Link Foundation Energy Fellowship

Fellow Report

Aerodynamics of biplane wind turbine blades

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1 Introduction

In order to increase energy capture and reduce the cost of wind-generated electricity, wind turbine blades have grown dramatically over time. This trend shows signs of continuing; current investigations include the development of a 20-megawatt turbine [1] and the design of a 100-meter blade [2].

As blades grow longer, the design of the inboard region (near the blade root) becomes a trade-off between competing structural and aerodynamic requirements thick airfoils are needed to support increasing loads but have inherently poor aerodynamic performance. In addition, structural, cost, and transport considerations require the inboard section of blades to be smaller than is required for optimal aerodynamic performance.

New blade designs are required to circumvent these design compromises and enable the next generation of very large wind turbine blades. Departing from traditional blade designs, our group proposed the biplane blade, a design which replaces the thick airfoils typically used in the inboard region with two thinner airfoils in a biplane configuration (see Figure 1). The use of biplane airfoils inboard allows for increased lift and aerodynamic efficiency – for the same chord length, these airfoils produce more lift and with less drag than traditional thick inboard airfoils. The biplane design also shows significant structural benefits, with an increased stiffness-to-mass ratio compared to traditional blades [3, 4].

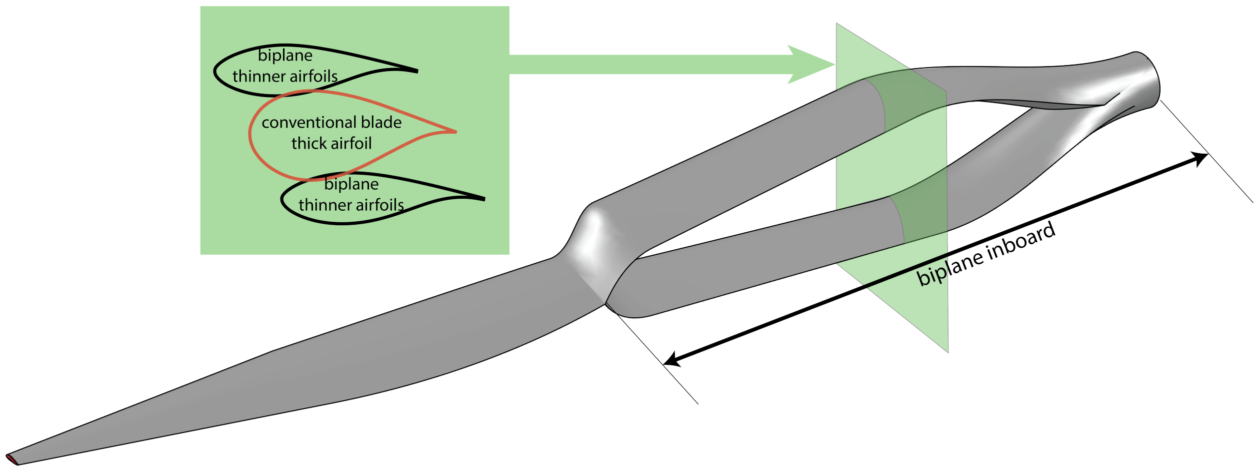

Figure 1: The biplane blade design uses a biplane inboard and merges to a single airfoil (monoplane) towards the tip.

Little is known about the aerodynamics of biplane wind turbine blades. Even more fundamentally, the two-dimensional aerodynamics of *thick* biplane airfoils are not well-understood. Supported by the Link Foundation Energy Fellowship, this research has sought to develop a better understanding of these aerodynamics through wind tunnel experiments and computational fluid dynamics.

An understanding of biplane aerodynamics is a key step towards the commercial implementation of biplane wind turbine blades. These designs could enable larger turbine designs, ultimately reducing the cost of wind-generated electricity and helping to displace conventional means of electricity generation.

2 Methods and Results

2.1 Background

Research in biplane aerodynamics was most active during the early years of aviation when biplanes were the preferred wing design for aircraft. Early work, motivated by the desire to design better aircraft, sought to understand how the relative positioning of biplane airfoils affected aerodynamic performance.

