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Design of a Biplane Wing for Small-Scale Aircraft

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Although the biplane wing configuration has seen little use on modern airplanes over the last 70 years, there are still a few applications where the configuration is the best solution. In the 2007 AIAA/Cessna/Raytheon Design/Build/Fly competition, a shorter wingspan yielded a better final score in the competition. The Penn State team decided on a biplane wing design for its entry, the Nittany Griffin. To properly design a biplane wing, a literature survey was completed to learn about the flow conditions unique to this configuration. The airfoil selection was based on predictions generated by XFOIL, and the wing geometry was finalized using predictions of the multiple lifting line code, FREEWAKE 2007. The configuration was driven by the goal to maximize the aircraft performance during takeoff and cruise. Minimization of induced drag was of particular importance during this process. The resulting wing geometry from the analysis was not intuitive, however, when flight tested on a remote controlled aircraft, it demonstrated much improved performance over previous wing designs.

Nomenclature

A, B, C	=	circulation coefficients
AR	=	aspect ratio
b	=	wing span
C_L	=	lift coefficient
c_l	=	sectional lift coefficient
C_{Di}	=	induced drag coefficient
K	=	induced drag factor
k	=	Munk's span factor
MEW	=	manufactured empty weight
n	=	number of spanwise elements
RAC	=	rated aircraft cost
S	=	wing area
α	=	angle of attack
ε	=	downwash angle
ε_b	=	biplane downwash angle
ε_m	=	monoplane downwash angle
$\Delta\varepsilon$	=	change in downwash angle
Γ	=	circulation
γ	=	vorticity, $d\Gamma/d\eta$
ξ, η, ζ	=	local reference frame
θ	=	angle of stagger
σ	=	$\Delta\varepsilon/\varepsilon_m$

I. Introduction

THE AIAA, through the Applied Aerodynamics, Aircraft Design, Design Engineering and Flight Test Technical Committees and the AIAA Foundation, invites all university students to participate in the Cessna Aircraft Company/Raytheon Missile Systems - Student Design/Build/Fly (DBF) Competition. The contest provides

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engineering students with a real-world aircraft design experience and gives them the opportunity to validate their analytic studies. Student teams design, fabricate, and demonstrate the flight capabilities of an unmanned, electric powered, radio controlled aircraft that can best meet a specified mission profile.[1] The goal is to develop a balanced airplane design that demonstrates good flight handling qualities, meets practical and affordable manufacturing requirements, and achieves high vehicle performance. To encourage innovation and maintain fresh design challenges, the design requirements and performance objectives are updated each year. The changes provide new design requirements and opportunities, while still allowing for the application of technology developed by the teams in prior years.

A. Mission Requirements

The 2007 DBF competition was the inaugural year for the Penn State team and its airplane, The Nittany Griffin. Composed of both graduate and undergraduate students, the team's ultimate goal was to build an aircraft that would compete in and win the competition. Every year, each team in the competition has to complete at least one of two flight missions (with a maximum of five flight attempts) and a ground mission, which is factored into the flight time. To determine the flight score, the best flight time for each mission is used. The overall score determines the winner of the contest.

$$\text{Final Score} = \frac{(\text{Written Report Score} \times \text{Flight Score})}{\text{Rated Aircraft Cost}} \tag{1}$$

The product of the total wingspan and the Manufactures Empty Weight (MEW) determines the Rated Aircraft Cost (RAC), where the MEW is the actual empty weight of the aircraft including batteries.

$$\text{RAC} = \text{MEW} \times \text{Wingspan} \tag{2}$$

Each mission consists of carrying a specified payload one time around a prescribed course. The aircraft must takeoff within a distance of 100 feet and land safely at the end of the mission. The complete system (airframe and payloads) must fit into a 2 ft. x 4 ft. x 1.5 ft. container. It may be broken down into components if desired. The two missions are described below.

