Construction of NACA 66-415
NLF Composite Wing for Acoustic Turbulence Testing

A Senior Project
presented to
the Faculty of the Aerospace Engineering Department
California Polytechnic State University, San Luis Obispo

by
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and
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Abstract

A design is developed for a Natural Laminar Flow (NLF) wing, to be used at California Polytechnic State University for acoustic turbulence testing. Composite materials are used to produce high-quality surface finishes necessary for laminar flow. A design for the test apparatus is presented and justified. A manufacturing procedure is proposed for the carbon fiber skin, using Vacuum Resin Infusion (VRI). This procedure is tested on a scaled part with satisfactory results; lessons learned are discovered and integrated into the final manufacturing process. The test section has been fit to the Cal Poly wind tunnel, but full implementation has not been completed. Once the proper microphone has been purchased, the final manufacturing to the airfoil can be completed. This will ensure full system integration and completeness.

I. Introduction

There is a need for a natural laminar flow airfoil to be manufactured for a thesis that requires acoustic testing of laminar and turbulent flow. To achieve laminar flow it is required that the airfoil be as smooth as possible, requiring a composite layup with a fine surface finish. The airfoil will have two high sensitivity microphones implanted into the surface, one at roughly ten percent of the chord distance, and one at 70 percent of the chord distance. Each microphone will be able to measure the acoustics of the surrounding flow; together, the two will ultimately demonstrate an acoustic difference between laminar and turbulent flow.

It is imperative that the airfoil chosen experiences laminar flow over the upper surface for a large portion of the chord length. Because of this, a NACA 66-415 NLF airfoil has been selected. Theoretical predictions place the transition point for this airfoil around 60% of the chord length; real-world considerations – in particular, surface roughness – move this point upstream. In order to maximize the extent of laminar flow over the airfoil, it is clear that ultra-smooth surface finishes are required; carbon fiber in an epoxy matrix has therefore been chosen for this experiment, with a manufacturing process tailored to produce a high-gloss finish. The combination of an NLF airfoil with this material is expected to obtain reasonable levels of laminar flow in the Cal Poly wind tunnel.

This paper will cover design of the NLF composite wing. An overview of composite materials and composite construction will be presented, followed by an introduction to the test apparatus and design constraints. The wing design will then be introduced, followed by a detailed description of the manufacturing process. Analysis of the performance of the wing will be postponed as part of the graduate work of Scott Sawyer. This paper will therefore close with an evaluation of the finished product, and offer analysis of both the manufacturing process and the system design with regards to manufacturability.

A. Introduction to Composite Materials

Composites, at their simplest level, are a blend of two constituent materials: a structural reinforcing agent, surrounded by a continuous supporting matrix. The reinforcing agent is primarily responsible for the structural properties of the material, i.e. stiffness and strength. The matrix exists to support and stabilize the reinforcing agent: to bind the reinforcements together, to transfer load to and between reinforcements,
and to protect the reinforcements from abrasion or other damage. Selection of materials for each phase is unique to the designer and the problem at hand; an endless list of combinations is theoretically possible. Reinforcing agents can be fibrous, particulate, laminate, or a hybrid combination of these. Matrices can be organic (polymers), metallic, ceramic, or carbon. And different composites can be selected for different components of the aircraft design, offering designers unprecedented capability to “tune” material properties to the characteristics desired. Indeed, the greatest strength of composite construction is its extreme versatility.

B. Advantages and Disadvantages of Composite Construction

1. Advantages

Composites offer a number of advantages for aircraft construction. Composites are generally lightweight, with high specific strengths and specific modulus. Reinforcing agents and matrices can be paired to obtain the optimal properties of each, combining for example the strength of carbon with the weight of epoxy. Indeed, composite materials exhibit the highest strength-to-weight and stiffness-to-weight ratios of any materials used in aircraft today.

Composites exhibit excellent fatigue behavior; while cycle loads are primarily assumed by the reinforcing agent, matrices are selected to absorb and distribute stresses, thereby cushioning the structure. Matrix shielding also makes most composites corrosion resistant. And depending on material selection, composites can be electronically transparent; wiring (i.e. antennas) can be hidden inside the structure, thereby streamlining the aircraft and minimizing drag.

Finally, and perhaps most important, composites can be manufactured to an unmatched surface finish. Composites can be compound curved to carry structural loads, producing light, strong, stiff surfaces with laminar characteristics. This is the primary reason that composites have found such favor in sailplane construction; the drag reductions associated with composite construction are arguably even more important than the weight savings.