Figure 2: The Sopwith Camel, a biplane aircraft from the early 20th century which exhibits the thin airfoils and external struts popular at the time.[2]

The aerodynamics of biplane airfoils was extensively studied experimentally and theoretically in the earlier half of the 1900s. On the experimental side, a number of wind tunnel experiments sought to quantify how the aerodynamic performance – lift, drag, and pitching moment – of biplane airfoils was affected by their relative positioning [5, 6, 7, 8, 9]. Important theoretical work using potential flow theory also developed during this time [10, 11].

Both experimental and theoretical studies showed generally increased aerodynamic performance (increased lift and reduced drag) was achieved when the airfoils were spaced farther apart. These studies, however, were somewhat limited in scope. The biplane wings of the time used very thin airfoils, with external struts providing the necessary structural support. As such, the experiments typically measured the aerodynamic performance of very thin airfoils (thickness-to-chord on the order of 10%). The theoretical studies of of the time often assumed infinitely thin airfoil profiles and neglected the effects of viscosity.

Biplane airfoils for wind turbine blades require thicker airfoils (thickness-to-chord on the order of 25%) in order to fit the internal spar needed for structural support. In this regime, the profile thickness and viscosity significantly impact aerodynamic performance. Through wind tunnel experiments and computational fluid dynamics, our efforts have sought to better understand the key factors affecting aerodynamic performance of such thick-airfoil biplanes.

2.2 Wind tunnel experiments

Tests conducted at the Lucas Adaptive Wall Tunnel at Caltech measured the performance of biplanes using airfoils with a thickness-to-chord of 25%. The experiments investigated in a parametric way how the aerodynamic performance of thick-airfoil biplanes varied with their spacings in the chord-normal and chord-perpendicular directions, commonly referred to as *gap* and *stagger* (see Figure 3). Since wind turbine blades, unlike aircraft, often operate at high angles of attack, the aerodynamic performance was measured up to an angle of attack of 35 degrees.

The measurements quantified the aerodynamic performance for a biplane with nine different gap/spacing configurations. The lift coefficient for the biplanes was shown to be 45% to 80% higher than that of the single airfoil. In addition to absolute performance, trends in aerodynamic performance were also examined and compared to results in the literature for thin-airfoil biplanes. At low angles of attack (pre-stall), our measured trends were generally in agreeement with the literature – increased lift was found with larger gap and stagger. This similarity in trends indicates that at small angles of attack, the relative positioning

[2](”Sopwith F-1 Camel 2 USAF”. Licensed under Public domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Sopwith_F-1_Camel_2_USAF.jpg)

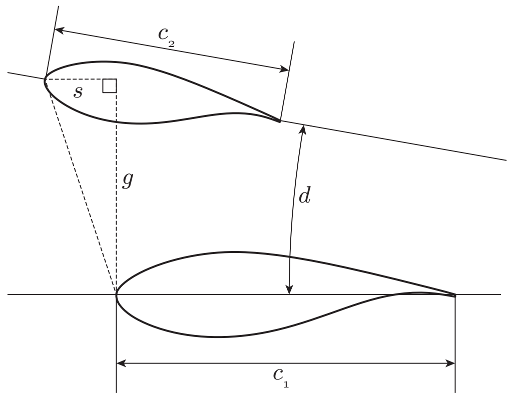

Figure 3: The relative positioning of biplane airfoil sections is often parameterized by the gap, g; stagger s; and decalage, d. The chord lengths of the airfoils are denoted c_1 and c_2.

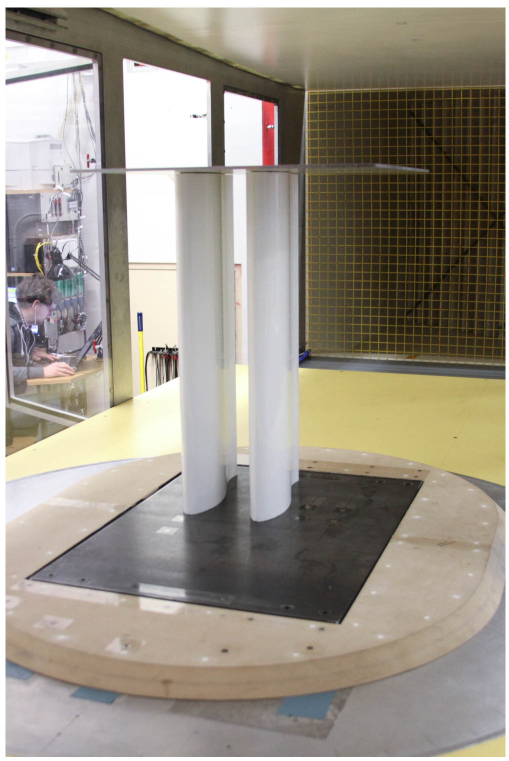

Figure 4: Biplane airfoil test section with 25% thick airfoils in the Caltech Lucas Adaptive Wall Wind Tunnel.

between airfoils is a stronger effect than those of of airfoil thickness and viscosity.

