

THE PENNSYLVANIA STATE UNIVERSITY  
SCHREYER HONORS COLLEGE  
DEPARTMENT OF AEROSPACE ENGINEERING

**DESIGN OF A SERIES OF AIRFOILS FOR THE PSU ZEPHYRUS  
HUMAN-POWERED AIRCRAFT**

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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

The Flight Vehicle Design and Fabrication class at The Pennsylvania State University (AERSP 204H/404H) is working on the design and construction of a human-powered aircraft (HPA) which will compete for The Kremer International Sporting Aircraft Competition hosted by the Royal Aeronautical Society. The aircraft design has matured over the last three years and the prototype design is being finalized. In an attempt to improve the performance of the aircraft, a series of airfoils for the major aerodynamic surfaces (wing, horizontal tail, and vertical tail) were designed specifically-tailored to the aircraft's operational envelope, structural requirements, and desired handling qualities. The baseline planforms and structures of the aerodynamic surfaces are not altered in the design process. To design the airfoils, the surfaces were first analyzed with a 3-D lifting-panel method to determine the local lift coefficients corresponding to the HPA's desired cruise range. Airfoil minimum thickness requirements are derived from minimum construction sizes for pre-preg carbon fiber and balsa wood. The handling characteristics were qualitatively considered into the airfoil design. The analysis showed that the wing airfoil should operate with a  $c_{lmax}$  of 1.6 at Reynolds number (Re) of 511000, a laminar drag bucket from  $c_l=1.0$  to  $c_l=0.6$  (within the range of Re=352000 to 716000) with a gentle exit at the higher corner of the bucket in all conditions, and a  $t/c_{min}$  of 12.3%. For the purpose of not introducing a higher load on the tail than previously designed, the pitching moment,  $c_{mac}$ , of the wing airfoil should be no higher in magnitude than the baseline airfoil, the E395. The horizontal tail airfoil should have a drag bucket of  $c_l=\pm 0.3$  in the Re range of 214000 to 385000 with a gentle exit on both sides, a  $c_{lmax}$  of 1.0 in the same Re range to give good tail authority, and a  $t/c_{min}$  of 10.6% to allow for structure. The vertical tail airfoil should be symmetrical and have low drag in at  $c_l=0$  while sloping off gently to a  $c_{lmax}$  of no less than 1.0 at a Re of 443000 to match the stability and control sizing used for the aircraft. Using these desired characteristics, pressure distributions are designed and, using the PROFIL program created by Dr. Richard Eppler, a series of airfoils were iterated upon until these requirements were met. The airfoils are analyzed in both PROFIL and XFOIL showing good agreement and generally successful satisfaction of design requirements. Further 2-D and 3-D analysis predict that these airfoils improve the performance of the aircraft at flight speeds from 10 m/s to 16 m/s while decreasing performance slightly at flight speeds below 10 m/s. Suggestions are made for future work that should yield improvements in airfoil and aircraft performance.

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This project would also have been impossible without the airfoil theory and computational work conducted by Dr. Richard Eppler for his development of the PROFIL program and Mr. Dan Somers for his contribution on the same. Also, I would also like to thank Dr. Mark Drela for his software, XFOIL, and Andre Depperiois who develops the XFLR5/QFLR5 program which allows XFOIL to be applied to 3-dimensional aerodynamic surfaces via lifting-line, vortex-lattice, and 3-D panel methods.

Lastly, I would like to extend thanks to the Royal Aeronautical Society for hosting the Kremer prize competitions.

## Nomenclature and Conventions Used

$c$  = chord

BL. = Boundary layer, the region of flow where viscous effects are important

HT = Horizontal Tail

VT = Vertical Tail

Re = Reynolds number. If no local position is mentioned, it refers to the Re with respect to the local chord

$c_l$  = nondimensional 2-D lift coefficient defined via  $c_l = \frac{L'}{\frac{1}{2}\rho V^2 c}$  where  $L'$  is the local 2-D lift (or lift-per-unit-span)

$c_{lmax}$  = maximum nondimensional 2-D lift coefficient

$c_d$  = nondimensional 2-D drag coefficient defined via  $c_d = \frac{D_p'}{\frac{1}{2}\rho V^2 c}$  where  $D_p'$  is the local 2-D profile drag (or profile-drag-per-unit-span). This is separate from vortex-induced drag.

$c_{mac}$  = nondimensional 2-D pitching moment coefficient

$C_L$  = nondimensional 3-D lift coefficient defined via  $C_L = \frac{L}{\frac{1}{2}\rho V^2 c}$  where  $L$  is the total lift produced by the surface

$c_{Di}$  = nondimensional vortex-induced drag coefficient

$c_{Dp}$  = nondimensional profile drag coefficient

$t/c$  = thickness-to-chord ratio

$S$  = aerodynamic surface's area

Xtr1 =  $x/c$  location of transition from laminar to turbulent BL on the upper surface

Xtr2 =  $x/c$  location of transition from laminar to turbulent BL on the lower surface

## **Chapter 1**

### **Project Background**

The Flight Vehicle Design and Fabrication honors course at The Pennsylvania State University (AERSP 204H/404H) was established in 1989 to provide a hands-on project-based learning experience to students in aerospace engineering similar to the Akademische Fliegergruppe of Germany. The class has two major components – general lecture and aircraft project work. Lectures are scheduled in regular class time while students work in the laboratory outside of class to design, build, and fly aircraft projects. One of the class's strengths is its multi-year format that allows students from freshmen to seniors to work together. This environment promotes team skills are learned and knowledge is passed from upperclassmen to underclassmen before the underclassmen would otherwise learn in class, giving them a head start in their studies.

For most of its history, the class has been focused on the design and construction of sailplanes. In the spring of 2007, the class started on the design of a human-powered aircraft (HPA) dubbed Zephyrus in response to the Kremer Sporting Aircraft competition, hosted by the Royal Aeronautical Society of the United Kingdom. The first design iteration was completed in 2009 and a second iteration shall be concluded at the end of the academic year (spring 2010) along with the initialization of prototype construction.

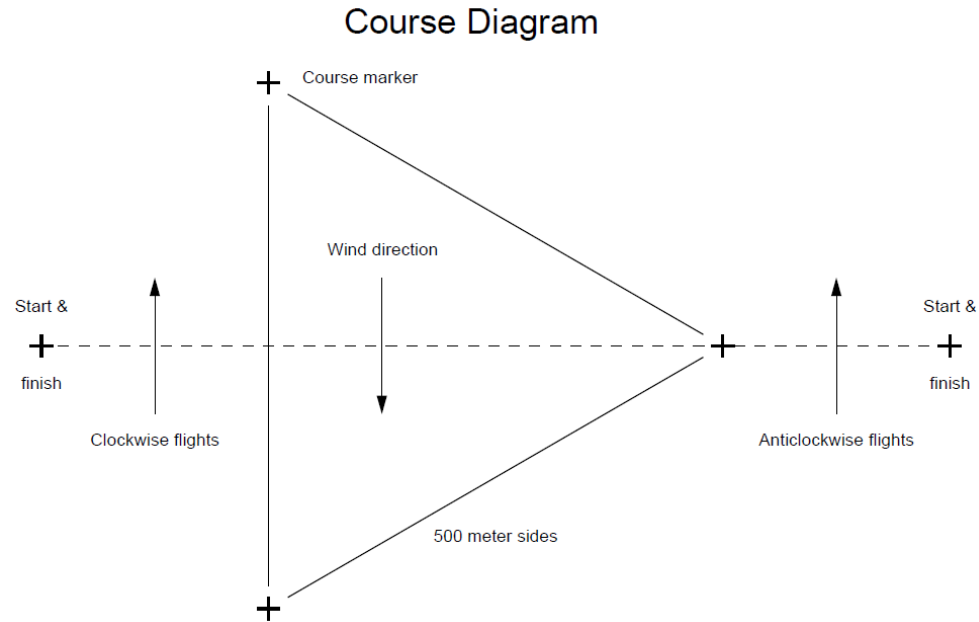
### **The Kremer Sporting Aircraft Competition**

The Kremer prizes are a series of awards established in 1959 by industrialist Henry Kremer for the purpose of generating interest in human-powered aircraft. The first Kremer Competition required that the aircraft must fly a figure-8 course around two pylons, half a mile apart; this prize was won by Paul McCready and his team using the Gossamer Condor (shown in Figure 1) in 1977.



**Figure 1: The Gossamer Condor in flight**

The latest competition, the “Kremer Sporting Aircraft Competition” was opened with the hope that the aircraft and interest generated would start a sport of human-powered flight. As such, the mission requirements are much more demanding than the original and require a generally more robust aircraft capable of negotiating more adverse weather conditions. The required flight course is an equilateral triangle, 500 m on a side as shown below in Figure 2.



**Figure 2: Course Diagram for the Kremer Sporting Aircraft Competition**

The rules state that aircraft must complete two laps of the circuit (one clockwise and one counterclockwise) with a total in-course flight time of no longer than 7 minutes. There is a maximum of one hour in between flights in which the pilot may rest. The aircraft must fly at an altitude of at least 5 meters when entering and exiting the course.

To ensure that the aircraft would be one that would be capable in non-ideal weather, the rules state that, during a flight attempt, there must be a 5 m/s wind (measured at 10-m above ground level) which must not fall below 5 m/s for more than 20 continuous seconds.

These required times and required wind speeds drive the aerodynamic performance and stability and control design of the Zephyrus.

### **Objectives and Scope of Work**

As the preliminary design of the HPA is closing and the production of a prototype is underway, the scope of this project will be limited to designing one airfoil for each of the HPA's major aerodynamic surfaces (wing, horizontal tail, and vertical tail) such that net performance of the aircraft is increased from the baseline design and its construction made feasible. These airfoils

should therefore be “swap-in” replacements for the airfoils originally chosen for the HPA and should require minimum alteration of the existing design.

There is one notable omission from the wing airfoil design; whereas the real wing shall have ailerons, the airfoils will not be designed for them because the turning aileron requirements have not been fully defined.

Since these are the first airfoils designed by the author, and there are academic and practical deadlines (as to not delay the construction of the prototype aircraft), one would expect, naturally, that these airfoils will be imperfect and there will be much room for improvement in future iterations. Possible areas of improvement for the airfoils are discussed in the Future Work section.

### **Software Used**

The primary tool used for airfoil design is the PROFIL program (2007 version) developed by Dr. Richard Eppler (Eppler, Airfoil Design and Data, 1990). A description of its operation is described in later sections.

XFOIL (ver 6.94) airfoil analysis program was also used to predict airfoil characteristics and to generate data for the 3-D analysis. XFOIL was written by Dr. Mark Drela of MIT, released under the public GNU public license.

3-Dimensional analysis of surfaces was conducted via modeling in XFLR5 (specifically, QFLR5 version 0.04 beta) developed by Andre Deperrois, released under the public GNU public license. The program works by running XFOIL to populate a data space of 2-D airfoil data which is then used to calculate influence matrices over a wing which are solved and cross-checked with the 2-D data to find wing drag and moment distributions (Deperrois).

Structural layout drawings were made in SolidWorks.

Drag-buildup analyses were conducted in Microsoft Excel using large tables.

## Chapter 2

### Low Reynolds Design Considerations

HPAs, remote-controlled aircraft, and sailplanes operate with relatively low Reynolds numbers (below  $Re = 1,000,000$ ). In this region, the viscous forces are in higher proportion to the inertial forces than in larger, faster human transport aircraft (general aviation and commercial transport). Aerodynamic coefficients are very sensitive to  $Re$  in this low- $Re$  range. Therefore, specific attention is paid to  $Re$  in the following analyses.

In this low- $Re$  region, the flow is characterized by long runs of laminar boundary layers and transition (usually) via laminar separation bubbles. The presence of long runs of laminar flow has the advantage that the skin-friction drag component from a laminar boundary layer is much lower than that of the turbulent boundary layer. An airfoil may be designed such that there are long runs of laminar flow on both the upper and lower surfaces of the airfoil yielding lower drag than at other points in its operating range. This range of low-drag due to a predominance of laminar flow is called a “drag bucket.” A diagram showing the drag bucket and selected transition points is shown below in Figure 3.

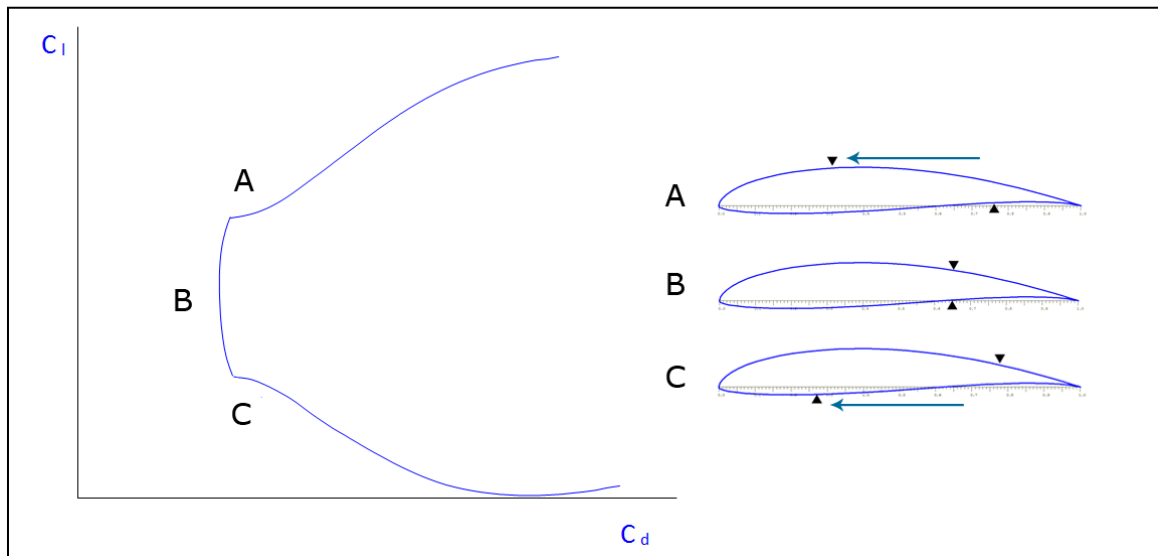


Figure 3: A laminar drag bucket

In the above figure, the bucket extends from point A to point C on the  $c_l$  vs  $c_d$  polar. Example transition points on the airfoil are denoted by the black triangles on the right side of the

figure. At point B, both the upper surface and lower surface have long runs of laminar flow, yielding lower drag. Between point A and C, as the angle of attack (and therefore  $c_l$ ) is increased, the transition point moves forward on the upper surface, the transition point on the lower surface moves back, yielding near-constant drag. At point A, as the airfoil moves to higher angle of attack, the transition on the upper surface (denoted by the black triangle on the upper surface of the airfoil) moves forward rapidly, yielding more turbulent flow and therefore increased skin friction drag on the airfoil. At point C, as the airfoil moves to a lower angle of attack, the transition point on the lower surface (denoted by the black triangle there) moves forward rapidly, yielding a similar increase in drag.

While a laminar BL produces less drag than turbulent BL, a laminar BL is less able to negotiate an adverse pressure gradient than a turbulent one. In the Re range the HPA shall be operating, in a pressure-recovery area of the airfoil, transitions usually occur with a laminar separation bubble (LSB); an illustration is shown in Figure 4.

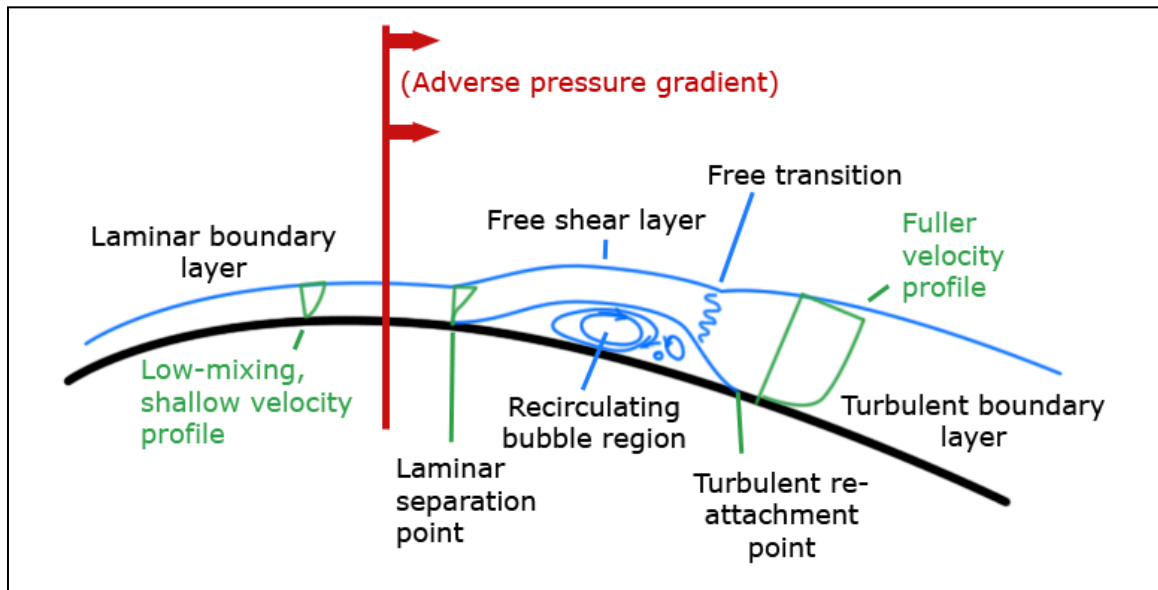
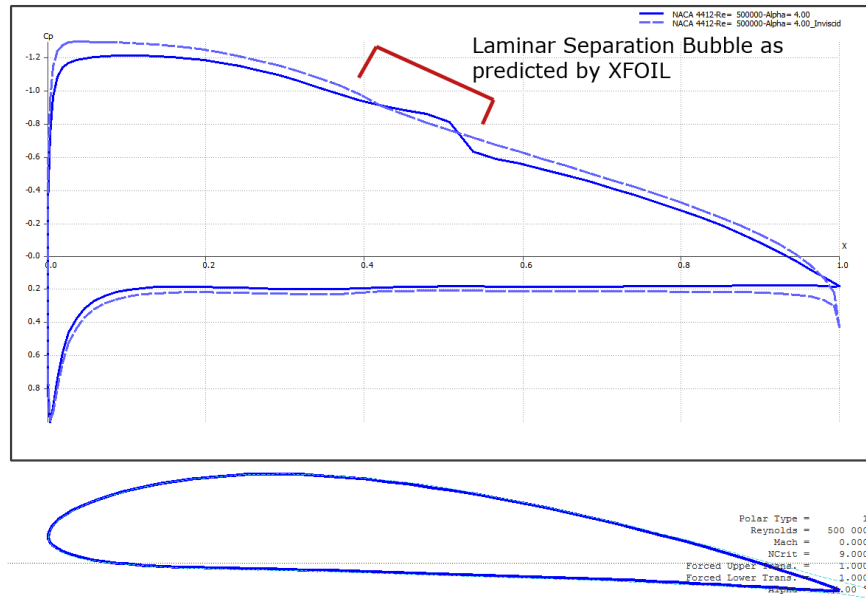


Figure 4: Illustration of a Laminar Separation Bubble

LSBs arise when the laminar boundary layer runs out of momentum in an adverse pressure gradient and leaves the surface of the airfoil. In the free stream, the free shear layer transitions from laminar flow to turbulent flow and a low-pressure zone at the rear of the separated region brings the BL back in contact with the airfoil surface. (If the airfoil surface is sufficiently steep so that the flow is unable to reattach, the airfoil would be stalled laminarly.) This reattached turbulent flow has flow mixing which brings higher-momentum fluid from the

upper (faster) air and energizes the lower layers, allowing it to better negotiate an adverse pressure gradient. Thus, it is often beneficial to have the BL transition (via LSB or otherwise) at the start of the pressure recovery region of the airfoil.

There is a drag penalty associated with the LSB. Both XFOIL and PROFIL are capable of taking into account the effects of the LSB. Figure 5 below shows a large LSB predicted by XFOIL for an NACA 4412 airfoil operating at a Re of 500,000.



**Figure 5: XFOIL results showing an LSB**

As can be seen in the above figure, the inviscid (dashed line) and viscous (solid line) pressure distributions are the same (to first-order accuracy). The LSB from  $x/c$  of 0.45 to 0.55 causes the displacement thickness to grow larger and yields an increase in lift and drag.

All these flow features must be taken into account when designing airfoils for low-Re applications. A properly-designed low-Re airfoil will take advantage of the laminar boundary layer characteristics and negotiate the LSB carefully to reduce the drag caused by them.

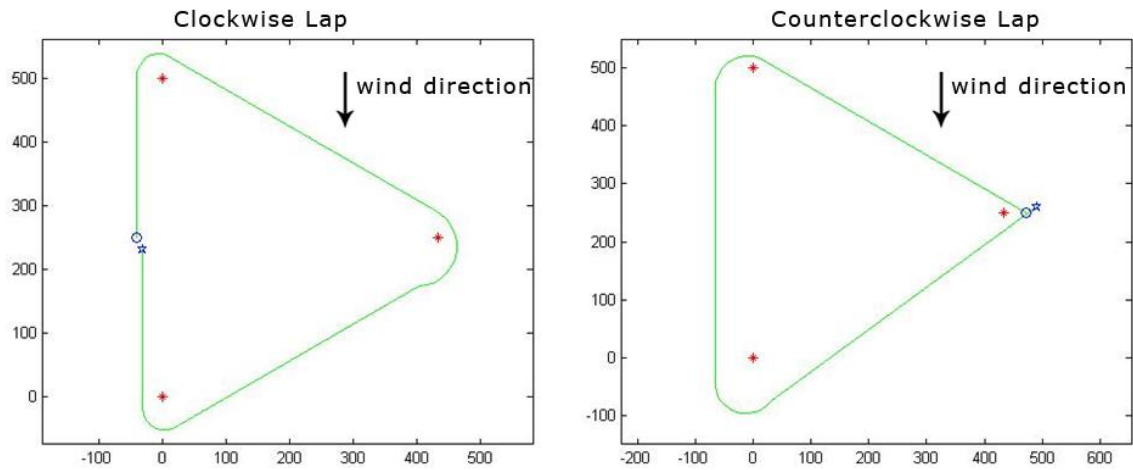
## Chapter 3

### Baseline Aircraft Design

This section outlines the baseline design of the HPA as designed in the 2010 iteration.

#### Mission Path and Operational Range

To determine the flight speeds the HPA will require to complete the mission, a MATLAB code was written by Andrew Weinert to simulate the flight path of the HPA taking into account the wind velocity as constant from one direction at 5 m/s. Coordinated flight was assumed and the bank angle was assumed to be 15 degrees.



**Figure 6: Mission Path visualization in MATLAB**

Based on the simulations, a range of speed was defined which would allow the HPA to compete successfully for the Kremer prize. The speed range is shown below in Table 1.

**Table 1: Cruise speed range of the HPA**

| Speed          | Speed    | Time to complete course |
|----------------|----------|-------------------------|
| Cruise minimum | 10.5 m/s | 6.9 minutes             |
| Cruise medium  | 11.0 m/s | 6.4 minutes             |
| Cruise maximum | 11.5 m/s | 6.0 minutes             |

All components on the baseline aircraft were designed around these cruise speeds a take-off gross weight estimate of 220 lb. A flying altitude of 6 meters was assumed to generate an estimate for ground effect. This estimate should be conservative since the aircraft is allowed to dip below 5 meters altitude for the majority of the flight, allowing for more reduction in drag due to ground effect.

