Abstract –

A new method for manufacturing advanced composite propellers was developed. High-efficiency propellers frequently exhibit thin sections and small root sizes coupled with high stiffness and strength requirements. Accurately creating a precise airfoil cross-section and maintaining a flawless surface are also crucial to maximizing efficiency. Carbon-fiber composite materials are ideally suited to meet stringent performance requirements, but achieving consistent high-quality manufacturing can be difficult and expensive. In order to create a one-piece, two-bladed propeller, a novel method of tooling design using a three-piece mold was developed that reduces design time and simplifies machining of propeller molds. A computer program was written to evaluate the optimized propeller geometry and identify a pair of silhouette curves. These curves, along with the trailing edge of the blade, are used to define a new set of curves defining a core and two-piece cavity side of a mold. The new curves were output to a data file formatted for Pro/Engineer CAD/CAM software. Three mold sections are easily designed from the curve segments. Two sections comprise the recessed cavity and the third forms the protruding core side. By creating the cavity side in two parts, the mold can be easily machined with simple tooling and a three-axis computer numeric controlled milling machine, reducing both cost and time to manufacture the mold. The deep cavity simplifies the process of preparing the reinforcement layup and the three-part mold also makes it easier to remove the propeller from the mold. In place of the usual solid composite hub, integral metal hubs may also be included. These metal hubs simplify the molding process, increase the overall strength of the propeller, and allow for a more secure connection to the propeller shaft. Carbon composite propellers were successfully manufactured using vacuum resin infusion in a prototype mold. This innovative process demonstrated the ability to produce strong, high-quality, void-free propellers.

Introduction and Project Design Specification –

The development of a composite propeller construction method fulfilled a distinct Grove City College Mechanical Engineering Department need for efficient propellers suited for Human Powered Vehicles. High-efficiency propellers operating in water frequently exhibit thin, high-aspect blades with small cross-sections and roots coupled with high stiffness and strength requirements. Accurately creating a precise airfoil cross-section and maintaining a flawless surface are also crucial to maximizing efficiency. Adequate propellers are not available commercially. Previous attempts at machining metal propellers demonstrated that the process was very difficult, expensive, time consuming and produced structurally unsound parts. Carbon-fiber composite materials are ideally suited to meet the stringent performance requirements of propellers.
Composite parts are often planar resin infused fabric sheets molded about an external or internal form. Parts produced from this method tend to be similar to stamped metal parts in that the overall geometry can be quite complex but the material thickness must remain relatively uniform throughout. In general, this type of part can satisfy critical dimensions and surface finish requirements on only one face. Additionally, the pressure induced during vacuum-bagging or hand layup serves to compact the fibers into the dense, high fiber-to-resin ratio necessary for high strength and low weight.1 A high efficiency propeller, however, must be nearly perfect in all three dimensions; characteristics that only a closed-mold process can produce. In many respects, the closed-molding composite process is very similar to injection molding. Nonetheless, integrating a fiber reinforcement charge presents numerous additional considerations. Initially, manually inserting fibers into a simple clam-shell style mold seemed feasible. Regardless of the type or weight of fiber, however, it is extremely difficult to manipulate carbon fiber into a complicated mold because it unravels, frays, and tends to be too stiff to conform to small radii. The following figure illustrates additional difficulties associated with packing a mold with reinforcing fiber.

![Figure 1. Tendencies of reinforcing fiber to jam a typical clam-shell closed mold.](image)

A. A compacted laminate is crucial in creating a part with maximum strength. To achieve this high fiber-to-resin ratio, the mold must be filled with capacity with fiber.

B. Due to the stiffness and bulkiness of the fiber, the pile stands proud of the mold before being compacted.

C. Invariably, as the large pile of fiber is compressed between the two mold halves, some fiber escapes into the gaps outside of the cavity. This prevents the halves from completely closing and jams the mold together. As a result, the seal is compromised and a severely distorted product is produced.

D. Twist in the propeller blades means causes some sections to be at a more vertical angle. Gravity exacerbates the problem described above as more fibers fall into the gap.
A simple clam-shell style mold with two mating halves is inadequate due to the difficulties associated with inserting reinforcement fibers. The key to developing a successful closed-mold process was the invention of a “Piston Mold”. This design involves a deep female recessed cavity into which the reinforcing fiber is loaded. A protruding male plug compresses the fibers as the two halves come together.

Figure 2. A Piston Style mold with the male plug section being inserted into the female recess compresses the bulky resin charge into a compact laminate.

