A NEW METHOD OF DETERMINING ROUGHNESS HEIGHT FOR LOW-REYNOLDS-NUMBER FLOWS

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ABSTRACT

Prior investigations of forced transition on airfoils by Braslow and Knox have shown that fully developed turbulent flow can be achieved over an aerodynamic surface without significant increases in drag beyond that of the turbulent flow over the surface of the airfoil. It was thought that the roughness height needed to accomplish this, the critical roughness height, could not force transition at low Reynolds numbers. Experimental data measured at the Pennsylvania State University Low-Speed, Low-Turbulence (LSLT) Wind Tunnel proved that forced transition could occur with greater-than-critical roughness heights and without significantly increasing drag at low Reynolds numbers. Examples of this can be found in drag polar plots for the S407 and E387 airfoils with fixed transition. Analysis of this data was completed to understand the behavior and compare it to the established Braslow and Knox method. This report also offers method of determining the roughness height needed to fix transition for low Reynolds numbers based upon experimental results by relating the ratio of roughness height over roughness station to the Reynolds number at the roughness station.
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The author would also like to extend great gratitude to his family for their support in completing this thesis.
Chapter 1

Introduction

Fixed transition over airfoil surfaces is desirable under many circumstances: the ability to transition a flow before the start of pressure recovery can prevent separation, the developed turbulent flow can reduce the drag caused by laminar separation bubbles, and fixed transition can determine the effects of leading edge contamination on an airfoil’s performance.

As defined in research by Braslow and Knox [1], the critical roughness height is the height of a tripping device that will force transition at the location of the tripping device, but not increase the drag due to the trip itself. A method for determining critical roughness height is described in Ref. [1]; however, below a certain station Reynolds number, the critical roughness height is not able to force transition. Transition is able to occur, but not without the roughness contributing to the overall drag. As found in research completed at The Pennsylvania State University, detailed in Refs. [2-4], it is possible to force transition over laminar-flow airfoils without significantly affecting the drag or the maximum lift coefficient as was desired.

Experiments were run in the Low-Speed, Low-Turbulence (LSLT) Wind Tunnel at Penn State in the pursuit of finding smallest roughness height needed to force transition at desired chord locations on low-Reynolds number airfoils, 5% for the upper surface and 10% for the lower surface (from the leading edge). The height of the tape is increased until transition occurred at or closely behind the location of the tape. The results from this experimentation define the minimum roughness height needed to achieve fully developed turbulent flow. Although roughness of this height should contribute to drag, drag measurements in Refs. [2, 3] suggest
otherwise. Once these results were reduced to non-dimensional form, they provided a trend that could be used predict the roughness height needed to force transition for a given chord location and station Reynolds number. Additionally, the non-dimensional data exhibited close similarity to that of Braslow and Knox method [1] results at higher Reynolds numbers.

**Nomenclature**

- $k$: height of roughness (tape)
- $Re_k$: Reynolds number based upon the height of roughness and flow conditions at the top of the roughness, $u_k k/\nu$
- $Re_x$: station Reynolds number based upon the chord location from the leading edge to the roughness station, edge velocity, and boundary layer kinematic viscosity, $U_e k/\nu$
- $U_e$: local streamwise component of the flow velocity just outside the boundary layer (edge velocity)
- $U_\infty$: free stream air velocity
- $u$: local streamwise component of the flow velocity inside the boundary layer
- $x$: chord distance (station location) measured from leading edge to roughness
- $\eta_k$: non-dimensional height in the boundary layer based on roughness height, $k \sqrt{Re_x / 2x}$
- $\delta$: boundary layer height
- $\nu$: kinematic viscosity
- $C_p$: coefficient of pressure

**Subscripts**

- $k$: conditions at the top of the roughness (tape)
- $x$: conditions at a given chord location
Chapter 2

Testing Setup and Data Collection

The Wind Tunnel

The experiments for this thesis were conducted in Penn State’s LSLT Wind Tunnel. The LSLT Wind Tunnel can produce reliable experimental results due to its effective turbulent management devices and experimental agreement with other wind tunnels such as the NASA Langley Low-Turbulence Pressure Tunnel and that at Delft University of Technology [5].