### Wing

The baseline airfoil for the wing was the E395 airfoil designed for human-powered aircraft by Eppler, which is shown in Figure 7.

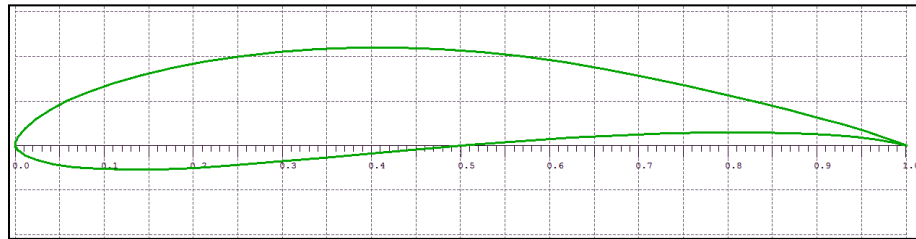


Figure 7: The E395 HPA airfoil

Using this airfoil, the wing of the HPA was designed to minimize total drag at 11.5 m/s so that the power required for the aircraft could be minimized for the maximum cruise speed. A drag polar of the wing is shown in Figure 8.

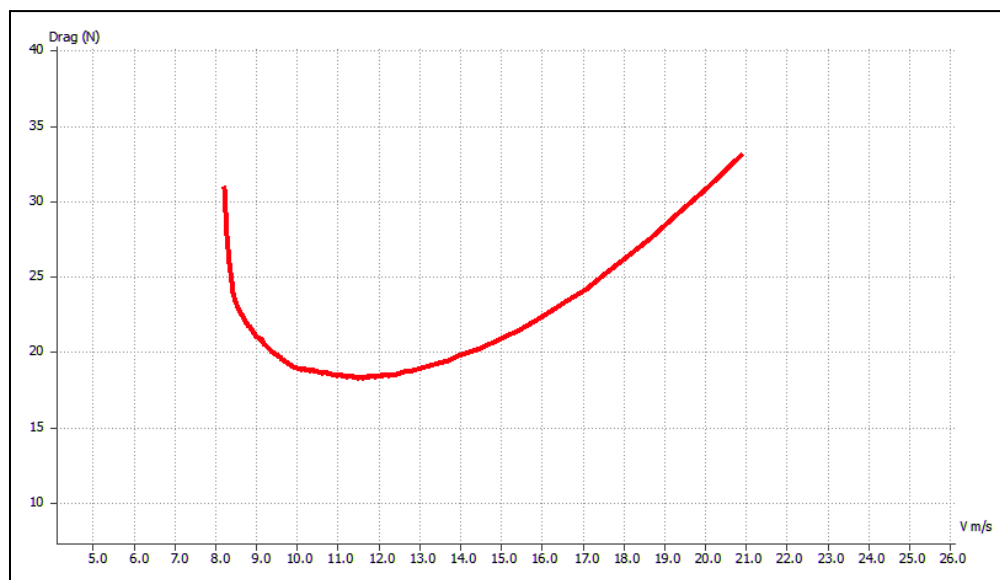


Figure 8: Total wing drag to lift 220 lb vs flight speed



The spanwise section construction is comprised of foam ribs, a D-tube for an aerodynamically-smooth surface, and a balsa mounting plate to strengthen the rib and transfer the loads from the rib and D-tube to the spar, as shown in Figure 11.

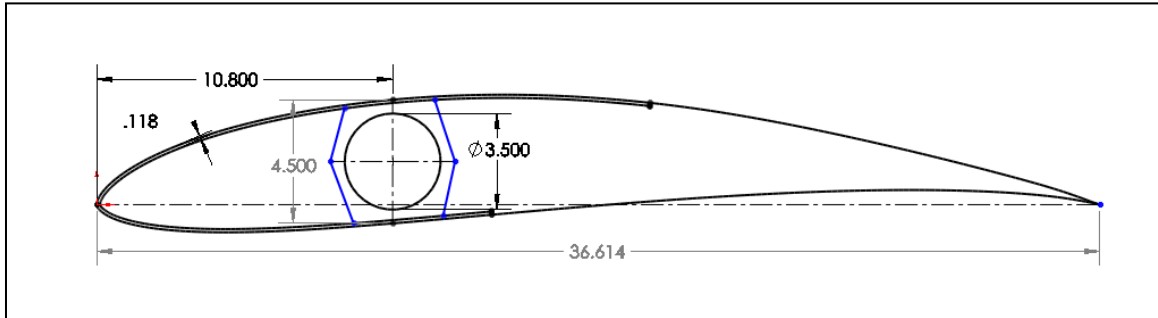


Figure 11: Rib section

### Horizontal Tail

A full-flying horizontal tail was sized by John F (Jack) Quindlen considering a balance between the drag of the tail, skin friction of the tail boom, structural weight of the boom, and maximum allowable length for the HPA. The horizontal tail is mounted on the boom, which provides a 4.6-meter moment arm from the aerodynamic center of the tail to the aircraft center of gravity. The planform of the horizontal tail is shown below in Figure 12 (all dimensions in meters). The resulting HT tail volume coefficient is 0.44.

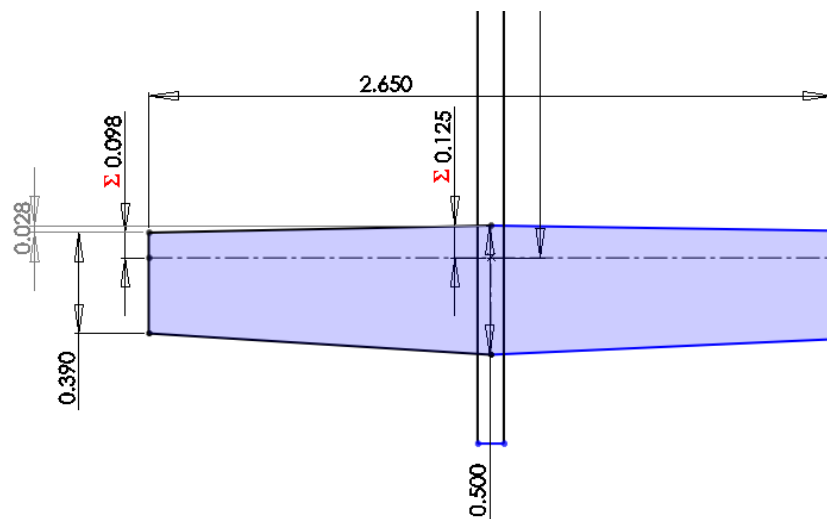
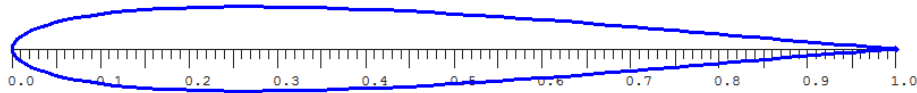


Figure 12: Planform of the horizontal tail

In the conceptual design phase, the S9026 airfoil created by Dr. Michael Selig of the University of Illinois at Urbana-Champaign had been chosen for the HPA horizontal tailplane. This airfoil (shown in Figure 13) is currently used on several remote-controlled sailplanes.

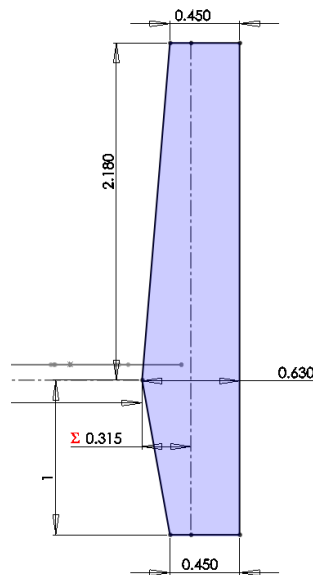


**Figure 13: The S9026 airfoil**

The construction method of the horizontal tail is planned to be the same as with the wing, except using balsa instead of foam for the rib and the D-tube.

### Vertical Tail

The full-flying vertical tail (planform shown in Figure 14, dimensions in meters) was also sized by Quindlen and is sized for maneuverability. The vertical tail was set to use the same airfoil and construction technique as the horizontal tail.



**Figure 14: Planform of the vertical tail**

## Pilot Pod

While not part of the redesign work conducted for this project, it is important to understand the pilot pod and its role in the aircraft as well as the drag it contributes. The pod's purpose is to house the pilot and the systems that must interface with him/her. The pedals, controls, and landing gear are contained within it.

The pod surface is designed in such a way as to generate the minimum drag possible for the contents within it. It is designed like a large vertical fin with airfoils that vary along the height that match the maximum thickness of the airfoils to the maximum thickness of the pilot and internal systems (pilot shoulders, controls near the hips, and pedals). A structural illustration of the pod is shown in Figure 15.

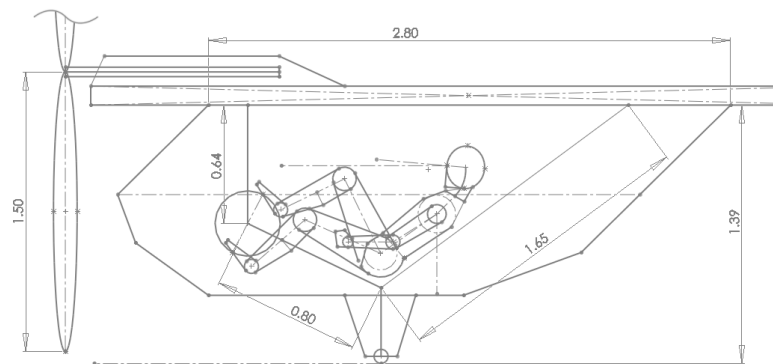


Figure 15: Pod structure and pilot

The pod was analyzed as a wing in XFOIL and its results were used to populate a 3-D panel method which was used to generate a drag estimate. A flow-visualization of the pod is shown in Figure 16.

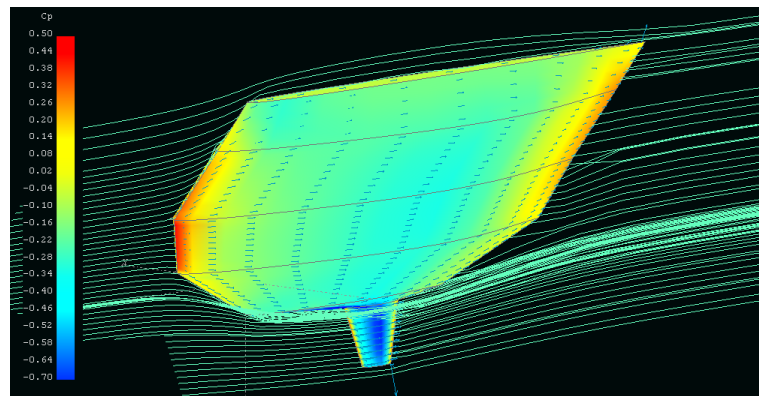


Figure 16: Pod aerodynamic visualization

### Entire Aircraft

A 3-view of the entire aircraft is shown below in the following figure (rotated).

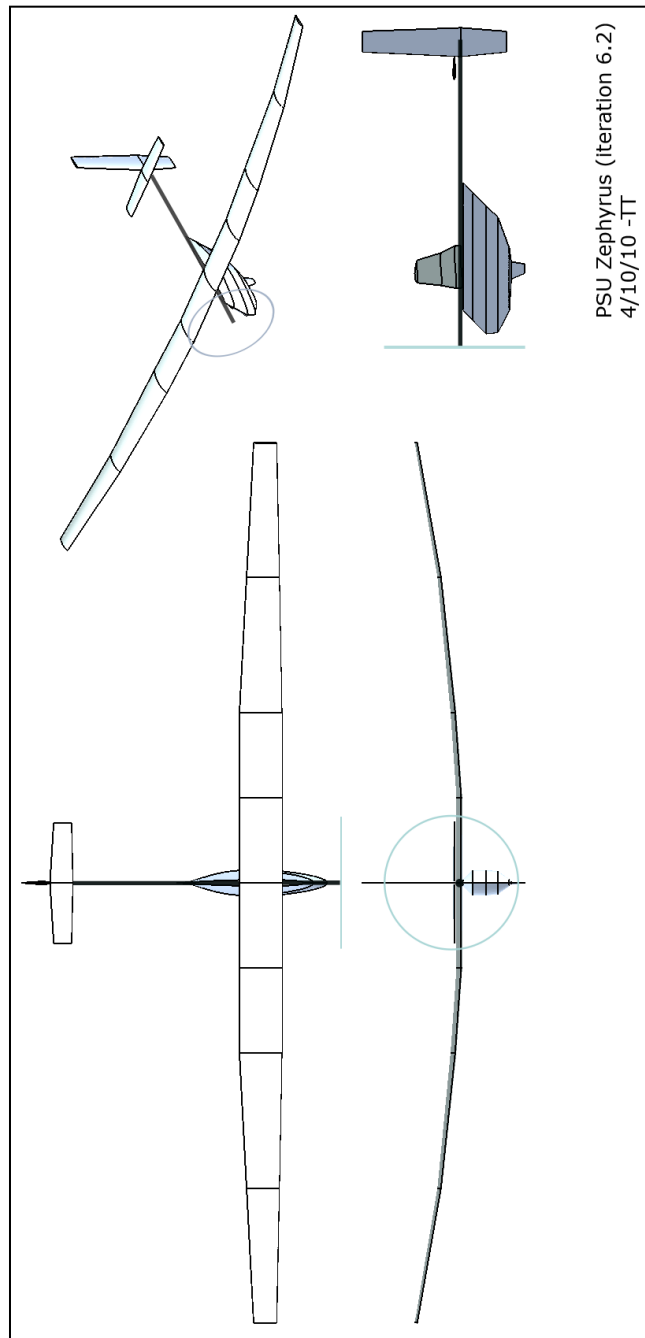


Figure 17: 3-view of the PSU Zephyrus

### Drag Buildup Analysis

A comprehensive drag buildup (Figure 18) was created with the given design, yielding the following drag buildup analysis. One point of adjustment must be noted. For reasons that will be discussed in the Structural Requirements section, the designed planform for the horizontal tail is incompatible with the S9026 airfoil (9.5% thick) and the available aluminum mandrels. The minimum structure requires an airfoil at least 10.6% thick. Therefore, the XFOIL-predicted performance characteristics NACA 0010 airfoil (scaled slightly to 10.6%) was used.

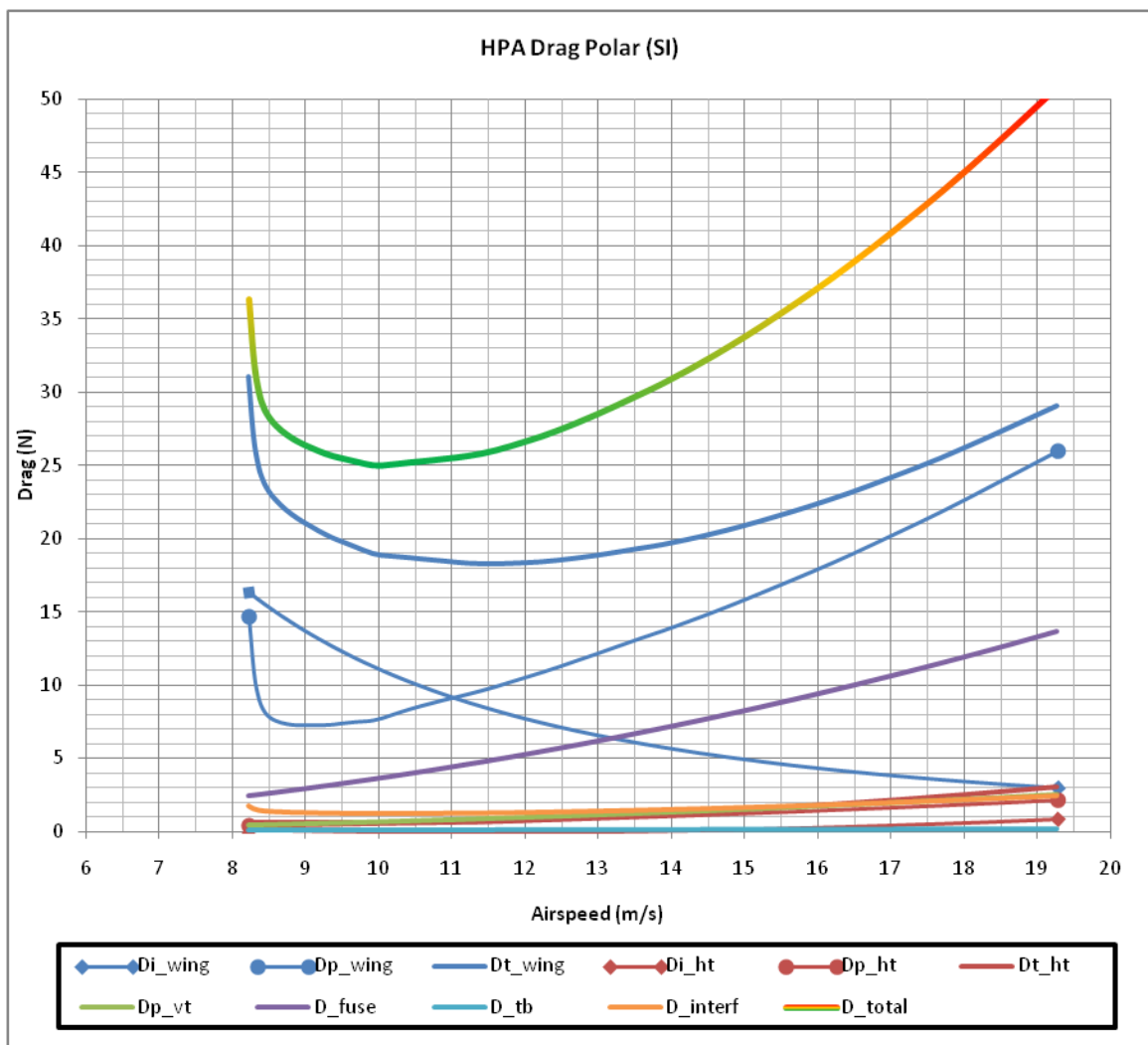


Figure 18: HPA Drag buildup (baseline)

In the above figure, “ $D_i$ ” for a particular surface is the vortex-induced drag as related to span efficiency, not induced drag as related to Oswald’s efficiency.

### Aircraft Power

The drag buildup was used to generate an aircraft power-required curve which was then compared against a power-available curve assuming a pilot-output power of 350 W. Various propeller RPMs were compared; the propeller RPM will be matched to the pilot's max-power RPM via gearing.

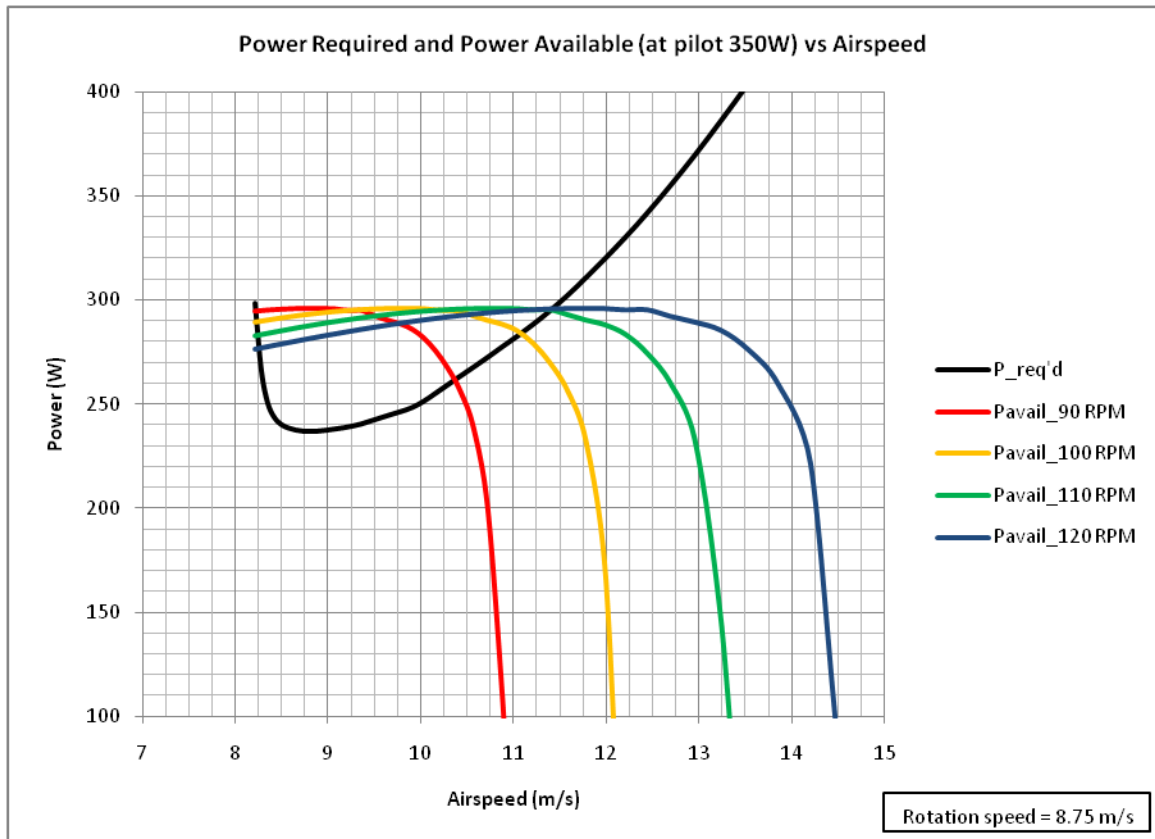


Figure 19: Aircraft power available and required

Tentatively, a propeller RPM of 110 was selected, yielding the following power-to-climb curve as shown in Figure 20.

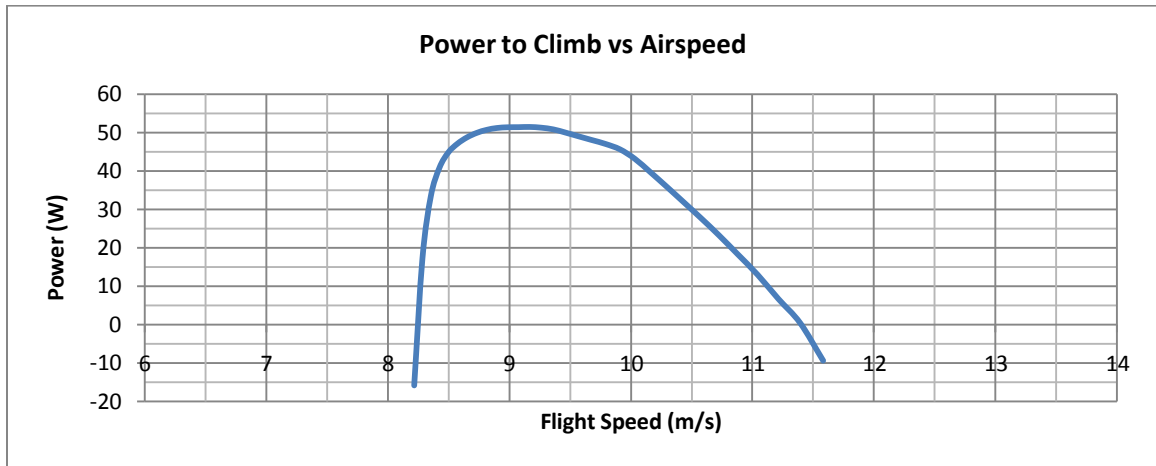


Figure 20: Power to climb vs airspeed

Based on the drag and power analysis, several key points of operation were selected, as shown in Table 2.

