ABSTRACT

This paper describes the systematic approach used by the author on the design and construction of the human powered submarine "Sea Panther". The order in which various items were examined was based on the author's knowledge, research and experience. As no two painters will pick the same colors, brushes or strokes to create their masterpiece, no two HPV builders will follow the same exact course. As such, each HPV designer may find his or her own preferred procedure. Utilizing a design spiral as an outline, the basic components and features of the "Sea Panther", as well as, some test results and construction techniques are presented. Ship design basics, test results and suggestions of previous HPV designers are examined, followed by the design decisions made for the "Sea Panther" and the rational for those decisions.

INTRODUCTION

The design and construction of a human powered vehicle (HPV), is the application of art and science to making compromises between the various vehicle components. Though there may be an art to making compromises, a more scientific approach to the overall design procedure of HPV's can be formulated. With the application of modern science to the art of HPV design, we have witnessed extraordinary advances in air, land, water, and now submerged vehicles. Although science has and will continue to have its impact on specific features such as size, shape, weight, construction materials, and propulsion, the art of design will remain as the blending of these features in the right proportions, to provide the optimal performance under selected conditions and acceptable costs.

Because a HPV is a combination of many interrelated systems and subsystems, the designer often makes a decision on one item only to find it adversely affects and perhaps makes conflicting requirements on another, which if changed, affects another and so on. In addition, the amount of initial design input data or requirements may be too limited or too general, allowing for a possible endless loop of "what if" questions.

DESIGN SPIRAL

The design procedure for the human powered submarine "Sea Panther" is best represented by a design spiral generally adopted in naval architecture and ship design as shown in Figure 1. The designer starts at the center of the spiral with whatever information, requirements, or conditions he may have been provided. From the center he begins his travel outward along the spiral looking at and making decisions on the various components. Two, three, four or more iterations around the spiral may be necessary to move from the concept stage to the full design stage.

Figure 1. DESIGN SPIRAL FOR A HUMAN POWERED SUBMARINE
(adapted from Rawson and Tupper [17])

INITIAL INPUT INFORMATION

In the case of the "Sea Panther" which was built to participate in the First International Human Powered Submarine Races held in June 1989, the primary input requirements and conditions were provided by the race committee. The most important ones were: the submarine was to be free flooding, carry a complement of two (only one person being allowed to propel the vehicle) and the vehicle was to be judged on speed around a given course, innovation, and cost effectiveness. Specific requirements on buoyancy control and escape features were also provided for maximum safety of the riders. With this input, the designer entered the design spiral and proceeded until a full design was completed and construction began. The individual design spiral items will be discussed in the following sections.

COMPLEMENT

The complement of two riders was specified by the race committee. Only one rider was allowed to do any work to propel the vehicle. The second was to act as the navigator, and would be a safety man in case of trouble. Because of the possibility of the peddler blacking out underwater while breathing with SCUBA gear, this requirement was prudent.
As a component of HPV's, the riders usually require the most volume, add the most weight, and generally have the largest impact on the overall shape and layout of the vehicle. With two-man submarines, the peddler must be in a position to maximize his power output, the navigator must be able to exercise efficient control, and both must be in positions that minimize the drag of the vehicle.

There are three basic positions for HPV peddlers: (1) conventional, with the rider upright; (2) supine, in which the rider lies on his back; and (3) prone, in which the rider lies on his stomach. The supine and prone positions are often referred to as recumbent. There have been several studies performed that compare how the peddler's position affects power output in air, but few studies underwater. In air, Kyle [1] found that the conventional position is superior for long periods of workout with supine close behind, followed by prone. The recumbent positions offer the advantage of reduced frontal area and body positions better suited to enclosure within conventional streamlined shells. Most studies on the two recumbent positions suggest the poorer results of the prone position may be due to lack of adequate body restraint and general discomfort of the rider. A prone rider suspended in water may not experience the discomfort of supporting his weight on hip and chest pads. One recent study in this area was performed at the U.S. Naval Academy [2]. The power output of six subjects was compared in both the supine and prone positions underwater while breathing SCUBA. It was found that four out of the six subjects produced more power and consumed less air in the prone position over a ten minute workout. "All the subjects said they felt more tired after pedaling in the sitting position than when prone [2]."