The LSLT Wind Tunnel has a 75’-by-25’ footprint and exhibits a test chamber cross-section of 58” width and 40” height. Additionally, the LSLT Wind Tunnel has a documented turbulence intensity of 0.045% at a 150 ft/s internal airspeed. Further details and an illustration of the tunnel can be found in Ref. [5].

Model Setup

Two-dimensional models are mounted vertically in the LSLT Wind Tunnel. Two turntables, attached to the top and bottom of the model, are flush with the floor and ceiling of the test section and rotate with the airfoil model. For the data presented in this thesis, an E387 model of 6 in. chord length and a S407 model of 6.3 in. chord length were used. Chord length markings on the airfoil’s surface account for the curvature of the airfoil. That is, the chord length markings on the airfoil’s surfaces do not reference distance on those surfaces, but rather the internal chord distance between the leading and trailing edges. The airfoil models have orifices over their upper and lower surfaces that are connected to precision transducers. These transducers provide the
data needed to generate pressure distributions for the airfoils at varying Reynolds numbers and angles of attack. The data produced by these transducers and other transducers located at different locations in the wind tunnel were collected and recorded by and electronic data-acquisition system (see Ref. [3]). A Pitot-static tube is connected to a traversing rig located above the wind tunnel’s test section. This device provides a wake survey of the airflow aft of the model for the purposes of computing profile-drag coefficients. Complete details on the model setup, instrumentation, and wake survey probe can be found in Refs. [2, 3].

**Corrections and Accuracy Considerations**

Data corrections were made to account for boundary-layer effects of the wall on the model. These wall corrections are outlined by Allen and Vincenti in Ref. [6]. The uncertainty analysis methods applied to the experiment are outlined by Kline and McClintock in Ref. [7]. Due the low-speed nature of the flow, compressibility and heating effects were ignored.

The accuracy of experimental results observed in the LSLT Wind Tunnel is very high [5]. Therefore, results discussed in this thesis, even at lower Reynolds numbers, are accepted to be accurate. Inconsistencies observed in experimental results may attributable to human error. Additionally, experimentally determined values of Reₖ needed to be considered in a realistic manner; experimentation by Braslow, Hicks, and Harris [8] demonstrated that a doubling of Reₖ (a dimensionless value) led to no significant change in drag.
Chapter 3

Testing

As this work only considers aerodynamic transition, all other results of the experimentation, along with specifics of the unrelated testing, in Refs. [2, 3] will not be presented or discussed.

Fixed Transition

For full details of the fixed transition testing procedure, see Ref. [2, 3]. To decrease the frequency of tape replacement, the airfoils are tested for a range of Reynolds numbers before the application of more tape layers (or thicker tape). Before the tapes (or tape assemblies) were applied to the model, one side of the tape was cut to a serrated edge using a pair of pinking shears. This serrated edge would be placed towards the leading edge when installed on the airfoil surfaces. This method allowed serrated tapes of varying thickness to be created. For both the E387 and S407 upper surfaces, tape was applied at 5% chord. The lower surface of the S407 airfoil was tested with tape applied at 10% chord. Earlier testing of the E387 airfoil with the lower surface tape positioned at 5% chord (see Ref. [2]) indicated that the boundary layer could “skip” over the tape with increasing angle of attack, preventing transition. This is attributed to the shifting of the stagnation point from near the leading edge on the lower surface towards the trailing edge at higher angles of attack.