i.) Sampling Mission- This mission requires that the aircraft carry an air sampler system, which consists of an "L" shaped tube. One end of the tube must protrude from the nose of the aircraft, and the other end must protrude out of the top of the fuselage. In addition, there must be a 3 lbs, 8 in. x 8 in. x 8 in. processor element that is stored within the aircraft. There must be a 3/8 in. outside diameter tube connecting the air sampler to the processor element. The score for the sampling mission is calculated by 1/(total lap time). "The scores will be normalized based on the on the time of the best scoring team such that the best scoring team will always have a score of 100. Score = 100/ (Team Time x Best Time)."

ii.) Surveillance Mission- For the surveillance mission, the aircraft must carry a camera ball system, consisting of a softball, half of which will protrude from the bottom of the fuselage and a processor element. This processor element will be 4 in. x 6 in. x 15 in. and weigh 5 lbs. There will be a 3/8 inch outside diameter tube connecting the camera to the processor element. The score for this mission is calculated by the inverse of the RAC. "The scores will be normalized based on the on the RAC of the best scoring team such that the best scoring team will always have a score of 100. Score = 100/ (Team RAC x Best RAC)."

B. Mission Emphasis

The goal in terms of aircraft design is to achieve the highest total flight score with the lowest rated aircraft cost. To achieve a low rated aircraft cost, emphasis in design must be placed on minimizing weight and span. The flight score is based on the two missions, the sampling mission and the surveillance mission. For both missions, if the aircraft does not successfully complete the course, it receives a zero score for that mission. As such, reliability is of the utmost importance in the design. Scoring for the sampling mission is based on the best time, while scoring for the surveillance mission is based only on RAC. Because RAC is already a priority and due to the large number of points available for completion of the surveillance mission, the team focus was mostly on building a reliable aircraft with a low RAC, but with the endurance necessary to complete the second mission. Looking at the possibilities of minimizing the RAC, reducing wingspan became a goal for the design. The viable design solution determined during conceptual design to reduce the wingspan for the PSU Nittany Griffin was a biplane wing configuration.

II. Biplane Aerodynamic Characteristics

The dominance of biplanes from the beginning of aviation into the 1930s can be attributed to aerodynamic misunderstandings that lead to structural problems seen in early aircraft. These problems were eventually overcome, and the monoplane became the predominate configuration for aircraft. This is mainly due to lower drag that is attained with the monoplane configuration. Nevertheless, there are still a few advantages with a biplane. First, a greater amount of wing area can be realized for the size of aircraft. This results in short takeoff and landing distances and oftentimes softer stall characteristics. Biplanes can also carry more payload without the use of high-lift devices because of this gain in wing area. A few studies in the past 30 years have shown that with the proper gap, stagger, and twist, biplanes can be more efficient than a monoplane.[2,3]

The aspect ratio of a biplane is defined as twice that of a monoplane of the same wingspan and total wing area[5]

$$AR = 2b^2 / S \tag{3}$$

This relation, however, cannot be directly applied to a biplane, because it would make it seem as if it was much more efficient than a monoplane, which is not true. Biplane theory is complicated by two main factors: interaction of the vortex systems between the wings and airflow around the airfoil sections increasing the total downwash and the induced drag. The interaction of the trailing vortex systems of each wing causes the biplane to fly at a higher angle of attack to produce the same amount of lift with the same airfoil section and wing area. The increase in angle of attack is proportional to the increase in downwash angle, $\Delta\varepsilon$.[4] This relationship is given by

$$\begin{aligned} \varepsilon_b &= (\varepsilon_m + \Delta\varepsilon)/\varepsilon_m \\ &= (1 + \Delta\varepsilon/\varepsilon_m) \\ &= (1 + \sigma) \end{aligned} \tag{4}$$

where ε_b is the downwash of the biplane and ε_m is the monoplane downwash. Figure 1 shows the increase in downwash due to the biplane configuration.