The author built a human powered submarine "Barracuda" in the summer of 1988 in which the peddler was prone. It was felt prone was the better position because of its similarity to the natural head-first stomach-down position of a scuba diver. Admittedly, the rider restraint system had short-comings, leading to the conclusion that the supine position would be more appropriate. Because of the less favorable results with prone in 1988, the "Sea Panther" built in 1989 had the peddler in the supine position with an adequate restraint harness, as shown if Figure 2. Additional tests into supine versus prone while underwater need to be conducted to resolve the question of best position.

The navigator performs a needed function, but since he is not allowed to help propel the vehicle, he could be considered just along for the ride. Therefore, the navigator's position should require the least amount of space possible while allowing for his function to be performed. We found that the minimum volume position, while allowing a view out of the submarine for control, was crouched on his hands and knees in front of the peddler (see Figure 2). Once the rider positions are chosen, a general layout of the submarine can be started.

The general layout should be properly scaled to allow for representative dimensions to be taken off the drawing. The layout should include both a side and top view of the vehicle. To start with, the layout should include the riders and all major mechanical components. The major mechanical components of a free flooding submarine are the pedal crank, transmission, propulsor (propeller, jet drive, flapping wing, etc.), control surfaces and the life support system. Each should be placed allowing for optimal mechanical/human interface with consideration given to the hull shape required to encompass all the items.

Table 1. PRIMARY DIMENSIONS OF THE HUMAN POWERED SUBMARINE "SEA PANTHER"

<table>
<thead>
<tr>
<th>Beam</th>
<th>B = 22 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>H = 26 inches</td>
</tr>
<tr>
<td>Length</td>
<td>L = 138 inches</td>
</tr>
<tr>
<td>Diameter</td>
<td>D = 24 inches</td>
</tr>
<tr>
<td>L/D Ratio</td>
<td>L/B = 5.75</td>
</tr>
</tbody>
</table>

FRONTAL AREA, SURFACE AREA, VOLUME

Once the major components are laid out, the designer is faced with streamlining the...
vehicle by enclosing the riders and gear in a hull for water, or fairing for land vehicles. Many papers have been presented on optimizing hull shape with various conclusions. In general to reduce vehicle resistance the designer should minimize frontal area and surface area and avoid stagnation flow distribution, have few opening allowing low intake, and have minimal hull appendages. As pointed out by Dr. Kyle [3] "HPV builders have generally employed efficient aerodynamic shapes and minimum frontal area. The belief is common that minimum frontal area will produce minimum aerodynamic drag. This is true up to a point. He goes on to explain how increasing length through frontal area reduction, often increases surface area and corresponding skin friction drag to a point where it doesn't matter how small the frontal area is. "This means that as the ratio of length to width increases, the skin friction becomes more significant compared to pressure drag, until at large values of a/L/D around 6 for conventional Navy submarines. If the designer can pick an appropriate NACA or similar foil shape such as found in Theory of Wing Sections [5] that perfectly encloses the riders and equipment then the job is easy. But in the case of the riders moving with a minimum family of shapes." Hoerner [4] suggests the optimum L/D ratio of airship and submarine bodies to be 4 with the optimum curve being rather flat between 3 and 5. These values are referenced to bodies in which volume is the decisive characteristic. Captain Arentzen of the United States Navy [6] suggested a L/D of around 6 for conventional Navy submarines. If the designer can pick an appropriate NACA or similar foil shape such as found in Theory of Wing Sections [5] that perfectly encloses the riders and equipment then the job is easy. But in the case of the riders moving with a minimum family of shapes." Hoerner [4] suggests the optimum L/D ratio of airship and submarine bodies to be 4 with the optimum curve being rather flat between 3 and 5. These values are referenced to bodies in which volume is the decisive characteristic. Captain Arentzen of the United States Navy [6] suggested a L/D of around 6 for conventional Navy submarines. If the designer can pick an appropriate NACA or similar foil shape such as found in Theory of Wing Sections [5] that perfectly encloses the riders and equipment then the job is easy. But in the case of the riders moving with a minimum family of shapes."

The hull of the "Sea Panther" was designed with minimal surface and frontal area in mind. The riders were positioned in line with each other to reduce frontal area and the hull was shaped as closely around them as possible to reduce surface area while maintaining somewhat of a moderate taper in the tail. The addition of the straight center section and moderate taper were compensated to minimize surface area and skin friction (80% of overall drag) while suffering increased pressure drag (20%).

