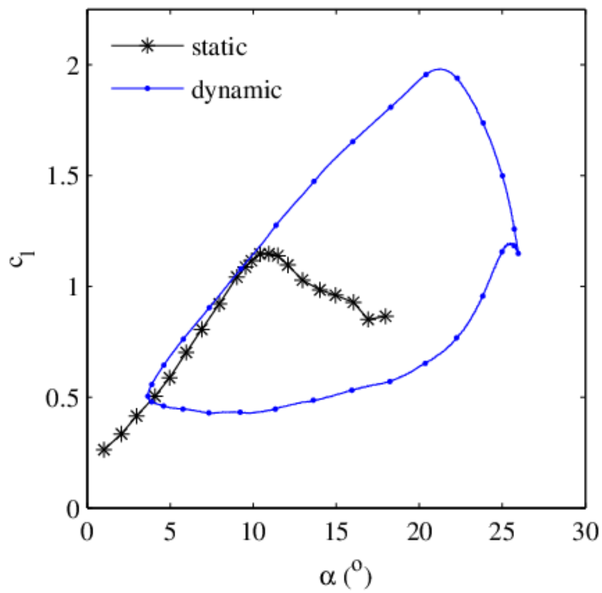

Figure 4 – Phase averaged lift curve for a 0.102 m chord DU97-W-300 airfoil oscillating 15°±10° at 20 Hz yielding a Reynolds number of 220,000 and a reduced frequency of 0.142.

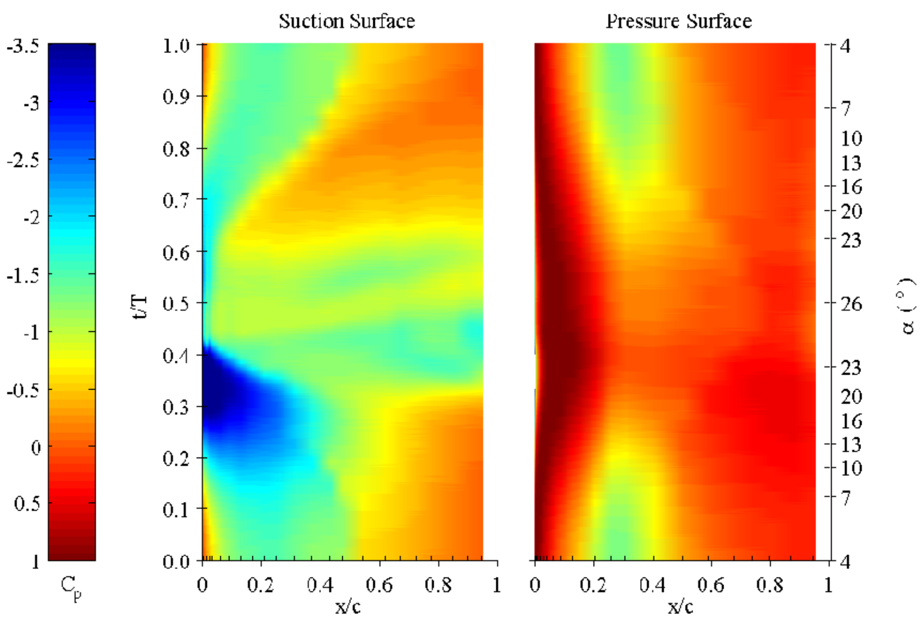

Figure 5 – Phase averaged pressure distribution for a 0.102 m chord DU97-W-300 airfoil oscillating 15°±10° at 20 Hz yielding a Reynolds number of 220,000 and a reduced frequency of 0.142

To provide this insight, the phase-averaged streamlines for the case discussed above, shown in Figure 6, are considered. As can be seen, the flow remains attached until well past the static stall angle with some evidence of trailing edge stall developing at approximately 18° rising. This stall region grows in size reaching its fullest extent just before peak angle of attack. At this point, we observe the development of a secondary vortex near the trailing edge, which is partially responsible for the low pressure observed on the suction surface near the trailing edge in Figure 5. Near the peak angle of attack (25° rising), the well-defined stall pattern appears to break down and is replaced by a second stall process that is fully established by 25.5° falling. Another secondary vortex is observed at 24° falling, that eventually sheds from the airfoil leaving a slowly decreasing stalled area that persists through the down stroke.

