Manufacturing Processes of Composite Materials for a Human-Powered Submarine

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Abstract – **Human-powered submarines are controllable underwater vehicles, which are designed and built to achieve maximum speed over a 100-meter course. Manufacturing the submarine as close to neutrally buoyant as possible has become a priority for competing teams. As human-powered submarines have decreased in volume to minimize mass, the insertion of buoyant materials during the manufacturing process has taken on a new importance.**

The most advanced submarine designs utilize several techniques to achieve a strong, yet lightweight structure. Strategic placement of buoyant materials during composite manufacturing has several advantages that are beneficial to the performance of the submarine. This paper describes the techniques used by the Human-Powered Submarine Team of Virginia Tech in the construction of Phantom 4.

I. INTRODUCTION

The Human-Powered Submarine Team of Virginia Tech has been in existence since 1989. Since that time, the team has produced five submersible vehicles using human power as the sole means of propulsion. Each successive submarine has been smaller and more complex. With each new design came more advanced manufacturing techniques. Phantom 4, the team's fourth propeller-driven submarine, was constructed using the most advanced techniques and materials. The hull is extremely strong, yet lightweight, and was produced in less than three weeks.

Composite materials were selected for this application because of their high strength-to-weight ratio, good formability, and ease of repair. Creating a neutrally buoyant vessel has great importance to the project for several reasons. A neutrally buoyant object is the easiest to control underwater. Neutral buoyancy eliminates the need for the control surfaces to correct for changes in depth, which significantly reduces the drag on the submarine as it moves down the course. The stability of a submarine is largely dependent on the location of buoyant objects, which necessitates strategic placement of such objects. This paper describes the composite manufacturing techniques used in the construction of Phantom 4, and discusses the use of buoyant materials to create a vessel with a buoyancy close to neutral.

II. MANUFACTURING TECHNIQUES

A. Materials Selection

Composite materials were chosen for the construction of the submarine for several reasons. Composites have a high strength-to-weight ratio, can be formed to nearly any shape, and can be altered or repaired relatively easily. Fiberglass and carbon fiber woven cloth were selected for their strength, cost, and availability. These fabrics, in combination with a two-part epoxy resin, are approximately 2 – 2.5 times the density of water. Fiberglass does not absorb water, which is particularly advantageous in this application. Several different weights of fiberglass were used throughout the manufacturing process, depending on the strength required.

While the fiber cloths make up the bulk of the hull structure, a buoyant material was necessary to counteract the weight of negatively buoyant objects inside the hull. A structural closed-cell foam was selected for this application. The foam was placed in between layers of fiberglass during the composite lay-up. Closed-cell foam is especially important for an underwater vehicle because if water were to penetrate the outer layers of fiberglass, the nature of the foam structure isolates the leak by preventing water from seeping farther

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into the foam. Trapped water changes the buoyancy of the submarine and has detrimental effects on its performance.

With a buoyant force of 62 pounds per cubic foot, only a few square feet of ½-inch foam is necessary to achieve neutral buoyancy. The incorporation of closed-cell foam into the hull and control fins is discussed later in this paper.

B. Vacuum-bagging Process

Vacuum-bagging is a common composite processing technique used in many industries. For the construction of Phantom 4, a female mold of half of the submarine was machined into high-density machining foam.

The molding surface of the foam was coated with a two-part epoxy resin to create a smooth, sealed surface for molding the hull. The initial hull lay-ups consisted of a bi-directional weave fiberglass with a matte backing. This provided a stiff shell for bonding subsequent layers.

A typical vacuum-bag lay-up consists of the bonding surface, material being bonded saturated with epoxy resin, peel ply, absorbent batting material, polymer vacuum bag, and vacuum fittings. The advantage to such a process is that a constant pressure from the vacuum is applied to the entire surface and evenly distributes the epoxy throughout the fabric during curing. Surface preparation is an important step of the process, as it will affect the strength of the bond. While epoxy manufacturers recommend many techniques, roughening the surface with sandpaper and wiping with a damp cloth is acceptable.

Fig. 1. Female mold of Phantom 4

Fig. 2. Vacuum lay-up

More than one vacuum fitting is recommended for more effective evacuation of air and a more uniform surface finish. While vacuum pressure will vary between vacuums and the size of the lay-up, standard vacuum pressures for a composite lay-up are approximately 20 psi.

Three layers of fiberglass compose the majority of the hull of Phantom 4. In areas of high stress, such as the dome lip, pilot hatch, and propulsion hatch, carbon fiber was used as reinforcement. As previously mentioned, carbon can absorb water so its use was reserved for areas requiring added strength.

C. Foam-composite Structures

Speed is the ultimate goal in the design of a human-powered submarine. Tests by the Virginia Tech Team as well as published data have shown the power output by a human underwater to be close to 0.3 hp. Given such a limited power supply, it is imperative that teams maximize the conversion of human power to thrust at the propeller. The simplest method to achieve this result comes from the equation

$$F = m * a, \tag{2.1}$$

where F is force, m is mass, and a is acceleration. By minimizing the mass of the submarine, acceleration is maximized. All human-powered submarines are flooded vehicles so the mass of the water inside the hull is significant. Phantom 4, for example, has a flooded mass of approximately

1400 lb. This considerable mass calls for a submarine design of minimal volume. In addition to the pilot, the hull must encapsulate the

Fig. 3. Closed-cell foam (green) and carbon reinforcement (black) visible

propulsion system, control system, and all life-support systems. Many components of these systems are negatively buoyant. Therefore, if a neutrally buoyant submarine is to be achieved, buoyant materials are necessary. Logically, extra space inside the hull for added buoyancy translates to greater mass and increased drag. Thus, incorporating the buoyant materials into the design eliminates the problem. The Virginia Tech team utilized several techniques to achieve this goal in the construction of Phantom 4.