Table 2: Key HPA operational points (k=thousand)

| Speed (m/s) | Significance                         | Wing Re tip | Wing Re root | HT Re tip | HT Re root | VT Re tip | VT Re root |
|-------------|--------------------------------------|-------------|--------------|-----------|------------|-----------|------------|
| 8.2         | Stall speed                          | 275k        | 511k         | 214k      | 275k       | 247k      | 346k       |
| 8.75        | Rotation speed                       | 293k        | 545k         | 229k      | 293k       | 264k      | 369k       |
| 10.5        | Minimum mission-capable cruise speed | 352k        | 654k         | 274k      | 352k       | 317k      | 443k       |
| 11.0        | Medium cruise speed                  | 368k        | 685k         | 287k      | 368k       | 332k      | 464k       |
| 11.5        | Maximum cruise speed                 | 385k        | 716k         | 300k      | 385k       | 347k      | 485k       |

As predicted in Figure 20, a 350 W pilot does not have quite enough power to fly at the 11.5 m/s desired maximum cruise speed, though the mission is still very feasible.

## Chapter 4

### Analysis of Aircraft Operating Range and Requirement Generation

To design airfoils for the HPA, the first step was to map out the design space in terms of what  $c_l$  ranges were required for any given point of operation as defined by Table 2. Structural requirements for the aerodynamic surfaces are also quantified in this section.

#### Structural considerations

The structural design of the HPA calls for pre-preg carbon tubes which are currently being built in the sailplane laboratory. Pre-preg carbon fiber is rolled onto polished aluminum mandrels and baked in an electric oven for a few hours to cure the carbon. An image of students working on the tube is shown in Figure 21.



**Figure 21: Students manufacturing carbon fiber tube**

The manufacturing process yields strong, lightweight, and easily-customizable tubes but has a few drawbacks. The biggest drawback, which presents a challenge to airfoil design, is that the mandrels only come in certain sizes. Therefore, there is a minimum spar thickness for which the airfoils should be designed in order to use this manufacturing technique.

## Vertical Tail

### Structure

The smallest mandrel available is 1.125" in diameter. In order to have the spar extend all the way to the wingtip and give room for balsa construction around the spar, the airfoil must be at least 9.2% thick, as shown in Figure 22.

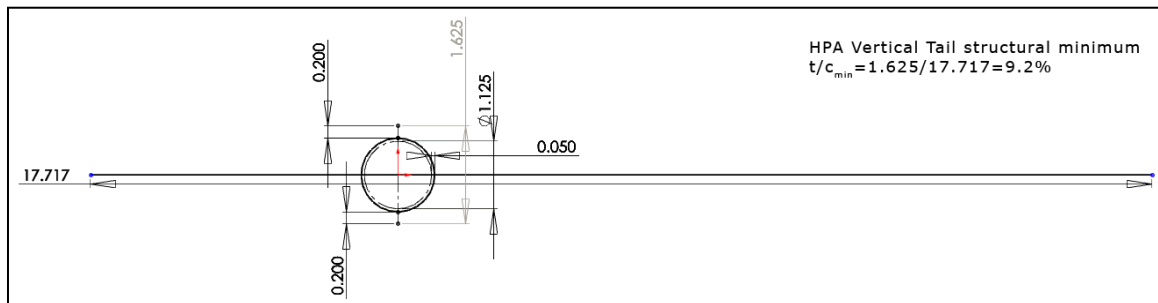


Figure 22: Vertical tail airfoil structural envelope

### Aerodynamics

When the vertical tail planform was sized, it was assumed that the maximum  $c_l$  for the airfoil at any point in the operating envelope would be 1.0. It was also important to have an airfoil that would be “docile” and “forgiving” so that the pilot would not be suddenly presented with high drag during a turn. Therefore, it was determined that the VT airfoil should have a rounded drag polar, as shown in Figure 23.

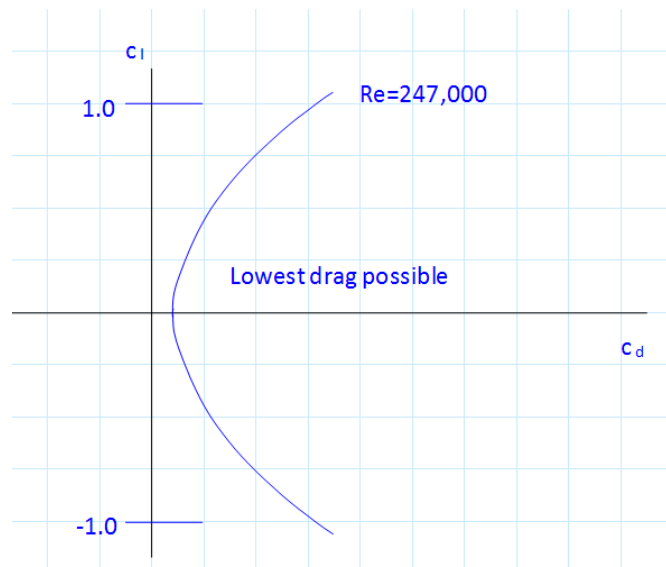


Figure 23: Desired drag polar for VT

## Horizontal Tail

### Structure

The same mandrel (1.125" in diameter) can be used for the horizontal tail. However, because the horizontal tail tip chord is shorter than the vertical tail tip chord, the airfoil must be thicker (10.6% thick), as shown in Figure 24.

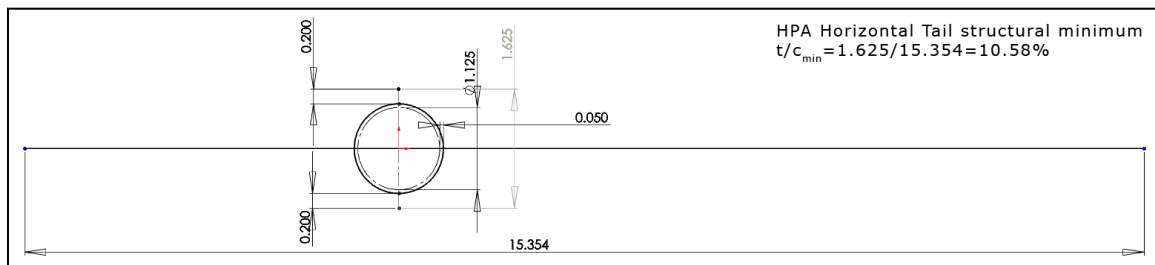


Figure 24: Horizontal tail airfoil structural envelope

Due to this minimum thickness, the S9026 airfoil (9.5% thick) originally selected for the horizontal tail was found to be unfeasible.

## Aerodynamics

The aircraft is designed so that the trim drag at the cruise speed of 11 m/s is zero. With the stability and control sizing conducted by Quindlen, trim calculations for the aircraft show that it should cruise with a  $c_L$  that ranges from 0.2 to -0.1 (+ meaning nose-down for the aircraft and – meaning nose-up). Of course, given more realistic conditions and dynamic motion of the aircraft, it is necessary to have an airfoil that performs in a wider range to provide ample tail authority.

A  $c_{Lmax}$  of +/- 1.0 was chosen as target specifications for this airfoil with a laminar drag bucket that extends from +0.3 to -0.3. The airfoil should exit the drag bucket softly. A desired polar is shown below in Figure 25.

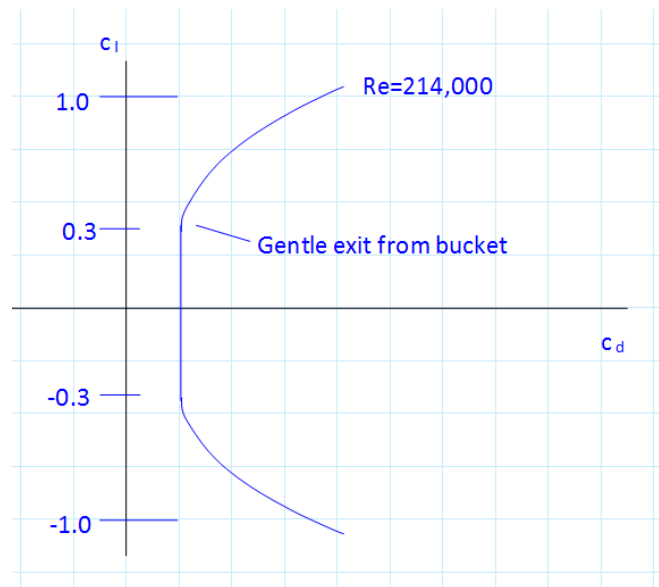


Figure 25: Desired drag polar for HT

## Wing

### Structure

The largest mandrel available is 3.5” in diameter. Given that changing to a smaller mandrel will necessarily increase weight, it was decided that the wing airfoil should conform to this size, yielding a minimum wing airfoil thickness of 12.3% as shown in Figure 26. The

thickness was sized at the wing root but the planform and spar tubes are designed so that the wing never requires a thicker section than at the root.

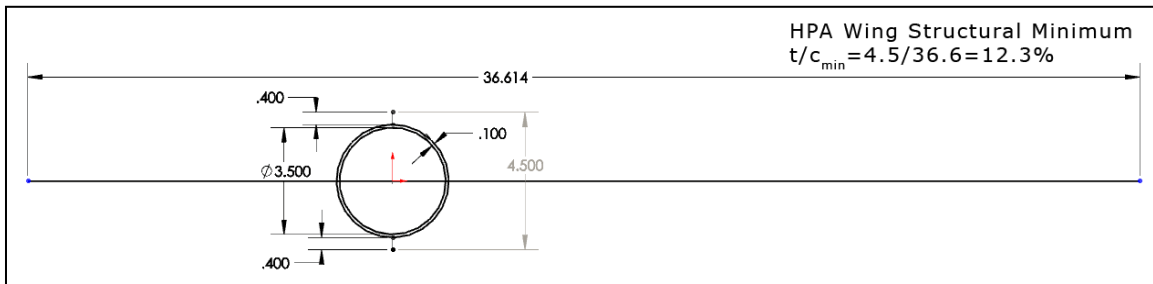


Figure 26: Wing airfoil structural envelope

## Aerodynamics

Because the wing's effect on the drag of the aircraft is so large, special care was taken to map out the  $Re$  and  $c_l$ s required for flight. A QFLR5 3-D panel method (with pressure data populated by XFOIL) analysis was used to determine the  $c_l$  vs span for various important points of operation as defined by Table 2. A plot of  $c_l$  vs span is shown in Figure 27.

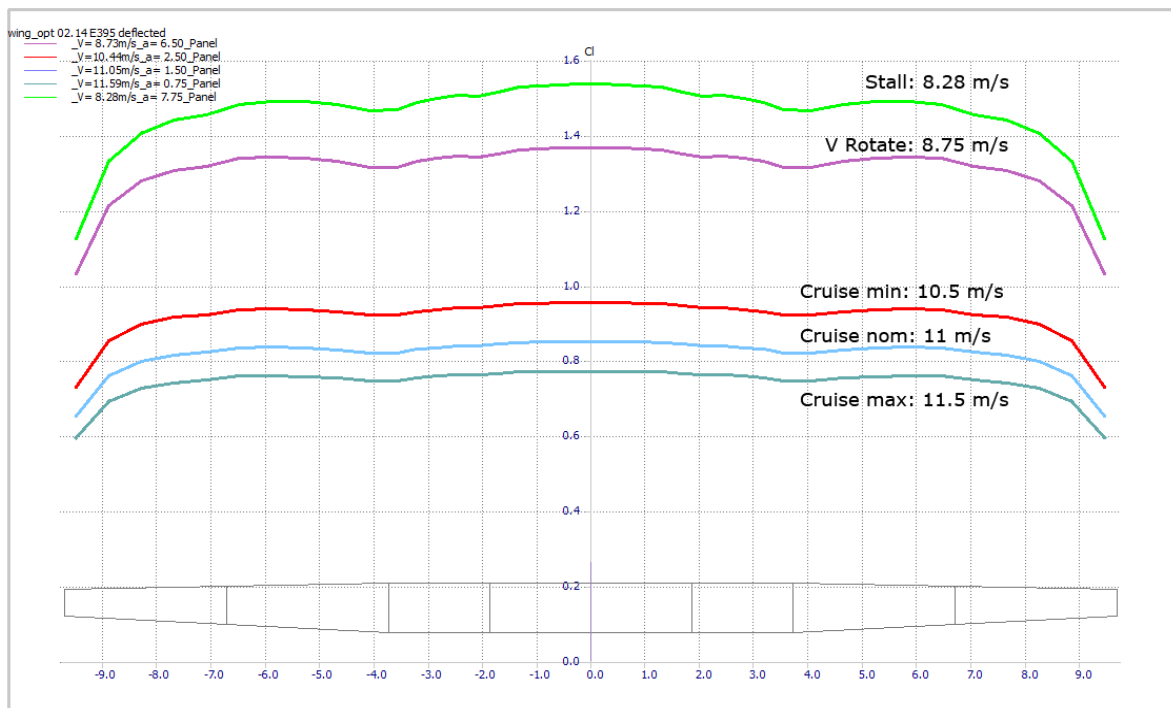


Figure 27:  $c_l$  vs span and flight speed of HPA wing

Because these operating points occur at different speeds and chords (and therefore  $Re$ ), the  $c_l$  vs  $Re$  were also calculated and plotted (in Figure 28) to provide a more comprehensive look at the operational range of the wing airfoil.

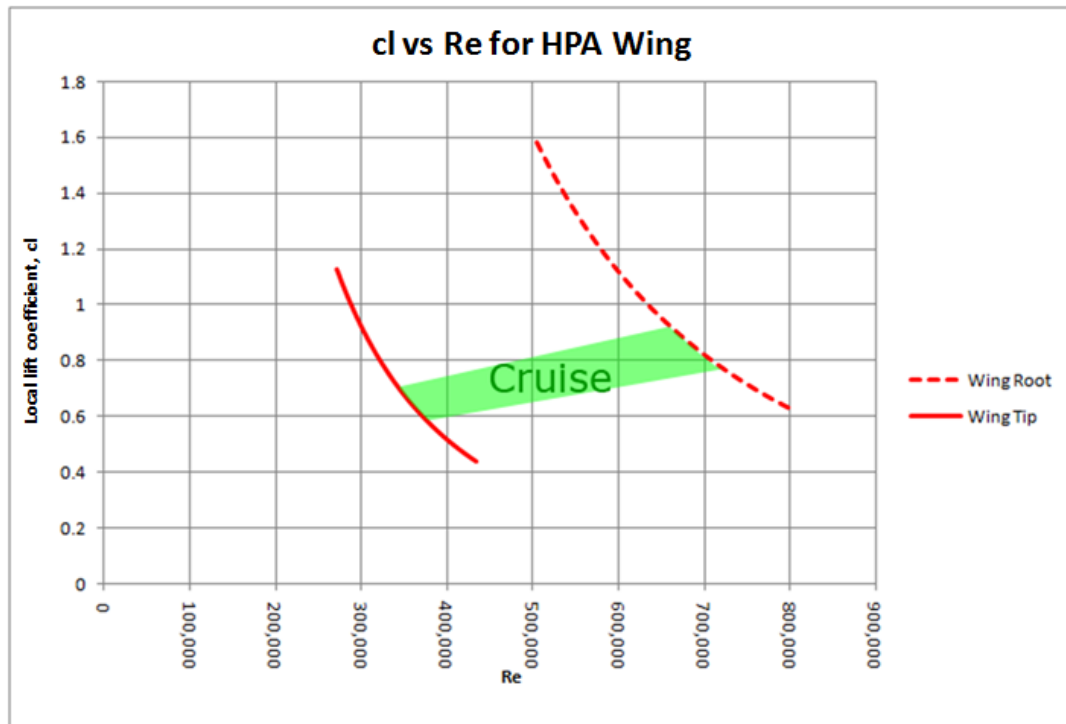


Figure 28:  $c_l$  and  $Re$  envelope for wing airfoil

To make handling better for the pilot, it was decided that the drag bucket should be rounded on the upper side so that the aircraft drag does not increase quickly as the pilot performs low-speed maneuvers or when the pilot tries to land. The lower corner of the drag bucket was set to be 0.5 or lower (to give a margin from the  $c_l=0.6$  necessary). The bottom of the bucket can be exited sharply because the aircraft would never fly at those speeds and therefore would not need the capability (to give the airfoil such a capability costs drag). A summary of the desired polar is shown in Figure 29

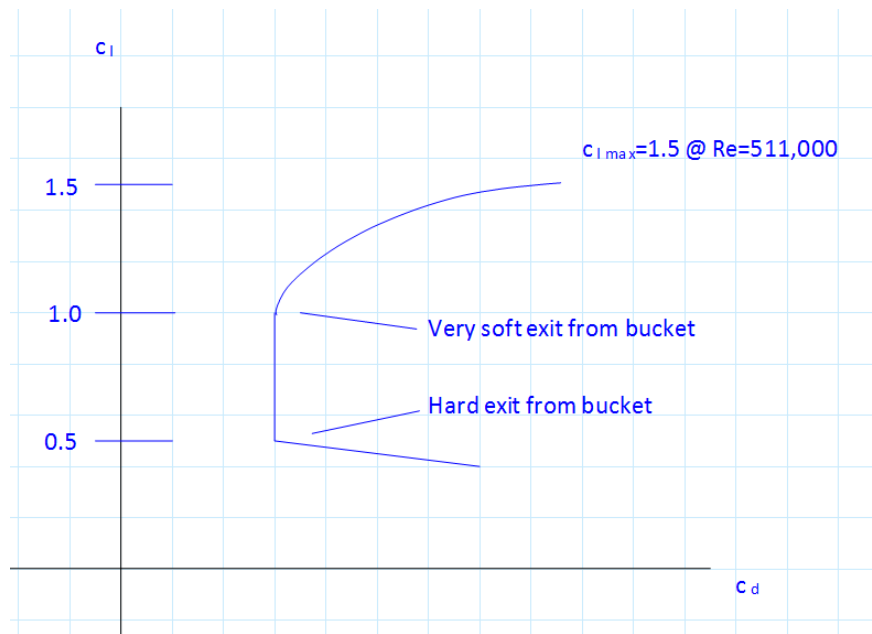


Figure 29: Desired drag polar for wing

## Chapter 5

### Airfoil Design

The airfoils are designed based on the requirements for the wing, HT, and VT airfoils generated in the previous section.

#### Foreword

The topic of airfoil design is a tricky one. Unlike other engineering disciplines (such as computer coding) that follow a linear path from requirement to product, airfoil design is much more (no pun intended) fluid because there are many interdependencies and nuances in the flowfield for which one needs to account. No sufficiently intelligent, efficient, or comprehensive automation exists for such a complex design space as this (Maughmer, AERSP 425 lecture, 2009).

To paraphrase Maughmer, one designs an airfoil like the way an artist creates a clay sculpture. First, the main features are created (laminar flow region, recovery region, etc). Then, the designer must make adjustments while considering the physics of the flow (How adverse of a pressure gradient can exist before premature separation? How far can the airfoil be aft-loaded before the pitching moment is too high? Etc.)

As in sculpture, the first lines drawn are only the rough starting point and are rarely kept in the finalized version. Unlike sculpture, the change of one section of the airfoil will usually alter the performance in another part of the operational range; leading to a situation akin to “squeezing Jell-O” until a satisfactory solution is found.

While the design work is complex, several general rules of thumb are useful. First, a drag bucket’s depth is inversely proportional to its width. Second, a drag bucket’s vertical location on a drag polar is related directly to its camber; a highly-cambered airfoil will have a drag bucket higher in  $c_l$  than one with lower camber. Third, a thin airfoil will have less drag than a thicker one. These rules break down in cases of extremely high camber or extremely thick airfoils.

### The Eppler Airfoil Design Code PROFIL

The PROFIL program was created by Dr. Richard Eppler and has been developed over the past 50 years. Version 2007 was used for the airfoil designs in this project. The Eppler code works via a conformal mapping of a circle to an airfoil where various specified arcs of the circle correspond to respective neutral pressure gradients at respective angles of attack from the zero-lift angle of attack. Because the airfoil geometry does not change and the angles themselves define how far away they are from the zero-lift angle, the system is fully defined and the actual values of the pressure coefficients are not defined by the user. (Eppler, Airfoil Design and Data, 1990)

Because various arcs of the circle are defined separate in angle from each other, it would be purely accidental if the airfoil were able to close. Therefore, another line iterates for a pressure recovery and trailing edge closure-condition that allows the airfoil to become a simply-closed shape. An illustration of the system is shown below in Figure 30 and Figure 31 (Eppler, Airfoil Design and Data, 1990).