Clearly, the combination of the pressure distribution and flow-field images provides information that can be used to explain why the lift and moment curves appear the way they do. For example, results like this for multiple wind turbine blades under different oscillation conditions have been used to identify different kinds of stall patterns (see reference 5) thus increasing our knowledge of the dynamic stall physics. Such data are also useful for assessing the ability of the computations to capture the rich structure of dynamic stall (see reference *12*).

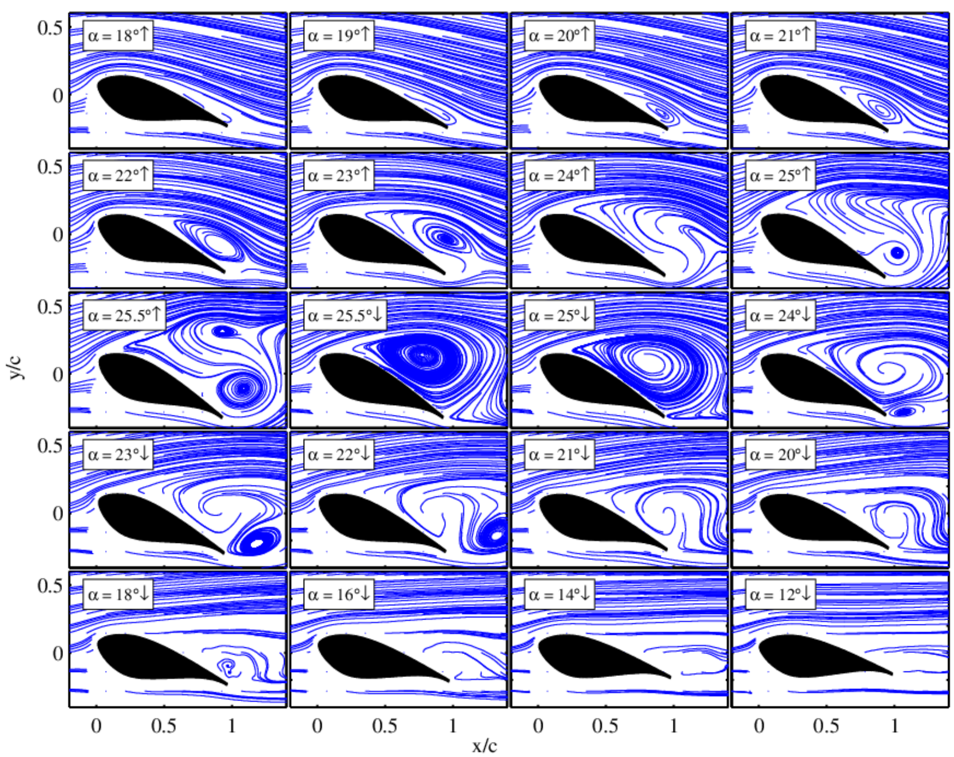

Figure 6 – Phase-averaged streamlines for a 0.102 m chord DU97-W-300 airfoil oscillating 15°±10° at 20 Hz yielding a Reynolds number of 220,000 and a reduced frequency of 0.142.

Blade Compliance Work

Compliance was added between the driving motor and the airfoil in order to simulate aero-elastic response. Differences between the rigid and compliant airfoils is discussed in depth in reference 6. Compliance was necessary in order to study control of the airfoil. To characterize the compliance effects, airfoils were tested under the same conditions both rigidly and with the compliant section present. An example of the results of such tests are shown in Figure 7 where the difference in the two cases is evident. The changes in the curve result from different angle of attack range allowed by the compliance.

