THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF AEROSPACE ENGINEERING

PERFORMANCE GAINS OF A STANDARD-CLASS SAILPLANE USING A SLOTTED, NATURAL-LAMINAR-FLOW AIRFOIL

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SPRING 2018

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Aerospace Engineering
with honors in Aerospace Engineering

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ABSTRACT

Natural laminar flow techniques have long been sought after as a means of improving racing sailplane performance. Slotted, natural-laminar-flow airfoils have the potential to be the next great technological advance in sailplanes because of their mechanical simplicity and ability to reduce wing profile drag. Wing and horizontal stabilizer areas are resized for a standard-class glider in this study to take advantage of the increased $C_{l,max}$ seen with the S414 airfoil as compared to current airfoils, $C_{l,max} = 1.842$ *vs.* 1.183 at $R = 1 \times 10^6$, respectively, while maintaining similar climb rates in thermals. An SNLF airfoil-based sailplane outperforms a competitive standard-class glider at thermal strengths above 2.5 m/s and having an average thermal radius of 150m. These results motivate future work in designing an SNLF airfoil specifically optimized for sailplane lift coefficient ranges, with the potential to increase the performance gains outlined in this study.

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b = span
c = local chord length
c_μ = mean aerodynamic chord
C_d = sectional drag coefficient
C_{Dp} = parasite drag coefficient
C_D = drag coefficient
C_{Do} = zero-lift drag coefficient
C_l = sectional lift coefficient
C_{L_H} = horizontal tail lift coefficient
C_{L_W} = wing lift coefficient
C_p = sectional pressure coefficient
C_m = pitching moment coefficient
C_{mo} = zero-lift pitching moment coefficient of the wing
l_t = wing root leading edge to horizontal tail ¼ chord
L/D = lift to drag ratio
r = radius
R = Reynolds Number
S = wing planform area
S_t = horizontal tail planform area
V = airspeed
V_C = climb rate
V_{CC} = average cross-country speed
V_S = sink rate in glide
V_{SC} = sink rate of circling sailplane
V_T = thermal strength
W = weight
x_{AC} = aerodynamic center position
x_{CG} = center of gravity position

ACKNOWLEDGEMENTS

I first must acknowledge Dr. Maughmer who from day one of my undergraduate career has been an exceptional mentor and advisor to the PSU Zephyrus project and this thesis.

Along with Dr. Maughmer, I must thank all the faculty and staff in the Aerospace Department who have motivated and provided me with the foundation to succeed in this undergraduate program, and with who I look forward to continue working with in my graduate study.

I next must acknowledge my friends, including Veronica, Matt, Victoria, Parth, and Luke. Their dedication to engineering and to improving the lives of the people around them has inspired me to work harder each day.

My parents and siblings have always been there for me and continue to serve as role models as I start my own family. Thank you for going above the call of duty, I would not have been able to finish this research without your support.

Lastly, I am grateful for the support of my daughter, Emma, and husband, Chris. Emma, thank you for your newborn smiles and snuggle sessions that never fail to brighten my day. I love getting to watch you grow and learn so much already. Chris, your faith in me has always been the encouragement and motivation I needed to finish this degree and pursue opportunities for graduate school. I am so grateful that I have you by my side to work through late-night study sessions and long days of research.

Chapter 1

Introduction

The recent development of slotted, natural-laminar-flow (SNLF) airfoils and potential applications on rotorcraft, business jets, and commercial aircraft motivated this project of studying their potential usefulness on a competition sailplane. Optimization of the design of an SNLF airfoil-based sailplane must include considerations of total aircraft drag and existing data from soaring competitions. Soaring strategies to take advantage of the potential performance gains from integrating an SNLF airfoil on a sailplane during both thermal and interthermal flight must be taken into account. To perform well in all portions of competition, and have the best average cross-country speeds, parameters such as wing loading and drag coefficients are considered during both glide and climb. The sailplane designed in this study will be for competition in the Standard-Class group, which limits the span of a sailplane to 15m and prohibits use of flaps. The resulting cross-country flight performance of this SNLF-airfoil equipped sailplane is compared with flight performance data of the Discus-2b sailplane. Data from previous competitions influences the thermal models that are used to verify the design's dominance in expected competition conditions. These data are simplified by considering only two thermal sizes to compare each sailplane and evaluate the influence of the changes made to the airfoil and wing planform.

Chapter 2

Background

Drag Components

The wing profile drag, which is given by

$$D_p = \frac{1}{2}\rho V^2 S C_{dp} \tag{1}$$

accounts for a significant portion of the total drag on a sailplane, greater than any other contribution [1]. Profile drag has the largest effect on sailplane performance during interthermal flight, corresponding to flight at high speeds and low lift coefficients, greatly influencing the performance at high speeds, displayed in Figs. 1 and 2. Techniques to reduce this drag, and thus greatly improve a sailplane's flight in cruise, are commonly used today.

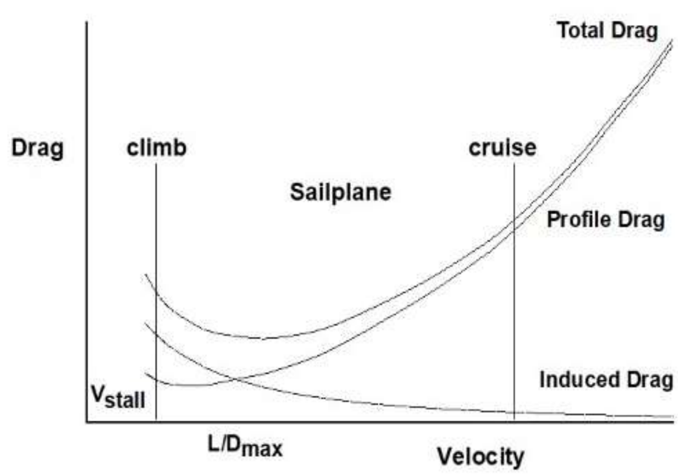

Figure 1: Trade-off between induced and profile drag [1]