The attachment of objects to the composite submarine hull is accomplished by the creation of hard points. A hard point in the hull is essentially an area that has been reinforced with an epoxy-milled fiber mix. Foam was placed in areas where hard points were not anticipated to be necessary.

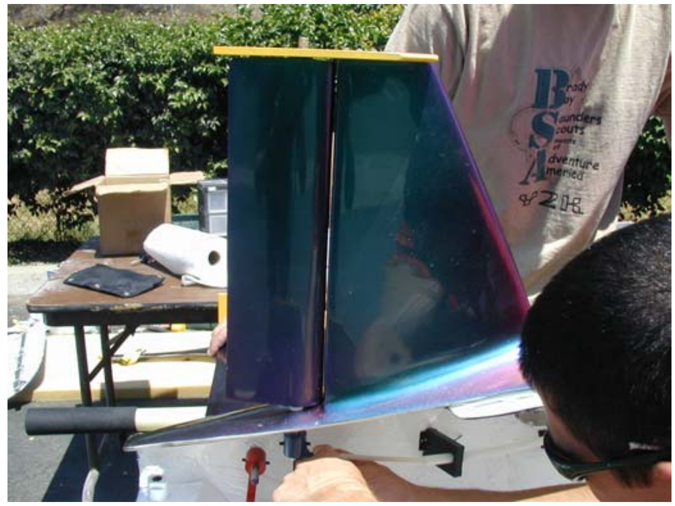

Fig. 4. Fixed control fin (right) and movable flap

Such areas include the section surrounding the pilot and the underside of the two hatches. The foam was initially coated with epoxy to ensure a good bond and fiberglass was laid on top. The area was placed under vacuum and allowed to cure. This process added buoyancy with very little additional volume.

The control fins are another component of the submarine's design that can be engineered to be positively buoyant. The design of the control system on Phantom 4 called for four sets of fixed-movable control fins at the stern of the boat. The fixed portion of each pair was structural and provided stability with its relatively large surface area. The movable portion of the pair was designed to deflect a maximum of 20° in either direction to control the submarine.

The design of the control fins necessitated that fixed portion be of structural quality as it had an aluminum end plate attached at its tip. The stern of Phantom 4 was inherently negatively buoyant due to the weight of the gearbox. Closed-cell foam was wrapped with carbon fiber and placed in a room-temperature-vulcanization (RTV) mold. This composite was surrounded with a matrix of chopped fiberglass and epoxy, creating a strong fin with approximately 3 lb of buoyancy. With four control surfaces mounted at the stern, this provided a significant amount of buoyancy to counteract the 35 lb gearbox and steel drive shafts.

The movable portion of the fin needed not be so structural so a different approach was taken. Closed-cell foam was cut to the proper airfoil shape, wrapped with a medium weight fiberglass, and placed under vacuum to create a reinforced, buoyant component.

While these three techniques provided buoyancy for Phantom 4, another was used to help with the stability of the submarine. The propulsion system for Phantom 4 was designed to mount to a structure extending down from the top of the hull, appropriately referred to as the “stalactite”. This structure was formed by sandwiching seven pieces of closed-cell foam together with epoxy. This volume of foam provided a significant amount of buoyancy in the top of the hull. The hull design of Phantom 4 has flat areas on the port and starboard sides. These were also optimal locations for foam. As a submarine accelerates, the propeller pushes on the water causing the hull to rotate in the opposite direction. These flat areas in combination with the stalactite “self-right” the submarine and prevent it from rolling during acceleration.

Fig. 5. Stalactite and the gearbox

Each of these manufacturing processes reduces the overall weight of the submarine, while simultaneously producing buoyant forces in critical areas on the boat. Integrating these small pieces of foam into pre-existing structures allows the overall volume of the submarine to be smaller. By creating a neutrally buoyant submarine, underwater handling is made easier and less deflection by the control surfaces is required to stay on course, further reducing drag on the boat.

It should be mentioned, however, that Phantom 4 is not perfectly neutralized by the incorporation of foam into the hull and control fins. It is actually buoyant by design, as it is much easier to add weight to the submarine than it is to add floatation. Designs are modified and objects inside the submarine are relocated, which changes the trim of the boat. Prior to operation, the submarine must be ballasted, which involves placing lead weights in the bow and stern to achieve neutral buoyancy.

III. CONCLUSION

Using common composite manufacturing techniques, as well as some creative materials engineering by team members, the Human-Powered Submarine Team of Virginia Tech successfully created a near-neutrally buoyant hull in Phantom 4. Composite materials have been demonstrated to be strong, yet very lightweight, and their processing techniques very robust. Minimizing mass to maximize acceleration requires a comprehensively designed hull form, including the incorporation of buoyant materials. Closed-cell foam can be used for floatation as well as stability purposes in the submarine’s design, and the incorporation of foam into pre-existing structures reduces the volume and drag on the submarine as it is propelled down the racecourse.