Precise knowledge of the quantity of reinforcing fiber required to fill the mold is necessary to achieve a high-quality laminate. Test molds with simple rectangular cross-sections were machined in order to determine the compressed density of different carbon fiber fabrics and yarn combinations. More importantly, these experiments proved that the novel piston style mold would be capable of closing and compressing reinforcing fiber without binding. Multiple test molds were machined, each with different tolerances between the male plug and female recess in order to determine the optimum gap width.

Although the piston style mold would produce the high-quality composite parts, propeller geometry presents significant machining challenges. The large depth of the female recess combined with small internal radii requires the use of impractically long, slender end mills. The solution to this problem was to machine the female mold section in two parts. By dividing the mold at the deepest section, which lies near the leading edge on a propeller oriented horizontally with the hub facing downward, all surfaces of the cavity could be easily machined.

Figure 3. Challenges inherent to machining a deep, complicated cavity.
The two-blade propeller specified for GCC human-powered vehicle use was defined at ten cross-sections between the hub and tip. At each station, the airfoil shape, chord-length, and twist were defined and the cross-sections were connected using a blended surface interpolation. A MATLAB computer program was written in order to identify parting lines. The program first loads stock data points of the upper and lower cambers for a specified airfoil. After this, a spline interpolation generates a smooth curve of closely spaced coordinate points. Next, the array of points are rotated and scaled to match the cross-section’s pitch angle and chord-length. Once the foil section is properly oriented, the trailing edge as well as the horizontal and vertical tangent points near the leading edge are found. These points define the parting lines between the mold sections as shown above in Figure 4. The points and mold surfaces are plotted to allow the user to verify the geometry. Finally, all critical points are output in a data file format that can be input into CAD software.

Vacuum infusion was used to introduce resin into the mold. Using a vacuum pump, air is removed so that resin is drawn into the mold cavity. Compared to resin injection, this process eliminates the large forces upon the mold. In fact, atmospheric pressure helps clamp the mold sections together which greatly increases the strength of the seal.

The schematic shown in Figure 5 illustrates the flow of resin during vacuum infusion. Resin flows from the supply cup into the hub and outward into the blade roots from which the majority continues radially to the tip. As shown in the detailed cross section, some resin flows chord-wise up into the gap between male and female mold sections before continuing to the tip. This secondary flow insures that resin reaches the thin extremes of the propeller where voids are most likely to occur. Any air that does become trapped tends to form bubbles in the gaps instead of compromising the leading or trailing edges. Eventually, after exiting the mold at the tips, excess resin accumulates in the resin trap so that only air enters the vacuum pump.
Resin inlets and outlets were engineered to simply and effectively permit the flow of resin without introducing air into the laminate or allowing resin to leak from the mold. More critically, in a manner similar to injected molded plastic, residual resin cures in the mold passageways to form solid sprues which must be easily removed. Channels of semi-circular cross-section on opposing mold sections form cylindrical passageways though which liquid resin flows into the cavity. When the mold is opened, the cured resin sprues easily lift perpendicularly from the mold mating surfaces as the part is removed. With access to the inside of the entire passageway, this reliable system greatly reduces the chance of cured resin becoming stuck in the channel and makes removing accidently adhered resin much easier. Positioning the resin inlets and outlets on the parting surfaces of the mold section allows for a very simple method of attaching the vacuum infusion tubes. Clamping pliable tube in between mold sections eliminates the need for special adapters such as expensive threaded metal barbed piped fittings. Test molds were machined to validate this extraordinarily simple concept. Different sized recesses were tested to determine the geometry that securely clamped the tubing yet did not jeopardize the seal between mold sections.

Figure 5. Vacuum Infusion Resin Flow Schematic
Mold Construction and Propeller Fabrication –

The final mold designs were modeled using Pro-Engineer Wildfire 4.0 CAD software and CNC machining operations were defined using MasterCam X4. The three mold sections were machined with the Grove City College machine shop’s 3-Axis Fadal CNC milling center. Aluminum was chosen for ease of machining, low cost, and low weight. Secondary machining operations involved drilling and tapping holes for the screws that clamp the three mold sections together. Finally, the mold cavity was manually sanded and polished to achieve a surface roughness of approximately four microinches.

Propeller layup is approximately a two-hour process followed by a twelve hour cure time before the mold can be opened. Once the molds are polished, the first step of the process is to apply multiple coats of mold release wax and one film of poly-vinyl alcohol (PVA). After these agents have dried, the two female mold sections are aligned and clamped together around the resin inlet tube at the tip of the hub. Next, pieces of fiber fabric are cut to match the exact blade planform and are laid carefully into the mold. The tip of the hub is filled at the same time with chopped strand fiber. After this, long strands of uni-directional fiber tow are run from tip to tip, through the hub, over the chopped strands. Once the mold cavity is filled to capacity with uni-directional tow, another set of blade planform fabric swatches is inserted. With the two resin outlet tubes positioned in their respective receptacles between the male and female mold sections, the mold is clamped closed. To ensure eliminate the possibility of air bubbles entering the mold cavity, the mold section joints are sealed with tape and the resin tubes are sealed with clay. Following resin infusion and removal from the mold, sprue and flashing removal yields a finished propeller.