RESISTANCE, POWER, SPEED

The speed of a HPV is dependent on the amount of power produced by the riders, how efficiently the power is transformed into thrust and the total drag of a vehicle for a given speed. The amount of power a human can produce in air has been documented in several studies. Over a ten minute workout, a healthy adult produces around 0.33 Horsepower [10]. What has not been determined is to what extent is the available output of humans underwater. A study conducted at Florida Atlantic University [11] found an average output of only 0.12 horsepower at a pedal cadence of 50 rpm for a group of male and female volunteers. A similar experiment conducted at Florida Institute of Technology confirmed FAU's findings with an output of 0.13 horsepower for a 10 minute workout at a pedal cadence of 54 rpm. Both tests were conducted with the riders in the supine position using rotary leg motion crank sets. As stated by Merry [11], "This figure correlates well with information from the Navy Experimental Diving Unit which suggests that only 50% of a diver's sustained gross power output (approximately 0.33 HP for an extremely fit male) can be converted to useful mechanical energy. The remaining 50% is wasted through resistance to motion underwater." In other words, due to the resistance on body motion underwater a rider can produce only about half the horsepower he can in air. Depending on how efficient the transmission and propulsion device is, the amount of horsepower converted to thrust can be as little as 50% of this already reduced output or only 0.06 horsepower. To convert horsepower to thrust the following formula can be used.

\[ P_t = \frac{(T \times V)}{550} \]

Where \( P_t \) is power in horsepower, \( T \) is the thrust in pounds force and \( V \) is the vehicle velocity in feet/second. A formula to predict overall drag is:

\[ \text{Drag} = C_d \frac{1}{2} q V^2 A \]

Where drag is in pounds force, \( C_d \) is a dimensionless coefficient of drag based on frontal area, \( q \) is the density of fluid in slugs/feet cubed, \( V \) is the velocity in feet/second, and \( A \) is the cross-sectional area in feet squared. Of course, picking an appropriate \( C_d \) is the difficult part for non-standard streamline shapes. A fully appended \( C_d \) of 0.12 was used in the study of Brooks [9]. With an available input power of 0.13 and a propulsion efficiency of 70%, a thrust horsepower of 0.09 predicted a top speed of around 3.5 knots.
The propulsion system is considered to be all the mechanical parts converting power from body motion to power delivered to the propulsor or propeller in the case of the "Sea Panther". The "Sea Panther's" system can be broken into the crank set and transmission/propeller shaft assemblies. The two basic types of crank sets are rotary leg motion, as on conventional bicycles, and linear leg motion. The linear leg motion in theory seems to be very promising, but the few racing vehicles using them have not won consistently enough to convince most people of their worth. The "Sea Panther" used a linear leg motion crank set for two basic reasons. First the linear set required less space because the riders legs moved back and forth in line with his body. This equates to a maximum required diameter of 26 inch and not the 29-30 inches required by the rotary crank. Secondly it is believed the linear leg motion is more efficient at low pedal rpm. The optimum cadence for area bikes is around 90 rpm while the submerged optimum is around 50 rpm. Test are currently underway at FIT to verify the assumption that the linear leg motion crank set is more effective than rotary in a underwater environment.

The linear crank set was connected to a bevel gear by a standard bike chain. Mounted on the input to the bevel gear was a derailleur and set of 6 chain rings as found on conventional 12 speed bicycles. The ability to easily change gear ratios was beneficial in the evaluation of various propellers. The one to one bevel gear output was connected to the propeller shaft with the shaft being supported by one bearing pillow block. It should be pointed out that chain alignment is critical and care is needed in laying out the propulsion system. Improper chain alignment leads to poor efficiency and the throwing of chains while underway.

In air, the use of hands in combination with the legs has shown a significant increase in maximum power for short periods of workout. But due to the increased amount of drag on body motion underwater, it was felt that arm power was not very viable. This feeling was verified by Nuckols and Miller [2] which states that tests conducted at the Navy Experimental Diving Unit show "... that arms are too inefficient during heavy work in a water environment".

PROPULSOR

The propulsor mechanism can be a single propeller, contra-rotating propellers, ducted propellers, or flapping wings to name a few. All of these propulsors where used during the submarine races by various groups. A large diameter, slow turning propeller will generally have the highest efficiency. Because submarines allow for the mounting of large diameter propellers, the actual shape of the propeller is less critical then with small diameter, fast turning propellers. In a private communication with Professor E. Eugene Larrabee discussing the use of a B-Series propeller on the "Sea Panther", he stated, "In the meantime I doubt that propeller design will be very critical. Anything with a diameter of 20 inches or so should do the job [15]. Professor Larrabee is one of the recognized leaders in HPV propeller design and his papers on the subject [12][13][14] are recommended readings for the designer wanting to build his own propeller.