2. Disadvantages

Composites have several major disadvantages, however, that must be considered during the design phase. The most important is the issue of inspection and repair. Composites exhibit a notorious lack of visual proof of damage, making maintenance complex and prone to error. For carbon fiber, for example, the greatest structural risk is delamination, a condition caused by a minor surface impact that results in laminate separation deep within the material. Delaminations are nearly impossible to see to the naked eye and inspections must therefore be conducted using other means (currently, acoustic methods are employed). The methodology and frequency of these inspections must be considered in a balanced life-cycle analysis of any new aircraft concept; for general aviation purposes, for example, these inspections are likely beyond the means of the average private owner.

Repairs to composite materials, similarly, can be complex. Composite repairs vary with the type of failure. Delaminations are typically repaired by injection; depending on the severity, these failures can generally be repaired with little or no effect on performance. Punctures or severe abrasions to composite
materials, however, require some kind of patch operation; in some cases, such repairs may impair laminar surface characteristics.

C. Material Types

The majority of composites used in aircraft today comprise fibrous reinforcing agents set in polymer matrices. Three materials dominate the market: fiberglass, Kevlar, or carbon fiber. Hybrids of these materials can also be found, for example the addition of Kevlar laminates to the outer layers of carbon fiber to increase penetration resistance: as discussed above, one of the greatest strength of composite materials is versatility. A brief comparison of fiber materials and their characteristics is presented in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (ρ) [lb/in³]</th>
<th>Tensile Strength (S) [10^3 lb/in²]</th>
<th>S / ρ [10^5 lb/in²]</th>
<th>Tensile Stiffness (E) [10^6 lb/in²]</th>
<th>E / ρ [10^7 in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.097</td>
<td>90</td>
<td>9</td>
<td>10.6</td>
<td>11</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.170</td>
<td>280</td>
<td>16</td>
<td>16.7</td>
<td>10</td>
</tr>
<tr>
<td>Steel</td>
<td>0.282</td>
<td>600</td>
<td>21</td>
<td>30</td>
<td>11</td>
</tr>
<tr>
<td>E-glass</td>
<td>0.092</td>
<td>500</td>
<td>54</td>
<td>10.5</td>
<td>11</td>
</tr>
<tr>
<td>S-glass</td>
<td>0.090</td>
<td>700</td>
<td>78</td>
<td>12.5</td>
<td>14</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.051</td>
<td>250</td>
<td>49</td>
<td>27</td>
<td>53</td>
</tr>
<tr>
<td>Graphite</td>
<td>0.051</td>
<td>250</td>
<td>49</td>
<td>37</td>
<td>72</td>
</tr>
</tbody>
</table>

Adapted from Jones, Mechanics of Materials

Of the many types of fiber materials, carbon fiber is increasingly the material of choice for composite construction, and is today used on everything from structural spars to fairings. Carbon is extremely strong and stiff; carbon fibers, in fact, are among the strongest and stiffest reinforcing agents available. Carbon is also very lightweight. These properties together give carbon fiber composites unmatched strength-to-weight and stiffness-to-weight. Structures manufactured from carbon fiber can be stronger and stiffer than equivalent steel parts, at less than half the weight.

Indeed, carbon fiber offers a number of advantages in aircraft construction. Carbon composites exhibit superior vibration damping, as well as fatigue resistance far in excess of either aluminum or steel. Additionally, carbon fiber experiences almost no thermal expansion; for surfaces exposed to large temperature variations, these composites offer design solutions with negligible expansion and contraction.

Carbon fibers are generally limited by poor impact resistance. However, this can be solved by the addition of hybridizing agents, particularly Kevlar. In fact, the addition of reinforcing Kevlar laminates, particularly to the outer surfaces, produces some of the strongest and toughest materials in use today.

In addition to fiber selection, it is important to consider matrix properties when designing composite materials for aircraft use. The matrix formulation affects such properties as creep, compressive and shear strengths, thermal resistance, moisture sensitivity, and UV sensitivity. Matrices can be organic or non-
organic; the latter are commonly used in high-wear environments, for example ceramic-metal composite brake pads. Organic (polymer) matrices are by far the most common in structural applications, and these come in two categories: thermosets and thermoplastics.