Although this process is also compatible with fiberglass and aramid, high-modulus carbon fiber was used to maximize strength and rigidity at the lightest weight. For the same structural reasons, West System #105 Epoxy was chosen. This process should be compatible with most mainstream resins including polyester or vinylester resin.

Preliminary Improvements –

Fabricating the hub with chopped strands as described above was difficult to execute and resulted in a hub of diminished strength. Although it is advantageous to have the roots completely filled with tip to tip uni-directional strands of carbon tow, the chopped strands spilled into the root and inhibited the structural strands. More critically, since the uni-directional fibers pass straight through the hub, a drilled a hole for the shaft will break the continuous fibers thereby substantially weakening the propeller. To simplify the fabrication process and make the assembly more robust, an aluminum hub insert was designed to be molded directly into the propeller. The insert nearly fills the entire cavity. A protrusion in the base of the hub divides the reinforcing fibers that run through the hub so that they are not broken when a shaft hole is drilled. So as to not plug the resin inlet, a hole in the hub along the propeller’s axis of rotation allows resin to flow from the tip of the hub and continue out into the blades. Resin cures in and around the hub insert so that the metal insert and carbon fiber blades become one integral unit. The propeller fabricated using the aluminum hub insert was noticeably stronger, albeit heavier, while the layup process was much less difficult.
Future Improvements & Tasks –

In the future, structural tests will be performed on the existing carbon fiber propellers to see if they are capable of handling the loads that will be presented when powering a human powered boat. Besides breaking at the root, the propeller blades must be resistant to torsional strain. Otherwise, the propeller will assume an angle of attack contrary to its design. Also, hub strength will be tested to see which configuration allows the most torque to be transmitted from the shaft to propeller. These structural tests will be performed using the Grove City College Instron Tensile Testing machine. The impact testing machine engineered and built as part of this independent study will be used to evaluate the strength of the thin leading and trailing edges. It is expected that the edges will be found to be sufficiently tough. Although the current 0.08 inch thick root section with a chord length of 0.67” is expected to have adequate strength, its resistance to deflection is suspect. Therefore, it is likely that the root size will be increased.

The concept of metal hub inserts was developed after the original propeller molds were machined. Therefore, the resin infusion flow pathway became quite convoluted when the hub inserts were integrated into the process. Future molds will be designed from the onset to seamlessly accept metal hub inserts.

Instead of relying on metal mating surfaces to form a seal between mold sections, a gasket system will be implemented on future molds. Despite the precision CNC machining and large clamping forces, the existing mold is not air-tight. The joints between mold sections must be sealed with tape and clay. Although an adequate seal is formed, the taping process is labor and material intensive. Also, on the existing mold, resin tends to leak into the holes for the screws that connect the mold sections. If the screws and holes are not sufficiently coated with mold release, the mold sections could become glued shut. Rubber gaskets on the mating surfaces of the molds sections should effectively seal the mold and eliminate both the need for taping the joints and the risk of the mold being stuck together.

Although only a negligible amount of air leaks into the existing mold, voids tend to be introduced into the layup due to small air bubbles suspended in the resin. During future construction, a resin degassing process, during which the epoxy is held under a vacuum, will eliminate air bubbles before they enter the mold.6

Conclusion –

Multiple successful propeller fabrications demonstrated the ability to produce strong, high-quality, void-free parts using this innovative closed-mold composite construction process. Despite being very thin with sharp edges, the resulting propellers are very strong and are not prone to chipping. Careful mold preparation results in a nearly flawless glossy surface finish. Mold flashing is trimmed and sanded so that with care, only a small portion of the surface is affected and the airfoil section is not altered.
The development of a new method for fabricating advanced composite propellers was the focus of a three credit independent research project. In addition to manufacturing sophisticated closed molds and fabricating multiple composite propellers, a detailed report and instruction manual was written so as to explain design rationale. This project is serves as an educational tool to increase Grove City College mechanical engineering department knowledge and exposure to closed-mold carbon fiber construction. The design process outlined in this paper is currently being used to fabricate blades for the wind turbine engineered by fellow GCC research students Chuck Witt and Josh Norman. This new method of closed mold composite fabrication has demonstrated the ability to produce strong, high-quality, void-free propellers and is suited to build premium composite parts for a wide array of applications.

References