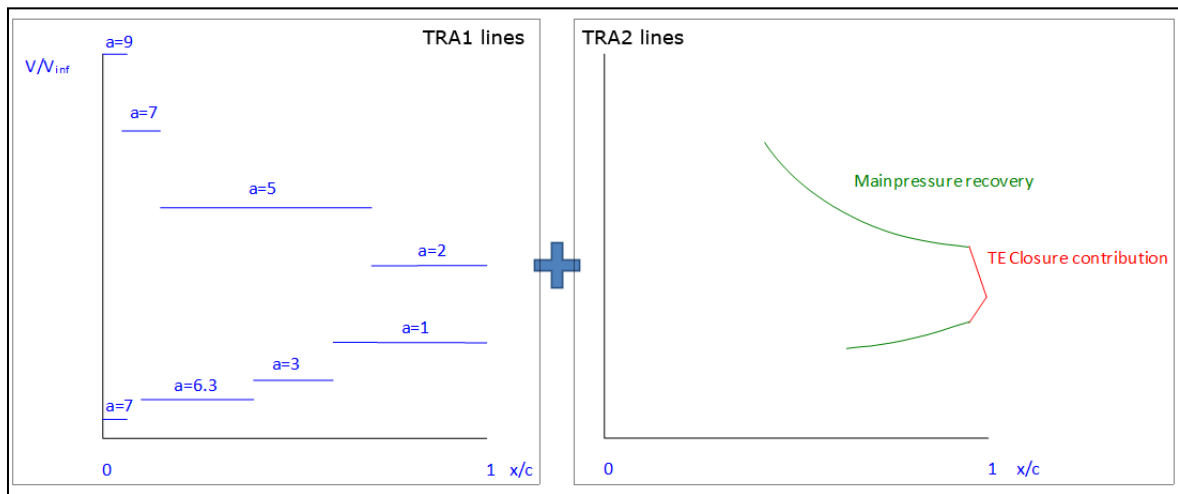
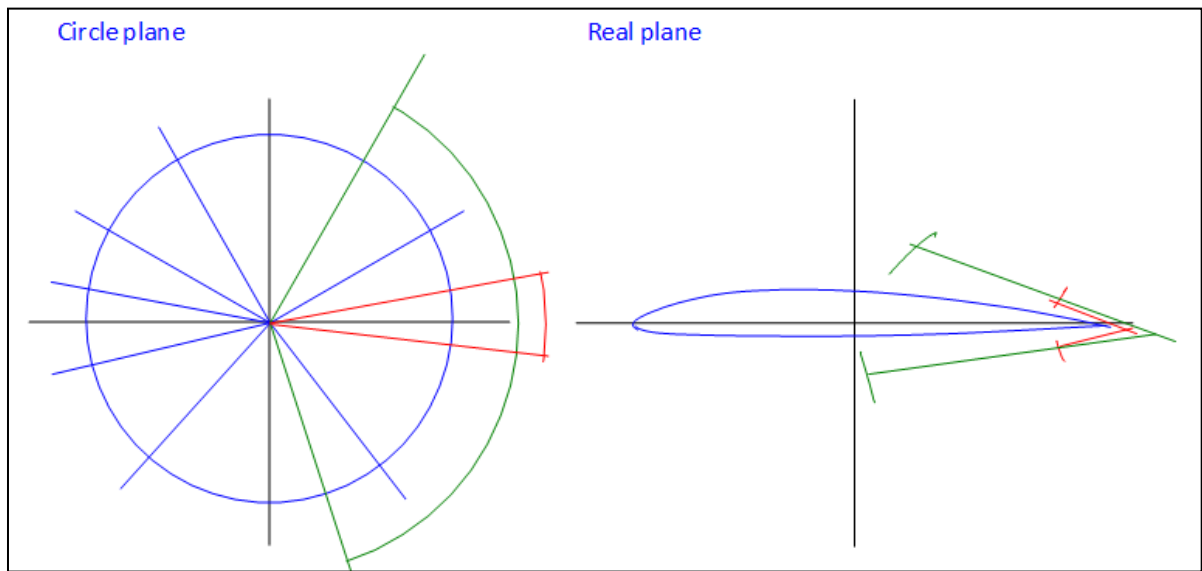


Figure 30: Eppler design lines

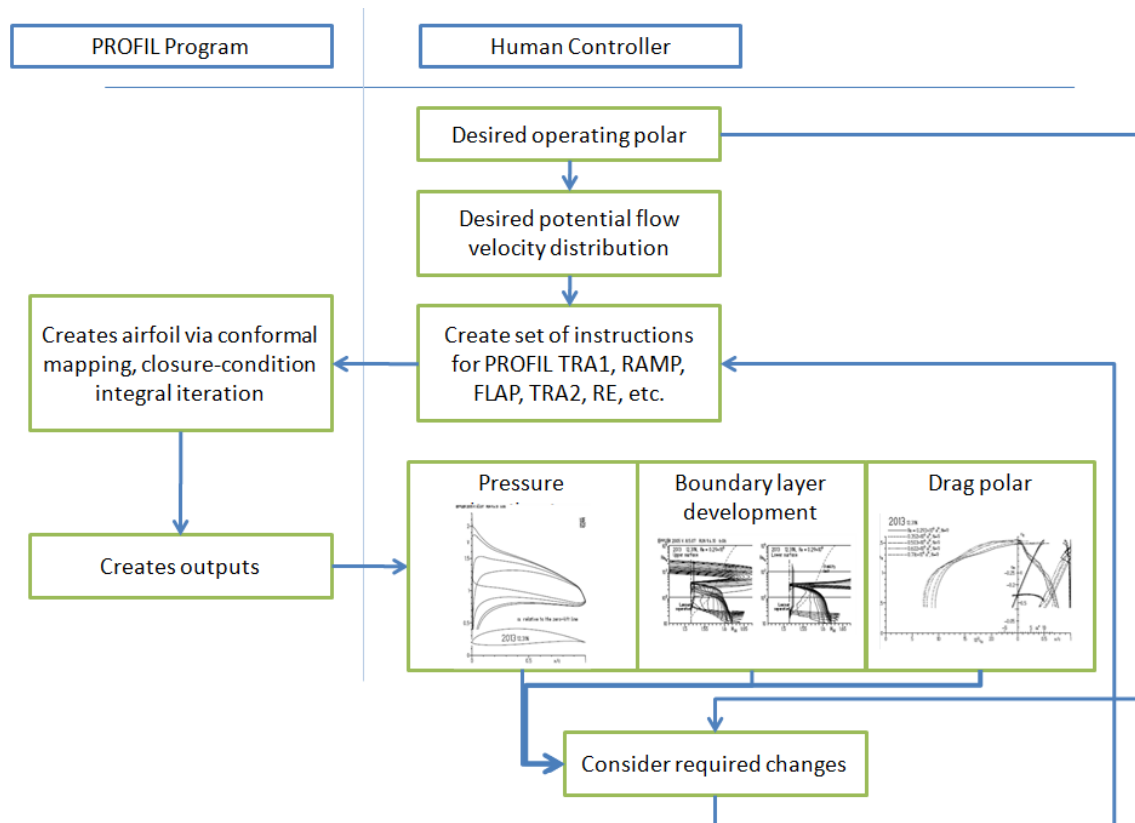


**Figure 31: Circle plane and resulting airfoil shape**

Other lines specify other features and functions such as transition ramps, flaps, cascades, and analysis modes (Eppler, Airfoil Program System "PROFIL06" User's Guide, 2006).

## Design Methodology

Airfoil design in PROFIL is conducted with a human-in-the-loop iterative process as illustrated in Figure 32 (Maughmer, AERSP 425 lecture, 2009).



**Figure 32: PROFIL program and human-in-loop iteration loop**

As shown in the figure above, the designer considers the problem and decides what kind of pressure distribution would yield the desired results. The designer then specifies command lines to try and capture the desired distribution and submits them to the program along with a requested list of feedback data. The program returns results, warnings, and plots which are post-processed and viewed by the designer. The designer then diagnoses the results and considers the physics of the flow to decide what in the original set of command lines should be changed to move the airfoil toward the desired goals. This loop is a highly involved iterative process where many hundreds of sets of instructions may be tested before the results are able to meet the requirements for the airfoil. In the following airfoils, a “major” iteration may involve 20 or so smaller iterations and attempts to move the pressure gradients to their desired locations.

## Designed Airfoils

### Vertical Tail Airfoil

The final (21<sup>st</sup>) major iteration yielded the V21 airfoil. Its shape and pressure distributions for several angles of attack are shown in Figure 33.

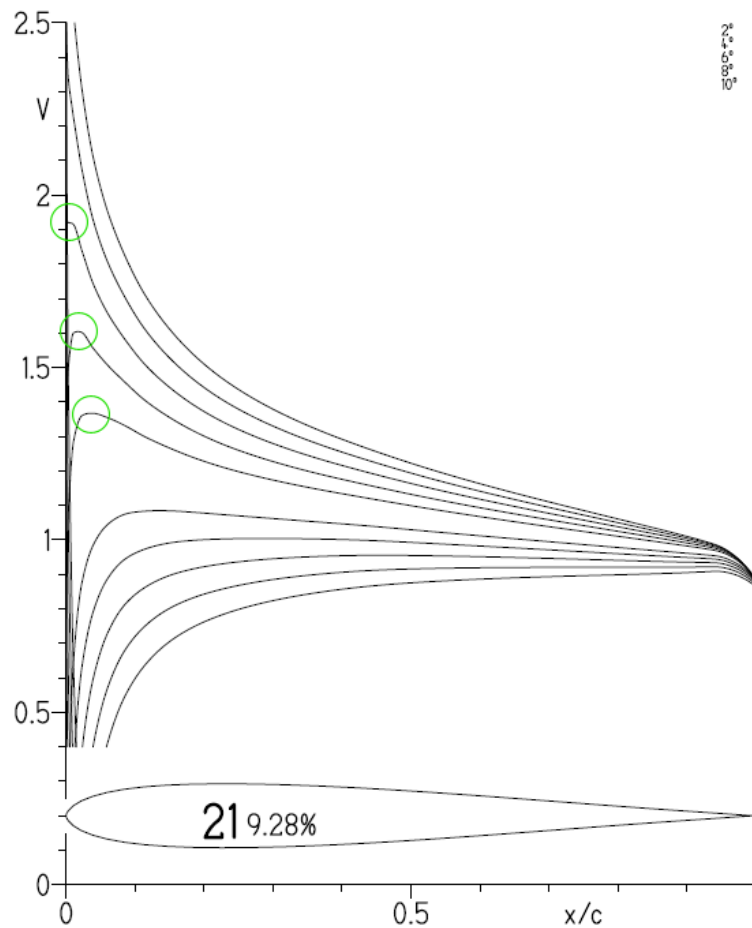


Figure 33: The V21 airfoil for the vertical tail

The V21 airfoil was designed to minimize drag by being as thin as possible (up to the minimum required 9.2% thickness) while maintaining a  $c_{lmax}$  as high as possible up to  $\pm 1.0$ . The airfoil was designed with low Re effects in mind; at the low local Re near the leading edge of the airfoil, the flow will stay laminar even in a moderately adverse pressure gradient. After the initial increase in pressure, the pressure recover is made smooth to maintain laminar flow for as long as

possible. Thin airfoils generate high lift by producing a large pressure spikes near the leading edge; these spikes would cause flow separation at an angle of a few degrees. These pressure spikes were suppressed by specifying a neutral pressure gradient at a high  $\alpha$  (circled in green in Figure 33), yielding the rounded leading edge that allows the airfoil to obtain higher  $\alpha$ s and  $c_l$ s.

The airfoil's performance was simulated in PROFIL for  $Re=317,000$ ,  $Re=400,000$ , and  $Re=485,000$ . These points correspond to the minimum  $Re$  (tip at 10.5 m/s), maximum  $Re$  (root at 11.5 m/s) and a point in the middle. These results are compared against the S9026 airfoil in Figure 34 below.

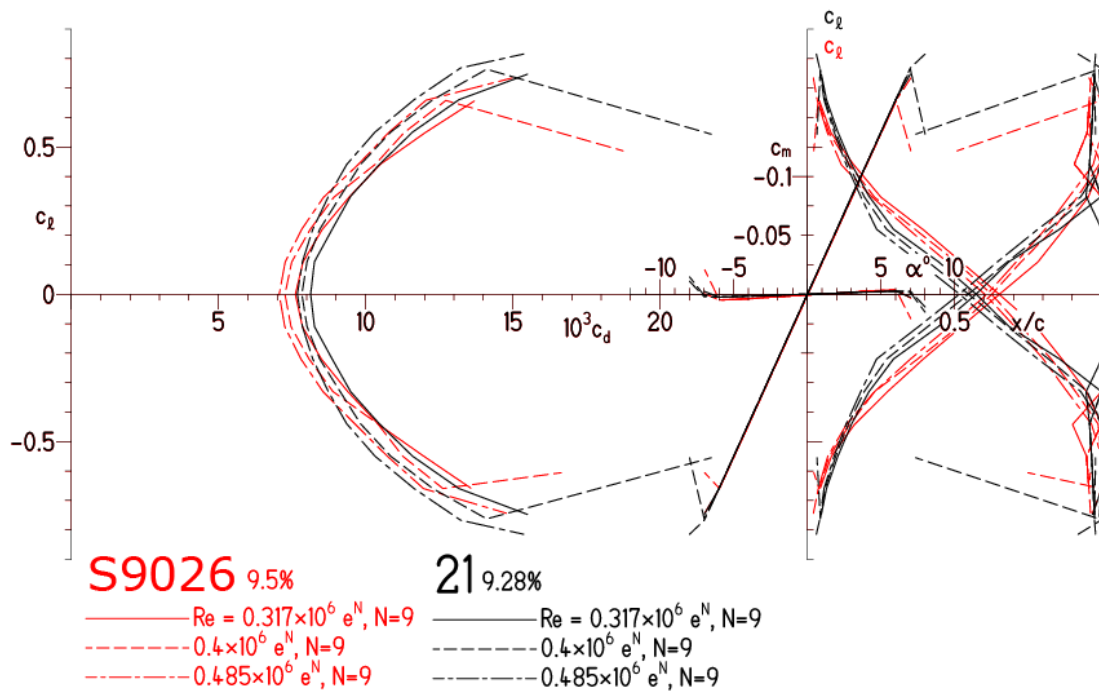


Figure 34: Vertical tali airfoil compared against S9026 airfoil

PROFIL predicts that the V21 airfoil stalls at a higher  $c_{lmax}$  than the S9026 by approximately 0.1 in all  $Re$ , yielding a  $c_{lmax}$  of 0.8 to 0.9. It predicts that the V21 will have slightly higher drag than the S9026 between  $c_l=-0.5$  to  $c_l=0.5$ , but will have less drag at  $c_l$ s higher than 0.5 or lower than -0.5.

The two airfoils were also compared in XFOIL alongside an NACA 4-series symmetrical airfoil scaled to 9.28%. The results are shown in Figure 35 through Figure 37 below. XFOIL predicts nearly the same results with the S9026 having slightly less drag until  $c_l=\pm 0.5$ , at which point the V21 has noticeably less drag. XFOIL also predicts that the V21 will have a higher  $c_{lmax}$

of approximately 1.2, which is higher than the S9026. The NACA airfoil has higher drag than both the V21 and S9026.

Since the results from both simulations are consistent, it can be expected that the V21 airfoil would have slightly higher drag than the S9026 with no deflection, but at higher levels of deflection (above  $c_i=0.5$ ), the V21 will have lower drag. Since the value of  $c_{lmax}$  is difficult to predict using software, and XFOIL is known to overpredict  $c_{lmax}$  (Maughmer, AERSP 404H Lecture, 2009), the only conclusion could be that the V21 has a higher  $c_{lmax}$  but its value may not reach the  $c_{lmax}=1.0$  target.

In summary, the V21 successfully meets the structural requirements and is predicted to have lower drag than the baseline airfoil at high deflections. The value of  $c_{lmax}$ , though, may not reach the required value, though it should be higher than what can be achieved with the S9026.

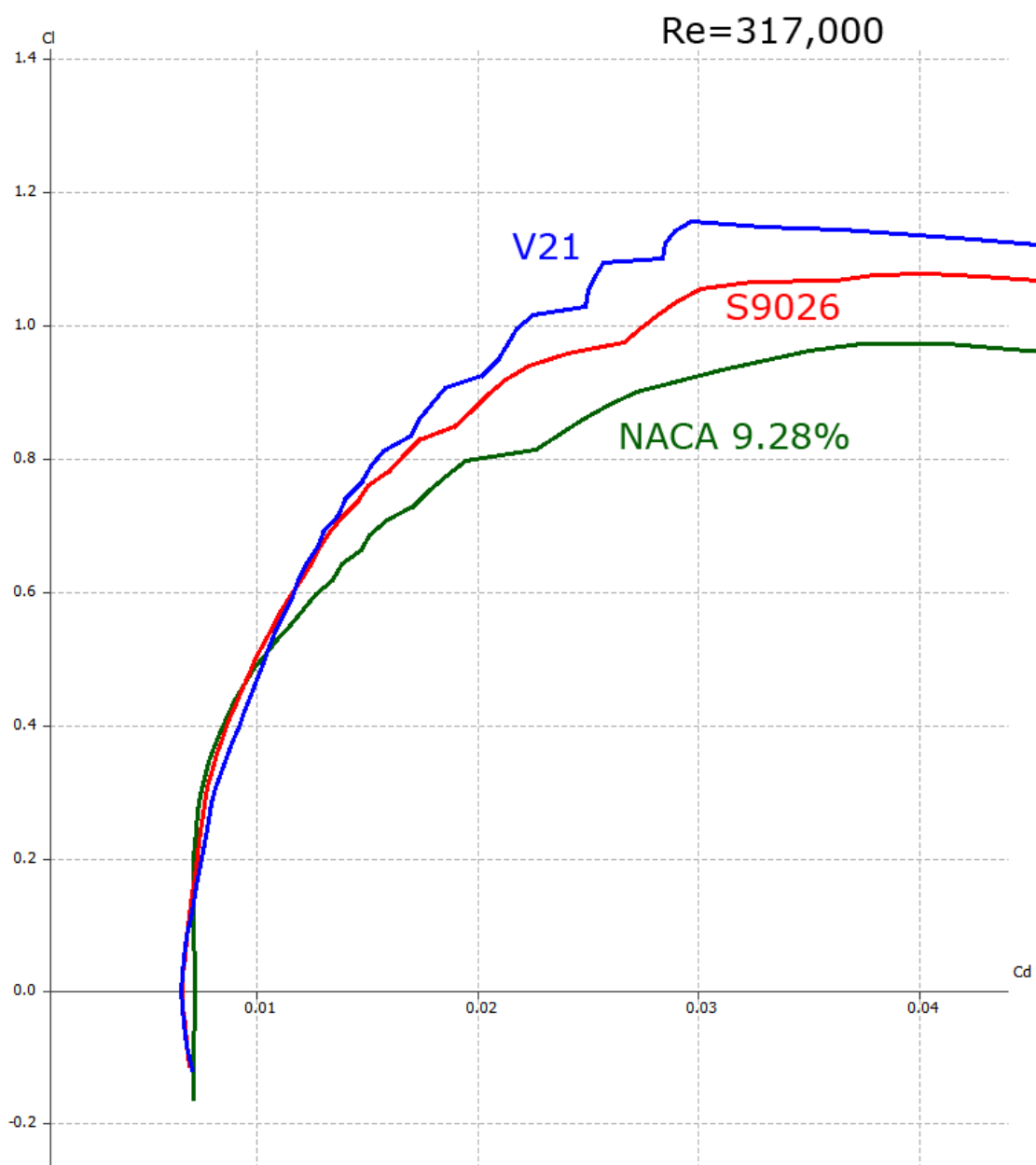


Figure 35: V21, S9026, NACA 9.28% compared Re=385k

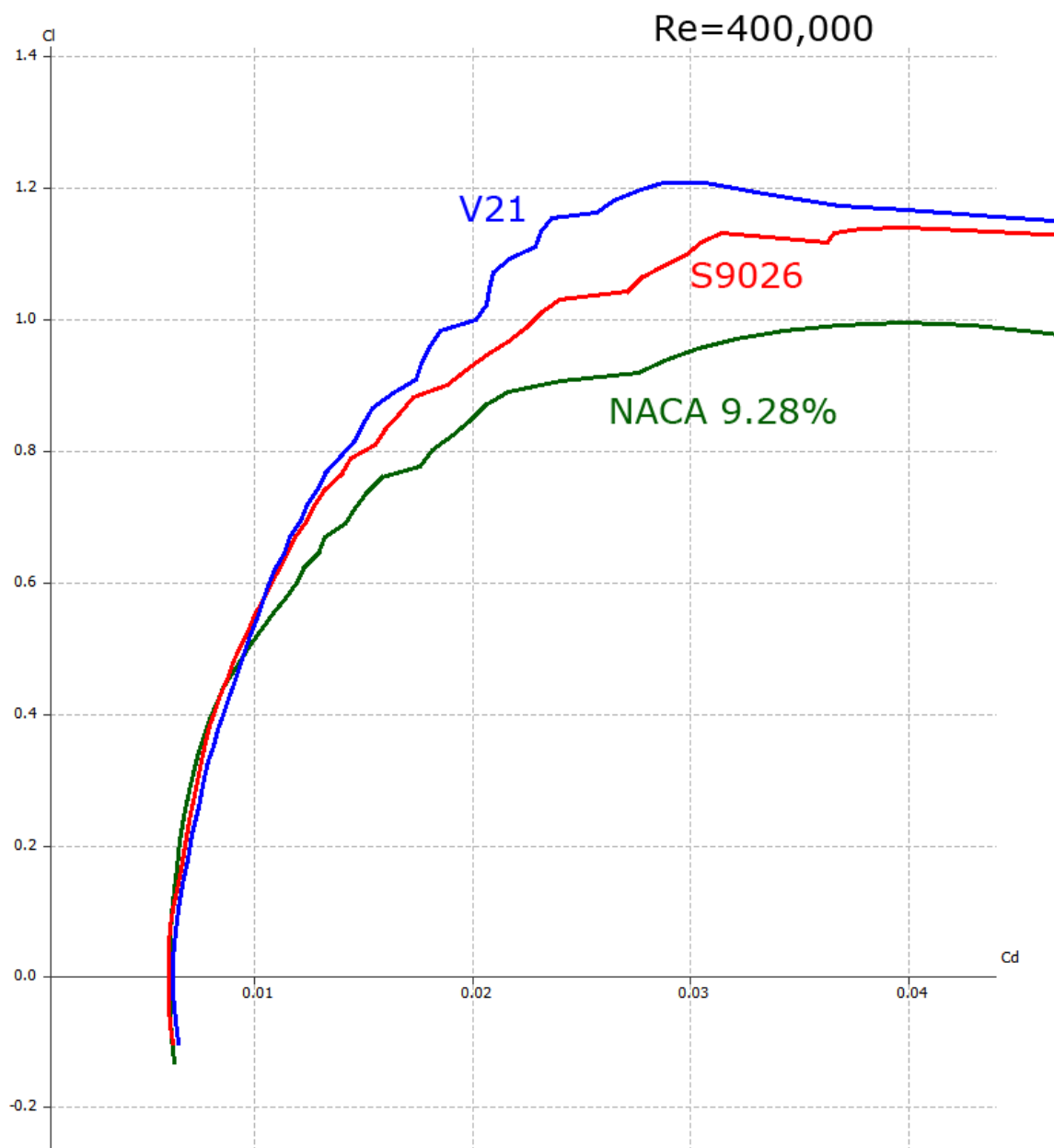


Figure 36: V21, S9026, NACA 9.28% compared Re=400k

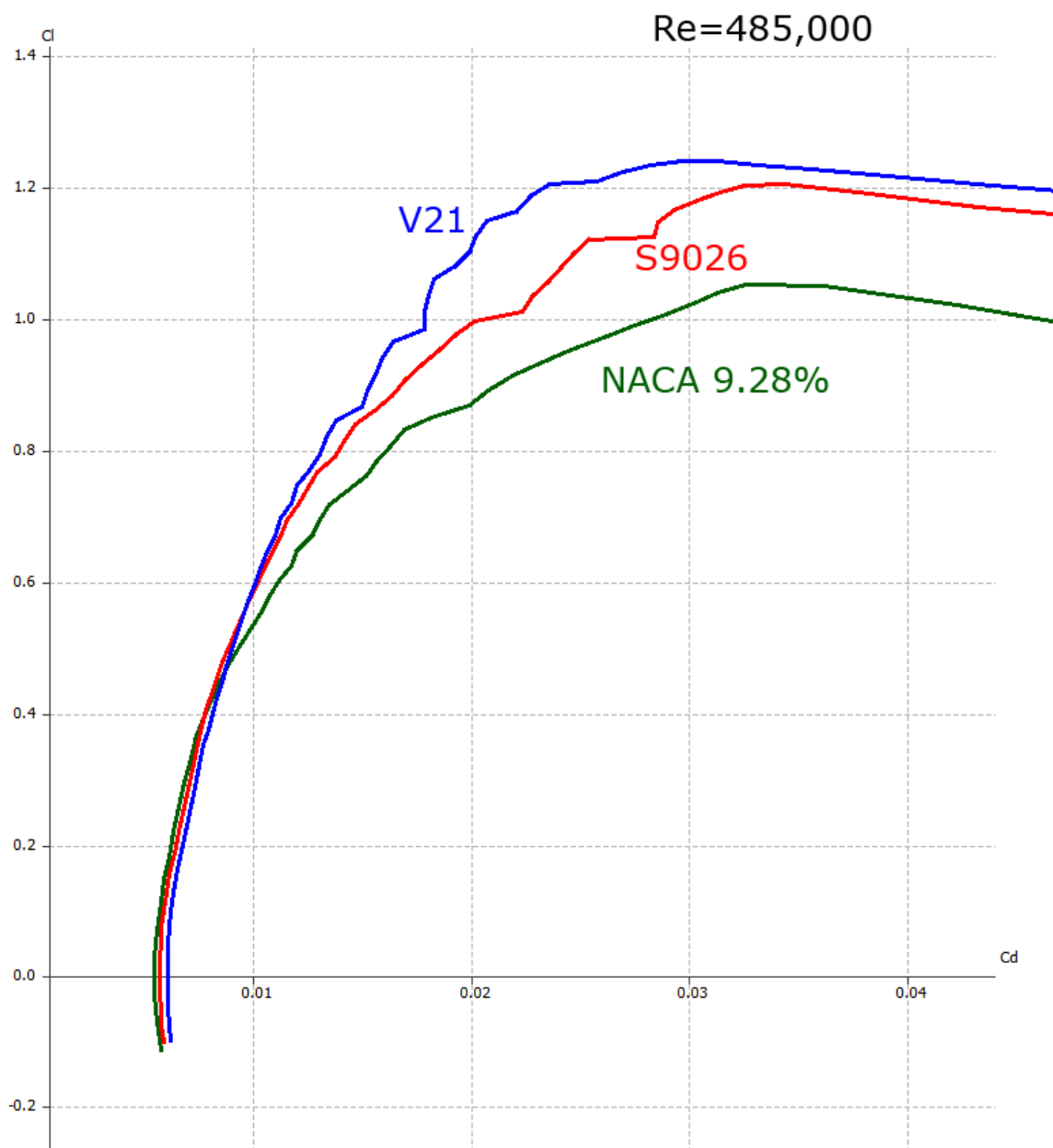


Figure 37: V21, S9026, NACA 9.28% compared Re=485k

## Horizontal Tail

The horizontal tail airfoil is a symmetric airfoil also designed keeping in mind low Re laminar flow. Laminar flow was maintained by having a weakly adverse gradient up to  $x/c=0.75$  corresponding to a bucket region of  $c_l=-0.3$  to  $0.3$ . A transition ramp was used to smoothly blend the forward region to the recovery region and to prevent laminar separation.