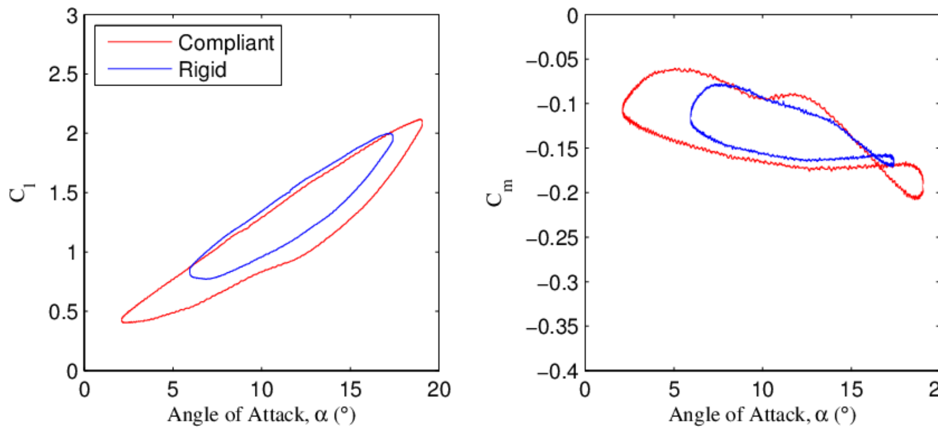

Figure 7 – Effect of compliance on lift and moment curves for a DU-97-W-300 for α = 12° ± 5°, and a reduced frequency of 0.21.

Gurney Flap Actuator Work

To change the lift and moment on the airfoil necessary to control its motion, Gurney flaps were investigated. Gurney flaps are short surfaces that extend upward from a location near the trailing edge of an airfoil. Details of the Gurney flap work carried out as part of this effort are provided by references 9, *10*, and *11*. The Gurney flap has been studied while the airfoil was fixed [*11*] and while it was undergoing dynamic pitching [*10*]. The results for the fixed airfoil confirmed the authority of the Gurney flap under a wide range of angle of attack. Currently, a Gurney flap whose height is controllable is undergoing testing on an airfoil at fixed angle of attack to determine the time response of the airfoil to Gurney flap deployment.

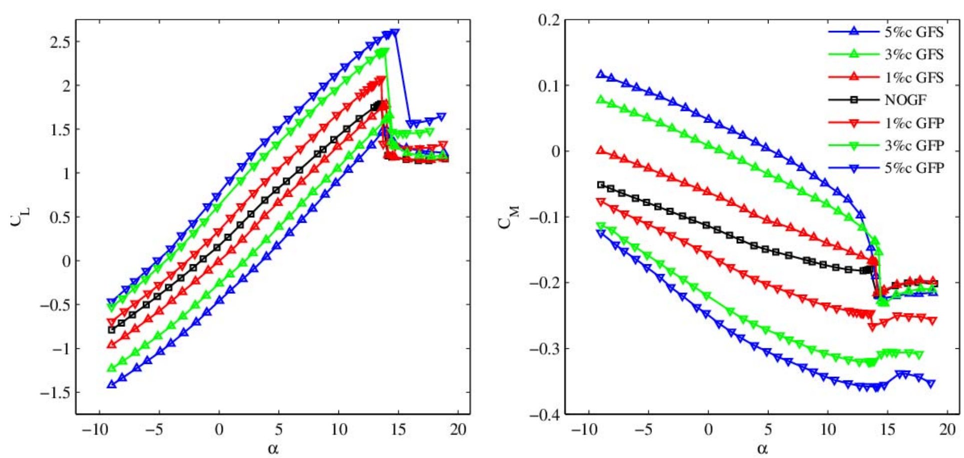

Figure 8 – Effect of different Gurney flap height on a DU-97-300 at various angles of attack.