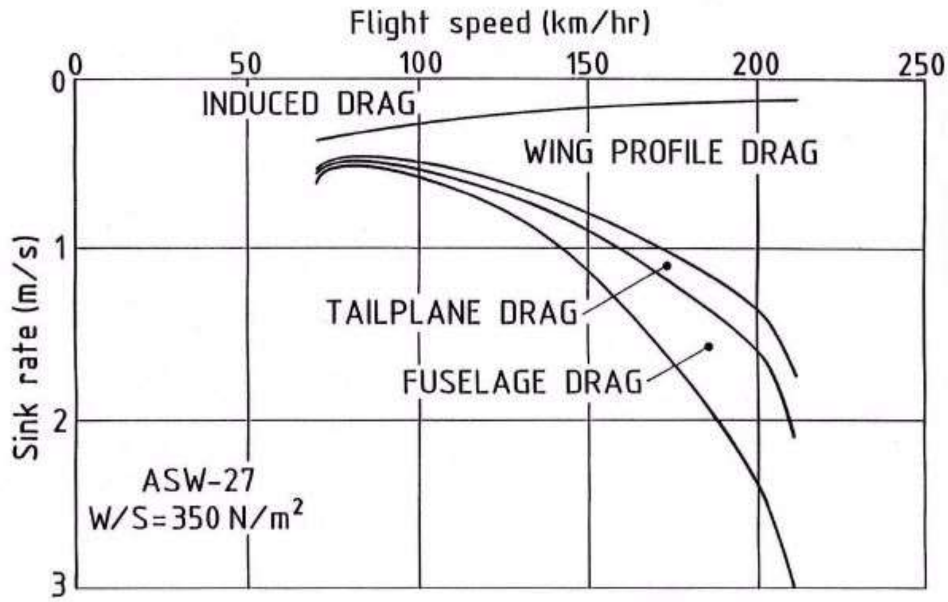

Figure 2: Drag components on a sailplane as portions of sink rate [1]

The reduction of induced drag, as expressed by

$$D_i = \frac{1}{2}\rho V^2 S\left(\frac{kC_L{}^2}{\pi eAR}\right) = \frac{2}{\pi\rho V^2 e}\left(\frac{W}{b}\right)^2 \qquad (2)$$

is a major consideration for sailplane design as well. A sailplane must be able to circle with a low sink rate in thermals that will change dramatically in size and strength depending on the weather. This turning flight occurs at low speeds and high lift coefficients where induced drag dominates. Induced drag is typically reduced by increasing the span, or in the span-limited case, by incorporating winglets.

Airfoil Selection, S414 SNLF Airfoil

Natural laminar airfoils, commonly used to maximize laminar flow, are limited to the extent they can maintain laminar flow along the chord of the airfoil by the need to recover the pressure to freestream at the trailing edge. The slotted, natural-laminar-flow airfoil is not held to the same limitations as single-element airfoils, and is able to maintain a favorable pressure gradient further along the chord of the airfoil as shown in Fig. 3.

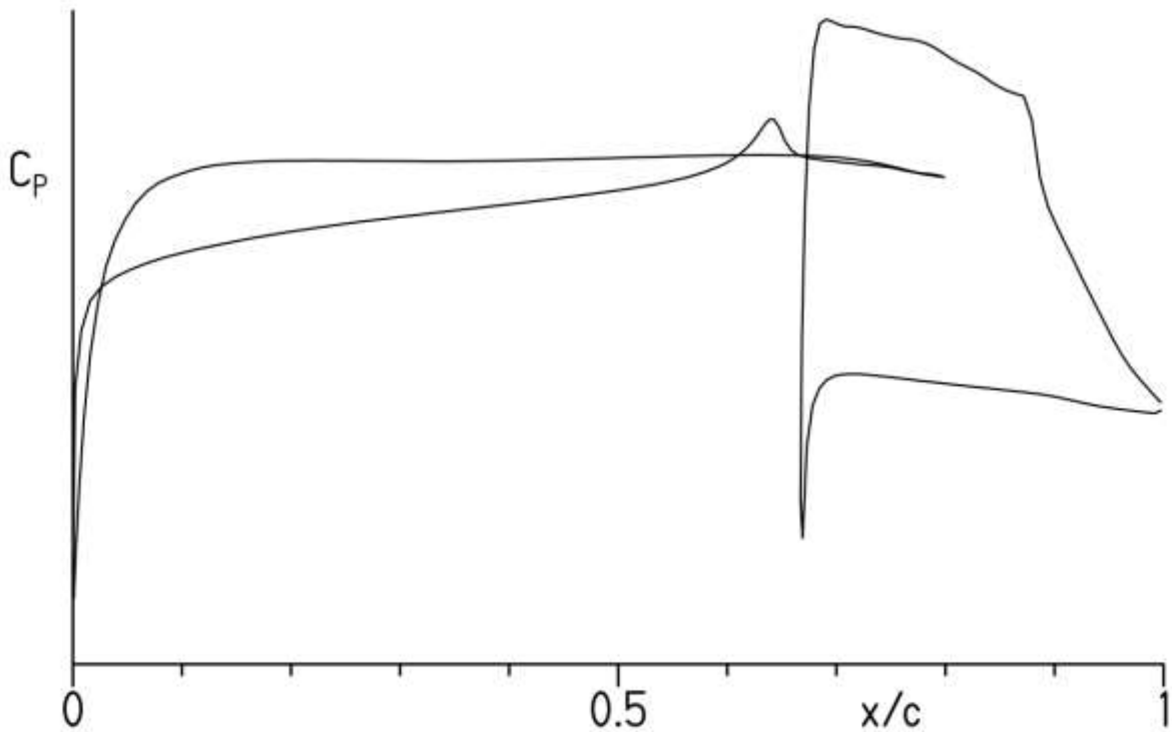

Figure 3: S414 pressure distribution near the middle of the low drag, low coefficient range [2]

This correlates to almost entirely laminar flow along the front element while remaining mechanically simple. The SNLF airfoil concept is a passive concept designed to maintain extensive laminar flow in cruise, achieve a high maximum lift coefficient, and be less susceptible to leading edge contamination than currently employed airfoils [3]. The SNLF airfoil provides a greater $C_{l,max}$ than a same thickness single-element airfoil, while simultaneously reducing the sectional profile drag without the added complexity that are a consequence of active laminar-flow techniques.