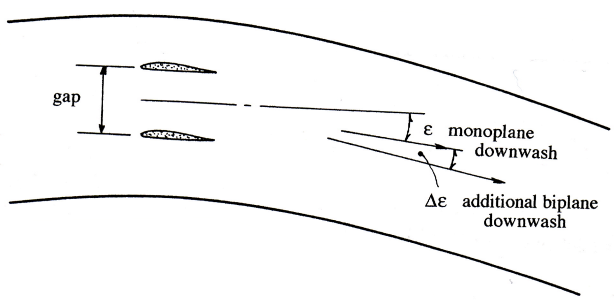

Figure 1. Additional Downwash Due to Biplane Configuration[4]

The biplane downwash is given by

$$\varepsilon_b = \frac{KC_L(1+\sigma)}{\pi AR} \tag{5}$$

where K is the induced drag factor.

To simplify the biplane calculations, an equivalent monoplane model can replace the wing arrangement. This model has the same wing area and induced drag. First proposed by Max Munk, the model shows that the maximum span must be replaced by a monoplane wing of a span kb, having the same area and induced drag as the biplane. For a monoplane, k =1, while for a biplane it depends on the gap/span ratio and stagger.[5]

The most simplistic biplane arrangement is that of two wings of equal span (orthogonal). The induced drag coefficient for this sort of configuration, in terms of both the biplane and equivalent monoplane definitions, is obtained using

$$\text{Biplane}: \; C_{Di} = \frac{KC_L^2 S(1+\sigma)}{2\pi b^2}$$
$$\text{Equivalent Monoplane}: \; C_{Di} = \frac{KC_L^2 S}{\pi k^2 b^2} \tag{6}$$

where Munk's span factor, *k*, is defined as

$$k = \sqrt{\frac{2}{1+\sigma}} \tag{7}$$

Most conventional biplanes have a σ value of approximately 0.5, with a range of 0.4 to 0.6.[5]

As mentioned, the performance of a biplane and the value of Munk's span factor depend on gap/span ratio, span ratio, and the area ratio of the two wings. Figure 2 shows the dependence of *k* on the gap to mean span ratio. The further apart the wings are, the greater *k* becomes and therefore, the more efficient the wing.

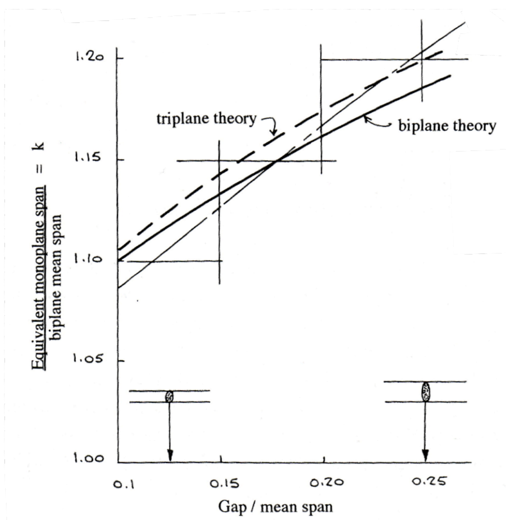

Figure 2. Munk's Span Factor Dependence on the Gap-to-span Ratio[5]

Figures 3 and 4 show the effect of stagger on the biplane. Essentially, the most efficient configuration is that where the wings are directly over one another, as seen in Fig. 3.