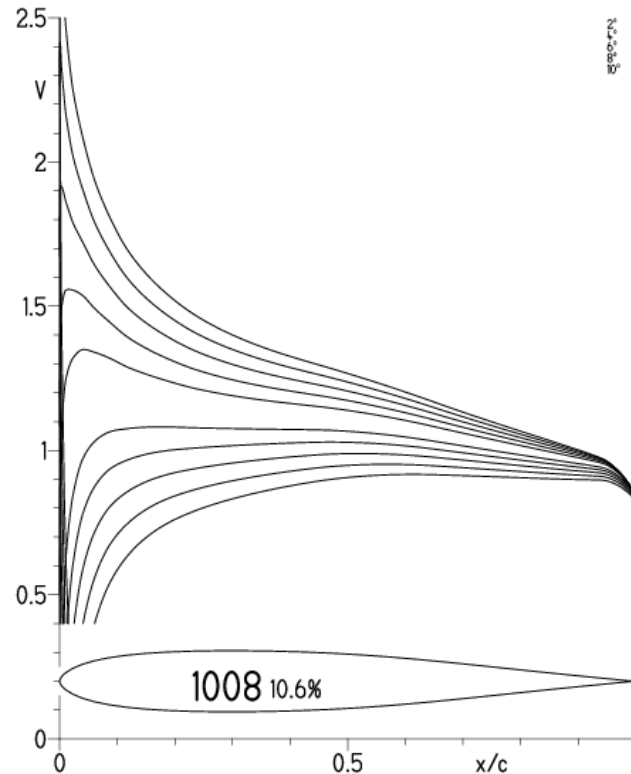


Figure 38: Horizontal tail airfoil H8

The airfoil was compared in PROFIL and XFOIL against an NACA 4-series airfoil scaled to 10.6% as a benchmark since, as discussed before, the structural requirements make the S9026 unfeasible for the HT airfoil.  $Re=274,000$  (the tip of the horizontal tail at the slowest cruise speed),  $Re 385,000$  (the root of the horizontal tail at the maximum cruise speed), and a point in the middle were analyzed. The results from the analysis are shown in the following figures.

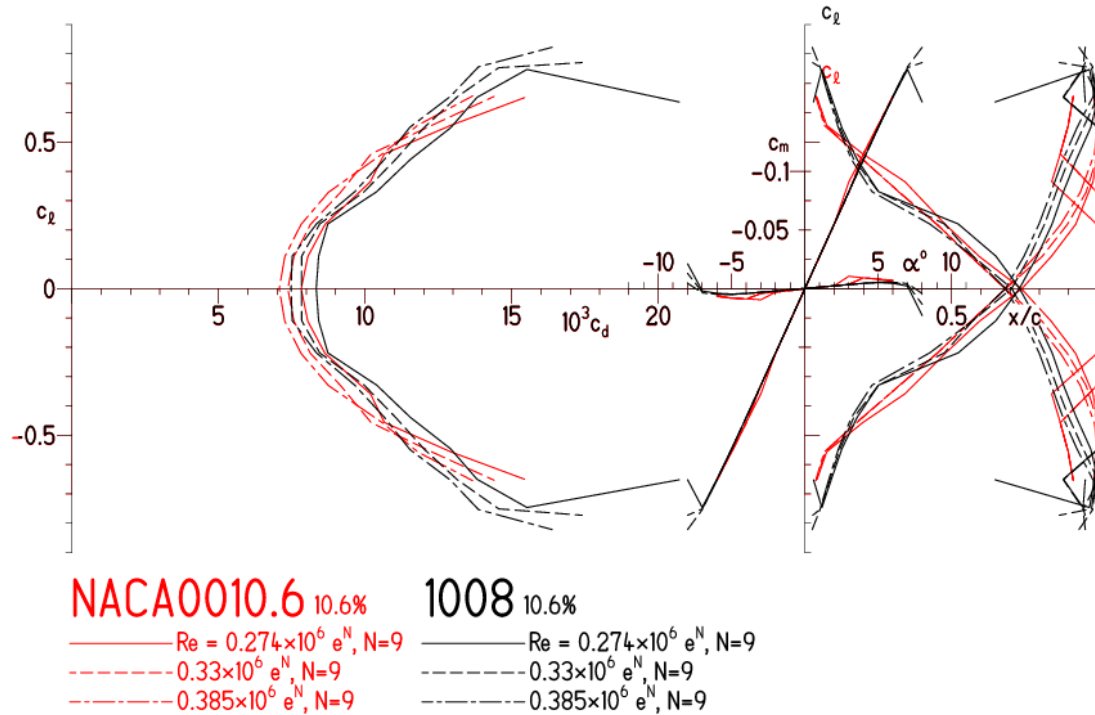


Figure 39: Horizontal tail airfoil (H8, or 1008) compared against scaled NACA airfoil

As shown in the PROFIL results in Figure 39 and the XFOIL results in Figure 40 through Figure 42, the H8 is consistently predicted to have lower drag at higher  $c_l$ s (above  $c_l=0.55$ ). PROFIL also predicts it to have a higher  $c_{lmax}$  than the NACA airfoil. PROFIL also predicts that the H8 airfoil will have less separated flow on the upper surface, as indicated on the right side of Figure 39 which causes some concerns about stall of the NACA airfoil. Unfortunately, the H8 airfoil is also predicted to have a higher drag coefficient at 0-deflection by about 6 counts.

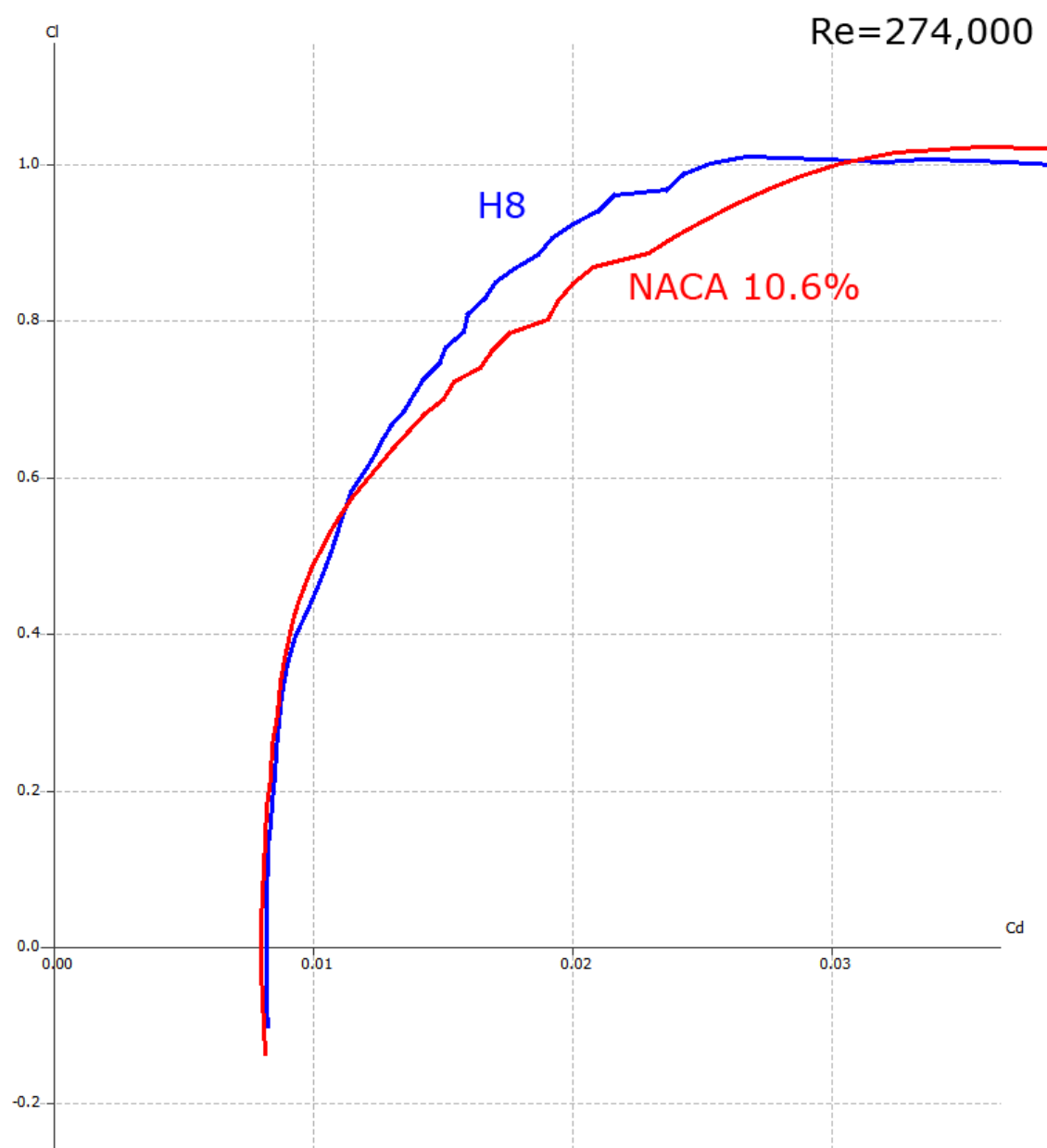


Figure 40: H8 compared against NACA 10.6% at Re=274k

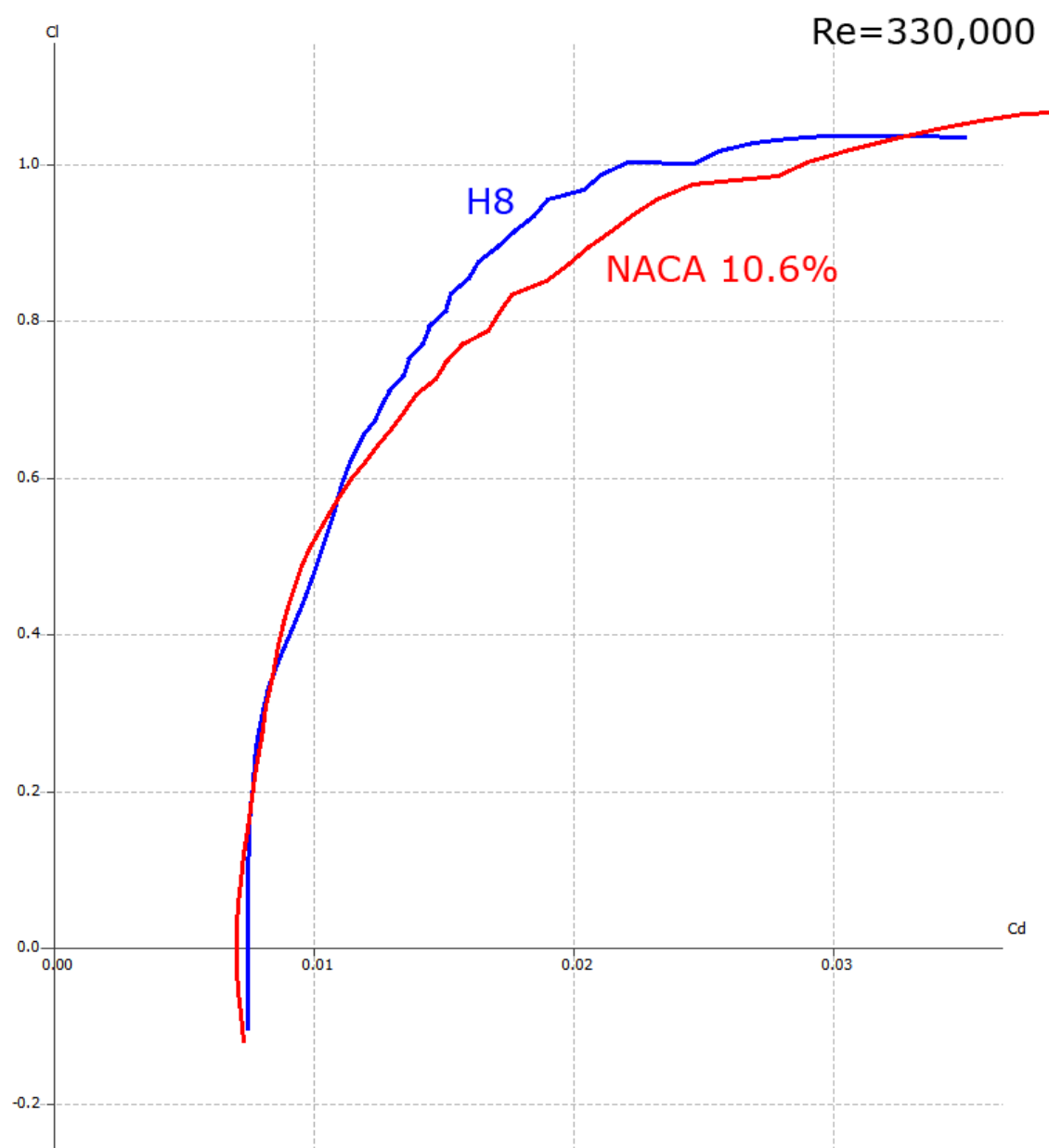


Figure 41: H8 compared against NACA 10.6% at Re=330k

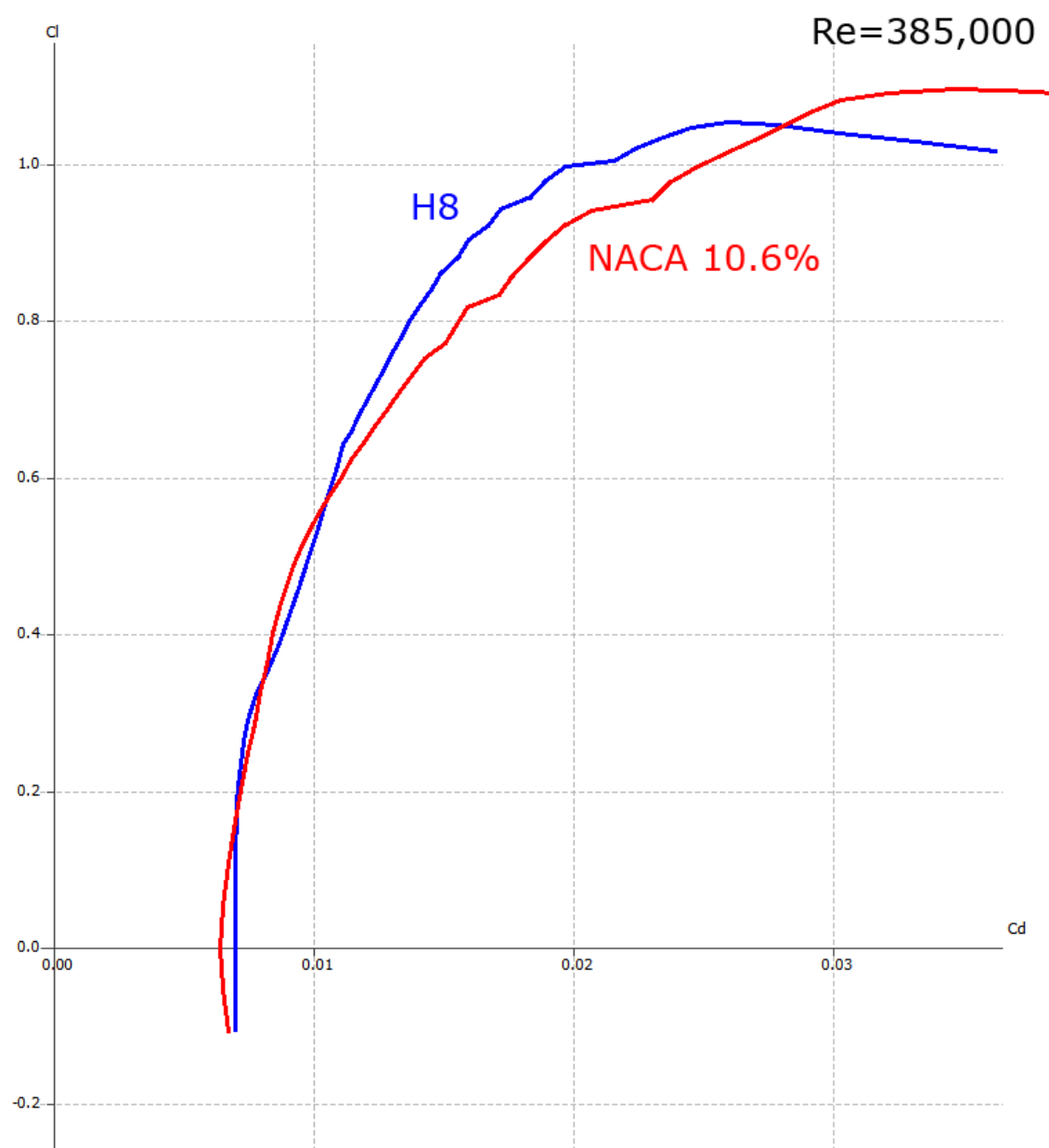


Figure 42: H8 compared against NACA 10.6 at  $Re=385k$

## Wing Airfoil

The wing airfoil was created to move the laminar drag bucket into the range defined in Figure 29 above so that the drag can be reduced in the cruise range. The finalized airfoil, the W13, is shown below in Figure 43.

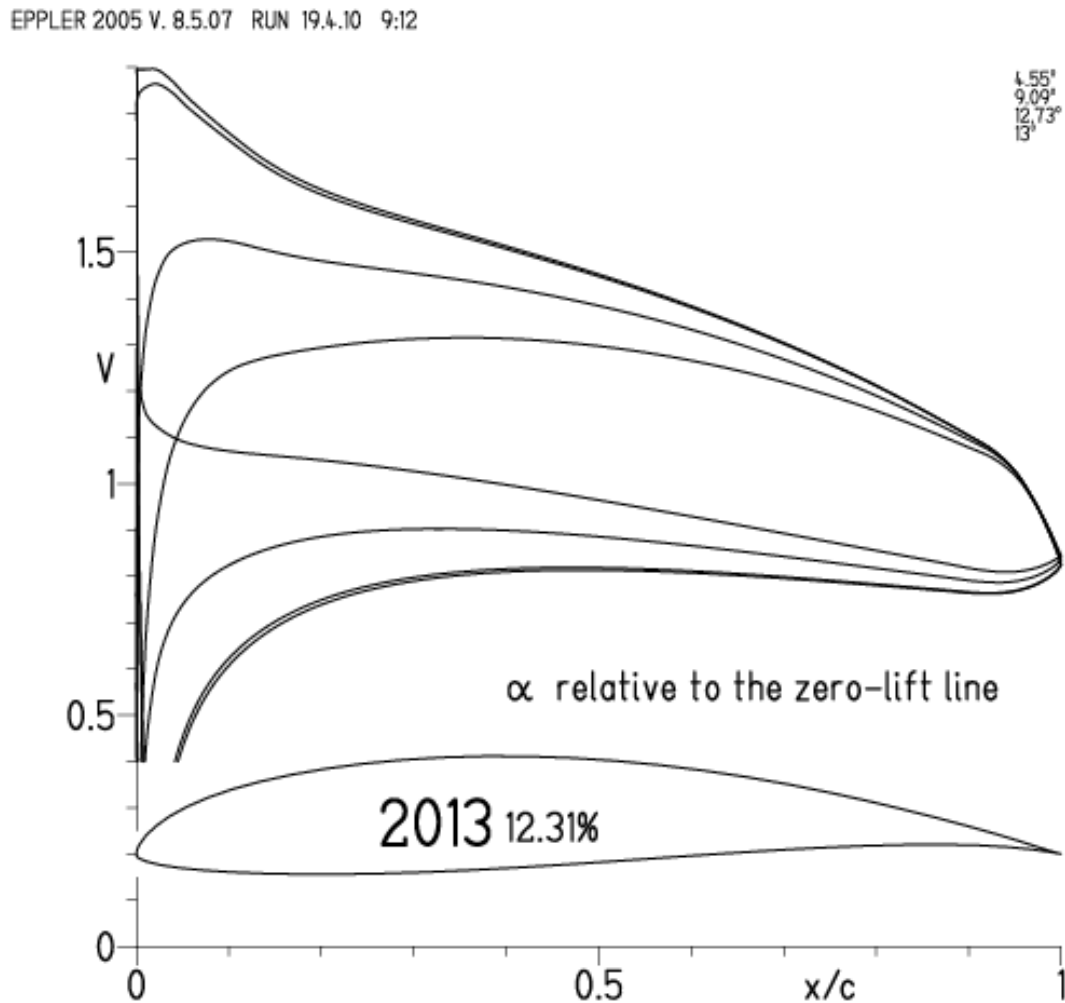


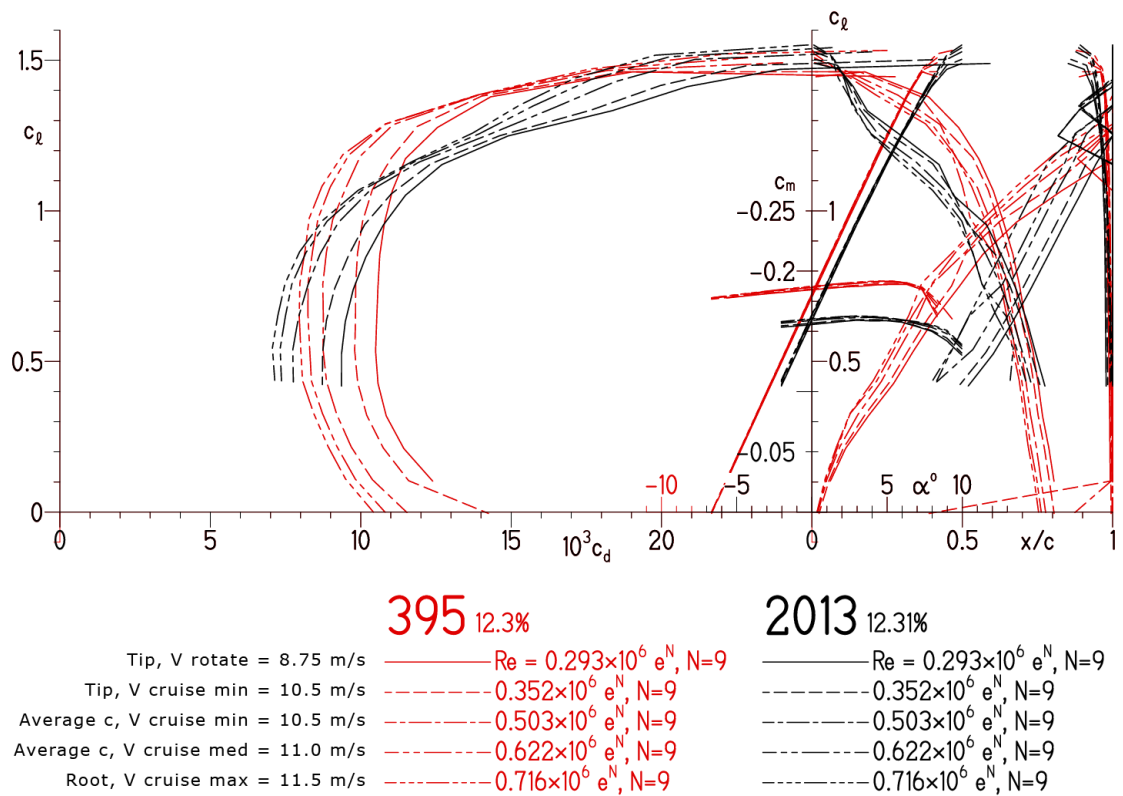
Figure 43: The W13 (or 2013) airfoil

The W13 airfoil was made to have a long, gentle pressure recovery on the upper surface to avoid a sharp top-corner of the bucket as was discussed before. Having this pressure recovery should cause the transition point to move forward slowly rather than abruptly. The lower surface pressure gradient is defined so that the drag bucket has a sharp corner at the bottom to deepen the drag bucket since the HPA should never fly fast enough to use those lower  $c_s$  (below 0.4). To

make sure the airfoil has equal or less pitching moment than the E395, the airfoil is more front-loaded than the E395, yielding a slightly adverse pressure gradient from  $x/c = 0.02$  to  $x/c = 0.2$ . However, due to the low-Re the airfoil will operate at, the flow remains stable and laminar.