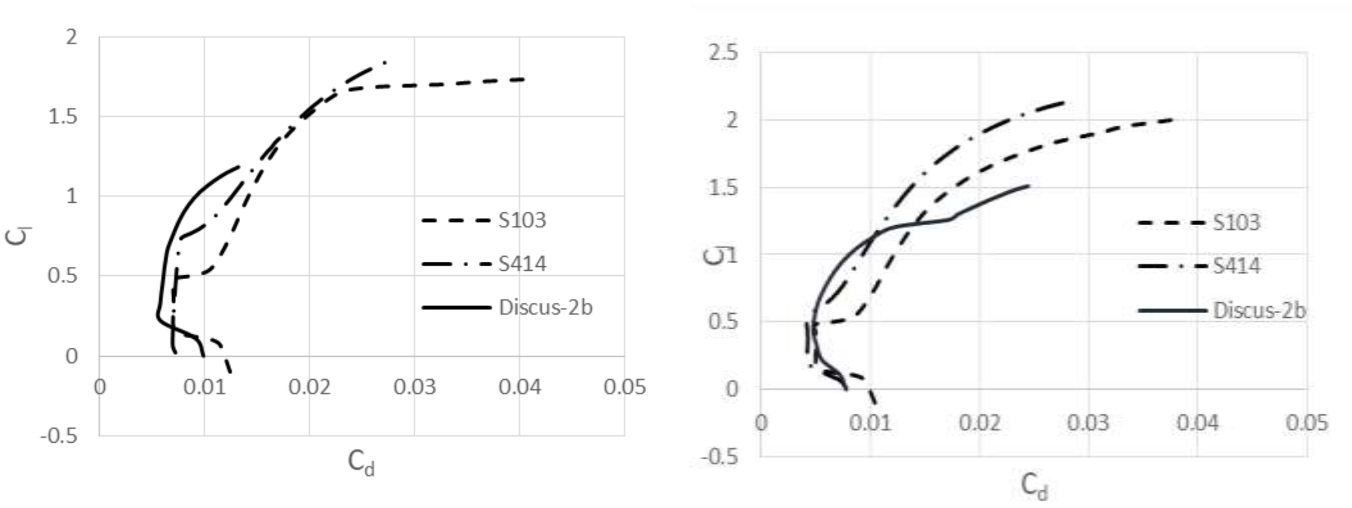

Figure 4: Drag polar; comparison of the Discus-2 Inboard, S103, and S414 Airfoils at R = 1x10^6 (left), R = 3x10^6 (right)

As can be observed in Fig. 4, both the S103 and S414 SNLF airfoils have larger $C_{l,max}$ values and comparable drag compared to the current inboard Discus-2b airfoil for lift coefficient ranges expected for interthermal flight (at R = 3x10^6, low C_l) and moderate thermal conditions (at R = 1x10^6, high C_l). The S414 airfoil maintains lower drag over a larger C_l range and a higher $C_{l,max}$ values compared to the S103, which suggests it as the more appropriate for use in this study of the application of SNLF airfoils to sailplanes. All sectional data for the S414, which is shown in Fig. 5, is taken from theoretical results from MSES, a well-verified, multi-element code and experimental results from the Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel [4]. It was optimized for rotorcraft applications, with a low drag range at lower lift coefficients than desired for a sailplane application [2]. Lower drag could likely be traded off with a lower $Cl_{,max}$, as the value obtained on the S414 is probably higher than necessary for this application. While the S414 is a good option, performance gains could be increased further if a design optimized for a typical sailplane cruise lift coefficient range was pursued.

Figure 5: S414 Slotted, Natural-Laminar-Flow Airfoil [2]

Thermal Model

Soaring is an international sport, testing the performance of both the thermal and interthermal flight performance of a sailplane and its pilot. A typical course challenges pilots to reach different waypoints while trying to achieve the fastest cross-country speed possible. Weather will have a great impact on the strength and size of thermals on a given competition day, and consequently on the speeds achieved by the competitors. For analysis purposes, designers must chose thermal characteristics to be used to calculate performance in climb. Turning flight performance of the sailplane is obtained by adjusting the straight-flight speed polar at optimal bank angles. Typical sink rates, various bank angles, turning radii, and airspeeds are presented in Fig. 6. This information is overlaid with that of the thermal characteristics to obtain the conditions of the glider's best climb rate in a given thermal, as summarized in Fig. 7.

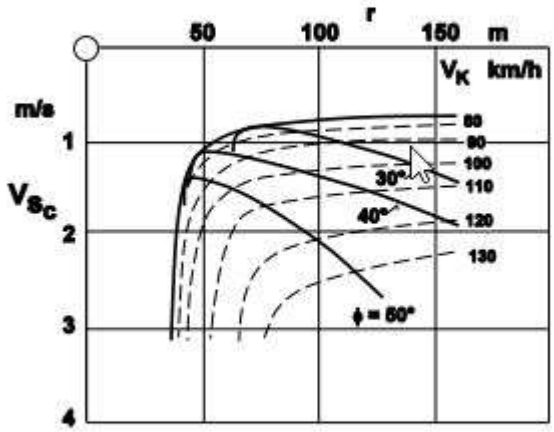

Figure 6: The sink rate as it depends on turning radius, bank angle, and airspeed [5]

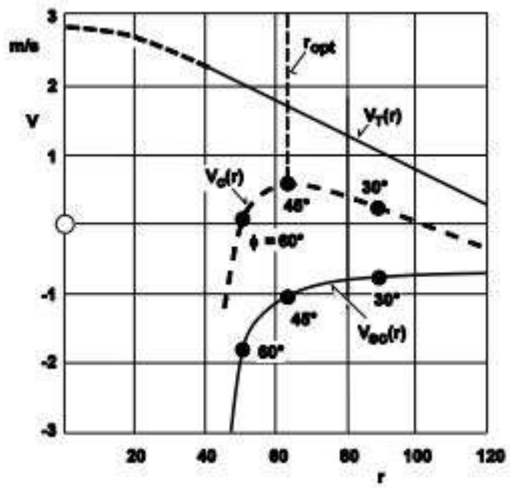

Figure 7: The glider rate of climb as it depends on turning radius for a typical glider [5]

Because detailed flight data has only become available recently with the advent of flight-data loggers, designers in the past largely analyzed competition performance using standard thermal profiles defined by thermal strength and size. These models still present useful information, including simple models of the distribution of thermal strength outwards from the core, such as what is displayed in Fig. 8.