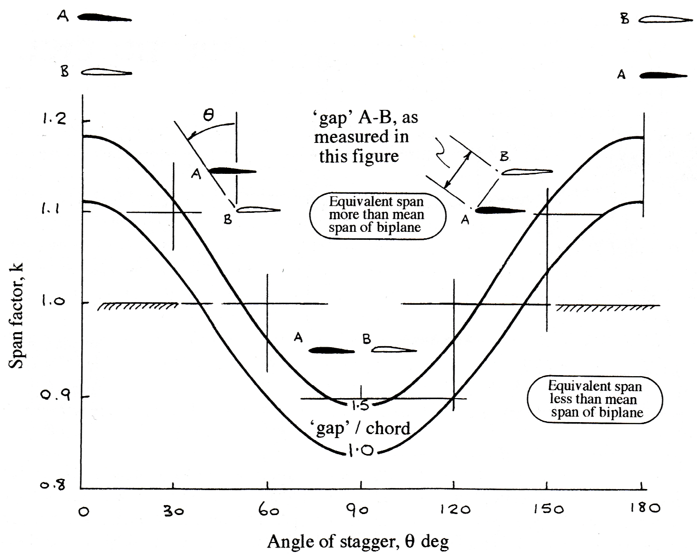

Figure 3. Munk's Span Factor Dependence on Stagger Angle[5]

Figure 4 shows the difference in lift curves of the top and bottom wings as stagger is increased. The lower wing carries less load than the top wing at a set angle of attack.

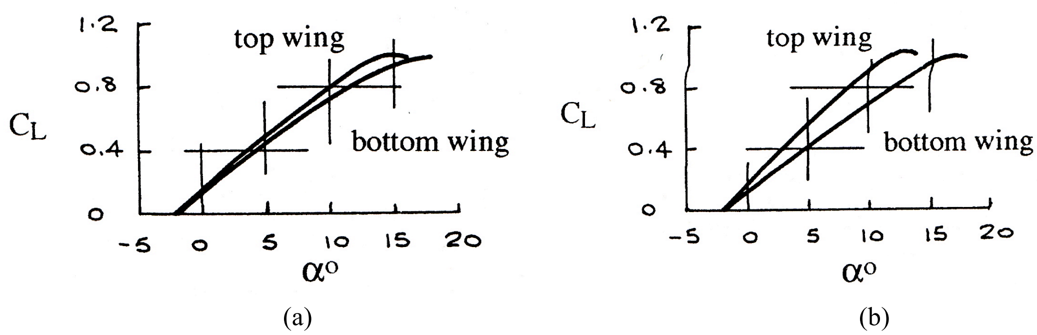

Figure 4. Difference In Lift Curves Between Wings With (a) No Stagger and (b) 30° Stagger[4]

Stagger is often used to allow increased visibility for the pilot. Since the Nittany Griffin is unmanned, this is not a factor.

III. PSU Nittany Griffin Wing Design

Paying attention to the special considerations required in biplane wing design, the PSU team proceeded with planform design and airfoil selection for the Nittany Griffin.

A. Wing Planform Design

1. FREEWAKE 2007

Accurate modeling of the trailing vortex system is particularly important to the design. Fixed wake vortex-lattice models are accurate to about 10% of experimental results. With the use of free or relaxed wake models, computed results can be within 2%. For this purpose, a relaxed wake multiple-lifting-line code, called *FREEWAKE 2007*, was used.[6] The predicted results of this code have been validated for a number of cases using available experimental data.[12] The key element of the method—the distributed vorticity element—consists of vortex filaments along its leading and trailing edges (shown in Fig. 5). These filaments have spanwise circulation distributions that are parabolic and of opposite orientations. The advantage of using distributed vorticity elements to model a flow field is that the two velocity components induced by a continuous vortex sheet are finite.