Thermosets are polymers formed by irreversible curing processes. Curing transforms the resin into a highly rigid, cross-linked 3D structure, giving these polymers extremely high temperature resistance. Melting points for thermosets are typically high, higher in fact than the decomposition temperatures; thermosets, as a result, cannot be melted down for recycling. Thermosets are highly popular for matrix formulations, the most common of which is epoxy resin, widely used as a binder for carbon fiber.

Thermoplastics, by contrast, are polymers that turn to liquid at high temperatures; at room temperature, these materials are glassy solids. Examples include polycarbonate and polyester. Thermoplastics offer the possibility of recyclable and remoldable matrices, as well as potential increases in strength and toughness. Some composite manufacturers, in fact, boast toughness increases of over 200% through the use of thermoplastic matrices. While composite aircraft structures are currently formed using thermoset bases (typical), developments in thermoplastic manufacturing hold considerable promise for future applications.

D. Forming Processes

A variety of manufacturing processes exist for forming composite structures. These processes can be classified into two main categories, based on the method of fiber build. In a layup process, fibers are pre-woven in tape or cloth mats; build is accomplished by applying this cloth or tape to the desired form. The fibrous cloth can be either dry, requiring resin coating after application, or pre-impregnated with resin (“pre-preg”). The latter is increasingly common as it considerably shortens construction time and eliminates the need for large-scale resin applicators. Fabrics can be woven in any orientation: unidirectional fabric, for example, is made of strands oriented in the same direction, but other fabrics may have strands interwoven at 45, 90, or arbitrary angles. Once build is complete (and resin applied, if necessary) the assembly is cured at elevated temperature and pressure.

A second method involves the application of individual fibers to the form, strand-by-strand. Although far more difficult to accomplish, this process, called an oriented strand layup or windup, results in a stronger product; the directed weaving tailors the material axis to the desired design load paths, resulting in unidirectional material characteristics. Mat layup processes, by contrast, tend to exhibit less efficient bidirectional characteristics as a result of their pre-existing weaves.

After the form has been established, either through layup or windup processes, the assembly must be cured. For thermoset matrices, high temperatures are typically required for the resin transformation. Elevated pressures are also commonly used, to aid in compacting the fibers and driving out excess resin. Additionally, modern processes perform this operation in a vacuum, to promote uniform resin spread and absorption. These three conditions – elevated temperature and pressure in a vacuum – require specialized machinery, and the process is generally accomplished by means of an autoclave.
E. Vacuum Resin Infusion

A specialized form of resin application, finding increasing favor in the aerospace community for its speed and relative simplicity, is Vacuum-Resin Infusion (VRI). VRI is performed under ambient temperatures, with special self-setting resin. Advantages of VRI include:

1. Improved fiber-to-resin ratio
2. Reduced waste
3. Consistent results
4. Unlimited setup time
5. Cleaner operation

In VRI layup processes vacuum is applied to the system prior to resin application: rather than starting from a saturated state and attempting to pull out excess resin, VRI processes start with no saturation and push resin in. Only the minimum amount of resin is required, therefore, leading to lower composite weight, increased strength, and maximum material properties.

VRI processes exhibit some disadvantages, however. Foremost of these is increased manufacturing complexity. VRI layups are single-shot affairs; once resin flow is initiated, the process must be continued to completion. Small mistakes in setup or eventualities unplanned for can ruin an entire part. The layup must therefore be carefully planned ahead of time, and often trial-and-error is required to obtain the optimal setup. Similarly, in-process manufacturing defects – for example, an improper resin mix for one layup – can ruin an entire flow; VRI, then, introduces an additional level of process control.

II. Airfoil Selection

As stated earlier, it was imperative that laminar flow established over the chosen airfoil. Because of uncertainties with the wind tunnel performance as well as real world factors that might decrease the actual laminar flow experienced, an airfoil with upwards of 60 percent laminar flow was desired. This would ensure that the microphone, being placed very near the leading edge, would experience laminar flow in its cleanest state.