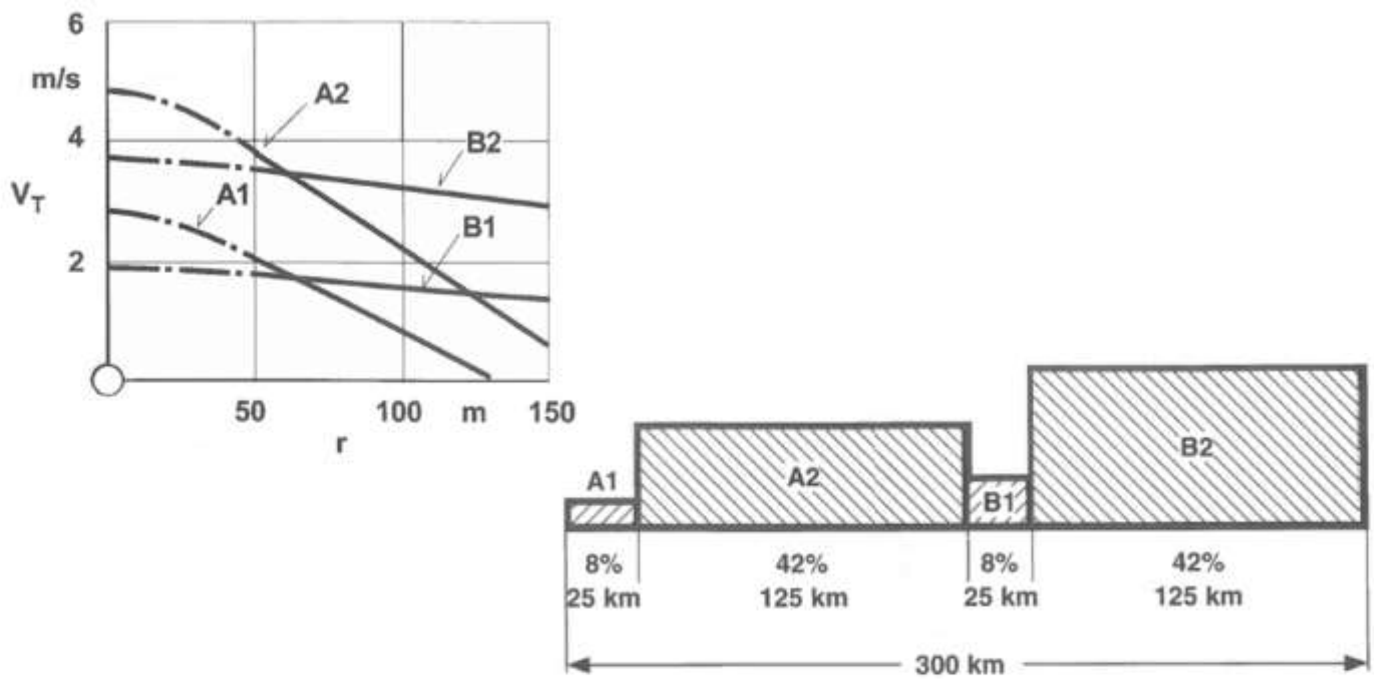

Figure 8: Horstmann thermal-mix profiles applied to a 300km flight [5]

Chapter 3

Design

PGEN and ACCS

Polar Generation Software (PGEN), an internally developed program, is used in this study to analyze the performance of the base and designed aircraft. This program uses tabulated airfoil data and aircraft geometry input by the user. The data includes *Cl*, *Cd*, and *Cm*, fuselage drag as an equivalent flat plate area, and the wing and tail planforms. Non-planar, multiple lifting-line methods are used to calculate the induced drag, and the profile drag is obtained from the tabulated airfoil data. Trim drag is calculated by determining the lift of the wing and the resulting lift force necessary on the tail. PGEN ultimately generates the straight and turning flight polars for any number of flight conditions. Sample input files can be found in Figs. 19 and 20.

ACCS takes the output of PGEN and a user selected thermal radius to calculate the average cross-country speeds at varying thermal strengths. The use of a single thermal profile still provides a meaningful comparison between aircraft and way to measure the impact of integrating the SNLF airfoil. The thermal profile is superimposed over the predicted turning polars to obtain an optimal climb rate, while the optimum inter-thermal cruise speeds are determined using speed-to-fly theory and the straight flight polar. These speeds are combined to obtain the average cross-country speed. Both of these programs have been well validated with flight-test data and provide enough accuracy for comparing the baseline and SNLF-incorporated aircraft flight performance [7].

Integrating the S414 Airfoil into the Discus-2b

The Discus-2b, shown in Fig. 9, is a highly competitive, Standard-Class sailplane (wingspan limited to 15m, no flaps), manufactured by Schempp-Hirth. This aircraft is an appropriate baseline to compare against an SNLF airfoil-based design.

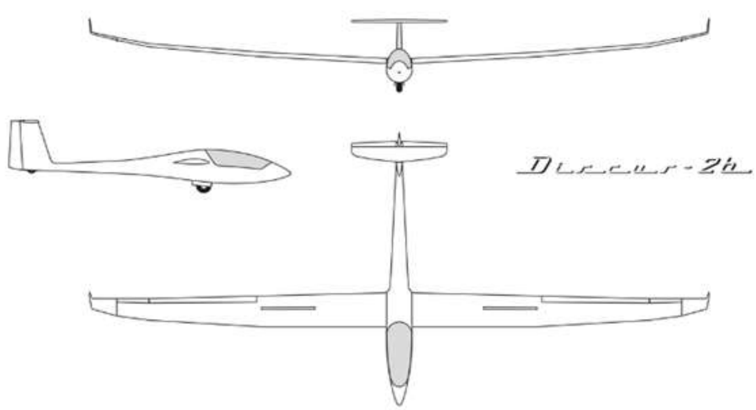

Figure 9: Discus-2b Standard-Class Sailplane by Schempp-Hirth [8]

The guidelines used for designing the SNLF glider presented below are:

1) b = 15m (Standard-Class requirement)

2) Aft element fixed (no flaps for standard-class requirement)

3) Same fuselage as the Discus-2b

4) Same empty weight and maximum ballast as Discus-2b

5) Similar climb rates as the Discus-2b

In soaring competitions, a successful strategy involves staying close to other competitors throughout the course to help find lift. This makes it difficult to take advantage of gains in climb performance, where a given thermal may have several competitors flying in it at the same time. Safety is a first priority and so, while it is important to climb efficiently, it is also important to obey certain “rules of the road” and this can be difficult with a significantly better rate of climb than other gliders in the thermal. Consequently, achieving a significantly better climbing ability is not necessarily of great advantage. Interthermal flight, especially the final glide, is where a pilot will be able to benefit from gains in high speed performance. The requirement to cruise at speeds much greater than that of the L/D_{max} forces a sailplane to have a reasonably flat speed polar. Smaller sink rates at high cruise speeds allow a pilot to complete glides with fewer stops to find and climb in thermals, which will win competitions if their competitors need to climb in the last glide portion to finish the course.

Wing and Horizontal Stabilizer Re-Sizing

For this research, the current inboard and outboard airfoils of the Discus-2b wing are both replaced by the S414. The winglet for the Discus-2b is maintained but would be worth redesigning in the future. The S414's larger $C_{l,max}$ allows the wing loading and *AR* to be increased without sacrificing performance in climb or increasing stall speeds. As previously discussed, it is more beneficial to sacrifice performance in climb for better performance in glide. To achieve a similar climb rate to the Discus-2b with the incorporation of the S414 airfoil, the wing area was reduced by 15% while maintaining the same taper ratio. The main benefit in the decrease of wing area is the decreased wing profile drag it contributes to, calculated by

$$D_p = \frac{1}{2}\rho V^2 (2 * \sum_{i=1}^{N} \Delta b(i) c(i) c_d(i)) \tag{3}$$

in PGEN.

