Human Powered Submarine Hull Construction

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***Abstract*- The application of emerging technologies and materials to HPS hull construction can lead to gains in hull strength and robustness, while also eliminating many of the constraints of conventional construction methods. We will here describe a successful hull construction technique as used by the 2001-02' University of California, San Diego HPS Team. This procedure as well as past conventional procedures will be compared and the gains specifically outlined.**

I. Introduction

The construction of a human-powered submarine (HPS) hull is a complicated and important task. The hull shape and surface finish are key parameters relating to the drag force that must be overcome by the pilot inside. Accordingly, a well-designed hull shape and a construction method that can accurately produce this shape are important requirements. Unfortunately, it can be easy to design a part using modern CAD software that would be practically impossible to fabricate. To ensure that a particular hull design can actually be fabricated, specifics of the fabrication process should be considered during the design process. After completing the hull design with construction techniques in mind, the next step is to construct the actual hull. This paper will discuss conventional construction techniques, as well as the applications of emerging technologies and materials to the construction of a HPS hull.

II. Basic and Conventional Construction Techniques

Composites of various matrix and fiber materials are used to create the rigid hull to which internal components will be housed and mounted. Use of both female and male molds is common practice to form the composite materials to the proper shape. Male molds are a positive of the intended shape; in the case of a submarine the mold would be shaped like the end submarine and composite would be made over the surface. Female molds are a negative of the intended shape; in the case of a submarine the mold is a solid block with the volume of the submarine cut out of it. Typically a female mold is only a mold of half of the volume. Two halves would be made with the mold and then bonded together. Male molds, being a mold of the internal volume of the shape, can be difficult to use as the mold has to somehow be removed once the composite has been made. With a female mold, once the composite has been made it is simply lifted away from the mold and the mold can be reused. Also, female molds are easier to finish and surface coat such that they yield a more suitable composite surface finish for a HPS hull.

Most HPS hulls are made from fiberglass, Kevlar and/or carbon fiber, thus molds for HPS hulls are typically made out of foam for its machineability and chemical properties. The first step in making a hull mold is making a foam block from which the mold can be made. Fairly high-density foam should be used in order to ensure a smooth and rigid molding surface, and to allow for easy machining and/or handsanding. In the absence of a properly sized foam block, a large block can be made by epoxying together smaller foam pieces until the required volume is obtained. After the proper sized block is made, the actual mold can be made. This can be done by hand or by machine, with the latter being much faster and accurate, however, in many cases much more expensive.

To create the designed shape by hand, extensive measurements from a variety of reference points must be made and continually checked. Saws and routers can be used to remove large chunks of foam, and hand sanding is used to make finer passes as the foam nears the final hull shape. Finer and finer grit sandpaper should be used to take off the small amounts of excess material and to create a smooth mold surface that will eventually determine the surface finish of the hull.

Creating the mold by machine is a less arduous and more exciting task, but finding a suitably sized computer numerically controlled (CNC) mill can create a barrier to utilizing this valuable construction method. U.C. San Diego's Inviscid is a relatively small submarine at 9.5 feet. The mold for Inviscid had to be cut on a Haas Automation VF-11, their largest 4-axis vertical machining center with 120" of travel. The mold and mill are shown in Fig 1.

Fig 1- CNC Machining of mold at HAAS Machining in Oxnard, California

Once a large enough mill has been located and appropriate arrangements have been made, creating the mold requires two major items: the proper tooling and compatible G-code. G-code is 3-dimensional cutting code used by most CNC machines and can be created using a variety of CNC simulation and coding software.

Upon programming and debugging the CNC milling machine, the mold can be machined out very close to its intended shape. Depending how detailed the G-code is, the surface will have small ridges and grooves from the cutting head making steps over the foam, producing a rippled surface. The small grooves left with each pass of the machine tool must be sanded away by hand, taking care to retain the proper shape of the mold while creating as smooth a surface as possible. Whether the mold is made by hand or by machine, the smooth surface is important because of hydrodynamic considerations and also because it allows for easy removal of the composite hull from the mold.

After a suitably smooth mold surface has been created, the mold should be wiped clean of any loose particles or dust. To create as smooth a surface finish as possible the mold should be painted with the appropriate paint and covered with mold release. Covering the mold with mold release should be done in several passes. Each pass includes the following steps: application, drying, and smoothing. At each pass it is necessary to ensure that there are no loose particles in the mold, as they will create defects in the surface finish of the hull. After applying mold release to all areas of the mold that will contact the fiber and matrix mixture (epoxy, polyester resin, etc.), the entire mold should be wiped down with the proper cleaning solvent and an additional releasing agent, such as Polyvinyl Alcohol (PVA) should be applied. This keeps the final hull shape from sticking to the mold, which could result in damage to the mold and/or the hull itself.

With the core of the mold complete, the reinforcing fiber should be cut to size, labeled, and organized with the exact order of layers and positions in mind. For a female mold the first layer to be put in the mold will be the outermost fiber in the composite and the last layer will be the inside surface of the hull. The fiber should be laid out in the mold as close to its final position as possible and should be ready to be positioned immediately once the matrix has been properly mixed.