The analysis for various Re corresponding to key points of the aircraft's operating envelope is shown below in Figure 44. The points and their corresponding significances are listed in Figure 44 as well as Table 2.

PROFIL and XFOIL both predict that the W13 airfoil has consistently lower drag than the E395 within the region of  $c_l=1.0$  to  $c_l=0.5$  and the operating Re of the HPA main wing. Much of the drag reduction can be attributed to the transition point on the lower surface, which is pushed backward as can be seen in both the PROFIL and XFOIL results. The W13 is also predicted to have less nose-down pitching moment than the E395 due to the way the pressures are distributed, as discussed above.



**Figure 44: PROFIL drag polars of E395 and 2013 compared**

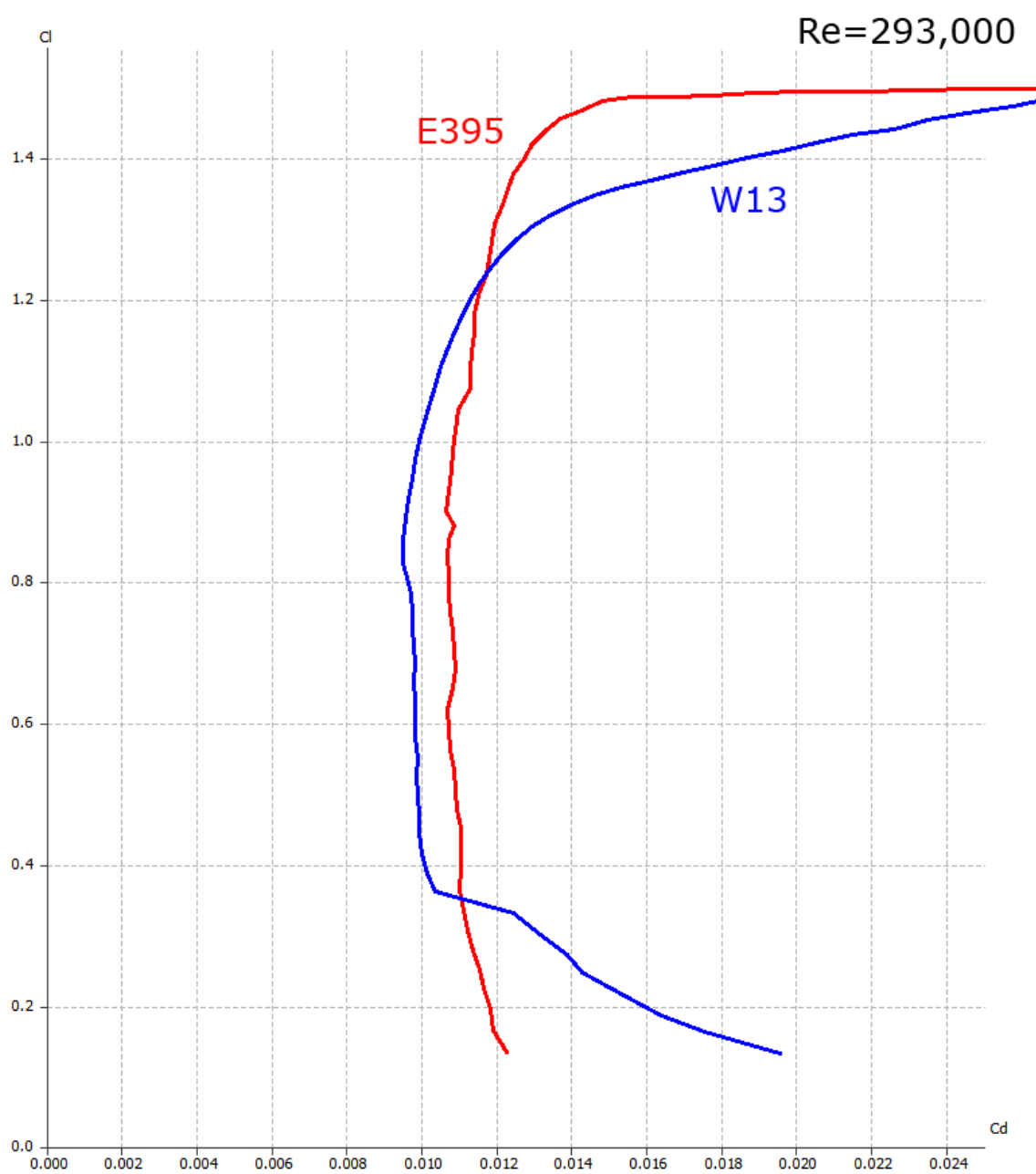


Figure 45: XFOIL drag polar of W13 compared against E395, Re=293k

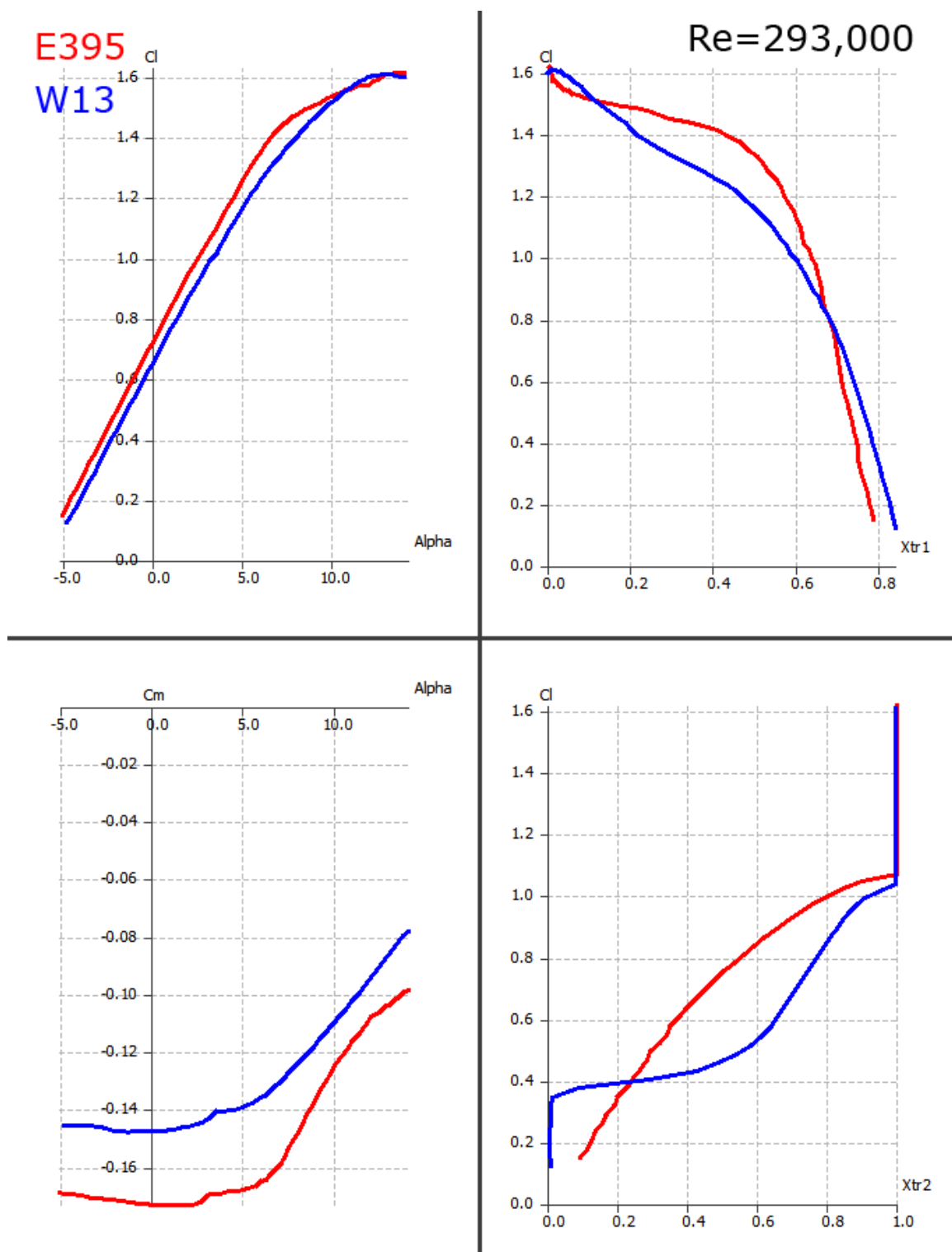


Figure 46: XFOIL results of W13 compared against E395,  $Re=293k$

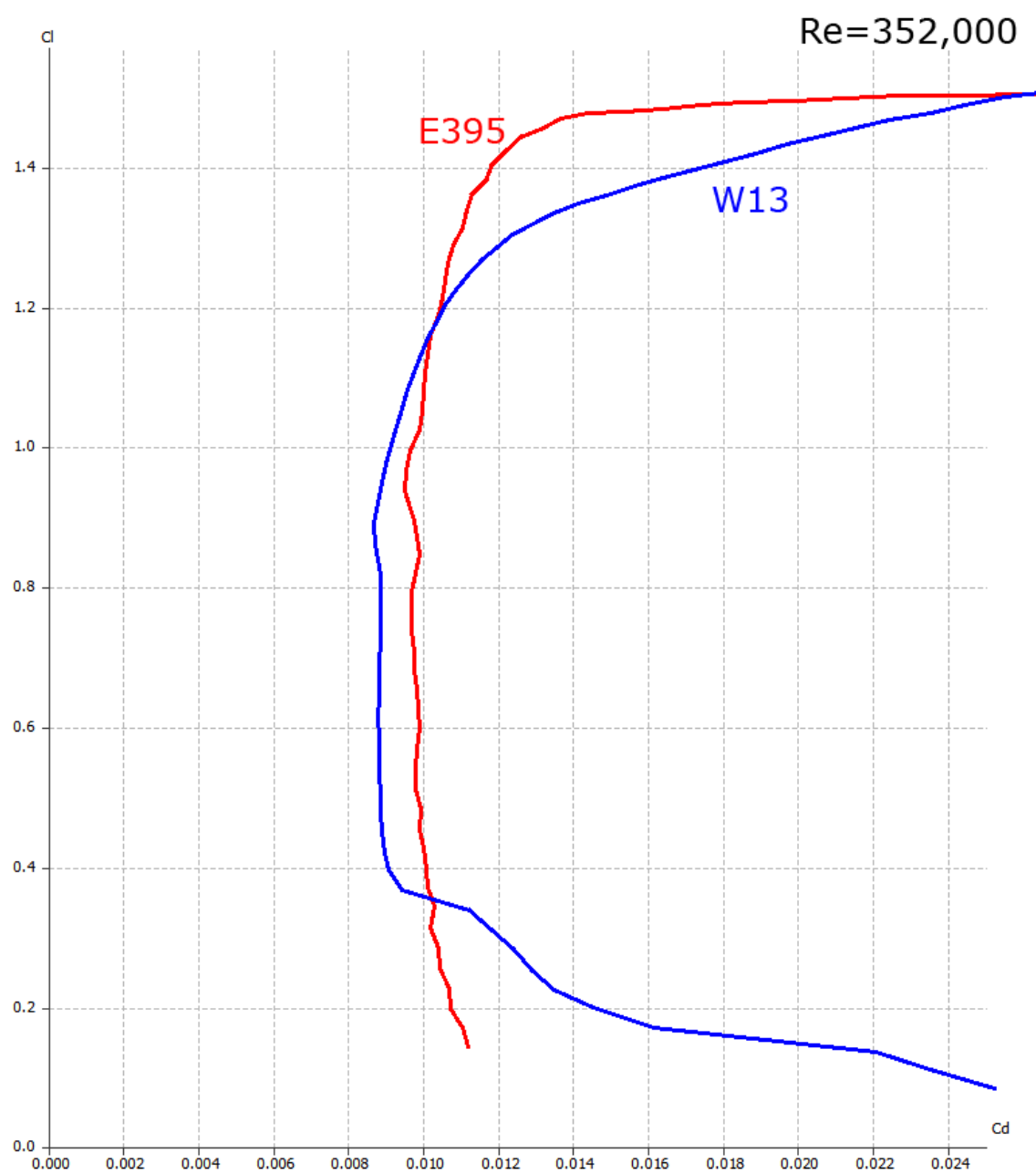


Figure 47: XFOIL drag polar of W13 compared against E395, Re=352k

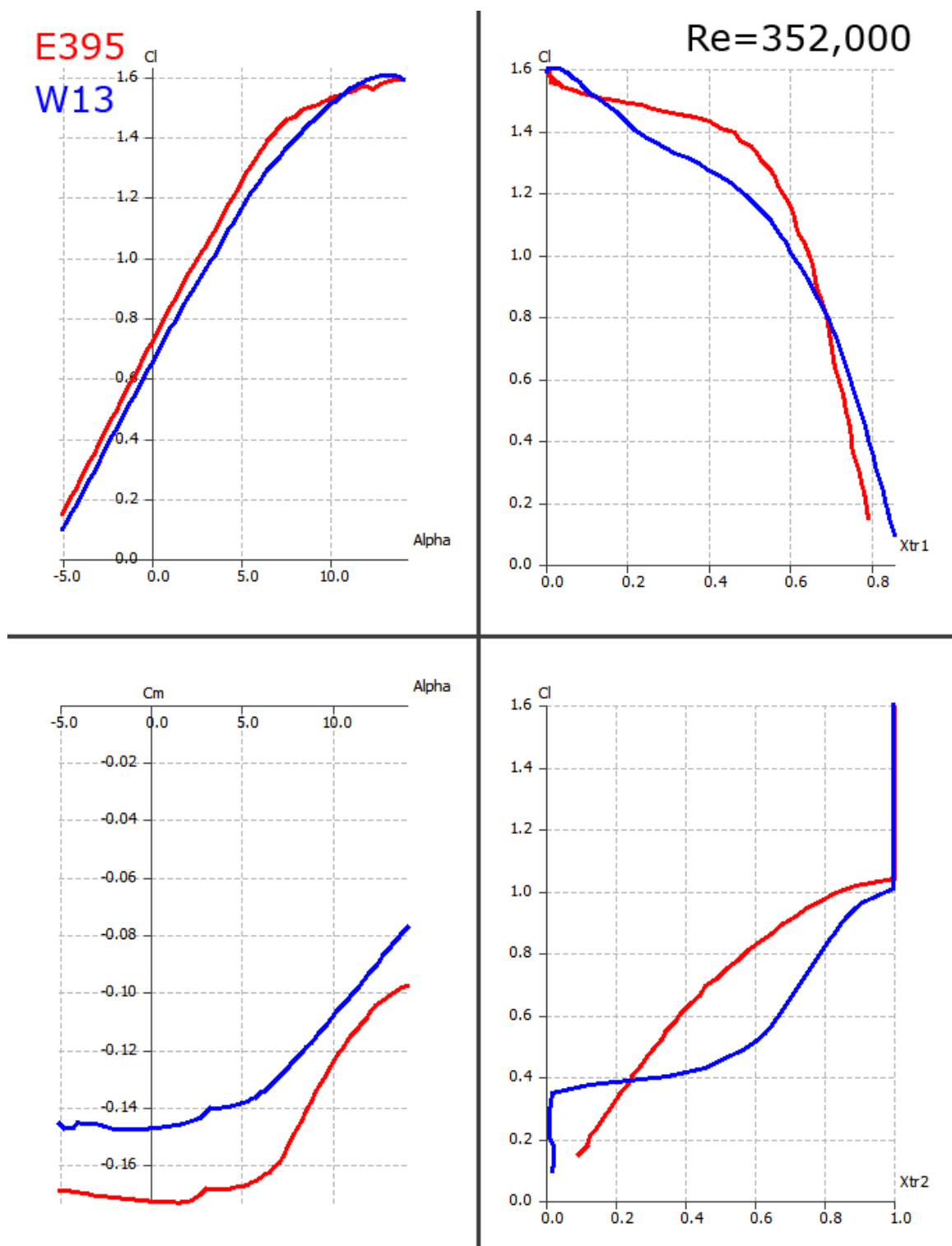


Figure 48: XFOIL results of W13 compared against E395,  $Re=352k$

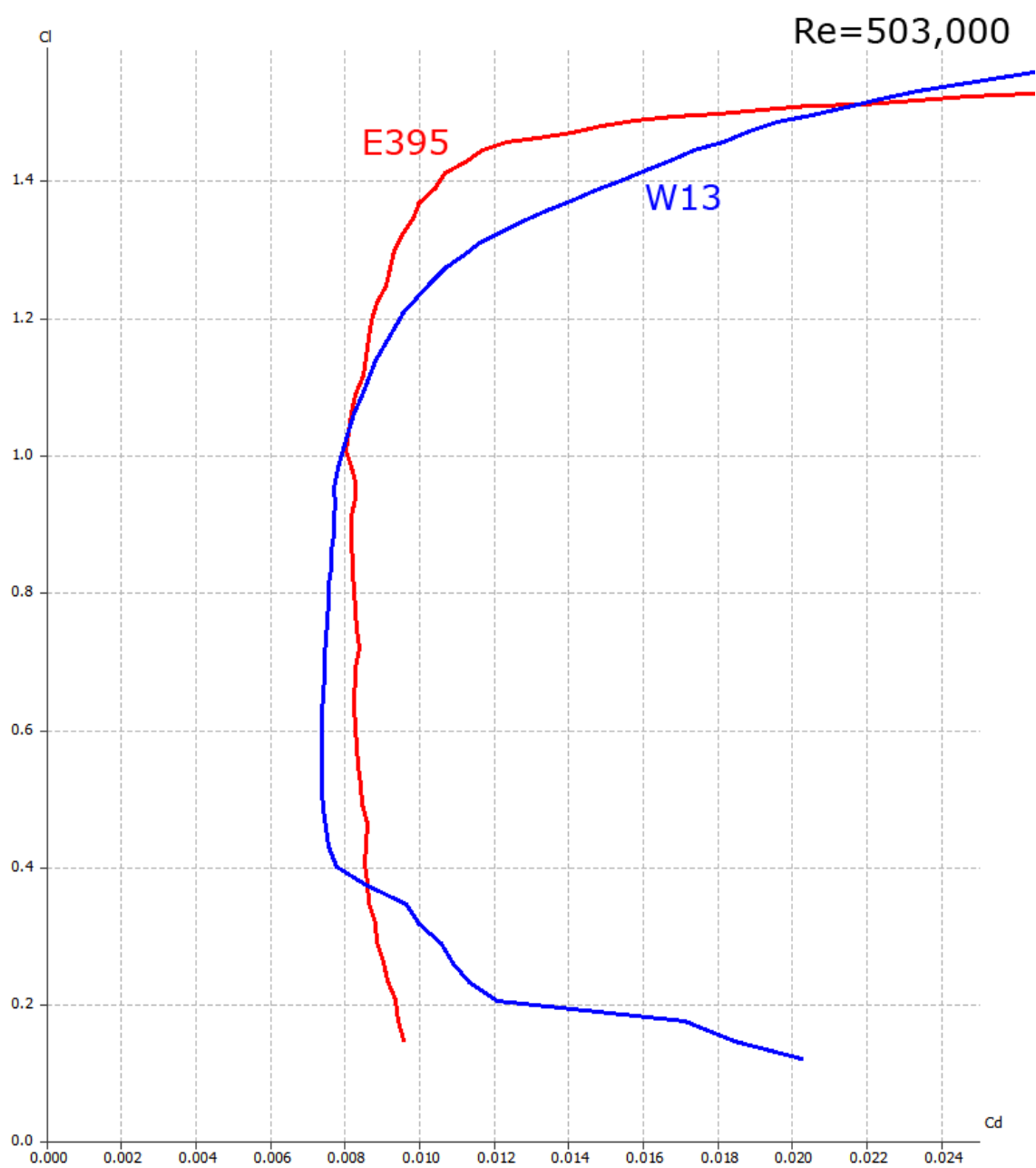


Figure 49: XFOIL drag polar of W13 compared against E395,  $Re=503k$

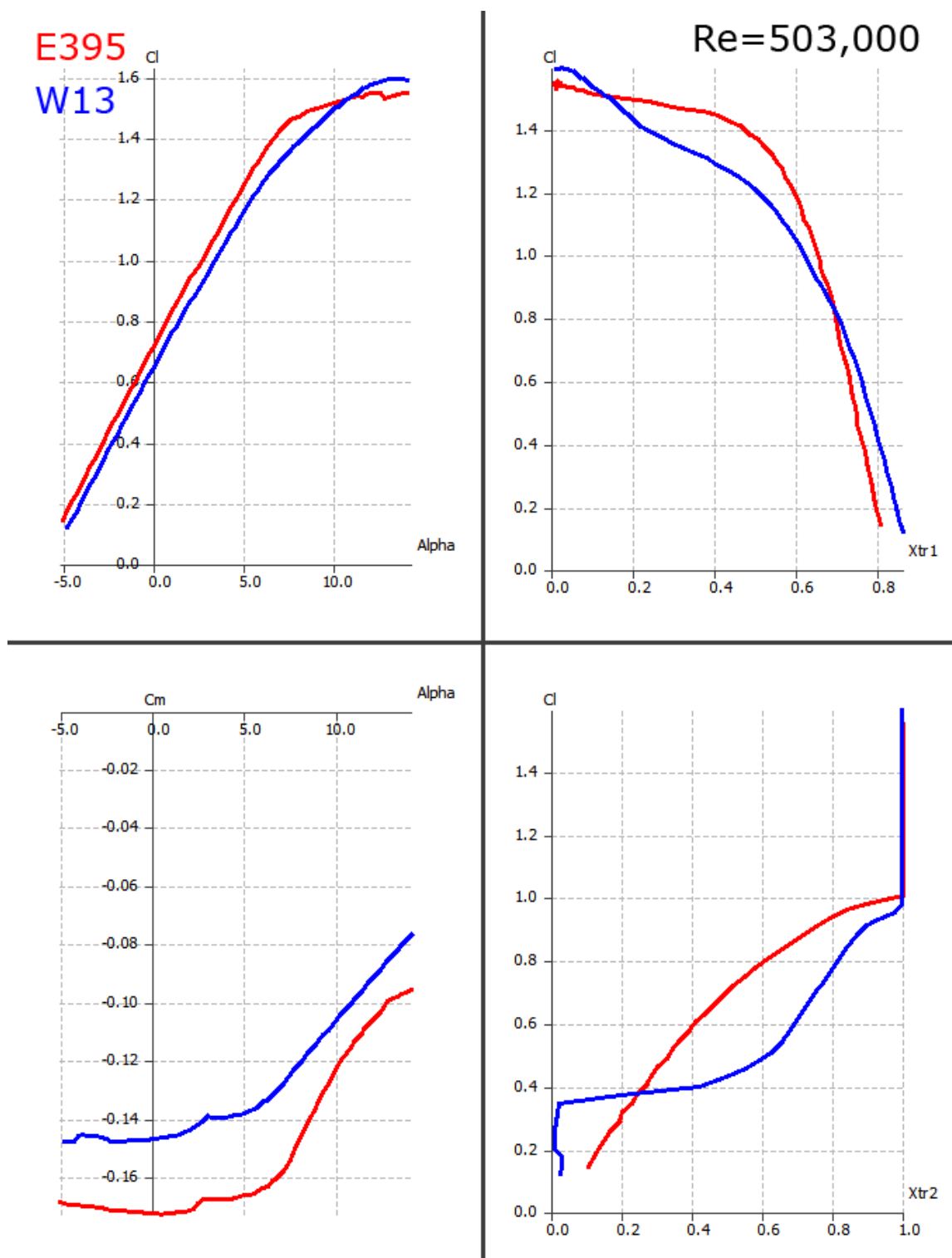


Figure 50: XFOIL results of W13 compared against E395,  $Re=503k$

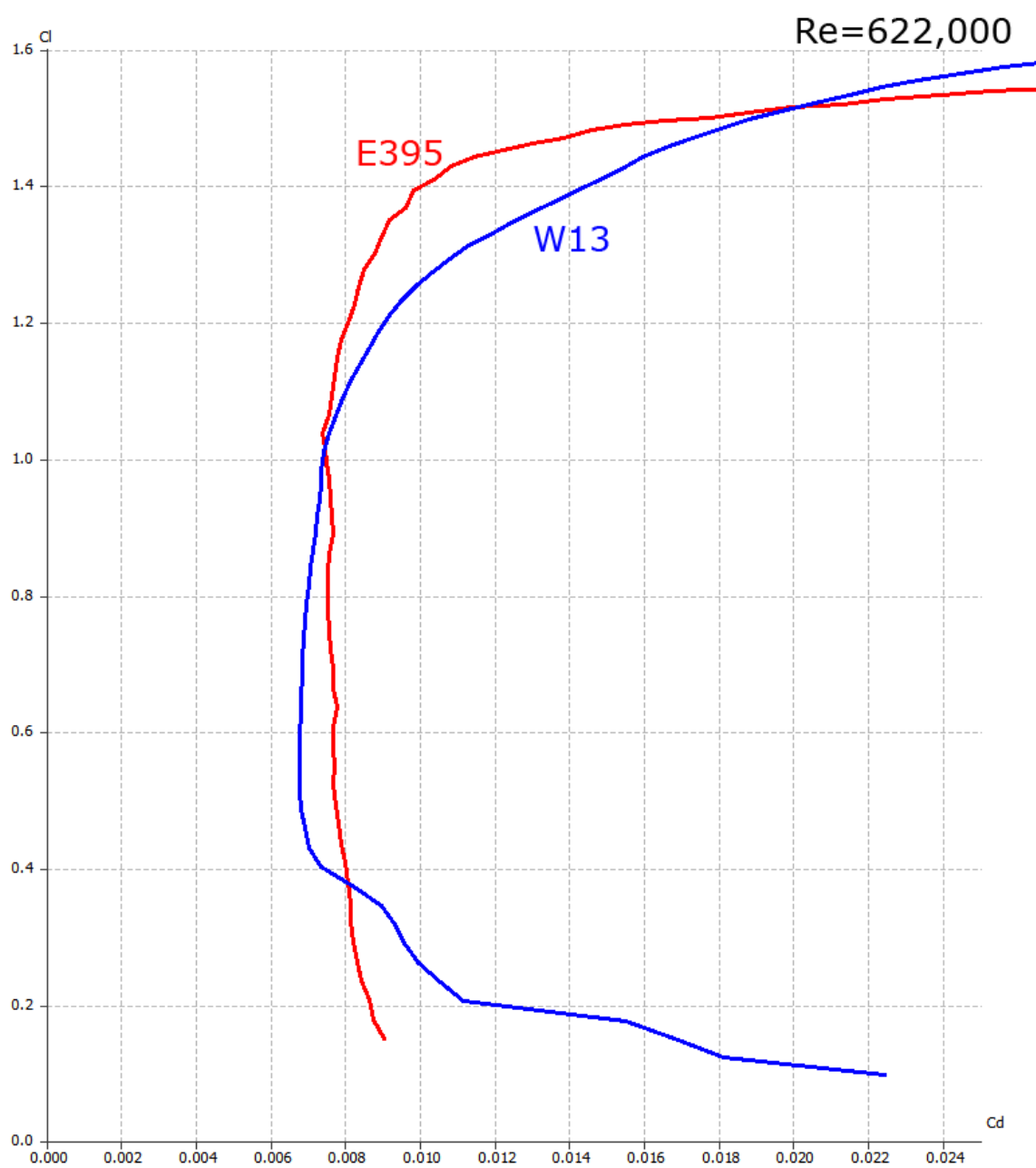