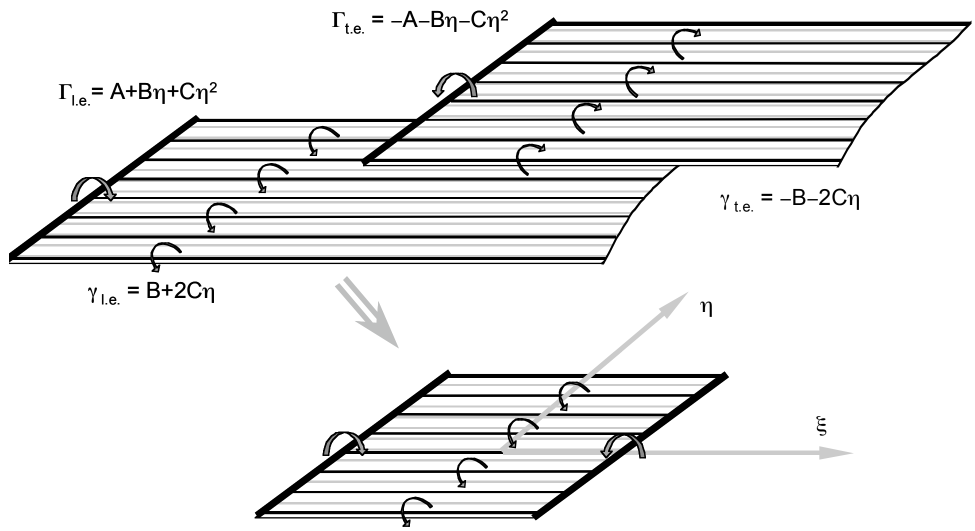

Figure 5. A distributed vorticity element is composed of vortex filaments along its leading and trailing edges, as well as of two semi-infinite vortex sheets.[6]

2. Nittany Griffin Wing Design

Along with the goal of keeping the wingspan as low as possible for RAC considerations, the wing design is based upon the constraint analysis having a design wing loading of 40oz/ft^2. Initially, a biplane wing was designed with two symmetrical planar wings and analyzed utilizing *FREEWAKE 2007*. To minimize induced drag, the wing was modified to produce an elliptical loading and constant c_l across the span at cruise. With the biplane configuration and short span, the minimization of induced drag is a major hurdle to overcome during the design process. Changes in twist, taper, and wing spacing were used to offset these effects while keeping the total wing area and span constant.

To account for the increased downwash produced by the biplane configuration and produce an elliptical lift distribution, twist was varied on both the top and bottom wing of the configuration. On a monoplane, a wing is usually set with washout to unload some of the lift at the tips. However, it was found that wash-in on the top wing increased the aerodynamic efficiency of the wing. The optimum solution calls for 8° of wash-in, although the Nittany Griffin wash-in was set at 4.5°. Figure 6 shows the twist distribution from the center of each wing to the tip.

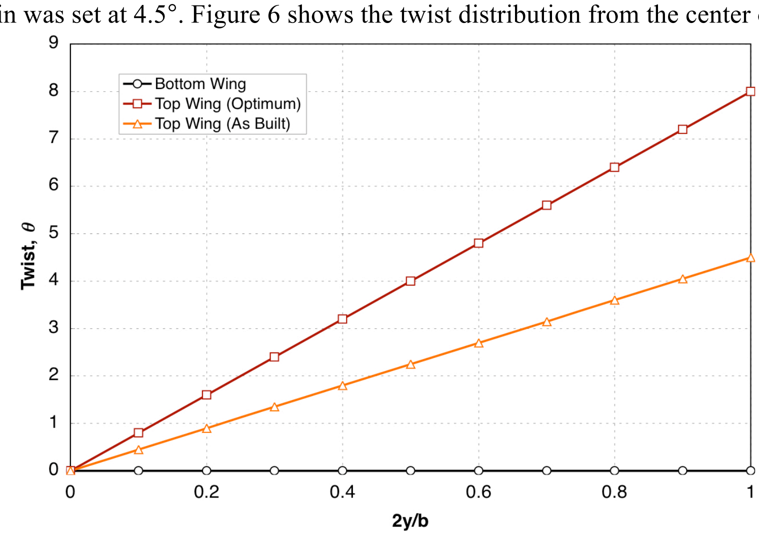

Figure 6. Wing Twist Distribution

The wing spacing is constrained by the height of the box the Nittany Griffin was to be stored in before assembly and set at a distance of one wing chord. The taper ratio between the root and tip chords is set to 0.5 to produce more uniform c_l's along the span of the wing while avoiding low Reynolds number issues associated with a small section chord. End plates were added between the two wing sections for structural purposes and to slightly decrease the induced effects. The final wing configuration can be seen in Fig. 7.