Research was done on historically laminar airfoils, and it was found that the NACA 66-415 airfoil would be the best choice. Ideally, this airfoil experiences a transition point at roughly 65 percent of the chord. In order to validate this, the airfoil coordinates were read into XLFR5 and analyzed. A Reynolds number of 856,000 was calculated, based upon a 12 inch chord and a 30 mph air flow over the airfoil. In addition, the airfoil was analyzed at a zero degree angle of attack, as to ensure maximum laminar flow. According to XLFR5, the theoretical transition point on the upper side of the airfoil was found to be at 75 percent chord. However, with real world considerations, such that the Cal Poly wind tunnel not being perfectly clean, that transition point is expected to move down to about 35 to 40 percent chord. The results from the XLFR analysis can be seen in figure 1 below.
III. Fabrication of Composite Wing

A. Design of NLF Composite Wing

The composite NLF wing of this project is designed for interchangeability with Cal Poly’s existing NACA 4412 test apparatus. In particular, the spar system has been design to match the 4412’s in order to mate with the existing mounting system. The 4412 contains three metal spars that run the length of the wing and interface with the wind tunnel mounting plates. The NLF wing matches this configuration; 3 metal spars are used for spanwise support, with the layout template-matched to the wind-tunnel mounts. During experimentation, microphone and pressure transducer wiring will be run through these spars to equipment outside the wind tunnel.
A schematic of the NLF composite wing is presented in Fig. 1. Three foam ribs are used, spaced one to either end and one in the center. These ribs give the wing shape, support the composite skin, and transfer torsional loads to the wing spar system. The spar system is comprised of three metal rods. These rods are sized and located to match the existing NACA 4412 wing so as to be interchangeable with the existing mounting brackets. The spars carry all spanwise loading, and are hollow in order to house wiring from the microphones and pressure transducers. The wing is covered with a carbon fiber/epoxy skin for maximum surface smoothness. Minimal loading is expected in the skin during testing conditions; as a result only four layers of carbon are used. The carbon is 3.5 oz. plain-weave fabric; the matrix is Pro-Set 117 LV Infusion Resin epoxy. An ultra-smooth surface finish is obtained by using a layer of Mylar in the manufacturing process as outlined in the following section. The wing is capped with aluminum ends to protect the wingtips from damage during handling; these will be machined in future work.

For experimentation, microphones and pressure transducers will be mounted as-needed on the center section of the wing. Preservation of the laminar boundary layer is critical to the success of this experiment; all equipment will therefore be flush-mounted to the wing surface. Holes will be drilled in the carbon-fiber skin and the required equipment mounted underneath, with coatings applied as necessary to smooth any surface irregularities. This work will be done as part of the experimental preparation.

B. Manufacturing of Composite Skin

The composite skin and foam ribs are manufactured simultaneously. An oversized block of blue foam is used as the material for the ribs. The foam for this project was generously donated by the Cal Poly Design-Build-Fly (DBF) Club, with special thanks due to Cory Seubert.
The block of foam is cut to the shape of an airfoil, using a CNC hotwire machine. Brian Borra was instrumental in this process, and his help is much appreciated. The foam block is placed in the hotwire space and the system aligned. The cut is computer-controlled; an airfoil coordinate file is read into the program, and scaled to the desired size. Allowance is provided at the back for “cut-in” – a straight horizontal cut from the foam edge to the airfoil trailing edge, the start of the airfoil path. A cut file is generated that contains the correct cut path. The hotwire is activated and set to 20 V, and cutting is initiated at 5 in/min; this heat and speed were determined experimentally, through trial-and-error cutting of test samples. The cut is monitored to ensure wire lag and excessive melting do not occur. Following completion of the cut the block is removed and the wire deactivated. The core is then removed from the block and inspected for surface imperfections. For a laminar flow airfoil this step is critical; it is imperative that the surface be free from lag marks and other turbulent trips. Again, trial-and-error is essential; multiple scale trial cuts during this experiment produced a final full-size airfoil of impressive finish. The finished mold is shown in Fig. 2.

![Figure 3. Negative foam mold after hotwire cutting](image)

Both the core and the negative mold are used in the manufacturing process for the composite skin. The skin is first laid up dry as a flat plate and prepped for a VRI process. A schematic of the stack is shown in Fig. 3.
Vacuum bag begins the stack, cut considerably oversized to allow margin for taping and other manufacturing techniques. Next is stacked a sheet of flow media; this layer is specific to the VRI process, and provides a matrix through which resin flows during the epoxy application. On top of this – last before the carbon fiber – is a sheet of peel ply. Peel ply is a specialty fabric that is treated to ensure easy removal from the cured carbon fiber; this is stacked directly against the carbon fiber layers, allowing the lower stack to be removed after the VRI process is complete. On top of the peel ply are stacked four layers of carbon fiber, carefully oriented to ensure proper strand alignment. The carbon is 1000 tow plain-weave fabric; material properties are given in Table 2.