At higher angles of attack, the experiments yielded more interesting results. For biplanes with small gaps, the lift performance at high angles had significant variation in magnitude and shape when their stagger was changed. These drastic differences, shown in Figure 5, indicate that the flow characteristics of biplane airfoils can be altered significantly by small changes in airfoil positioning. This is particularly true at smaller gaps when interactions between the airfoils are significant.

These results lead to an interesting idea – could the geometry of biplane airfoils be designed, or *tuned*,

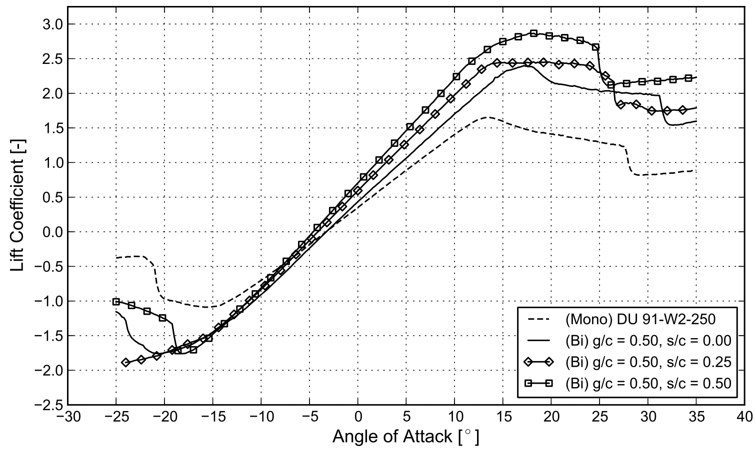

Figure 5: Wind tunnel lift measurements for biplanes with small gap and varying stagger. The configuration with medium stagger ($s/c = 0.25$) demonstrates favorable flat stall behavior, which demonstrates the potential for *tunable* performance.

for a specific stall performance? Our wind tunnel results demonstrate one particular biplane configuration with extremely flat lift in the stall region; it's possible that airfoils could be designed for this characteristic. This is a potentially exciting area for future research, since strong dynamic loading on wind turbine blades is often driven by lift oscillations around the point of airfoil stall.

2.3 Computations

While the wind tunnel experiments revealed interesting behavior in lift performance, particularly in the stall region, they were unable to provide detailed information about the flow field around the airfoils. In order to get a better idea of the significance of various flow phenomena, we investigated the performance of thick biplanes using computational fluid dynamics (CFD) simulations.

These computational investigations sought to isolate the various effects – airfoil thickness, relative positioning, and viscous phenomena – on airfoil performance. Modeling a canonical biplane comprised of symmetric 25% thick airfoils, we investigated the mechanisms responsible for the aerodynamic performance exhibited by thick biplane airfoils. A key result of these investigations was the identification of a flow phenomenon which we call the "channel effect," which is a primary mechanism affecting aerodynamic performance when the airfoils in a biplane are thick.

The channel effect describes the effect of increased velocity between airfoils as air is forced between them. This increase in velocity causes a suction force between the two airfoils and also affects the pressure gradient over the surfaces between airfoils. The suction force significantly affects the loading on the individual airfoils; our results demonstrate that at low angles of attack, this suction can be responsible for negative lift, or downforce, on the upper airfoil, as shown in Figure 6. The modified pressure gradient accelerates the onset of stall on the lower airfoil; this increases the profile drag of the system, particularly at low angles of attack.

Our results show that the channel effect is significant not only when the airfoils in a thick, but also when the thickness-to-gap ratio is small. These effects should be considered by those designing biplane airfoils, not just for biplane wind turbines, but for other applications as well; while motivated by the concept of the biplane wind turbine blade, the biplane wing configuration has recently seen resurgence in popularity in the form of joined-wing aircraft.