The data presented for the E387 airfoil was evaluated at 0° angle of attack, whilst the data presented for S407 airfoil was evaluated at 4° angle of attack. This data, along with the Reynolds number ranges evaluated for the E387 and S407, are tabulated in Table 1.
Table 1: Testing Reynolds Numbers and Angles of Attack

<table>
<thead>
<tr>
<th>Airfoil</th>
<th>Reynolds Number Range</th>
<th>Angle of Attack</th>
</tr>
</thead>
<tbody>
<tr>
<td>E387</td>
<td>[60,000, 100,000, 200,000, 300,000, 460,000]</td>
<td>0°</td>
</tr>
<tr>
<td>S407</td>
<td>[70,000, 100,000, 150,000, 200,000, 300,000, 600,000]</td>
<td>4°</td>
</tr>
</tbody>
</table>

Once flow equilibrium is reached for a specific Reynolds number, a stethoscope is traversed along the surface of the airfoil, searching for the point of transition using the audible rumbling of the turbulent flow as a guide. Once the point of transition is identified, the chord location of said point is recorded. This process continues for the Reynolds number range and for all pre-determined tape thicknesses. The roughness (or tape) height is determined as the minimum height at which fully developed turbulent flow occurs. The tape thicknesses which achieved this for various Reynolds number conditions in Refs. [2, 3] were selected for analysis and compared to the critical roughness height method described by Braslow and Knox [1].
Chapter 4

Analyzing the Forced Transition Airfoil Data

Testing Results

The tabulated data in Tables 2-4 represent the two-dimensional roughness height required to trip the flow and achieve a fully developed turbulent boundary layer over the airfoil surfaces. The thickness of the various tape types are listed in Table 5, and the heights needed to trip the flow were created using various combinations of these tapes.

Table 2: Tape Thickness for the E387 Upper Surface

<table>
<thead>
<tr>
<th>E387 Upper Surface</th>
<th>60,000</th>
<th>100,000</th>
<th>200,000</th>
<th>300,000</th>
<th>460,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape Thickness (k, inches)</td>
<td>0.0255</td>
<td>0.017</td>
<td>0.0138</td>
<td>0.0085</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Table 3: Tape Thickness for the S407 Upper Surface

<table>
<thead>
<tr>
<th>S407 Upper Surface</th>
<th>70,000</th>
<th>100,000</th>
<th>150,000</th>
<th>200,000</th>
<th>300,000</th>
<th>600,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape Thickness (k, inches)</td>
<td>0.0156</td>
<td>0.0138</td>
<td>0.0111</td>
<td>0.0086</td>
<td>0.0053</td>
<td>0.0017</td>
</tr>
</tbody>
</table>

Table 4: Tape Thickness for the S407 Lower Surface

<table>
<thead>
<tr>
<th>S407 Lower Surface</th>
<th>70,000</th>
<th>150,000</th>
<th>600,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape Thickness (k, inches)</td>
<td>0.0336</td>
<td>0.0255</td>
<td>0.017</td>
</tr>
</tbody>
</table>
### Table 5: Tape Thickness

<table>
<thead>
<tr>
<th>Tape</th>
<th>Tape Thickness (k, in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dymo Tape</td>
<td>0.0085</td>
</tr>
<tr>
<td>Masking Tape</td>
<td>0.0053</td>
</tr>
<tr>
<td>Packing Tape</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Pressure distribution data for the E387 airfoil was obtained via work by McGhee, Walker, and Millard [9]. Pressure distribution data for the S407 airfoil was obtained via work by Somers and Maughmer [2]. These distributions were used to find the edge velocity ratio, required for the calculation of $\text{Re}_x$.

### Analysis

The data collected in the LSLT Wind Tunnel was evaluated using a process similar to the methodology described by Braslow and Knox [1]. This evaluation was completed using purpose-built MATLAB code. The edge velocity was found using pressure coefficient plots for the E387 and the S407 airfoils under the given aerodynamic conditions at the defined roughness locations. These pressure coefficients were converted to edge velocity ratios using the formula

$$\frac{U_e}{U_\infty} = \sqrt{1 - C_p}$$

Because the exact boundary layer height, $\delta$, is not known, estimations are made using a flat plate Blasius profile [10], for which
\[ \delta = \frac{4.91x}{\sqrt{Re_x}} \]

where \( x \) is the chord location from the leading edge and \( Re_x \) is the station Reynolds number.