Active Controls Development

The final piece required for closed loop control of the airfoil is the control approach itself. The aeroelastic system used to represent the rotating blade was a structural vibration model with several degrees of freedom, coupled with the periodic time-varying unsteady aerodynamic load over the rotating blade. With the time-varying parameters and strong nonlinearity, it is very difficult to control the vibration of the rotating blade. In this project, Adaptive Control is chosen as an effective and efficient control algorithm to suppress the vibration of the blade. Traditional PID controllers are not considered due to the fact that the gains for PID are only constant, and cannot adapt quickly to the variance of the aeroelastic system, whereas Adaptive Control is suitable and powerful for the system with unknown or time-varying parameters.

Here, the adaptive controller is designed to reduce blade vibrations and input disturbances, which may be caused by wind gusts or actuation. The control goal is to make the vibration deflections of the blade converge to zero asymptotically and to reject the possible input disturbance at the same time using time-varying adaptive gains, which are defined and adjusted by the Adaptive Control Law. Good performance of the Adaptive Controller has been shown in closed-loop simulation tests. The robustness and effectiveness of the controller are also revealed by the achievement of multiple control aims and its applicability in a wide range of wind velocity cases. The stability of the adaptive controller was proved using the Adaptive Stability Theorem, and the theorem was also illustrated by the blade aeroelastic system case. In summary, the Adaptive Control has been shown to be capable of suppressing blade vibrations theoretically and numerically.

The final piece of demonstrating control is to couple the control algorithms developed as part of the control work with the actuated airfoil wind tunnel model. It is anticipated that this demonstration will show the possibility of closed-loop control for local flow control.

Papers Published as Part of this Work

The papers listed below are a directly related to the current effort.

1 J. A. Strike, M. D. Hind, M. S. Saini, J. W. Naughton, M. D. Wilson, and S. A. Whitmore. Unsteady surface pressure reconstruction on an oscillating airfoil using the Wiener deconvolution method. AIAA Paper 2010-4799, Jun 2010. 27th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, Chicago, Il.

2 A. L. Babbitt, J. A. Strike, C. E. Mertes, M. D. Hind, M. .J. Singh, and J. W. Naughton. Dynamic characterization of a wind turbine blade section. AIAA Paper 2011-350, Jan 2011. 49th AIAA Aerospace Science Meeting, Orlando, Fl.

3 M. D. Hind, J. A. Strike, M. S. Singh, and J. W. Naughton. Characterizing dynamic flow conditions on oscillating airfoils. AIAA Paper 2012-0695, Jan 2012. 50th AIAA Aerospace Sciences Meeting, Nashville, TN.

4 A. L. Babbitt, J. A. Strike, M. D. Hind, and J. W. Naughton. Pressure distributions on a wind turbine blade section for various pitch oscillation conditions. AIAA Paper 2012-234, Jan 2012. 50th AIAA Aerospace Sciences Meeting, Nashville, TN.

5 J. Naughton, J. Strike, M. Hind, A. Magstadt, and A. Babbitt. Measurements of dynamic stall on the DU wind turbine airfoil series. May 2013. Presented at AHS Forum 69, Phoenix, AZ.

6 A. S. Magstadt, J. A. Strike, M. D. Hind, P. Nikoueeyan, and J. W. Naughton. Compliance effects in dynamically pitching wind turbine airfoils. Number AIAA Paper 2013-2994, Jun 2013a. 43rd AIAA Fluid Dynamics Conference, San Diego, CA.

7 A. S. Magstadt, P. Nikoueeyan, L. F. Soares, and J. W. Naughton. The effects of pitch axis location on a dynamically pitching wind turbine airfoil. October 2013. International Conference on Future Technologies for Wind Energy.