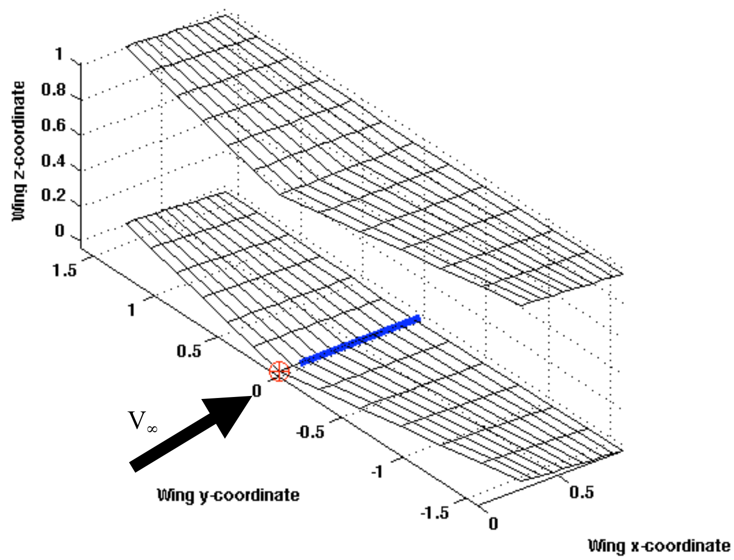

Figure 7. Final Wing Configuration

Along with a comparison of elliptical loading for minimum induced drag, the load distribution on both wings and that of the entire configuration is presented in Fig. 8. The total lift coefficient (C_L = 0.4) was set to simulate cruise conditions. The total lift distribution shows a good comparison to the elliptical loading producing an increase in the overall aerodynamic efficiency of the wing and reducing the negative effects of a biplane configuration.

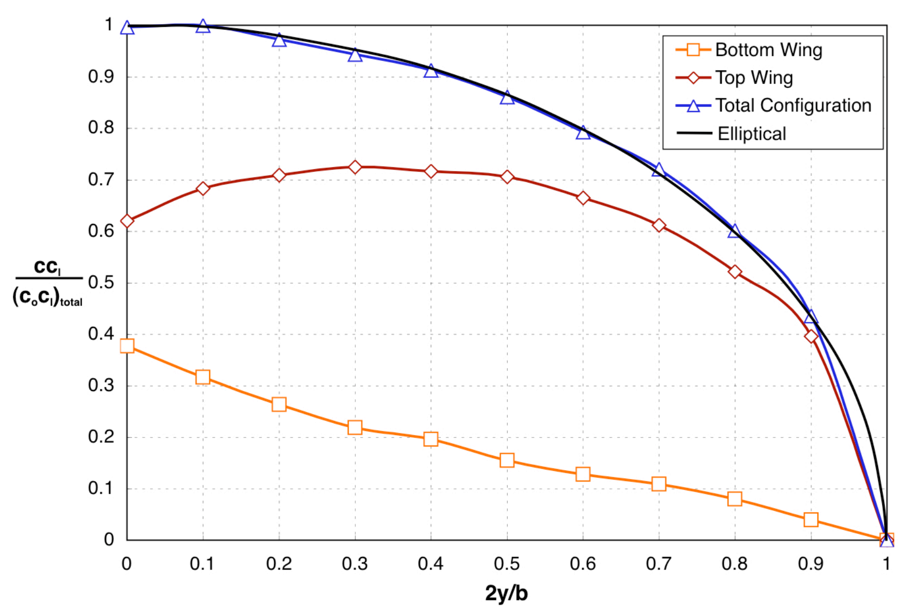

Figure 8. Cruise Lift Distribution (C_L = 0.4)

B. Airfoil Selection

During the design of the wing, the airfoil was selected to best complement the wing planform. Desirable characteristics were a high $c_{l,max}$, low drag for operational c_l's, and low pitching moment to keep trim drag to a minimum. All of these characteristics needed to be available at low Reynolds numbers (200,000 to 500,000) due to the Griffin's size and speed. After looking at the literature available, four airfoils were found that could meet the required operational requirements: the NACA 3709, the Eppler 387, the SD7043, and the PSU 94-097 airfoils.