In order to illustrate the differences between the findings of Braslow and Knox [1] and the experimental results from the LSLT Wind Tunnel, the predicted roughness heights needed to force transition over a range of Reynolds numbers were calculated using the methodology described in Ref. [1]. Using the method in Ref. [1], \( Re_k \) was assumed to be 600, as this is the minimum \( Re_k \) required to generate a fully developed turbulent boundary layer using three-dimensional roughness. \( Re_x \) was calculated using

\[ Re_x = \frac{U_e x}{\nu_0} \]

which considers the chord location and the local edge velocity. Using this information, and Fig. 3a from Ref. [1], the non-dimensional critical roughness heights for the Reynolds number range were found. These coefficients were then used to find the dimensional heights of the tape height needed to achieve a turbulent boundary layer

\[ k = \frac{2\eta_k x}{\sqrt{Re_k}} \]

These predicted roughness heights were then compared to experimental values. Similar plots were generated for Braslow and Knox methods using fixed \( Re_k \) values of 60, 200, and 1,000.

The experimental data was processed in a reverse manner to compare the results with Fig. 3a in Ref. [1]. \( Re_k \) for the experimental data was calculated using the Blasius boundary layer velocity profile of Nikuradse [10], and the known height of both the tape and boundary layer thickness. By relating the ratio of tape height over boundary layer thickness, \( \frac{k}{\delta} \), to the velocity
profile, the ratio of velocity at the height of the tape versus the edge velocity, \( \frac{u_k}{U_e} \), could be found.

This was used to solve for the experimental roughness Reynolds number,

\[
Re_k = \frac{u_k k}{\nu}
\]

where \( \nu \) is assumed to be that of the freestream. This, combined with the known tape position, provided all the necessary components for determining the experimental non-dimensional height of the roughness

\[
\eta_k = \frac{k}{2x} \sqrt{Re_k}
\]

With this, the experimental, non-dimensional roughness height could be compared to the ratio of roughness Reynolds number over the square root of station Reynolds number.
Chapter 5
Discussion of Analysis Results

As mentioned by Ref. [11], Braslow and Knox methodology [1] states that an $Re_k$ of 600 is required for fully developed turbulent flow at a minimum and, under low-Reynolds number conditions (such as those near the leading edge), $Re_k$ values of “about” 1,000 are required. An $Re_k$ of 600 is attributed to three-dimensional roughness particles in Ref. [1] at larger Reynolds numbers. An $Re_k$ of 200 is attributable to two-dimensional (constant step) tape roughness under similar circumstances, while an $Re_k$ of 60 is attributable to zig-zag tabulator tape. Hence, comparisons of experimental data were made with Ref. [1] method results using these fixed $Re_k$ for context. The experimental tape, under higher Reynolds number conditions, is expected to have a $Re_k$ somewhere between that of the zig-zag tape and the constant step tape, around 125 or so. The experiments at the LSLT Wind Tunnel demonstrate that the critical roughness heights determined by methodology of Ref. [1] are too small to effectively trip the flow. Additionally, the need for roughness that extends beyond the boundary layer for the S407’s lower surface (see Fig. 1) flouts the possibility of a constant roughness Reynolds number.
Figure 1: Tape Height Ratio vs. Station Reynolds Number

It must be noted that the boundary layer height and displacement thickness in this figure are not equivalent for the airfoil surfaces; the relation shown is non-dimensional. Fig. 1 illustrates how both the S407 and E387 upper surface tape protrude well past the height of the displacement thickness for the vast majority of operating conditions. This, in turn, means that in order for fully developed turbulent flow to occur at small station Reynolds numbers, the height of the tape must exceed that of the boundary layer displacement thickness.