Figure 51: XFOIL drag polar of W13 compared against E395, Re=622k

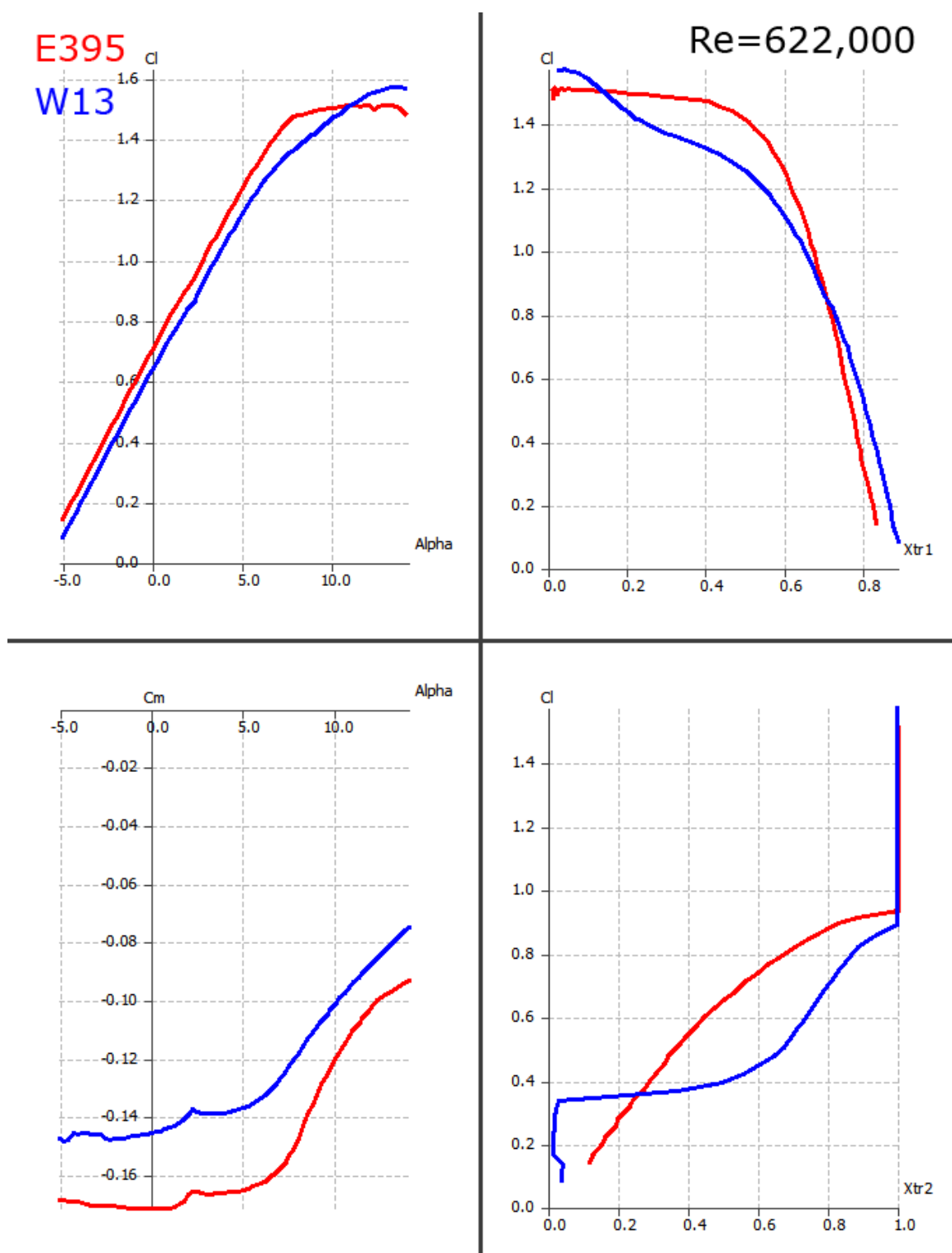


Figure 52: XFOIL results of W13 compared against E395,  $Re=622k$

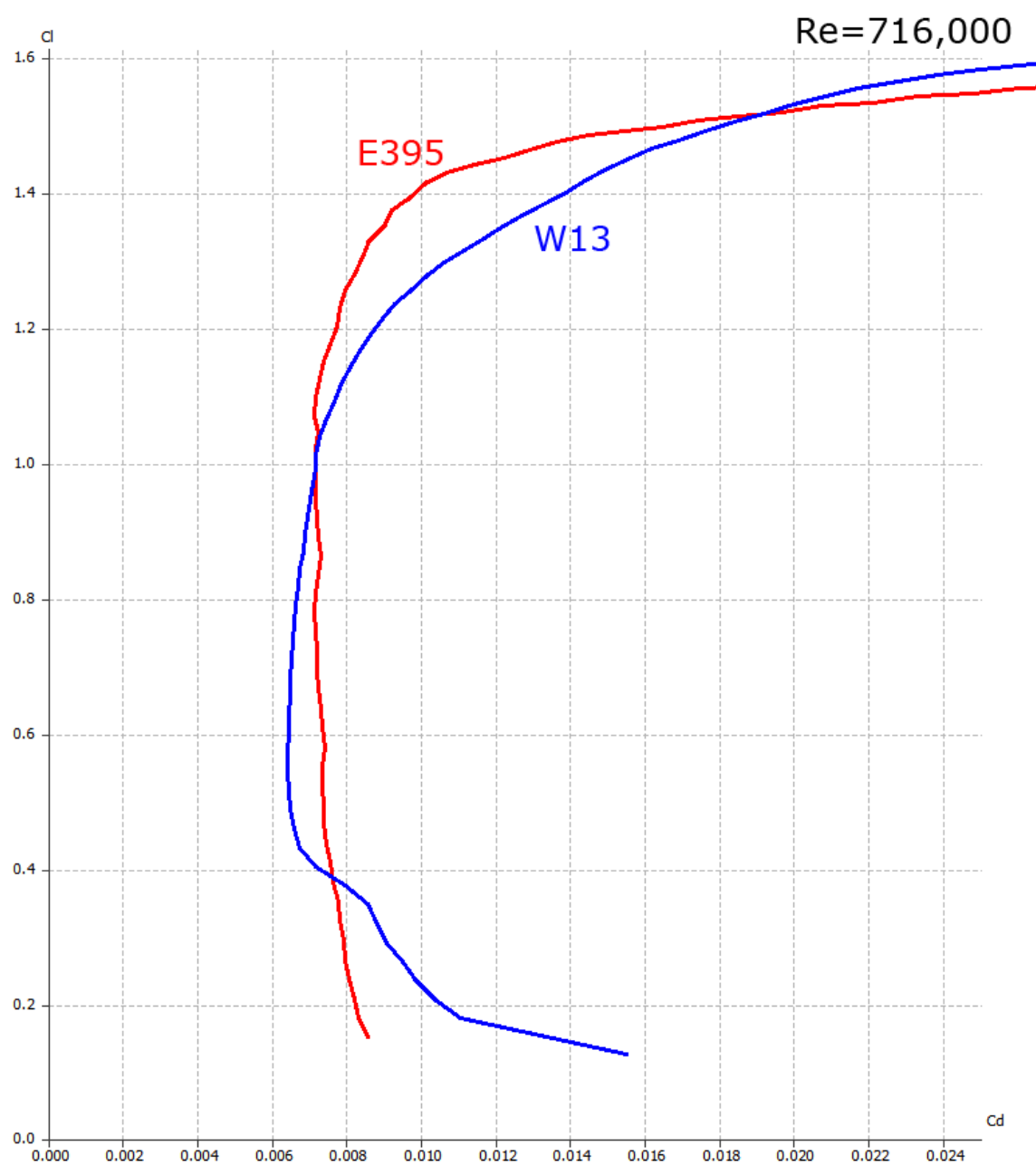


Figure 53: XFOIL drag polar of W13 compared against E395,  $Re=716k$

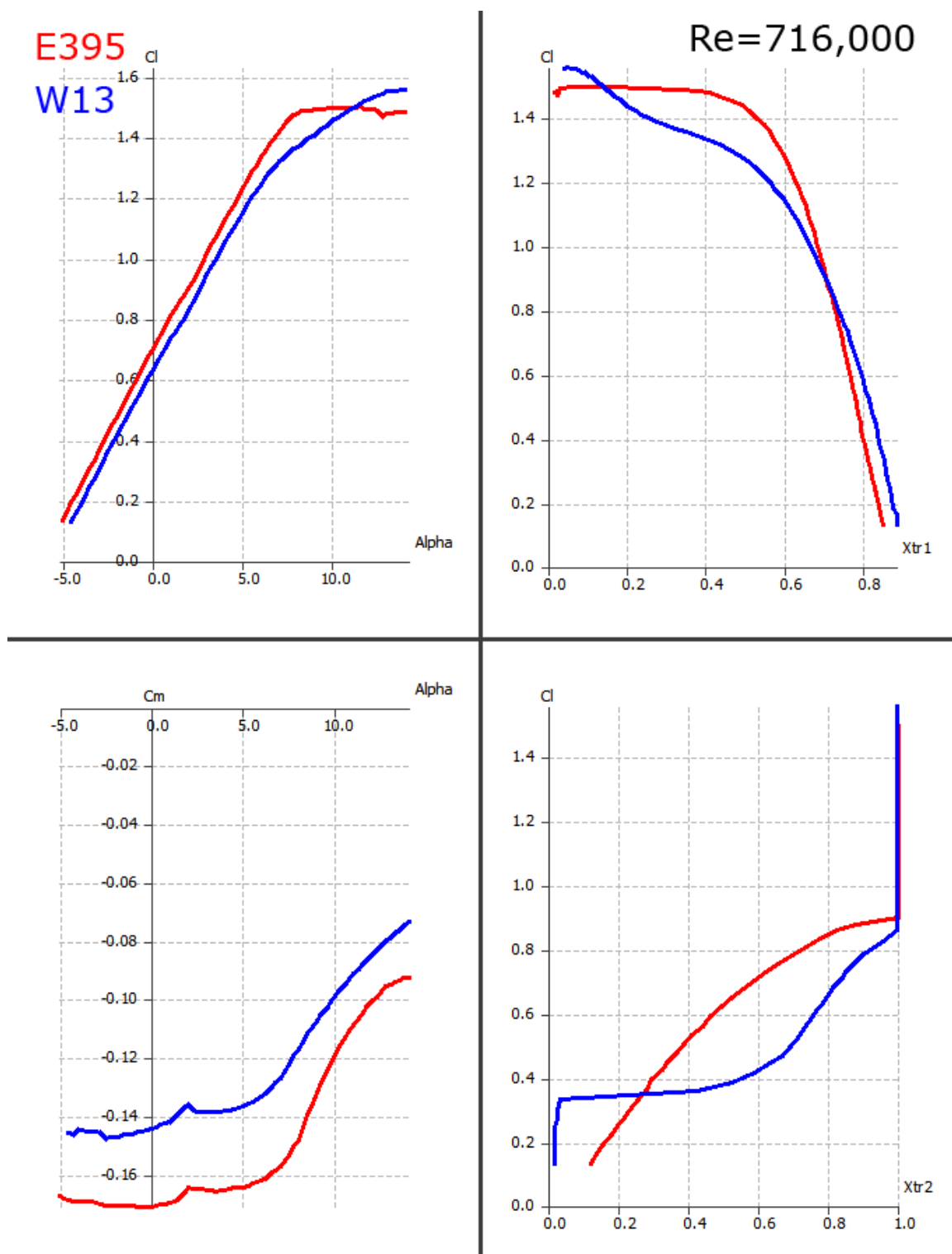


Figure 54: XFOIL results of W13 compared against E395,  $Re=716k$

The W13 airfoil meets the thickness requirement and is consistently lower in drag than the E395 airfoil in the  $Re$  and  $c_l$  ranges in which the HPA operates. The W13 also has a lower nose-down pitching moment than the E395. The  $c_{lmax}$  for the W13 is predicted to be approximately the same as the E395 (approximately 1.6), so the stall speed for the HPA is unchanged.

## Chapter 6

### Resulting Change in Aircraft Performance Characteristics

#### Drag Buildup

To determine the net effect of the airfoils designed, another drag buildup and power analysis was conducted using the same technique developed for the first drag buildup.

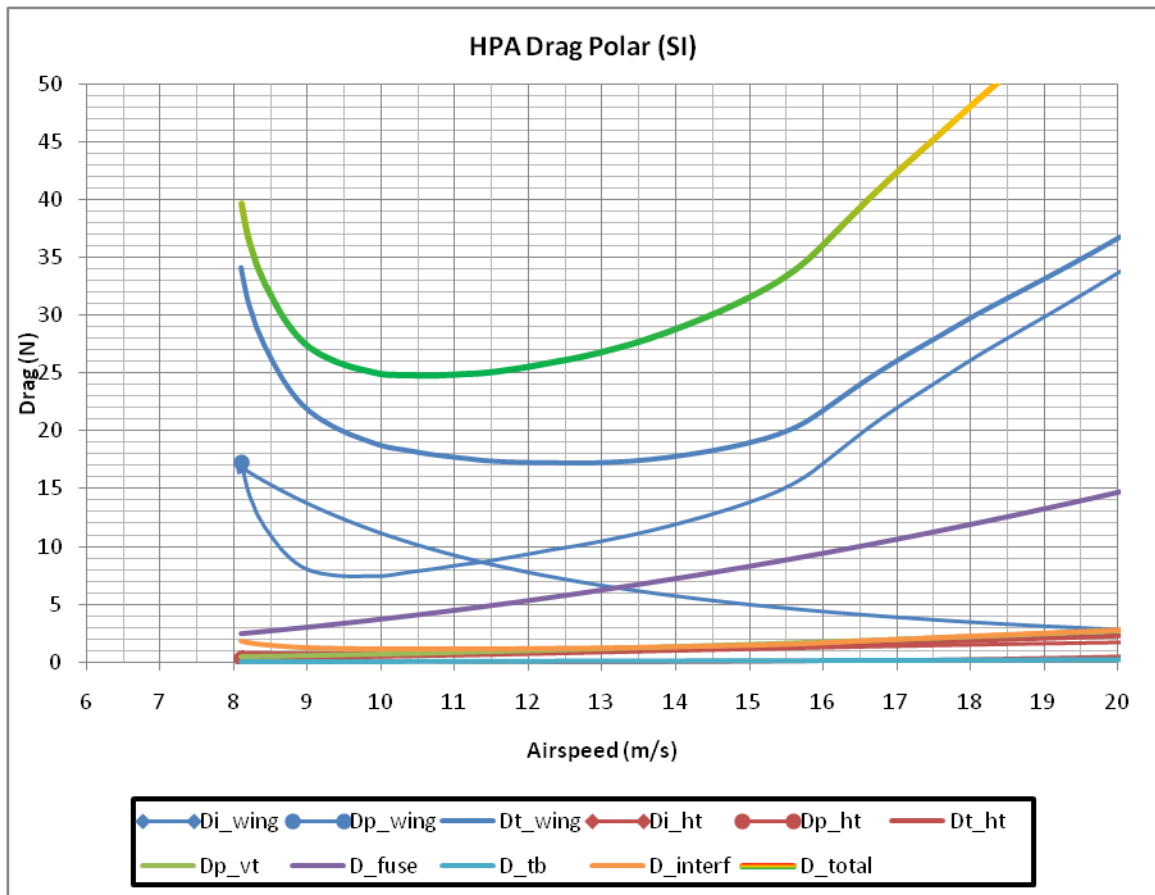
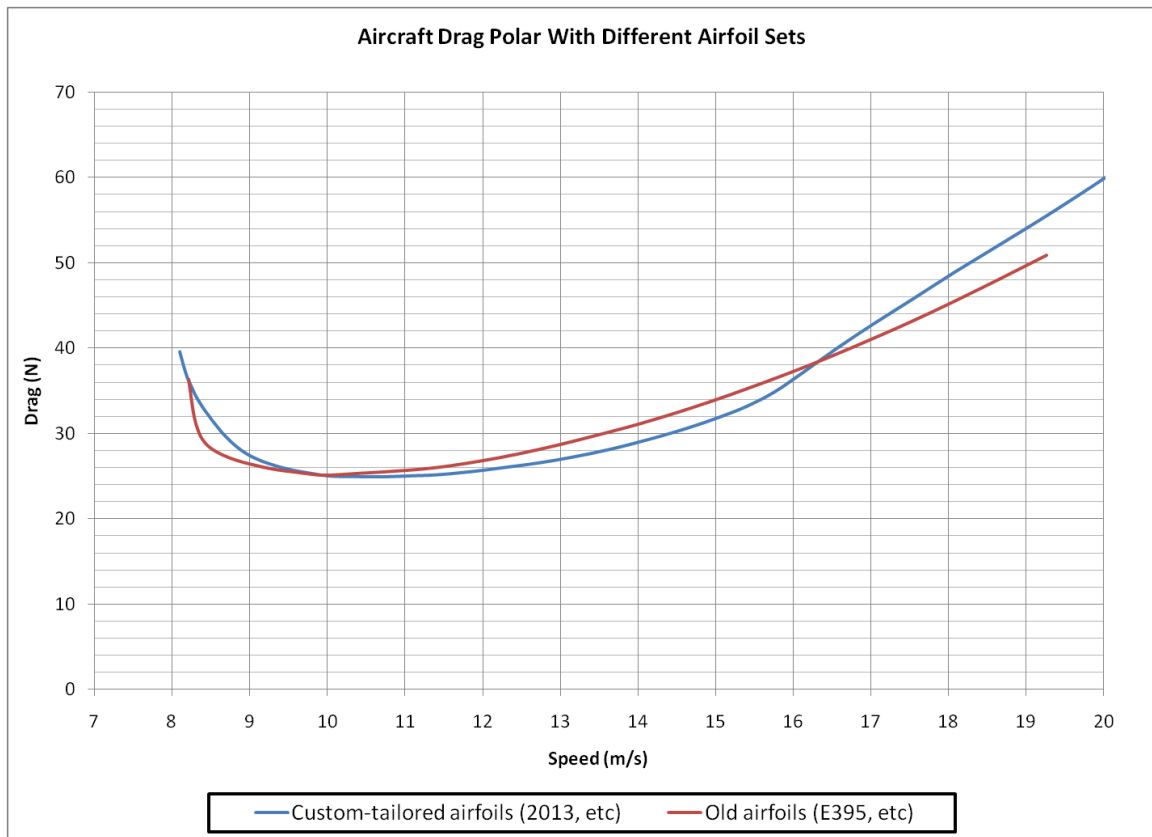


Figure 55: Drag buildup of HPA with new airfoils

Also visible in Figure 55 is the result from the hard-exit of the lower corner of the laminar drag bucket for the wing, which causes a sharp bend upward of drag at approximately 15.5 m/s. This does not detrimentally affect the aircraft, however, since that is outside of the aircraft's power-capable flight envelope.