These airfoils were analyzed using *XFOIL*[9] to compare their aerodynamic characteristics. *XFOIL* is a potential flow analysis code that utilizes an integral boundary layer model to calculate the lift and drag of a 2D airfoil. The PSU 94-097 is interesting because even though it was originally designed for use on sailplane winglets, its aerodynamic characteristics aligned with the design requirements. The results for a Reynolds number of 300,000 are plotted in Fig. 9.

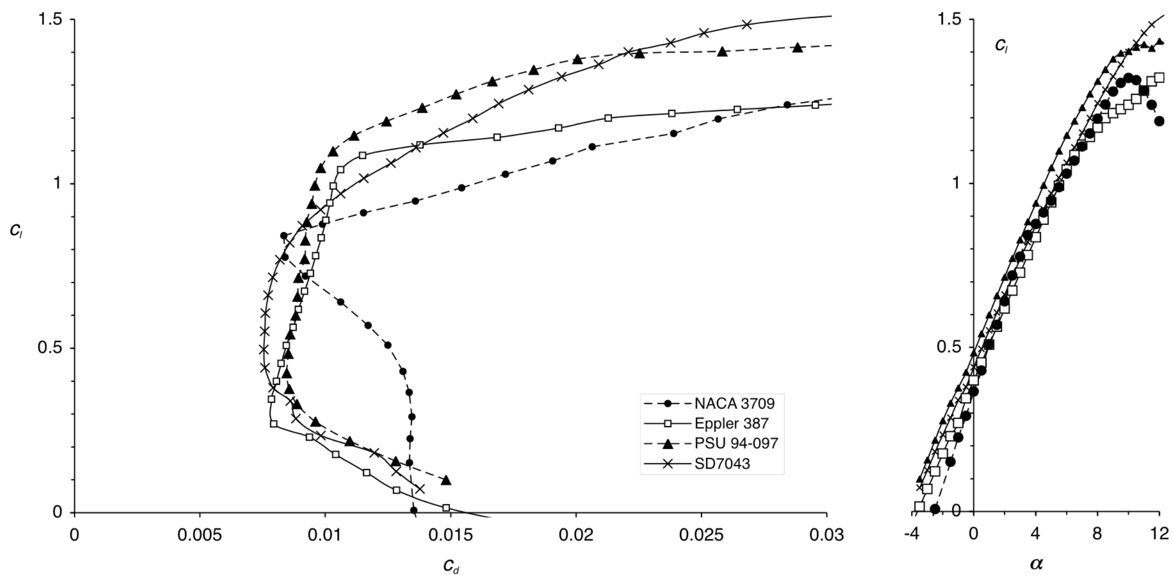

Figure 9. Drag Polars of Airfoils

It was clear from these results that the NACA 3709 airfoil's lack of a low drag range and low $c_{l,max}$ was not a good match for the Griffin's needs and was dropped from contention. The last three airfoils all had low drag regions in the desired c_l range for cruise; however, the Eppler E387 airfoil had a lower $c_{l,max}$ than desired and was also dropped. The last two airfoils, the SD7043 and PSU 94-097 airfoils, both had the $c_{l,max}$ desired and low drag regions in the desired c_l range. The deciding factor was the airfoils' performance change to Reynolds number, since the tips of the wings are at low speeds and high loads during certain maneuvers, such as turning flight. Since wind tunnel data was available for both airfoils, it was used to help determine these Reynolds number effects.

According to published data for the SD7043 airfoil (tested in the Princeton smoke tunnel), the airfoil responded relatively well to lower Reynolds number with respect to the drag.[11] However, it was seen in the data and noted by the designer, Dr. Michael Selig, laminar separation bubbles were present and, at Reynolds numbers of less than 300,000, the airfoil had a fairly abrupt stall. He also recommended the use of trip strips to "improve" the performance of the airfoil. The PSU 94-097 airfoil was tested in the Penn State Low Speed, Low Turbulence Wind Tunnel, and the airfoil's drag also responded well to lower Reynolds numbers.[12] Also, $c_{l,max}$ held at a constant value for varying Reynolds numbers as seen in Fig. 10.