Upper Surface Results

The comparison of actual experimental tape heights needed to trip the flow and results of Braslow and Knox methodology [1] at $Re_x$ 60, 200, 600, and 1,000 can be seen in Fig. 2 for the
E387’s upper surface and Fig. 3 for the S407’s upper surface. As expected, the tape thickness required to achieve fully developed turbulent flow increases as Re_x decreases in value.

\[ \text{Tape Thickness vs. } \frac{Re_k}{\sqrt{Re_x}} \text{ (E387 Upper } \alpha=0^\circ, x=5\%) \]

Figure 2: Tape Thickness vs. Reynolds Number Ratio for E387

The experimental data demonstrated a trend similar to that of a fixed 600 Re_k Knox & Braslow method until 200,000 chord Reynolds number (or a Reynolds Number Ratio of roughly 5), at which point the tape thickness required for fully developed turbulent flow diverges and begins to trend towards a fixed 200 Re_k Ref. [1] method result. The chord Reynolds number for some of the data points were included to aid in the illustration of the trend; as Reynolds number increases, tape height and Reynolds number ratio generally decrease. As made visible by the experimental data, the roughness height needed to trip the flow is almost always greater than the
Ref. [1] method would suggest with a fixed $Re_k$ of 60 and 200. The only exception to this behavior occurs near 460,000 chord $Re$, where the height needed to trip the flow (as determined by the Ref. [1] method) for a fixed $Re_k$ 200 flow is greater than that of the experimental data. Similar behaviors precipitated from the S407’s upper surface data, as seen in Fig. 3.

![Tape Thickness vs. $Re_k$/sqrt($Re_x$) (S407 Upper $\alpha=4^\circ$, $x=5\%$)](image.png)

**Figure 3: Tape Height vs. Reynolds Number Ratio for S407 Upper Surface**

Again, the experimental tape thickness needed to generate turbulent flow over the entire airfoil behaves similar to a fixed 600 $Re_k$ Ref. [1] method until roughly 200,000 chord Reynolds number (or a Reynolds Number Ratio of roughly 3.3), at which point the required tape thickness trends towards a fixed 200 $Re_k$ result from the Ref. [1] method. As with Fig. 2, the chord Reynolds number for some of the data points were included to illustrate that, as Reynolds
number decreases, the tape thickness needed to force transition and the Reynolds number ratio generally increase. Like what is observed in Fig. 2 at 460,000 Reynolds number, the height required to trip the flow (as determined by the Ref. [1] method) with a fixed 200 $Re_k$ is greater than that found by experimentation at 600,000 Reynolds number. At 70,000 $Re$, the height required to trip the flow between these datasets is indistinguishable. In general, though, the height found to achieve fully developed laminar is greater than that of the prediction ($Re_k$ of 125). The converging trend of the plots in Figs. 2 and 3 with increasing Reynolds number shows that the method described by Braslow and Knox is increasingly accurate with increasing Reynolds number. The experimental results and Ref. [1] method results converges considerably at $Re_k$ values of roughly 25,000 for the E387 airfoil and roughly 45,000 for the S407 airfoil.

Figs. 4 and 5 depict the non-dimensional roughness height as a function of the Reynolds number ratio for the upper surface of both the S407 and E387 airfoils in precisely the same manner as Fig. 3a of Ref. [1].
Figure 4: Non-dimensional Roughness Height vs. Reynolds Number Ratio for the E387 Upper Surface
Both figures illustrate the trend similarities with the experimental results and results from the method outlined by Braslow and Knox [1]. However, upon closer examination (aided by Figs. 6 and 7), the trend of increasing non-dimensional tape thickness with increasing Reynolds number ratio (and hence station Reynolds number) reverses course around 200,000 chord Reynolds number.
Figure 6: Non-dimensional Roughness Height vs. Reynolds Number Ratio for the E387 Upper Surface (Detailed)
As demonstrated by Figs. 6 and 7, the non-dimensional tape thickness and Reynolds number ratio increase with decreasing Reynolds number until roughly 200,000 chord Reynolds number, at which point the trend reverses. Additionally, the experimental data appears to trend in precisely the opposite manner of the Ref. [1] method predicted results below 200,000 chord Reynolds number.

The inversion seen in Figs. 2 through 7 can be attributed to a changing roughness Reynolds number that “peaks” at roughly 12,000 Re\(_x\) for the E387 and S407 upper surfaces (see Fig. 8).