Several lift forces contribute to longitudinal stability, displayed in Fig. 11. To maintain longitudinal stability with the changes to the airfoil and wing area, the horizontal tail must also be resized. Tail area must be large enough for trimming the aircraft in steady, level flight ($C_{M_{CG}}$ = 0) and for maneuvering with changes in pitch. The horizontal tail size can be obtained using the expression,

$$C_{M_{CG}} = C_{M_0} + C_{L_W} \frac{x_{CG} - x_{AC}}{c_\mu} - \frac{l_t S_t}{c_\mu S} C_{L_H} \tag{4}$$

which provides a starting point for resizing the horizontal tail based on the increases in the nose-down pitching-moment coefficient, shown in Fig. 10, and wing lift coefficient, as well as the reduction in wing area and mean aerodynamic chord [5]. C_{LH} and l_t are maintained for the SNLF aircraft because the horizontal tail airfoil and fuselage are kept the same as the Discus-2b, respectively. The changes to aircraft parameters based on the results of these resizing efforts are listed in Table 1. It is assumed for this study that the changes to wing and horizontal tail areas do not affect the overall weight of the aircraft.

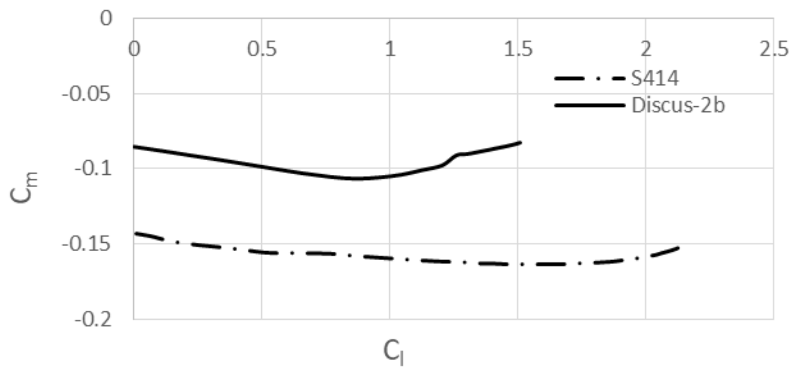

Figure 10: Pitching Moment Coefficient Comparison between the inboard Discus and S414 Airfoil

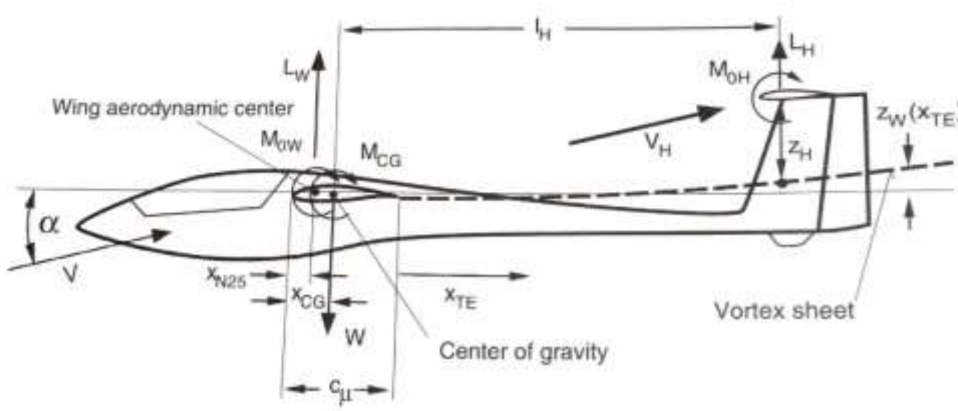

Figure 11: Force and moment definitions for longitudinal stability analysis [5]

Summary of Technical Data

Table 1 Aircraft Parameters of the Discus-2b and the SNLF Aircraft

	Discus-2b	SNLF Aircraft
Span (m)	15	15
S (m^2)	10.12	8.602
c_μ (m)	0.68	0.57
AR	22.2	26.2
l_t (m)	4.204	4.204
S_t (m^2)	0.99	1.20
W/S (kg/m^2)	30.7-51.7	36.0-59.3

Chapter 4

Cross-Country Performance

The average cross-country speed of a sailplane is a function of both the climb rate achieved in thermals and the glide speed, shown in Fig.12.

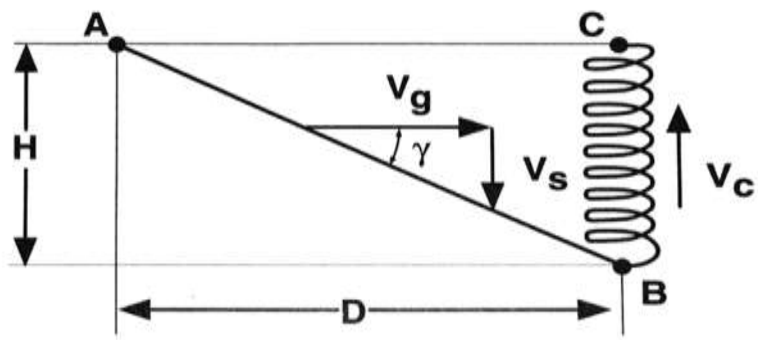

Figure 12: Idealized segment of cross-country flight [5]

For determining the climb rate, V_c in Fig. 12,

$$V_C = V_T - V_{S_C} \tag{5}$$

where V_T is the thermal strength and V_{SC} is the turning sink rate. The thermal model used in this analysis has a distribution of lift that varies parabolically with thermal radius. Each thermal is defined by the strength of lift at the core and its radius, a user input in the programs discussed above. The thermal profile is clearly an important feature in determining the cross-country performance of a sailplane and is typically a combination of several thermal strengths and profiles. A single, representative thermal profile is instead used in this study to simplify the results and still provide a meaningful comparison between the two sailplanes. The average cross-country speed is given by the expression,

$$V_{cc} = \frac{V_c}{V_c - V_s} V_g \tag{6}$$

ACCS superimposes the thermal profile over the predicted turning polars to obtain the optimal climb rate for a particular configuration. The straight flight polar is used to find the inter-thermal cruise speed needed to optimize the MacCready speed-to-fly.

Speed Polar

A different polar exists for the same sailplane at each gross weight. L/D_{max} remains the same for each weight condition, but the condition with the larger wing loading achieves this at a higher speed. On good weather days (strong thermal strengths), a pilot will use this to their advantage by carrying water ballast to take advantage of the better glide ratio at higher speeds without sacrificing more performance in climb than is gained in glide.

The SNLF aircraft has a slightly greater speed at L/D_{max} compared to the original Discus-2b, better observed in Fig. 14. Pilots often fly at speeds greater than this speed during glide portions of a competition, and so it is more important that the speed polar is flat (increase V_s) past L/D_{max}. Both Fig. 13 and 14 show how the SNLF aircraft, light and ballasted, is more forgiving to pilots flying at higher cruise speeds. This is especially beneficial in the final glide of a competition where a pilot will need to fly at high speeds without sinking below minimum height requirements at the finish line.