<table>
<thead>
<tr>
<th>CST CF14X Carbon Fiber</th>
<th>Weight</th>
<th>3.5 ounces / square yard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tow Size</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Tow Count / Inch</td>
<td>24 x 24</td>
</tr>
<tr>
<td></td>
<td>Weave</td>
<td>Plain</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>0.007 inches</td>
</tr>
</tbody>
</table>

An ultra-smooth surface finish is created by application of a layer of Mylar to the top of the carbon fiber stack. This shapes the outer surface of the composite. Like peel ply, Mylar does not stick to the cured composite; it also provides a moldable, ultra-smooth surface for the resin to cure against. After manufacturing the Mylar is peeled off the carbon fiber, leaving a high-gloss finish that is ideal for laminar flow. Clear Duralar Grafix Mylar is used for this experiment; a thickness of .005” is used to balance the material’s formability against its masking of surface defects.

The finished stack is weighed to determine the necessary resin volume. The unbagged stack is shown in Fig. 4.
The vacuum bag edges are taped, and the bag is folded over itself. Tubing is inserted into the bag, with the open end protected by cotton to prevent bag choking; a double layer of tape is used around the tube/bag junction to protect against leaks. The bag is sealed, and vacuum is applied to the tubing. Care is taken during vacuum application to remove all wrinkles and creases from the bag surface, which might otherwise propagate to the finished composite. At full vacuum the system is checked for leaks.

This assembly is then wrapped around the foam core. This entire assembly is placed inside the negative mold. The mold itself is then bagged, using an extremely oversized bag to avoid sealing difficulties. Care is taken during this process to ensure the skin does not shift inside the mold and all materials remain properly aligned; special attention is given to the airfoil leading edge.

The outer bag is taped and the edges sealed. Pleating is used to overcome the geometric difficulties of wrapping the bag around the block edges. A vacuum tube is again inserted into the bag, with the open end covered with cotton to prevent bag choking; an additional tube is also provided for resin insertion. The inner vacuum tube is carried outside the outer bag. Double layers of tape are used to ensure good seals at all bag/tube interfaces. Vacuum is applied simultaneously to the inner and outer bags, and the outer bag is inspected for leaks.

Resin content is calculated from the total carbon weight, using a 100:30 target mixture ratio (by weight) per manufacturer specs. Pro-Set 117LV Laminating Resin is used as the matrix substance, with Pro-Set 226 Hardener as the curing agent. Material properties of this system are given in Table 3. Care is given to stay within the allotted working time of the epoxy in order to avoid premature setting.
Table 3. Material Properties of Resin/Hardener System

<table>
<thead>
<tr>
<th></th>
<th>Pro-Set 117LV / 226*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Working Time</strong></td>
<td>60 minutes (at 72°)</td>
</tr>
<tr>
<td><strong>Target Mix Ratio</strong></td>
<td>100:30 (by weight)</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>9.1 lbs/gal</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>84 Shore D</td>
</tr>
<tr>
<td><strong>Compression Yield</strong></td>
<td>14 920 psi</td>
</tr>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>8 234 psi</td>
</tr>
<tr>
<td><strong>Flexural Strength</strong></td>
<td>13 636 psi</td>
</tr>
<tr>
<td><strong>Tensile Modulus</strong></td>
<td>5.28E+05 psi</td>
</tr>
<tr>
<td><strong>Flexural Modulus</strong></td>
<td>5.66E+05 psi</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>0.007 inches</td>
</tr>
</tbody>
</table>

*values for standard cure schedule (room temp (70°-75°) x 2 weeks)

Resin is applied to the system after full vacuum has been achieved. The resin tube (installed in the bagging procedure) is submerged in the resin pot to initiate flow; the vacuum draws the resin from the pot and through the flow media, gradually bathing the carbon fiber in epoxy. Flow is monitored for penetration and to ensure uniformity. Flow is continued until the resin reservoir is depleted; if calculations are performed correctly, the weighed amount of resin should result in complete carbon fiber coverage. No excess resin should be needed or used.

The completed layup is left vacuumed and sealed for a minimum of 24 hours to ensure proper curing. All tubes and vacuum and resin systems are left connected in order to prevent vacuum disturbance.