**Figure 7: Non-dimensional Roughness Height vs. Reynolds Number Ratio for the S407 Upper Surface (Detailed)**

![Non-dimensional Roughness Height vs. Reynolds Number Ratio for the S407 Upper Surface (Detailed)](image)
Figure 8: Roughness vs. Station Reynolds Number for the Upper Surfaces

The behavior illustrated may be attributable to the large disturbances needed to fix transition near the leading edge (i.e., experimental error), but the presence of a relatively smooth curvature in the plots and similarities between the two datasets (of different airfoils at different angles of attack) suggests otherwise. Upon examination of the analysis data, the lack of consistent $Re_k$ can be traced to relatively low edge velocities at lower Reynolds numbers ($<100,000$) and relatively low non-dimensional roughness heights at higher Reynolds numbers ($>300,000$).
Lower Surface Results

Fig. 9 illustrates the tape thickness/Reynolds number ratio behavior on the lower surface of the S407 airfoil with comparison to Braslow & Knox methodology [1] predictions at fixed Re_k of 60, 200, 600, and 100,000:

Figure 9: Tape Thickness vs. Reynolds Number Ratio for S407 Lower Surface

Clearly, the data does not follow the trend exhibited by the upper surfaces of the E387 or S407. However, as with the Ref. [1] method of determining critical roughness height, the experimentally determined tape thickness required to trip the flow increases with decreasing Reynolds number.
When the $Re_k$ required to trip the flow for a given $Re_x$ on the lower surface is compared to that for the upper surfaces (see Fig. 10), there exists some similarity at lower station Reynolds numbers; however, this similarity vanishes as the station Reynolds number increases beyond 12,000. The abnormalities exhibited by the S407 lower surface data may be attributable to experimental error or distance from the leading edge, but further research is needed to confirm this.

Despite the variation, when the tape thickness needed to force transition on the S407 airfoil’s lower surface for a given $Re_x$ is compared with that of the S407 and E387 airfoils’ upper surfaces, some consistency appears, as shown in Fig. 11:

**Figure 10: Roughness Reynolds Number vs. Station Reynolds Number**
As expected, the tape thickness required to trip the flow increases with decreasing station (and chord) Reynolds number. This can be attributed to the increase in boundary layer height with decreasing Reynolds numbers. The tape thickness required to trip the flow on the S407 lower surface is significantly higher than that of the upper surfaces. This is also illustrated above in Fig. 1, where the thickness of the tape for the S407 lower surface nearly matches or exceeds the predicted boundary layer height for the entirety of its Reynolds number range. Whether this is a result of the change in stagnation point at higher angles of attack is unknown. Alternatively, it is known that the height required to achieve fully developed turbulent flow is greater on the
The lower surface of the S407 because this trip is located at 10% chord, where the boundary layer is thicker, rather than 5%.

The tape thickness required to trip the flow on the upper surfaces of the E387 and S407 airfoils is relatively similar as-is. If the height required to trip the flow on all surfaces is made non-dimensional by relating it to the station distance from the leading edge (shown in Fig. 12),

![Non-dimensional Roughness Height (k/x) vs. Reₜ](image)

**Figure 12: Non-dimensional Tape Thickness vs. Station Reynolds Number**

the tape thickness required to trip a flow for a given station Reynolds number collapses to a more narrow trend over Reₜ values of roughly 5,000-50,000. This plot provides the basis for a model that could be used to accurately predict the roughness height needed to fix transition at a given chord location for a given station Reynolds number between 5,000 and 50,000.
Chapter 6

Conclusion

As demonstrated by analysis conducted on fixed-transition data observed at the LSLT Wind Tunnel, roughness heights greater than critical value are required to achieve fully developed turbulent flow over an airfoil surface at low Reynolds numbers. Additionally, results from this experimentation suggest that \( Re_k \) cannot be treated as a constant value at low station Reynolds numbers, even when the trip in question is submerged in the boundary layer. In order to size roughness with the intention of achieving fully developed turbulent flow between 5,000 and 50,000 \( Re_x \), it appears advisable to reference Fig. 12.