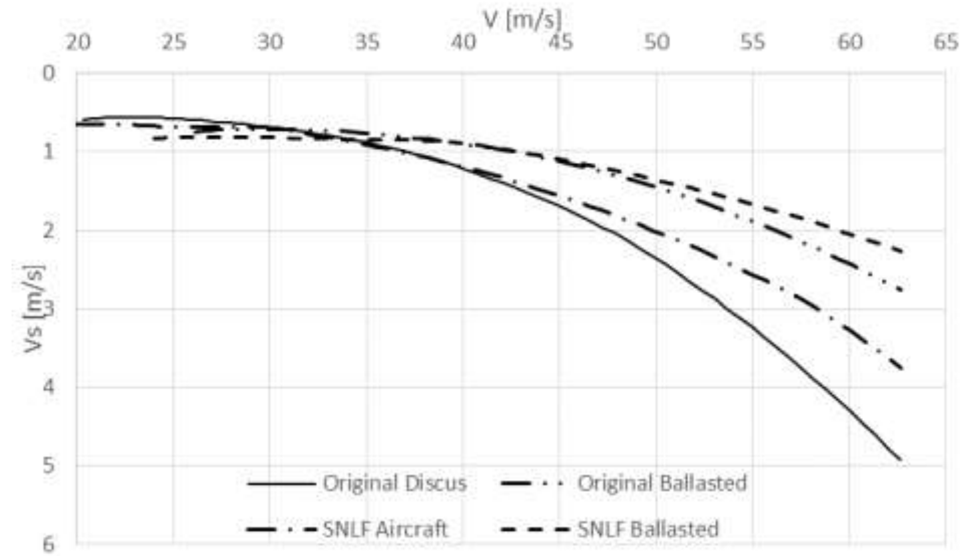

Figure 13: Speed Polar Comparison between the Original Discus-2b and SNLF Aircraft

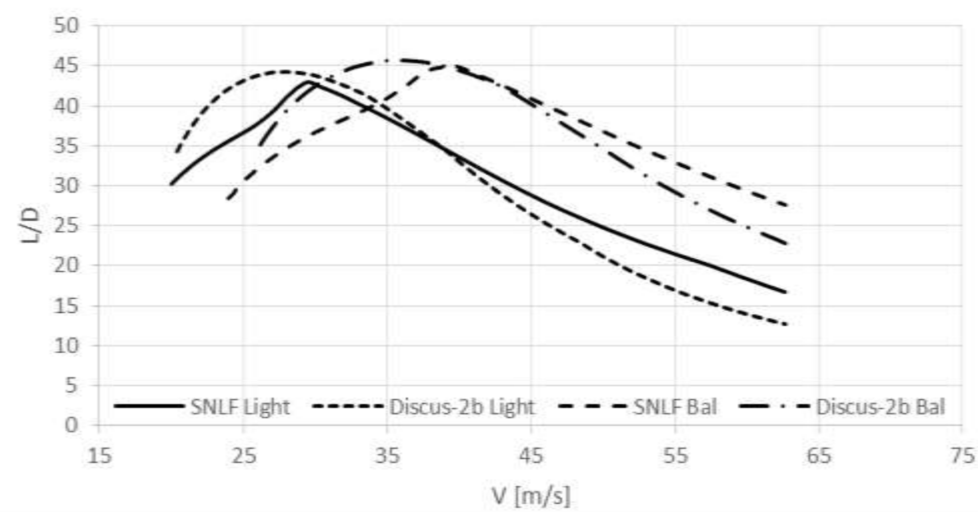

Figure 14: Comparison of predicted lift-to-drag ratios between the Original Discus-2b and SNLF Aircraft

Cross-Country Speeds

The average speed of a glider in competition flight is a function of the speed in climb and speed in glide between thermals. The rate of climb is a function of the thermal strength and the sink rate of the sailplane circling, as described in eqn. 5. This result depends on the thermal radius, thermal strength, sailplane mass, circling speed, and bank angle. ACCS takes a thermal radius as user input and data from the PGEN output file including the optimum bank angle and turn radius to calculate the sink rate of a sailplane at varying thermal strengths. Cross-country speeds are then calculated based on the glide, sink, and climb rates in a given segment of flight. Cross-country results for a thermal radius of 100m and 150m are presented, chosen based on data taken from previous competitions that shows these as being a typical width of thermal. Here, the actual thermal strength experienced by a pilot would be much smaller than the core thermal strengths used to compare cross country speeds, due to the decrease in thermal strength outwards from the core and the glider's sink in climb.

At a thermal radius of 100m, only the unballasted SNLF aircraft outperforms the baseline aircraft at a core thermal strength above 3 m/s, as shown in Figs. 15 and 16. At a radius of 150m, the SNLF-light aircraft outperforms its competitor at core thermal strengths above 2.5 m/s, and the SNLF aircraft wants to carry ballast at lower thermal strengths than the Discus-2b would, as shown in Figs. 17 and 18. These results are promising for good-weather days, but future work should be done to improve this aircraft in weak weather days.