8 J. Strike, M. Hind, M. Singh, A. Babbitt, A. Magstadt, P. Nikoueeyan, and J. Naughton. Aerodynamic testing of unsteady airfoils. October 2013. International Conference on Future Technologies for Wind Energy.

9 P. Nikoueeyan, J. A. Strike, A. S. Magstadt, and M. D. Hind. Steady and unsteady flow characteristics of wind turbine blades with Gurney flaps. October 2013. International Conference on Future Technologies for Wind Energy.

10 P. Nikoueeyan, J.A.Strike, A.S. Magstadt, M. D. Hind, and J.W. Naughton. Gurney flap control authority on a pitching wind turbine airfoil. May 2014a. Presented at AHS Forum 70, Montreal, Quebec, Canada.

11 P. Nikoueeyan, J. A. Strike, A. S. Magstadt, M. D. Hind, and J. W. Naughton. Characterization of the static aerodynamic coefficients of a wind turbine airfoil with Gurney flap deployment for flow control applications. Number AIAA Paper 2014-2146, Jun 2014b. 32nd AIAA Applied Aerodynamics Conference, Atlanta, GA.

12 P. Davidson, J. A.Strike, M. D. Hind, J. Sitaraman, and J. W. Naughton. Characterization of dynamic stall on 9-12% thick airfoils through computational and experimental methods. Number AIAA Paper 2014-3248, Jun 2014. 32nd AIAA Applied Aerodynamics Conference, Atlanta, GA.

13 J. Naughton, J. Strike, M. Hind, A. Babbitt, A. Magstadt, P. Nikoueeyan, P. Davidson, and J. Sitaraman. Characterization and control of unsteady aerodynamics on wind turbine aerofoils. In Journal of Physics: Conference Series 524, 2014. doi: 10.1088/1742-6596/524/1/012025. Science of Marking Torque from Wind, 10-18 June, 2014.

14 N. Li, M. J. Balas. Aeroelastic control of a wind turbine blade using microtabs based on UA97W300-I0 Airofoil. *Wind Engineering*, 37(5), pp. 501-516, 2013.

15 N. Li, M. J. Balas. Adaptive control design for aeroelastic suppression of wind turbine blade. *Wind Engineering*, 37(2), pp. 183-197, 2013.

16 N. Li, M. J. Balas, Aeroelastic control of wind turbine blade using trailing-edge flap. Wind Engineering, 2014 (Accepted).

17 Li, Nailu, Balas, Mark J. Adaptive flow control of wind turbine blade using microtabs with unsteady aerodynamic loads. Proceeding-2013 IEEE Green Technology Conference, pp.134-139, Denver, CO, USA, 2013.04.04-05.

18 Li, Nailu, Balas, Mark J., Flutter suppression of rotating wind turbine blade based on Beddoes-Leishman model using microtabs, AIAA Modeling and Simulation Technology(MST) Conference, Boston, MA, USA, 2013.08.19-22.

19 Balas, Mark J., Li, Nailu, Adaptive control of flow over a wind turbine blade. AIAA Atmospheric Flight Mechanics Conference, Minneapolis, MN, USA, 2012.08.13-16.

In addition, two posters were presented at the North American Wind Energy Academy held in Boulder, CO in Summer 2013.

1. P. Nikoueeyan, J. Strike, M. Hind, N. Li, and J. Naughton. Load control of dynamically pitching wind turbine blades using Gurney flaps. Aug 2013. Presented at the NAWEA Symposium 2013.

2. J. Strike, M. Hind, M. Singh, A. Babbitt, C. Mertes, A. Magstadt, P. Nikoueeyan, and J. Naughton. Unsteady aerodynamic testing of wind turbine airfoils. Aug 2013. Presented at the NAWEA Symposium 2013.

Presentations of this work (no paper or poster) have been made at several venues.