After curing is complete the tubes are removed and the outer bag cut. The mold is opened and the core – now covered in cured carbon fiber skin – removed. The inner bag is cut, with caution taken to avoid damaging the high-gloss composite finish. The Mylar sheet is peeled away from the composite. On the inside, the use of peel ply allows the removal of the flow media as well; while effort is required to separate this system, but the peel ply and substack are broken away from the carbon fiber skin. The resulting skin is therefore carbon fiber/epoxy only, complete with an ultra-smooth outer surface finish. The completed composite wing, after removal from the mold, is shown in Fig. 5; the inner (peel-ply) and outer (Mylar) wraps have not been removed yet.
IV. Analysis of Manufacturing Procedure

A. Scale Test Layup and Lessons Learned

In order to minimize surprises in the final manufacturing process, a small-scale test layup was conducted on a single airfoil section prior to the full-scale wing layup. This layup yielded close-to-ideal results, validating the process and justifying its use on the final wing. The surface finish in particular was found to be flawless. Four layers of carbon fiber were tested on the scale model and found to be adequate for flexural concerns, particularly after inclusion of ribs and spars. The Mylar sheet separated easily from the composite, eliminating concerns about resin adhesion. The inner peel ply was less accommodating but was eventually removed with no damage to the part.

Several process improvements were discovered during the test layup. First, difficulties were encountered in bagging the mold; a larger, considerably oversized outer bag was proposed to rectify this problem. Second, (outer) mold closure impediments were created by the insertion of vacuum tubes and resin tubes to the inner bag; an oversized mold was therefore proposed, allowing room to cut in notches at the trailing edge for tubing as required. Third, sizeable layup degradation was noticed at the carbon fiber edges; again, use of an oversized mold, together with oversized carbon fiber mats, was predicted to solve this problem. This solution was predicted to produce an oversized part with margin at the edges, which could be trimmed to the desired size on a wet saw.

Despite these notes, the test layup was an overwhelming success. The manufacturing process was updated with the lessons learned, and manufacturing proceeded to the full-scale model.
B. Final Wing Layup and Process Analysis

Use of a test layup proved to be a valuable strategy in identifying potential failure points in the more elaborate full-scale wing layup. As a result of the lessons learned, the bag sizes for both the inner and outer molds were increased to aid sealing. Similarly, the mold itself was cut several inches large in order to produce an oversized part with trimmable margin for imperfect edges.

The problem of fiber saturation along the layup boundary, however, proved persistent. The wing layup proceeded smoothly from layout to bag closure; the larger vacuum bags solved the problems encountered during the trial layup. Problems were encountered, however, at the resin flow stage. The size discrepancy between the scale and final wing layup proved problematic; additional processes were required for the final (larger) layup, including dual-ports and spiral tube injection. The effect of these techniques was to reduce the uniformity of resin flow. Resin was found to flow far more readily along the right wingtip than the left, leading to concerns mid-process about “dryness” in the latter. Additional resin was added to the system (both sides) to combat this effect. While resin was observed in the exit tubes on the right wingtip after 5-10 minutes (typical), the left wingtips took approximately 30-40 minutes to saturate. This increased concerns regarding proper cure.

These concerns were validated upon opening of the mold 48 hours later. The majority of the wing was found to be properly cured. The surface was found to have an extremely high-gloss finish, perfect for laminar flow; in this regard, the manufacturing process was deemed an overwhelming success. Furthermore, the wing leading edge – a point of particular concern for turbulent trips – was found to be flawless. The double-vacuum was therefore effective in “setting” the form inside the mold, and provided sufficient pressure to engage both surfaces.

Flaws were discovered, however, along the left wingtip. The trailing edge of the extreme left boundary was found to be largely dry, likely due to the resin flow problems encountered during layup. This revealed the biggest weakness of VRI processes; even with preliminary testing, planning and development of reliable procedures, unforeseen or uncontrollable in-process manufacturing variations can potentially ruin an entire part. In this case, the inclusion of significant margin in the wing size proved foresighted and allowed the dry areas to be trimmed from the part with no adverse effects.
Figure 7. Trimming the edges to size.

Slight flaws were also discovered in the wing surface, attributed to surface imperfections in the mold itself. Inspection of the female mold revealed a series of linear “jumps” instead of smooth curves, due either to (1) wire lags in the cutting procedure or (2) propagation of coordinates from the airfoil data file. While the presence of these imperfections suggested further improvements in the manufacturing process, the surface quality was judged sufficient for the laminar characteristics required.