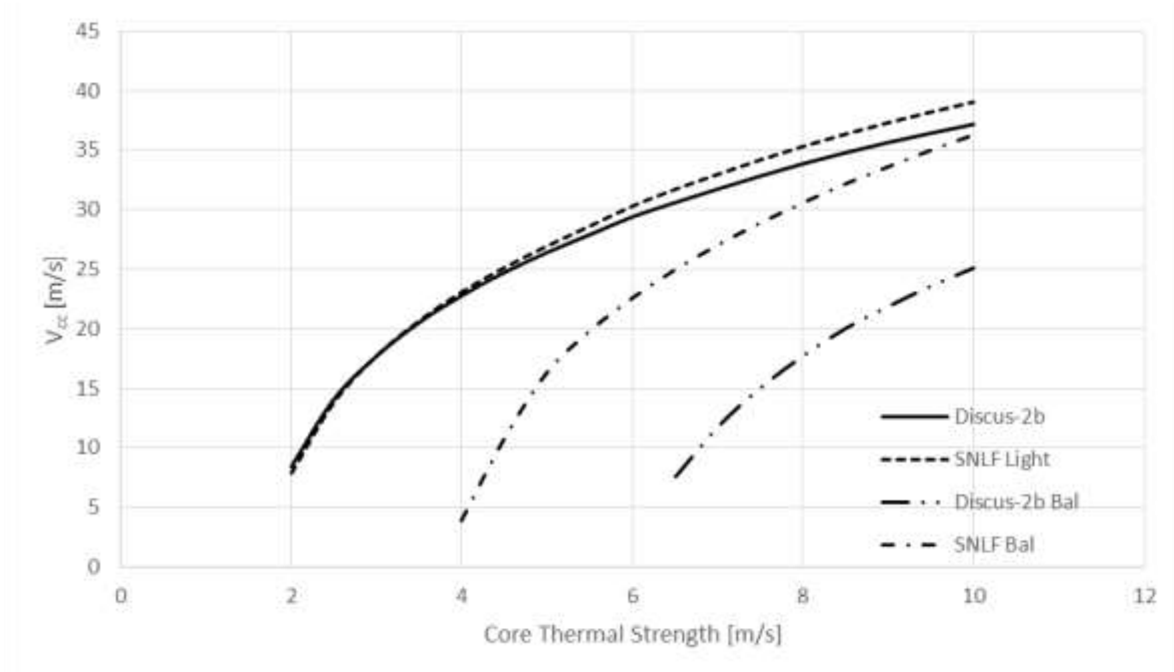

Figure 15: Average V_{cc} for varying Thermal Strengths, Thermal Radius = 100m

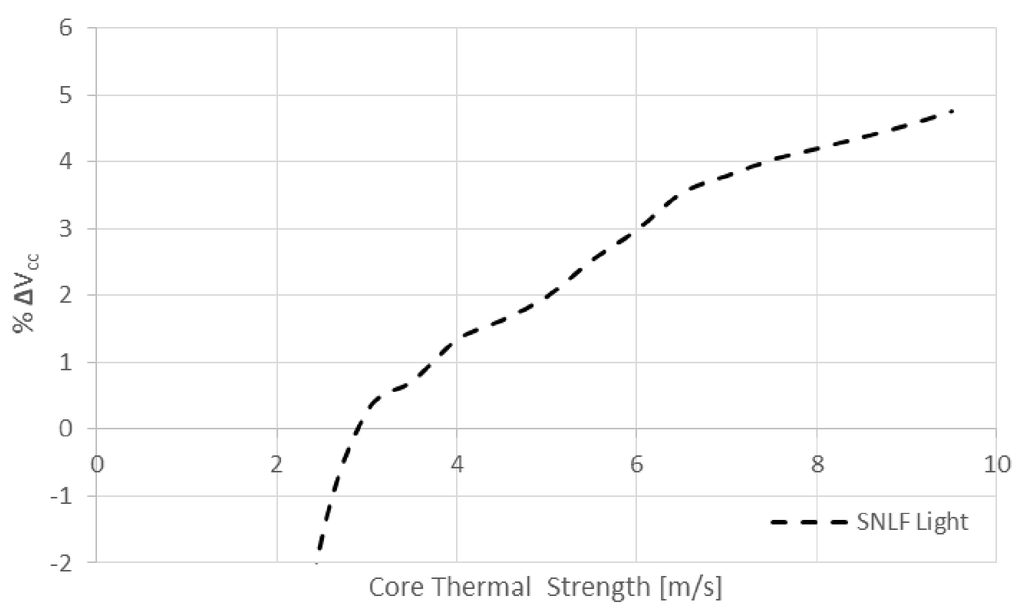

Figure 16: %ΔV_{cc} Compared to the Discus-2b light, Thermal Radius = 100m

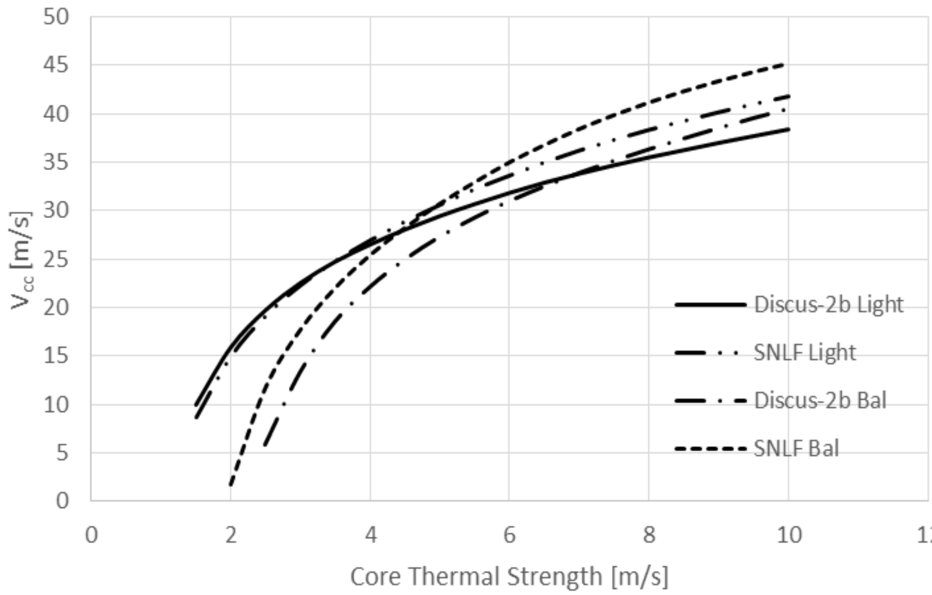

Figure 17: Average V_{cc} for varying Thermal Strengths, Thermal Radius = 150m

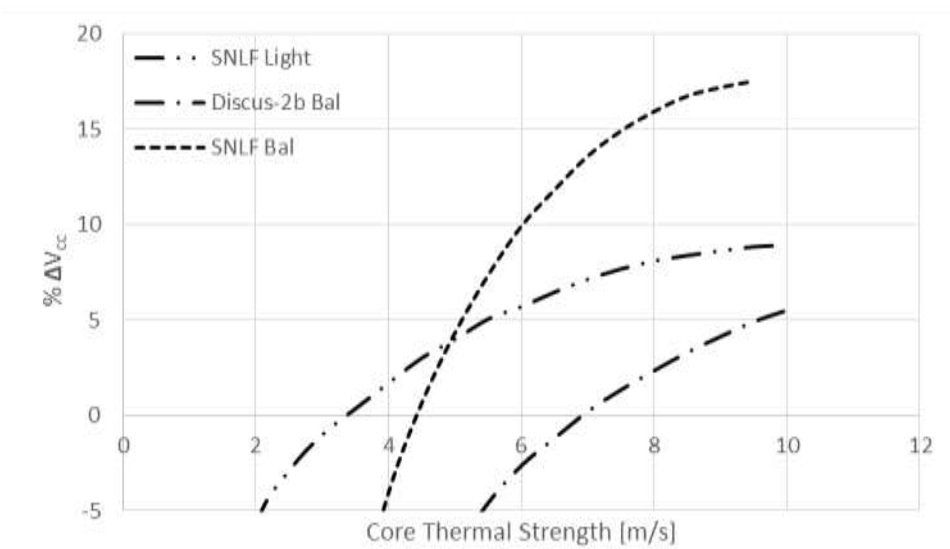

Figure 18: %ΔV_{cc} Compared to the Discus-2b light, Thermal Radius = 150m

Chapter 5

Conclusion

Although the performance gains seen from incorporating the S414 Airfoil are limited to moderate thermal strengths or greater, the magnitude of these gains suggest this as a worthwhile future area of research and test. Wing profile drag is a significantly large portion of overall drag, especially in interthermal flight and makes the SNLF airfoil a good candidate for improving sailplane performance. Desirable performance in moderate and good weather is achievable by incorporating an existing SNLF airfoil on a currently competitive aircraft, with increases in cross-country speeds around 3.0% at an average thermal strength of 4.5 m/s. An important area of improvement is the aircraft's larger lift-to-drag ratios at high speeds where a pilot will want to fly during glide, especially during the final glide.