The "Sea Panther's" B-Series propeller is 28 inches in diameter, 2 bladed, with a blade area ratio of 0.2 with a designed rotation velocity of 100 rpm. A B-Series propeller was designed and built because of the author's previous knowledge of the B-Series design procedure. The propeller was constructed by laminating mahogany planks on top of each other. A profile of the propeller was drawn on each side. A one inch grid was drawn over the profiles. The depth of each intersection of the grid to the top on the propeller blades was calculated [16]. Each intersection was drilled to the proper depth using a vertical milling machine. The excess wood was then chiseled away and the remaining shape was sanded and fiberglassed.

TRIM, STABILITY

The trim of a submarine is controlled by ballast and control surfaces. Ballast can be permanent or variable. Control surfaces work like airplane wings providing positive and negative lift to change the trim and depth. Since the race committee did not allow for "air pockets", a variable air ballast system such as on conventional submarines was not used. Permanent ballast was provided by Poly Vinyl Chloride (PVC) foam fiberglassed to the interior of the submarine. The foam was placed fore and aft of the geometric longitudinal center of buoyancy (LCB) to provide a zero trim angle without riders in the vessel. A zero angle or level trim is obtained by setting the longitudinal center of gravity (LCG) to be vertically in line with the LCB. By treating the foam as positive weights and multiplying all the individual component weights times their distance from a selected center line, then dividing the product by the sum of the weights, the distance the LCG is from the selected center line is determined. Through an iterative process, the foam amounts fore and aft can be calculated. A proper trim is then obtained. The "Sea Panther" riders attained neutral buoyancy by wearing diver's weight belts and horse collar buoyancy control devices. Having neutral buoyancy upon entering the submarine, they had no affect on trim. With a fixed ballast system, change of trim and depth was performed by the control surfaces. These are discussed with maneuvering in the next section.

In the "Sea Panther" transverse stability was provided by placing the PVC foam in the top of the submarine, and the negative weights as low and as stable in the submarine as possible. The righting moment is maintained. The second and less efficient way to right the vessel is to use the control surfaces. This can be accomplished by placing a downward angle of one dive plane and an upward angle on the other. The "Sea Panther's" dive planes are located horizontally just forward of the
propeller.

MANEUVERING

As stated earlier, maneuvering around a given course was one of the judging criteria. Maneuvering both in the vertical and horizontal planes can be controlled by the control surfaces on the "Sea Panther", and/or by articulating the propeller in the case of some of the other vessels. To determine the needed surface area of control surfaces, it is suggested that the profile area of the surfaces be:

$$A_C = 0.07 A_1 \text{ to } 0.11 A_1$$

Where $A_C$ is the projected area of the control surface, and $A_1$ is the projected vertical or horizontal area of the vessel. From utilizing the upper end of this range, the "Sea Panther" has a rudder projected area of 2.25 square feet and dive plane of 2.0 square feet. Both sets of control surfaces are located at the tail of the submarine. A greater moment arm is obtained in this configuration as compared to bow mounted control surfaces. In addition, any turbulence from bow mounted surfaces travels down the length of the hull, possibly increasing the drag. The use of only one set of control surfaces in horizontal and vertical planes keeps the amount of appendages to a minimum.

Although bow mounted surfaces have drawbacks, there is a feeling at FIT that bow mounted horizontal control surfaces (dive planes) may have one major advantage. Because the vessel was required to be positively buoyant, it had to dive from the surface on occasion. When diving with aft mounted planes, the planes are lifting the propeller out of the water resulting in lost propulsion. Without flow over the planes from forward movement, they simply don't provide the lift needed to dive the vessel. With bow mounted planes, it is felt that less tendency to lift the propeller out of the water will be experienced. Of course, this feeling must be verified by experimentation.

LIFE SUPPORT SYSTEM

The race committee required the use of standard SCUBA gear tested and approved by the Navy. Most vessels, including the "Sea Panther", used standard first and second stage regulators. Some submarines employed second stage regulators built into the masks (dive planes) may have one major advantage. Because the vessel was required to be positively buoyant, it had to dive from the surface on occasion. When diving with aft mounted planes, the planes are lifting the propeller out of the water resulting in lost propulsion. Without flow over the planes from forward movement, they simply don't provide the lift needed to dive the vessel. With bow mounted planes, it is felt that less tendency to lift the propeller out of the water will be experienced. Of course, this feeling must be verified by experimentation.