When the matrix has completely finished reacting, or "gone off," the hull is ready to be removed from the mold. Before the hull is removed completely, care should be taken to gently separate the composite material from the mold across the entire surface. This will decrease the possibility of damaging either of the two and will make complete removal of the hull a much easier task. If the entire hull has been created from a separable mold, then the construction process is complete.

Due to the difficulty in creating the entire hull as a unit from one mold, the hull may be created in sections; in which case, the sections must be properly joined using any of several techniques. Many methods can be used, such as bolting the sections together, or using more composite material to create the finished hull shape. The latter method was used in the creation of Inviscid. The hull was made in two halves (Fig. 2), with the meeting surface being slightly inset from the rest of hull. This allowed fiberglass to be laid into inset area, bonding the two halves while maintaining a smooth outer surface.

Fig. 2 Joining the two halves. With the two halves held together by C-clamps, 4" wide strips of composite are run lengthwise along the hull after removing the excess flange material.

III. Applications of Emerging Technologies and Materials

Two new technologies were used in the creation of the Inviscid hull: 4-axis CNC milling machines and Ultraviolet activated catalysts for polyester resin. The combination of these two technologies, particularly the latter composite technology, allowed certain hull optimization measures to be made which would have been exceedingly difficult by conventional measures.

As previously stated, the female mold for Inviscid was cut on a Haas VF-11 4-axis mill. By using a CNC mill, the mold for a fairly complicated hull design could be made. The hull shape is composed of several lofted ellipses along multiple axes combined with special ergonomic protrusions from the surface and a 15° tapered tail cone. This design was optimized for volume minimization, pilot ergonomics, and smooth fluid flow. Without a 4-axis CNC mill, however, it would not have been possible to manufacture the mold, and the hull design would have been purely academic.

The hull itself was made from fiberglass and polyester resin composite. Conventional polyester resin is hardened by mixing in a catalyst, or hardener, which starts the polyester hardening chemical reaction. This chemical reaction takes a short time to finish, explaining the euphemism that it has "gone off". Once hardener has been mixed into the resin it must be quickly applied to the fiberglass before it solidifies. The hardening reaction can complete to the point that the resin is unworkable in less than one minute.

The new material science technology used in the construction of Inviscid came from SunRez, who has created an ultraviolet light activated catalyst for polyester resin. This means the resin can be kept in liquid form for as long as is desirable and finally set to cure by shining UV lights to the composite surface. This meant that the time constraints associated with the polyester resin curing process were eliminated.

Normally, because of the previously discussed resin curing time constraints, fiberglass layers are laid one or two layers at time and quickly "painted" with resin as it is curing. To even out the concentration of resin matrix in the fiberglass, the fibers are pressed down with fiber-glassing rollers. This process is imperfect, obviously, as some areas of resin have had more time to cure than others and it is difficult to apply even pressure with rollers.

Using UV curing resin, all of the fiberglass layers could be laid at once. The entire hull section in the mold was thoroughly painted with resin and pressed with rollers. The entire mold was then vacuum bagged, evenly applying a 101.3 kPa (14.7psi) compressive force over the still wet fiberglass and resin. With the vacuum on, ultraviolet lights were then shined on the composite surface, starting the curing process. Vacuum bagging and having wet resin soaked through all of the fiberglass layers produced a solid, consistent strength composite.

The bottom half of the hull was actually made in three stages. First, quarter inch thick strips of clay were laid into the mold in three locations perpendicular to the central axis of the hull. These strips of spanned the width of the hull. Fiberglass was laid over the clay, vacuum bagged and cured. The resulting solid fiberglass pieces were the "stiffening ribs"as shown in Fig 3.

Fig. 3 Creating the Strengthening Ribs

The stiffening ribs were then removed from the mold. Half of the fiberglass layers for the hull were laid and vacuum bagged. The specific sections, which would be covered by the ribs, were cured. The ribs were placed into the mold with the fiberglass, covered with the remaining layers of fiberglass, and soaked with resin. Finally, the entire mold was again vacuum bagged and hit with UV light to cure the resin.

The windows and hatches of the Inviscid hull were constructed to seamlessly mate into the hull. In fact, the primary pilot hatch acts as a structural member in the hull. The pilot hatch and the drive-train access hatch were made in three stages just like the bottom half of the hull. Stiffening ribs were made around the perimeter of the hatches rather than crosswise, however. The upper half of the hull was then made by heavily coating the two hatches in release wax, laying fiberglass into the mold on top of the hatches, vacuum bagging and curing the composite.

Fig. 4 Pilot and drive-train hatches prior to lay up of top half.

The composite of the hull, then, was cured while mated to the hatches, guaranteeing a seamless fit. The stiffening ribs of the hatches then act to strengthen the entire structure rather than just themselves. Recesses for acrylic windows were built into the hull shape by cutting high temperature wax into the window shapes, laying the shapes into the mold, and curing the fiberglass over them just as with the hatches. This was an additional step in the fabrication of lower half of the hull, though of more aesthetic than structural significance compared to the other steps.

CNC milling technology and UV curing resin enabled the Inviscid hull to have a surface design and structural strength which would have been nearly impossible to produce by conventional methods. The success of the Inviscid submarine is owed to the designers ability access and utilize these new machining and materials technologies.