Computational fluid dynamics (CFD), using newly developed transition modeling necessary for analyzing sailplane flight, could be used to further predict and validate this aircraft's performance. Additional work should include analyzing the winglet's performance and designing a new one specifically for the new wing planform presented in this study. Further study should include designing an airfoil optimized for glider flight and completing a similar comparison study as the one presented here, as well as developing SNLF airfoils with movable aft elements or a simple flap for gliders competing in soaring classes that allow flaps. If this concept went into ground or flight test, a new wing and horizontal stabilizer could be incorporated on the current Discus fuselage without too many other modifications.

APPENDIX

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Figure 19: Sample PGEN wing geometry input file

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File Edit Format View Help
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2 2
1 2
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0.0
------------------------------------------------------------------------------------------
----Wing Span, Xcg(pos. aft from root leading edge(m)), GVM (kg)------------------------
15.0  0.35  310.0
--------------------------------------------------------------------------------
----Lt (wing root L.E. to 1/4 Ht),  Ht root chord, Ht tip chord, Ht span (m)----
 4.204  0.571  0.351  2.60
--------------------------------------------------------------------------------
----Vt root chord, Vt tip chord, Vt height------------------------------------
1.037  0.6582  1.097
----------------------------------------------------------------------------------
-----Fuselage Base FPA (m**2), Fuselage CM/CL, Fuse Cmo----------------------------------
0.0190  0.03  -0.007
-------------------------------------------------------------------------------
```

Figure 20: Sample PGEN aircraft geometry input file

REFERENCES

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[9] Maughmer, M.D., "The Design of Winglets for High-Performance Sailplanes," *Journal of Aircraft*, Vol. 40, No. 6, Nov.-Dec. 2003, pp. 1099-1106.

ACADEMIC VITA

RACHEL M. AXTEN

EDUCATION

The Pennsylvania State University, *Schreyer Honors College* **University Park, PA**
Bachelor of Science in Aerospace Engineering *Graduation: May 2018*

TECHNICAL EXPERIENCE

Undergraduate Thesis **University Park, PA**
Performance Gains of a Sailplane Using a Slotted, Natural-Laminar-Airfoil *Aug 2017-present*
- Compared performance of a sailplane using a slotted, natural-laminar-airfoil against an existing, competitive sailplane
- Provided computational data to suggest further research towards proving the usefulness of natural laminar flow technology

The Boeing Company, Engineering Accelerated Hiring Initiative **Huntington Beach, CA**
Guidance, Navigation, and Controls Engineer SmallSat Pathfinder/502 Satellite *May 2017-Aug 2017*
- Completed verification of momentum management and orbit determination flight software algorithms
- Created disturbance torque models and GPS sensor abstraction software in support of verification work
- Communicated requirement compliance during an internal critical design review

Flight Test Operations P-8A Poseidon, **Patuxent River Naval Air Station, MD** *May 2016-Aug 2016*
- Worked predictions, completed risk analysis, and monitored real-time data for flying qualities and loads test points
- Trained in a fast-paced environment on flying qualities, data ops, loads, test conductor, and test pilot teams
- Wrote test cards and read documents on lessons learned in preparation for daily testing with test conductors
- Communicated procedures/risks during briefs, simulator test point practice, and test plan meetings

Human Powered Aircraft (HPA) Design and Fabrication **University Park, PA**
Teaching Intern *Aug 2016-May 2017*
- Managed team of ~35 undergraduate students towards assembly and testing of the PSU Zephyrus, a 74ft wingspan HPA

Wing Group Lead *Jan 2016-May 2016*
- Led lay-up of the carbon fiber spar and rib design/construction for 9 wing sections to prepare for flight testing Fall 2017

Pod/Keel Chief Engineer *Aug 2015-May 2016*
- Led redesign/3-D modeling of keel and fiberglass pod to surround the pilot and drive train system for a final aircraft design

Drive Train Group Member *Aug 2014-May 2015*
- Designed and manufactured drive train with gear ratio necessary to power the HPA at speeds around 30 mph
- Completed on-ground testing of full-sized propellers, gathering data on rpm/ground speeds achieved by the current design

AIAA Design, Build, Fly **University Park, PA**
Penn State Chapter Member *Aug 2014-May 2015*
- Competed on seven-member team, carrying out all design and testing on five iterations of a radio-controlled aircraft
- Completed airfoil analysis using XFOIL and constructed built-up balsa wood wings, depron foam/carbon roving horizontal and vertical stabilizers, ball drop mechanism, servo set-up, soldering, and electronic configurations

LEADERSHIP EXPERIENCE

Physics Instructor **State College, PA**
Grace Prep High School *Jan 2018-present*
- Designed and presented curriculum, assignments, labs and exams for a seven-person, algebra based physics course
- Prepared students for the AP Physics 1 exam with practice exams and extra in-class labs and demonstrations

Engineering Ambassadors (EA) **University Park, PA**
EA Student Leader, Recruitment Committee *May 2016-present*
- Motivated middle, high school, and college students to pursue a career in engineering using outreach activities and tours
- Created application and selected 80 students for interviews from 120 applications received for the 2018 recruitment cycle

American Institute of Aeronautics and Astronautics (AIAA) Student Chapter **University Park, PA**
Secretary *May 2016-May 2017*
- Coordinated and executed technical speaker series, student conference events, and aviation trips for the Penn State chapter

SKILLS/HONORS

- Student Pilot: completed 4 hours of flight training towards glider rating and 20 hours towards private pilot rating
- Undergraduate Student Member on the Aerospace Department Head Search Committee 2016-2017
- Intermediate skill in MATLAB/Simulink, SOLIDWORKS, Windows OS, Microsoft Office; novice skill in C++, XFOIL
- Member of national aerospace honors society, Sigma Gamma Tau (2017)
- Chappel Scholarship (2017), The Boeing Company Scholarship (2016), and Aero Pioneers Class of 1944 Scholarship Recipient (2015) – Merit awards sponsored by the Penn State Aerospace Department
- NASA Space Grant Undergraduate Scholarship (2017), Naval Helicopter Association Scholarship (2015)