### Aircraft Power

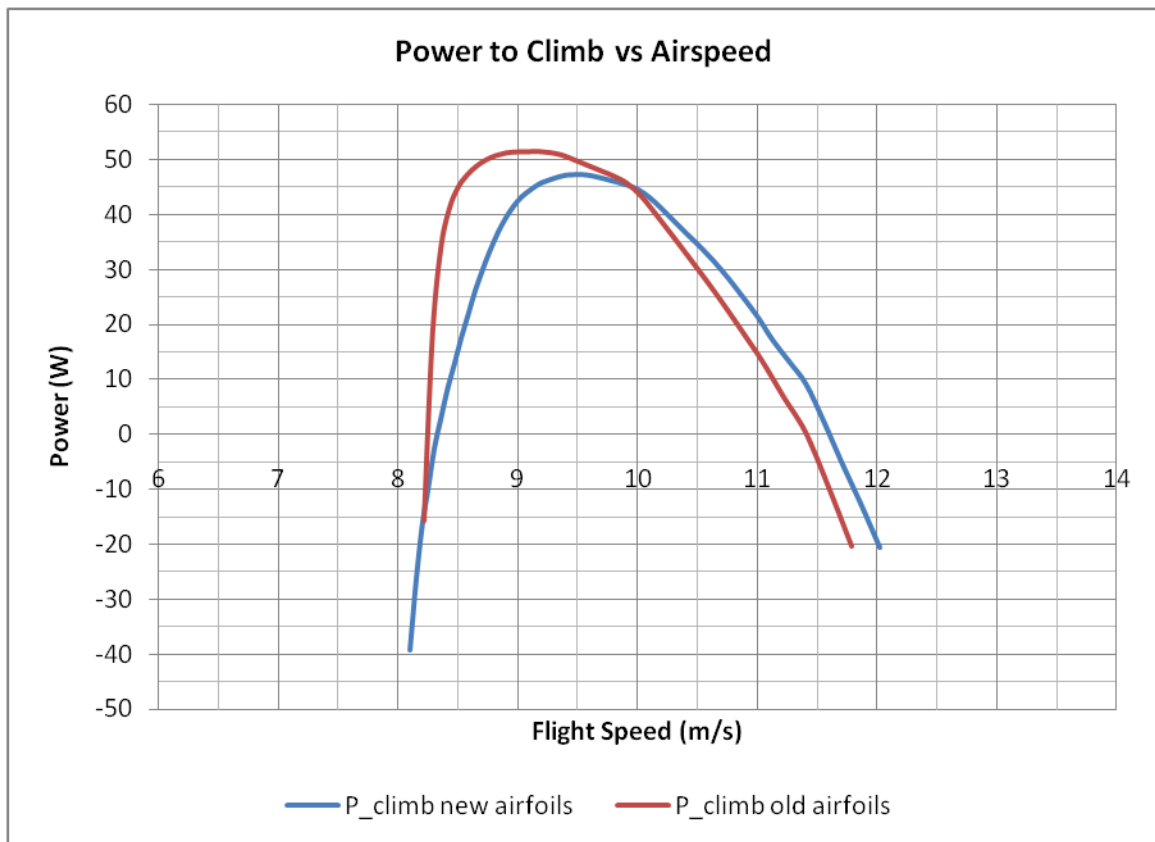
Aircraft power curves for the old and new airfoils are compared in Figure 56 which shows that, for flight speeds between 10 m/s and 16 m/s, the new airfoils produce a decrease in power-required for flight.



**Figure 56: Aircraft power required curves using new and old airfoils**

The power curves also show that, for flight speeds below 10 m/s, the airfoils detrimentally affect the performance of the aircraft since it takes more power to fly at those speeds due to the higher drag at a  $c_l$  of approximately 1.3.

Power-to-climb was also compared against the old airfoils in Figure 57, showing that the new airfoils allow the aircraft to reach the originally-desired maximum flight speed of 11.5 m/s.



**Figure 57: Power-to-Climb of old vs new airfoils for entire aircraft**

In total, the new airfoils should increase the feasibility of the aircraft to accomplish the mission because it increases the power margin between power-available and power-required in the cruise range, allowing the pilot to climb more readily without having to slow down. The new airfoils should also allow the aircraft to reach a higher maximum flight speed.

## Chapter 7

### Future Work

#### Airfoil Testing for $c_{lmax}$

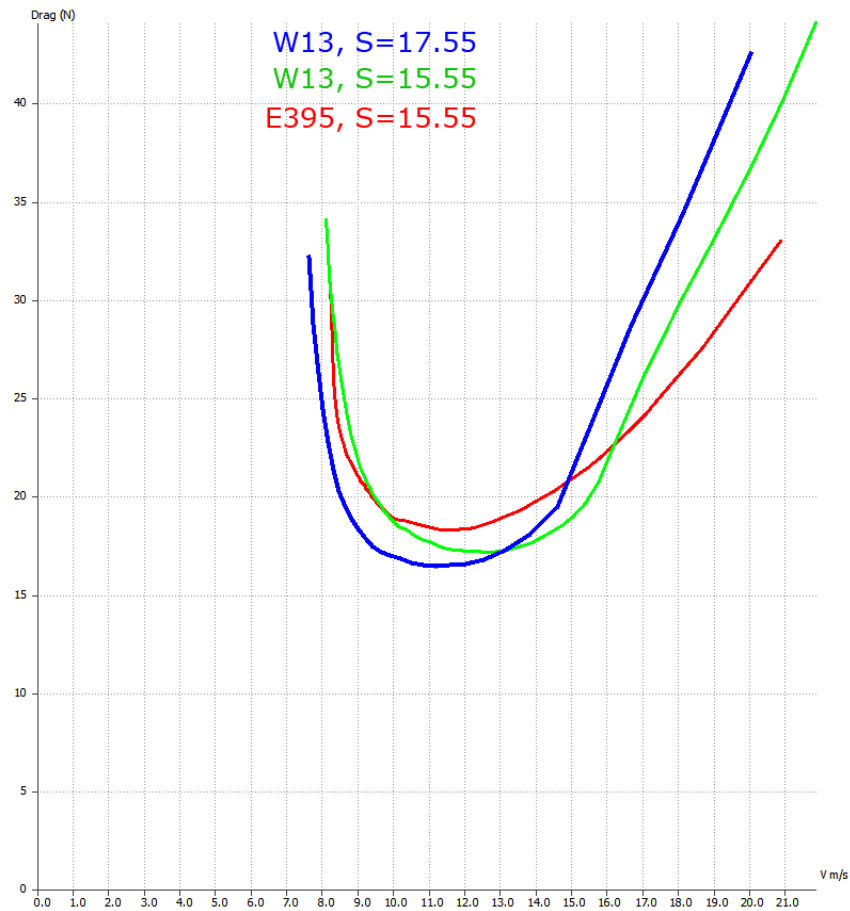
Even though accuracy for computational airfoil analysis has increased due to developments in XFOIL and PROFIL, the programs still struggle to give consistently-accurate results for  $c_{lmax}$  for many airfoils. Without wind tunnel and/or testing, there is no consistently-reliable way to determine whether the airfoils can reach their desired  $c_{lmax}$ s. Therefore, it is suggested that test sections for the new airfoils be built and tested before final integration into the aircraft.

#### Airfoil Refinement

The W13 wing airfoil's drag bucket is currently set a little too low and hurts the aircraft when it is not operating at above 10 m/s. It is suggested that the airfoil's drag bucket be moved up by approximately  $\Delta c_l = 0.2$ .

#### Wing Area Increase

One interesting result from developing the wing airfoil was the low drag that could be accomplished even at 12.3% thickness if only the airfoil could operate at a slightly lower  $c_l$ . A quick re-size of the wing was conducted simply by scaling the wing span from 19.5 meters to 22.5 meters, which increased the wing area from 15.55 m<sup>2</sup> to 17.55 m<sup>2</sup>, reducing the  $c_s$ s necessary for flight. The drag from the new (larger) wing was compared against the old wing with the E395 and the old wing with the W13 airfoils, as shown in Figure 58.



**Figure 58: Wing drag polars required to lift 220 lb compared**

As shown in Figure 58, it was found that this increase in wing area would yield a drag reduction of the wing of 9.8% at the cruise velocity of 11 m/s, which would allow for much better aircraft performance. It is urged that this change is investigated in the next iteration of the aircraft.

## Chapter 8

### Conclusion

By carefully analyzing the operational range of the aircraft, using a human-in-the-loop design process, and considering the flow physics and in the design of the pressure gradients, new airfoils were created that match the structural requirements of the HPA and enhance the

performance of the aircraft in its cruise range. The vertical tail and horizontal tail airfoils, V21 and H8, should reach a higher  $c_{lmax}$  than the baseline airfoils with less drag at those higher loadings, allowing for greater tail authority. The wing airfoil, W13, deepens the laminar drag bucket in the cruise  $c_l$  range and reduces the nose-down pitching moment of the airfoil, reducing overall flight power.

It is suggested that the airfoil and wing designs should be refined more before the final design is frozen. Especially, it might be fruitful to investigate a larger wing as it will reduce the  $c_l$  of the wing sections and allow the wing to capitalize on the deep drag bucket of the W13 airfoil.

## Works Cited

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## Appendix

### Coordinates of the V21 airfoil:

|            |            |            |             |
|------------|------------|------------|-------------|
| 1.00000000 | 0.00000000 | 0.00023340 | -0.00161166 |
| 0.99668789 | 0.00008613 | 0.00083314 | -0.00332426 |
| 0.98696748 | 0.00059913 | 0.00294719 | -0.00694053 |
| 0.97130181 | 0.00168768 | 0.01043670 | -0.01447815 |
| 0.95012655 | 0.00323209 | 0.02216401 | -0.02159662 |
| 0.92367620 | 0.00505328 | 0.03846644 | -0.02808893 |
| 0.89218105 | 0.00721088 | 0.05911012 | -0.03373860 |
| 0.85608229 | 0.00975732 | 0.08416563 | -0.03840144 |
| 0.81588011 | 0.01268458 | 0.11347087 | -0.04194723 |
| 0.77211653 | 0.01595330 | 0.14694053 | -0.04442771 |
| 0.72536610 | 0.01949885 | 0.18431230 | -0.04587983 |
| 0.67622614 | 0.02323421 | 0.22527838 | -0.04639609 |
| 0.62530503 | 0.02705776 | 0.26941852 | -0.04607391 |
| 0.57322072 | 0.03085695 | 0.31627000 | -0.04498611 |
| 0.52059054 | 0.03450824 | 0.36533936 | -0.04320725 |
| 0.46802378 | 0.03787919 | 0.41610380 | -0.04081590 |
| 0.41610380 | 0.04081590 | 0.46802378 | -0.03787919 |
| 0.36533936 | 0.04320725 | 0.52059054 | -0.03450824 |
| 0.31627000 | 0.04498611 | 0.57322072 | -0.03085695 |
| 0.26941852 | 0.04607391 | 0.62530503 | -0.02705776 |
| 0.22527838 | 0.04639609 | 0.67622614 | -0.02323421 |
| 0.18431230 | 0.04587983 | 0.72536610 | -0.01949885 |
| 0.14694053 | 0.04442771 | 0.77211653 | -0.01595330 |
| 0.11347087 | 0.04194723 | 0.81588011 | -0.01268458 |
| 0.08416563 | 0.03840144 | 0.85608229 | -0.00975732 |
| 0.05911012 | 0.03373860 | 0.89218105 | -0.00721088 |
| 0.03846644 | 0.02808893 | 0.92367620 | -0.00505328 |
| 0.02216401 | 0.02159662 | 0.95012655 | -0.00323209 |
| 0.01043670 | 0.01447815 | 0.97130181 | -0.00168768 |
| 0.00294719 | 0.00694053 | 0.98696748 | -0.00059913 |
| 0.00083314 | 0.00332426 | 0.99668789 | -0.00008613 |
| 0.00023340 | 0.00161166 | 1.00000000 | 0.00000000  |
| 0.00000000 | 0.00000000 |            |             |

**PROFIL Code input for V21**

TRA1 0021 10.5 .82 15.5 .9 21.5 1.7 23.8 2.2 25.5 4 27.5 6 29.5 9.6

TRA1 0021 0 10 30.5 -10 32.5 -9.6 34.5 -6 36.2 -4 38.5 -2.2 44.5 -1.7

TRA1 0021 49.5 -.9 60 -.82

TRA2 0021 4.5 22.5 2 -.6 .88 4.5 22.5 2 -.6 .88 3 .3 0 2

### Coordinates of the H8 airfoil

|            |            |            |             |
|------------|------------|------------|-------------|
| 1.00000000 | 0.00000000 | 0.00021251 | -0.00172145 |
| 0.99650143 | 0.00012546 | 0.00077702 | -0.00350729 |
| 0.98630784 | 0.00087244 | 0.00287618 | -0.00720916 |
| 0.97005205 | 0.00245306 | 0.01059386 | -0.01480893 |
| 0.94829368 | 0.00469453 | 0.02289578 | -0.02237358 |
| 0.92128560 | 0.00734896 | 0.03951243 | -0.02943184 |
| 0.88926753 | 0.01049782 | 0.06054336 | -0.03559560 |
| 0.85275297 | 0.01419533 | 0.08604976 | -0.04082925 |
| 0.81231279 | 0.01840030 | 0.11585821 | -0.04502703 |
| 0.76855163 | 0.02301761 | 0.14984995 | -0.04830813 |
| 0.72209528 | 0.02790607 | 0.18762699 | -0.05067551 |
| 0.67357774 | 0.03288006 | 0.22891316 | -0.05217104 |
| 0.62362320 | 0.03770016 | 0.27323617 | -0.05291081 |
| 0.57276201 | 0.04207643 | 0.32006982 | -0.05293579 |
| 0.52143072 | 0.04580396 | 0.36886448 | -0.05226366 |
| 0.47005458 | 0.04876048 | 0.41905031 | -0.05089111 |
| 0.41905031 | 0.05089111 | 0.47005458 | -0.04876048 |
| 0.36886448 | 0.05226366 | 0.52143072 | -0.04580396 |
| 0.32006982 | 0.05293579 | 0.57276201 | -0.04207643 |
| 0.27323617 | 0.05291081 | 0.62362320 | -0.03770016 |
| 0.22891316 | 0.05217104 | 0.67357774 | -0.03288006 |
| 0.18762699 | 0.05067551 | 0.72209528 | -0.02790607 |
| 0.14984995 | 0.04830813 | 0.76855163 | -0.02301761 |
| 0.11585821 | 0.04502703 | 0.81231279 | -0.01840030 |
| 0.08604976 | 0.04082925 | 0.85275297 | -0.01419533 |
| 0.06054336 | 0.03559560 | 0.88926753 | -0.01049782 |
| 0.03951243 | 0.02943184 | 0.92128560 | -0.00734896 |
| 0.02289578 | 0.02237358 | 0.94829368 | -0.00469453 |
| 0.01059386 | 0.01480893 | 0.97005205 | -0.00245306 |
| 0.00287618 | 0.00720916 | 0.98630784 | -0.00087244 |
| 0.00077702 | 0.00350729 | 0.99650143 | -0.00012546 |
| 0.00021251 | 0.00172145 | 1.00000000 | 0.00000000  |
| 0.00000000 | 0.00000000 |            |             |

**PROFIL Code input for H8**

TRA1 1008 10.5 2.82 15.5 2.9 21.5 3.7 23.8 4.9 25.5 6.7 26.5 8.6 28.5 10.2  
TRA1 1008 29.5 12.3 0 15.3 30.5 -15.3 31.5 -12.3 33.5 -10.2 34.5 -8.6  
TRA1 1008 36.2 -6.7 38.5 -4.9 44.5 -3.7 49.5 -2.9 60 -2.82  
RAMP 2 2 2 2  
TRA2 1008 4.5 13.5 2 -1 .883 4.5 13.5 2 -1 .883 3 .4 0 2

### Coordinates of the W13 airfoil

|            |             |            |             |
|------------|-------------|------------|-------------|
| 1.00000000 | 0.00000000  | 0.00304180 | -0.00491855 |
| 0.99656657 | 0.00083095  | 0.01106848 | -0.00835964 |
| 0.98671843 | 0.00364979  | 0.02602085 | -0.01201994 |
| 0.97136884 | 0.00850577  | 0.04647427 | -0.01511577 |
| 0.95128334 | 0.01492806  | 0.07210980 | -0.01767900 |
| 0.92679615 | 0.02228524  | 0.10254072 | -0.01970256 |
| 0.89794386 | 0.03033349  | 0.13735026 | -0.02115124 |
| 0.86515328 | 0.03904030  | 0.17610099 | -0.02194410 |
| 0.82894296 | 0.04817872  | 0.21839574 | -0.02199322 |
| 0.78980983 | 0.05745448  | 0.26384032 | -0.02125961 |
| 0.74820005 | 0.06655600  | 0.31202431 | -0.01974630 |
| 0.70454846 | 0.07520751  | 0.36251611 | -0.01749954 |
| 0.65928142 | 0.08314486  | 0.41485772 | -0.01460941 |
| 0.61280961 | 0.09013409  | 0.46855941 | -0.01120870 |
| 0.56553357 | 0.09598004  | 0.52309453 | -0.00746908 |
| 0.51784832 | 0.10053019  | 0.57789493 | -0.00359456 |
| 0.47014675 | 0.10367574  | 0.63234718 | 0.00018829  |
| 0.42282201 | 0.10535026  | 0.68579080 | 0.00364336  |
| 0.37626876 | 0.10552390  | 0.73751904 | 0.00654101  |
| 0.33086258 | 0.10420061  | 0.78678362 | 0.00867672  |
| 0.28698373 | 0.10144915  | 0.83280449 | 0.00989076  |
| 0.24502577 | 0.09736108  | 0.87478502 | 0.01008629  |
| 0.20537912 | 0.09205257  | 0.91193309 | 0.00923569  |
| 0.16844431 | 0.08565910  | 0.94339433 | 0.00734984  |
| 0.13462571 | 0.07829339  | 0.96822642 | 0.00483341  |
| 0.10427952 | 0.07002263  | 0.98595120 | 0.00239924  |
| 0.07764290 | 0.06088728  | 0.99650495 | 0.00065415  |
| 0.05484002 | 0.05102733  |            |             |
| 0.03594884 | 0.04066304  |            |             |
| 0.02104634 | 0.03004528  |            |             |
| 0.01008578 | 0.01953850  |            |             |
| 0.00305581 | 0.00971624  |            |             |
| 0.00008267 | 0.00133077  |            |             |
| 0.00000212 | 0.00020518  |            |             |
| 0.00011144 | -0.00140261 |            |             |
| 0.00028379 | -0.00211398 |            |             |
| 0.00055294 | -0.00273962 |            |             |
| 0.00097608 | -0.00329714 |            |             |
| 0.00154631 | -0.00384347 |            |             |
| 0.00203946 | -0.00423807 |            |             |

**PROFIL Code input for W13**

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TRA1 2013 26.68 9.2 28 10.5 29 12 0 13  
TRA1 2013 35 5.2 60 5.45  
RAMP 10 6.5 8 8  
TRA2 2013 5 11.5 2 1 .98 5 13 2 .5 .9 6 .2 0

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Design, Build, Fly Competition Team (PSU Sailplane Class) 2007-2010

- 2009-2010: Team Mentor “TurboKat”
- 2008-2009: “Hope of the Jackalope”
- 2007-2008: “Spirit of Happy Valley”
- 2006-2007: “Nittany Griffin”
- Roles:
  - MATLAB mission score optimization
  - Aircraft design and analysis with AVL, XFLR5
  - Propulsion system design, wind tunnel testing
  - Store deployment mechanisms design
  - SolidWorks CAD and FEA structural analysis
  - Laser cutting, composites fabrication

Caltech/NASA Jet Propulsion Laboratory 2008-2009

- HysplRI Mission Concept Design (Section 312)
  - System, data flow modeling for mission optimization
  - Telecommunications architecture design
  - GIS mapping and data system design
  - Thermal/structural analysis and design
  - Spacecraft pointing analysis
  - IEEE Aerospace Conference Published (Mar 2009, Mar 2010)

Student Space Programs Laboratory 2007-2010

- Systems Engineering Functional Group Lead
- OSIRIS Cube Satellite
  - Project Manager/Lead Systems Engineer
  - STK orbital analysis, mission design
  - Mission proposal writing
- NanoSatellite 5 Competition: NittanySat - Project manager
- HEMI instrument on JANUS SMEX - Lead systems engineer

Radio-Controlled Aircraft Builder, Pilot 2003-present

Sailplane Club 2007-2010

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## Awards

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Donald G. and Jayne L. Steva Scholarship  
Aero Pioneers of 1944 Scholarship  
Dean's List (2006-present)  
President's Freshman Award  
Evan Pugh Scholar