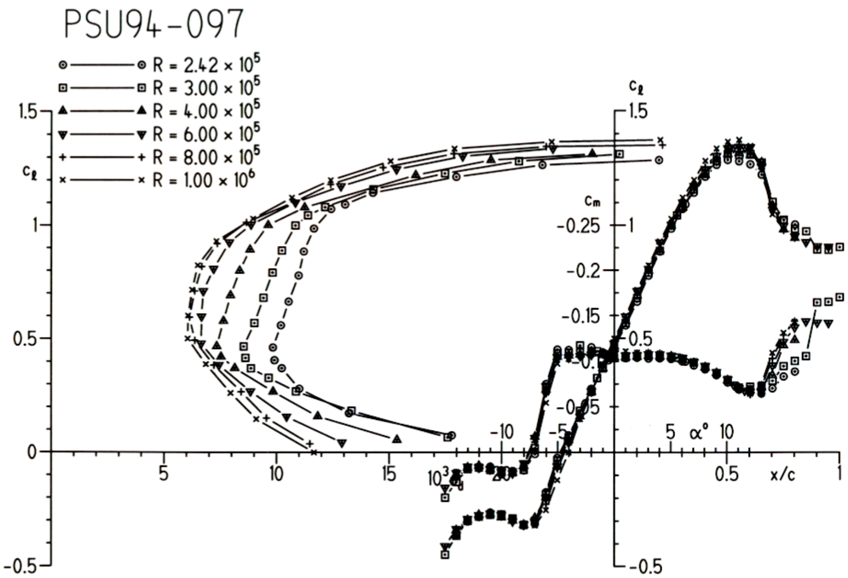

Figure 10. PSU Low Speed, Low Turbulence Wind Tunnel Results for PSU 94-097 airfoil[12]

The PSU 94-097 airfoil was designed to not require forced transition devices, and during testing, the use of tripping devices were explored; however, no benefits were found. With these data and real-life performance results on sailplane winglets, the PSU 94-097 airfoil was selected as the airfoil for the Nittany Griffin.

C. Final Design

After the PSU 94-097 was selected as the airfoil for the Nittany Griffin, the wing was tailored to meet the airfoil's performance. The need wing area was reduced 5 percent and the aircraft's tail was resized to provide the correct amount of stability and control. The final design of the Nittany Griffin's wing resulted in wing that has an equivalent monoplane span efficiency factor of 0.97, which is an improvement over conventional biplanes with span efficiencies ranging from 0.87 to 0.92.[5]

IV. Conclusion

While the biplane configuration has seen a reduced amount of use over the past 70 years, there are still a few design requirements that the configuration is well suited for. One such mission was that seen in the 2007 AIAA/Cessna/Raytheon Design/Build/Fly competition where a shorter wingspan yielded a lower rated aircraft cost and thus, a higher final score. The Penn State DBF team utilized the biplane configuration to minimize the wingspan while satisfying the needed wing area requirement for its aircraft, the Nittany Griffin.

A major goal of the design was to maximize the performance of the aircraft by minimizing the induced drag at cruise. To complete this goal, classical biplane analysis methods were investigated to understand aspects of the design effects the performance. The multiple lifting-line code, FREEWAKE 2007, was then used to design the planform of the wing, while the two-dimensional airfoil analysis code, XFOIL, was used to select the airfoil for the wing. During the design of the wing planform, it was found that the use of wash-in on the top wing minimized induced drag for the overall configuration. The wing was then tailored for the performance of the selected airfoil, the PSU 94-097 airfoil. The final product was a biplane wing that minimized induced drag and an aircraft that performed very well scoring very high in both flight missions.

Acknowledgments

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