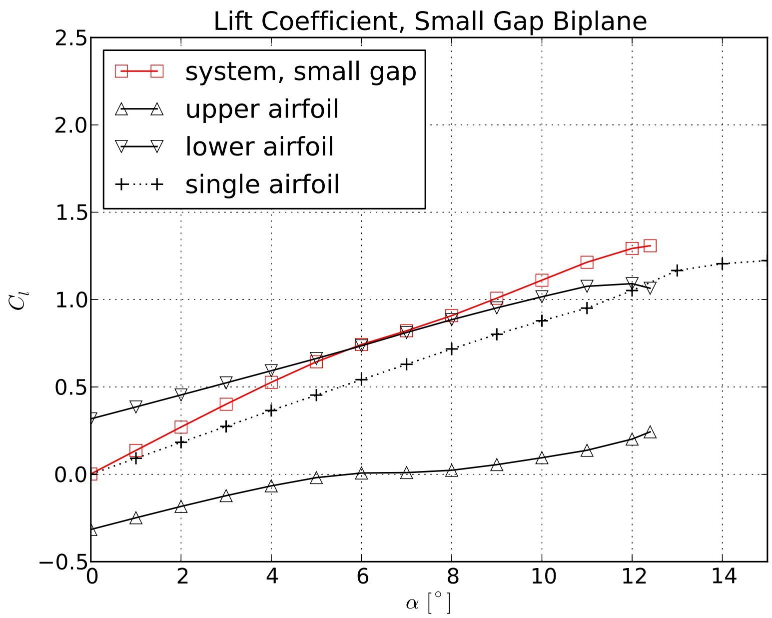

Figure 6: The lift contributions of each airfoil are decomposed through computational modelling. The channel effect causes a suction between the airfoils which is responsible for negative lift by the upper airfoil when the gap is small.

3 Significance and Impact

This work developed a better understanding of the aerodynamics of thick-airfoil biplanes, an airfoil configuration that had not before been thoroughly investigated. Through wind tunnel testing, we quantified the high lift performance of the configuration, and showed that the trends in lift with relative positioning from thin-airfoil biplanes are also applicable to those using thick airfoils. Through computional modeling, we demonstrated the primary design factors affecting the performance of such biplanes.

The results from our studies indicate that from the perspective of 2-D aerodynamics, the biplane concept is feasible. The increased lift of these biplanes correspond directly to possible chord length reductions in the inboard sections of biplane wind turbine blades, leading to lighter blade designs which extract more energy from the wind. Equally important is the understanding of the the aerodynamic phenomena affecting thick airfoil biplanes – this information is likely to be useful for future biplane airfoil and wing designers.

While these results are promising, a number of open questions remain. How should the designer choose suitable airfoil profiles for different radial locations along the blade? How should the aerodynamically complex merging region of the blade be designed. Ongoing research seeks to better understand these aerodynamic design considerations.

A thorough understanding of the aerodynamic performance of biplane wind turbine blades is critical to their implementation. Ultimately, the implementation of such blades could make wind-generated electricity cost-competitive with more conventional sources of generation.

4 Dissemination of Results

- P. Chiu and R. E. Wirz. *Aerodynamic Performance of Biplane Airfoils for Wind Turbine Blades.* Talk presented at: AWEA Windpower. Atlanta, GA, 2012

- P. Chiu, P. Roth-Johnson, and R. E. Wirz. *Overview of Research on Biplane Wind Turbine Blades.* Poster presented at: UCLA Cleantech and Advanced Materials Partnering Conference. Los Angeles, CA, 2013
- P. K. Chiu and R. E. Wirz. "Aerodynamic performance of biplanes with thick airfoils". in prep.

5 Discretionary Funds

Discretionary funds provided by the Link Foundation Energy Fellowship were used to purchase a small (four-node) cluster of computers for performing CFD and design studies. This cluster also supports the development and prototyping of software used in ongoing research. The use of travel funds is described in the following section.

6 Impact of Fellowship

I am grateful for the gracious support of the Link Foundation Energy Fellowship, which allowed me to pursue my personal research interests. I am especially thankful for the travel funds, which allowed me to present my work at the 2012 American Wind Energy Association Windpower Conference (Atlanta, GA), and to attend the 2012 Sandia Blade Workshop (Albuquerque, NM). The professional connections made at these conferences led to a summer research position in the Wind Energy Technologies group at Sandia National Laboratories, a leading institution of wind energy research in the United States.

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