The evidence presented in this thesis warrants further research. Subsequent testing on similar laminar-flow airfoils can help widen the \( Re_x \) range for which the model, depicted in Fig. 12, applies. Additionally, the testing of the airfoils presented (S407 and E387) at varying angles of attack would determine the consistency of the behavior at varying angles of attack. Testing additional airfoils at similar conditions (at low Reynolds number and near the point of maximum lift coefficient) could provide further validation and possible explanation of the trends found by these data. Further experimentation on the lower surfaces of airfoils could help make sense of the odd behavior illustrated in Fig. 9. Additionally, comparison of drag polar data from fixed transition experiments to that of XFOIL could determine what amount of the drag increase introduced by the roughness needed to fix transition at low \( Re_x \) is from the introduction of turbulent flow and what amount is from the roughness itself.
REFERENCES


ACADEMIC VITA

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Education:
- The Pennsylvania State University: Univ. Park (College of Engineering/Schreyer Honors College)
  - Planning to graduate in May of 2020 with a Bachelor's in Aerospace Engineering and a minor in Engineering Leadership Development
  - Beginning M.S. in Aerospace Engineering in Fall 2020

Special Coursework:
- Completed Technical Thesis specific to Aerodynamics
  - Described and predict fixed aerodynamic transition at low Reynolds numbers
  - Completed wind tunnel testing setup for PSU 094-97 Airfoil
- PSU Design Build Fly (AIAA DBF) RC Team Member 2017, 2018, and Team Lead for 2019
  - Designed and built multiple aircraft to complete mission requirements set forth by the AIAA
  - Attended 2018 competition in Wichita, KS, where our team placed 10th
- PSU Engineering Leadership Development Program
  - Formal Project Management and Leadership training, similar project experience to DBF
- PSU Zephyrus Human-Powered Aircraft Team Member (Sailplane Honors Course)
  - Currently building a pedal-driven ultralight aircraft

Applicable Skills:
- Soft Skills:
  - Advanced skills in leadership, project management, and communication from engineering internships, formal leadership and coaching coursework, leadership work in Scouts, and from earning Eagle Rank
- Engineering Processes:
  - Experience in RF/Electrical Engineering from Rosenberger engineering Internship
  - Skills in the engineering process from courses, the PSU DBF Team, and engineering internships
- Production Skills:
  - Training and experience in: RF testing, working under a microscope, resistive soldering, plastic molding, small parts manufacturing, creating and machining composites, CNC machining, milling, and lathe work
- Code Languages:
  - Working experience in machine learning and Python
  - C++ and Matlab experience from coursework
  - Macro (Visual Basic) experience and projects from Engineering Internship
  - Coding proficiency in RobotC
  - Currently in private sailplane pilot training
Work Experience:

- **Summer Intern with the U.S. Army (Summer 2018 & Summer 2019, Washington, DC, TS Clearance)**
  - Gained practical and professional experience contributing to engineering initiatives and projects
  - Expanded an understanding of the mission of the Army and career opportunities for future reference

- **Engineering Intern at Rosenberger North America (Summer 2017 and 2017/2018 Winter Break)**
  - Worked directly with the Engineering Leadership, other engineering and non-engineering interns, and Production Teams
  - Projects included shadowing all aspects of manufacturing, documenting calibration equipment, helping the process engineering team, and helping the engineers complete their customer projects

- **Head Guard at the Ephrata Community Pool & Ephrata Recreation Center (Summer 2015-2017)**
  - Responsible for and oversaw all lifeguards on duty during my shift
  - Position required leadership, coaching, first aid and lifeguarding experience, lifeguarding, customer service skills, and most importantly communication skills

- **Pool Maintenance at the ECP (Summer 2015 & 2016)**
  - Responsible for maintaining pool equipment, the pool itself, and pool grounds

- **Life Guard at the ECP & ERC (Summer 2013-2015)**
  - Responsible for the well-being of all patrons in the pool, and performing rescues

Other Activities:

- **University Affiliated:**
  - Current member and glider pilot trainee with the Penn State Soaring Club
  - Former member and mentor of the Penn State Engineering Orientation Network