Figure 8. Completed airfoil section.
V. Microphone Selection

In order to sense the difference in acoustics between a laminar and turbulent flow, a high intensity microphone is needed. Because microphones measure the variance in signal, it was imperative that a microphone was chosen had the proper decibel range to satisfy this experiment. In order to find the typical range of turbulent flow for the Cal Poly wind tunnel, data from previous experiments was analyzed. By looking at the pressure readings for similar experiments, the dynamic range of pressure could be found, and therefore the proper microphone decibel range that would be needed for clear, precise data was found.

It was decided that a Kulite microphone would be the best fit for this application. Kulite has a wide range of microphones, ranging from automotive, to aviation, to military applications. When looking into the aviation applications of their microphones, it was found that Kulite makes microphones that are designed just for flight testing and instrumentation. When using the product advisor, it was found that only 3 microphones matched the requirements that were needed: the MIC-062, MIC-093, and the MIC-152. Each of these microphones has the same specifications, the only difference being the size of each. The MIC-152 was chosen because it was the largest, thus making the implementation into the airfoil easier. The microphones specifications can be seen in the appendix.

VI. Conclusion

The main manufacturing of the wing is done. Once the microphone is obtained, the appropriate holes will be drilled, and the spars can be placed inside the airfoil section, completing the design. These steps will not be taken until the microphone is purchased however, in order to ensure perfect fitting between the microphone and the airfoil surface. Overall, the fabrication of the test section went well. The surface finish is smooth with very little imperfections, leading us to believe that laminar flow over the first 30 percent of the chord is easily obtainable. The airfoil has been test fitted within the wind tunnel, and it fits perfectly within the pre-existing frame for airfoils to go in the wind tunnel. All the milestones for this project have been met, and the airfoil is ready to be used for acoustic testing once the proper microphones have been purchased.

VII. References

VIII. Appendix

**MRC Series**

- Low Sensitivity
- Omni-directional Capability
- Small Size
- Fast Response

The MRC series is designed for the measurement of sound pressure where conventional microphones cannot operate due to dynamic pressures, high static pressure, or high temperature. Acoustic pressures over the dynamic range 0 to 194 dB can be measured. The sensor is extremely rugged and does not require additional protection except when used indoors containing particulates (e.g., dust, smoke, engine exhaust, etc.). Reasonable survival for all MRCs is anticipated.

### Specifications:

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>8 mV/decade</td>
<td>8 mV/decade</td>
<td>8 mV/decade</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>100 to 104 dB</td>
<td>100 to 104 dB</td>
<td>100 to 104 dB</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°F to 220°F (-40°C to 100°C)</td>
<td>-40°F to 220°F (-40°C to 100°C)</td>
<td>-40°F to 220°F (-40°C to 100°C)</td>
</tr>
<tr>
<td>Thermal Sensitivity</td>
<td>Less than 0.5 mV/°F</td>
<td>Less than 0.5 mV/°F</td>
<td>Less than 0.5 mV/°F</td>
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<tr>
<td>Excitation Voltage (2N or 4N)</td>
<td>1V</td>
<td>1V</td>
<td>1V</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>1000 Ohms (min.)</td>
<td>1000 Ohms (min.)</td>
<td>1000 Ohms (min.)</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>1000 Ohms (max.)</td>
<td>1000 Ohms (max.)</td>
<td>1000 Ohms (max.)</td>
</tr>
<tr>
<td>Minimum Sound Pressure</td>
<td>20 Pa (0.2mbar)</td>
<td>20 Pa (0.2mbar)</td>
<td>20 Pa (0.2mbar)</td>
</tr>
</tbody>
</table>

### SPL vs Pressure Levels

<table>
<thead>
<tr>
<th>SPL</th>
<th>Pressure (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>62.0 dB</td>
</tr>
<tr>
<td>115</td>
<td>65.0 dB</td>
</tr>
<tr>
<td>120</td>
<td>68.0 dB</td>
</tr>
<tr>
<td>125</td>
<td>71.0 dB</td>
</tr>
<tr>
<td>130</td>
<td>74.0 dB</td>
</tr>
<tr>
<td>135</td>
<td>77.0 dB</td>
</tr>
</tbody>
</table>

### Note:

- Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parentheses are in millimeters.
- Changes in design and configuration of component parts may result in specification changes without notice. All dimensions rounded. (R)

**KULITE SEMICONDUCTOR PRODUCTS, INC.**

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- Fax: 203-461-6300
- http://www.kulite.com
Note: Spar diameters and spar through holes are all template matched. Dimensions depend on wind tunnel end cap used.