1. University of Louisville, Invited Talk, February 2011.

2. Los Alamos National Laboratory Wind Energy Workshop, March 2011.

3. Texas A&M, Invited Talk, April 2011.

4. Texas Tech Wind Workshop, May 2012.

5. American Physical Society Division of Fluid Dynamics Meeting, November 2012.

6. California State University Northridge, Invited Talk, February 2013.

7. Iowa State University, Invited Talk, April 2013.

8. NASA Ames Research Center, June 2013.

9. North American Wind Energy Academy, August 2013.

10. WindEEE Grand Opening, University of Western Ontario, Invited Talk, October 2013.

11. Sandia National Laboratory, Invited Talk, June 2014.

Finally, a movie of this work was presented at the American Physical Society Meeting, Division of Fluid Dynamics Annual Meeting in Pittsburgh, PA, in November 2013.

1. Michael Hind, John Strike, Pourya Nikoueeyan, Andrew Magstadt, Ashli Babbitt, Phillip Davidson, Jonathan Naughton. Complex Structure of Dynamic Stall on Wind Turbine Airfoils. November, 2013. arXiv:1310.3343v1

Although no archival articles have been published to date, several are in various stages of preparation.

People Working on the Project

Jonathan Naughton	PI	1 month from this DOE grant per year
Mark Balas	Co-PI	1 month from this DOE grant per year
Vibhav Durgesh	Post-Doc Researcher	Not supported by this DOE grant (Funded by UW Match)
Anle Mu	Post-Doc Researcher	Not supported by this DOE grant (Funded by UW Match)
Michael Hind	Engineer	Not supported by this DOE grant (Funded by internal WERC funds)
Nailu Li	Ph.D. Student	Fully supported by this DOE grant
John Strike	M.S. Student	Not supported by this DOE grant (Funded by internal WERC funds)
Ashli Babbit	M.S. Student	Fully supported by this DOE grant
Andrew Magstadt	M.S. Student	Not supported by this DOE grant Supported by other DOE funds and internal WERC funds
Pourya Nikoueeyan	M.S. Student	Not supported by this DOE grant (Funded by internal WERC funds)

Other Sources of Support

Naughton

Jonathan Naughton has enjoyed support from several sources during this grant, of which the most directly related are discussed below. The Wind Energy Research Center (WERC) received a large gift from BP North America that was used to partially support this work (listed as internal WERC funds for the personnel listed above). In addition, funds from a workforce development grant from DOE were used to support one M.S. student (Andrew Magstadt).

Currently, Jonathan Naughton has three active projects that are summarized in the table below. The DOE EPSCoR Implementation award recently granted is believed to be due, in part, to Jonathan's interaction with various DOE programs in the course of the work described in this report as well as other related wind energy work. It is not a direct outgrowth of this work as it is focused on the wind plant level, transmission grid issues, as well as the economics of wind farm placement.

Table 1 – Summary of Jonathan Naughton's current and pending support

Funding Agency	Title	Current	Amount from external agency	Directly Related to this Work
DOE Naughton – PI 12 Co-PI	Atmosphere to Grid: Addressing the Barriers to Energy Conversion and Delivery	Yes	$4,250,000	Yes
Air Force Research Laboratory Naughton - PI	Developing an Approach for Assessing Effectiveness of Viscous Drag Reduction Concepts	Yes	$178,574	No
Wyoming Infrastructure Authority Naughton - PI	The Benefits of Diversity of Wind Resource	Yes	$20,000	Partially.Work is concerned with combining wind from different regions.

Balas' Additions
Mark Balas accepted a job at Embry-Riddle University in Daytona Beach, FL in December 2013 and is no longer associated with the University of Wyoming. However, all the portion of his work were complete prior to leaving the University, and thus there was no impact on his contributions to this effort.

Cost Summary
A summary of the anticipated and actual costs for this work is given in the table below.

	DOE	Cost Share	Total
Approved Budget	$ 450,000.00	$ 165,519.00	$ 615,519.00
Actual Expenses	$ 450,000.00	$ 178,414.00	$ 628,414.00