A few of the considerations to be made when selecting construction materials are withstanding the environment of operation (mainly corrosion), providing adequate structural strength, minimal weight, ease of construction and cost. The most common small craft construction materials in the marine environment are fiberglass and aluminum. Other composite materials such as aramid fibers and carbon fibers are found, but at greatly increased costs. Because fiberglass is low cost and usually easier to work with than aluminum, it is a favored material of HPV builders. Mechanical parts exposed to the environment should be of plastic composites or stainless steel with structural aluminum holding up pretty well. The "Sea Panther" hull was constructed of fiberglass reinforced with acrylic view ports. All the mechanical parts were either stainless steel or aluminum with the exception of the bevel gear and bike chain (off-the-shelf items) which were mild steel.

The acrylic view ports were thermo-formed to blend into the hull shape. The 1/8-inch and 1/4-inch plastic sheets were roughly cut to a size larger than needed. Wooden blocks were clamped along the edges, to provide handles to stretch the plastic. The pieces were then heated at 300 degrees (F) for 15 minutes in a wooden oven built at FIT. A local restaurant pizza oven was used by other human powered submarine builders. The now pliable sheets are stretched over a plug of the desired shape. The acrylic cools quickly (2-3 minutes), so one needs to work fast when stretching. Because the "Sea Panther's" hull was completely laid up in fiberglass initially, the fiberglass sections to be replaced with acrylic were used as the plugs. It is best to leave the hull intact until after the plastic is formed. By forming the acrylic, cutting it to shape and then marking that shape off on the hull, one insures that only the needed amount of fiberglass is removed. This avoids a lot of headaches and provides clean joints between the two materials. The more gentle the curvature of the plug, the better this method works. With careful surface preparation very few imperfections in the acrylic surface are made. Generally the acrylic will not pick up any plug surface imperfections smaller than scratches from 80 grit sandpaper.

SAFETY

Because the operators are working in a hostile...
environment (underwater) it was required and necessary to incorporate numerous safety features into the submarine. The "Sea Panther" was 2 pounds positively buoyant in its heaviest condition, so as to float to the surface if anything was to go wrong. In addition, escape hatches could be operated from inside as well as outside. Both riders were in clear view of outside safety divers due to the large acrylic view ports over each. Each rider had over 150% of the required amount or air on board, and each wore a 15 cubic foot pony bottle with separate regulator on his body at all times. Each rider held a "dead-man" switch, which if released, would in turn activate and release a buoyant strobe light. The floating strobe would inform surface personnel of problems. So each rider felt comfortable and understood their limitations in performing their jobs, a great deal of training in a controlled environment such as a swimming pool was performed by the riders at FIT.

COST

The cost of a vehicle is often referred to as "the bottom line". Very few designers have the luxury of designing under the pretense that cost is no object. Often less than optimal materials and components must be used to stay in budget. Perhaps the biggest problem the HPV designer is faced with, is learning to use to its maximum, what he has available and what he can afford.

A primary team of five people spent over 1000 man-hours designing and building the "Sea Panther". Carrying out sea-trials in the ocean required as many as 20 volunteers. Without considering this labor cost and operational costs, the "Sea Panther's" material costs would be over $1600.00 dollars. Many of the materials were actually donated to FIT by various local businesses. Without the support of local and national industries, many of the today's HPV's would not competing in events such as the submarine races.

SUMMARY

The amount of power a human can produce in air is basically cut in half underwater, accentuating the need for efficient hull shapes, propulsion machinery, and propulsors. With the longer two-man submarine hulls, the greatest drag reduction comes from reducing the surface area or skin friction component of drag. Additional tests comparing supine and prone rider positions, and rotary versus linear leg motion cranks sets needs to be conducted in an underwater environment.

The application of art and science to the design and construction of HPV's is a challenge being accepted by more and more people. Public interest in the sport is on the rise, the application and exchange of information between the builders is increasing, and perhaps most importantly, the sport's participants are simply having a lot of fun.

HPV speed records are being broken regularly and companies like DuPont are providing prize money for those who do. With the sport in its infancy, now is the time for designers and builders to make lasting, possibly historical advances in the field.

A great deal of additional available data, descriptions, and construction experiences were not discussed here. The author is currently working on his Master's thesis which will include the additional items. The paper should be of help, in particular to new HPV builders of all types of vehicles. The paper should be available in January 1990 by contacting the author at FIT.

REFERENCES