Human Powered Submarine Hull Design

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***Abstract*-As a human powered submarine has a limited and small supply of input power, it is necessary to utilize this power as efficiently as possible. In order to achieve maximum speed, losses from both surface and form drag on the outside of hull must be minimized. To design a hull well suited to human power, several key analyses are required. A well-designed hull shape can arise from considerations of pilot ergonomics, internal components space requirements, and hydrodynamic effects. Throughout the design process, examination of possible construction methods must be made. Additionally, the final hull design must be structurally robust to stand up to mounting of a variety of internal components, repeated use, and resulting stresses.**

I. Introduction

A human being, at a sprint, can produce nearly 0.5 horsepower for a limited duration. In order to design and build an efficient, fast, and robust human powered submarine (HPS) several key components must be given utmost attention to optimize the use of the limited power available. The propulsion and power conversion systems must impart the greatest amount of momentum to the surrounding water as possible. Additionally, the hull shape must minimize the thrust required to achieve the desired velocity. To design a hull well suited to human power, several key analyses are required. A well-designed hull shape must arise from considerations of the space requirements of the internal components, pilot ergonomics, and hydrodynamic effects. Throughout the design process, examination of possible construction methods must be made. Here we will discuss the hull design method used by the 2001-2003 University of California, San Diego Human Powered Submarine Team in their design of the submarine "Inviscid."

II. Volume Requirements

The first step in the hull design process is to determine the essential volume requirements as dictated by the spatial requirements of the pilot and internal components. The drive-train, propulsion system (excluding propeller for traditional designs), controls, and SCUBA must all be contained within the hull. An estimate of volume required for buoyancy control perhaps in the form of lead weight and foam blocks should also be made. Depending on the specifics of the race rules or plans for data analysis, space requirements of other auxiliary systems such as underwater electronics or safety features may also need to be accounted for. Plans for future addition of data acquisition or computer control systems must also be accounted for. During the design phase of Inviscid, the team specifically wanted to design the submarine such that it did not rely on electronic systems and any data acquisition would be done external to the hull. Many human-powered submarines, however, have been designed to rely, some quite extensively, on electronics and internal data acquisition systems as part of their propulsion, controls, and even ballast systems.

Once the necessary volume for the internal systems has been estimated, the space required by the pilot to generate thrust, and to drive safely and somewhat comfortably must be considered. The pilot must be allowed the full range of motion required by the drive train. Accordingly, the range of motion of the pilot must be determined prior to final hull design and in conjunction with the various aforementioned internal systems. After determining this range, the relative spatial requirements between the pilot and the internal systems can be identified and optimized to reduce unused space (especially cross-sectional area as will be addressed in section III) and maximize potential pilot power output.

III. Hydrodynamic Considerations

After an initial design has been made which satisfies the minimum volume constraints, the final design iteration should be dictated by hydrodynamic considerations. For a given human power output the net forward thrust will be determined by the efficiency of the drive-train and propeller, and the losses associated with the drag force on the submarine. The drag force that must be overcome by the pilot to produce forward motion is dependent on two quantities: the surface and pressure drag. The surface drag is a function of surface finish and surface area. The pressure drag is a function of the hull shape. Basic fluid dynamics tells us that the cross sectional area and length to width aspect ratio are dominant characteristics in determining the force due to pressure drag. To minimize the effects of drag, boundary layer separation should be delayed for as long as possible. Useful design techniques for hydrodynamic optimization can be found from marine design texts and basic fluid dynamics [1]. Recently it has become popular to us computer aided analysis packages as tools in determining the flow characteristics around the hull shape and to optimize the final hull shape.

IV. Specific Design Process

This section will provide a description of the hull design method as used by the 2002-2003 UCSD ASME HPS team. The method used follows the general procedures as outlined above. First, the general system requirements were estimated and pilot position determined. Internal components included a SCUBA tank and regulator, drive-train with bicycle style pedals, hand operated controls, and a large foam block for righting moment and buoyancy control. The pilot was to lie in a prone position with the controls to the front of the submarine, the SCUBA tank directly below the pilot's stomach, and the drive train and foam behind and between the pilot's legs.

To find the relative distances between each of the components and the volume required by the pilot, the measurements of each team member were taken and a model of an average-sized pilot was created in Pro Engineer as shown in Fig. 1.

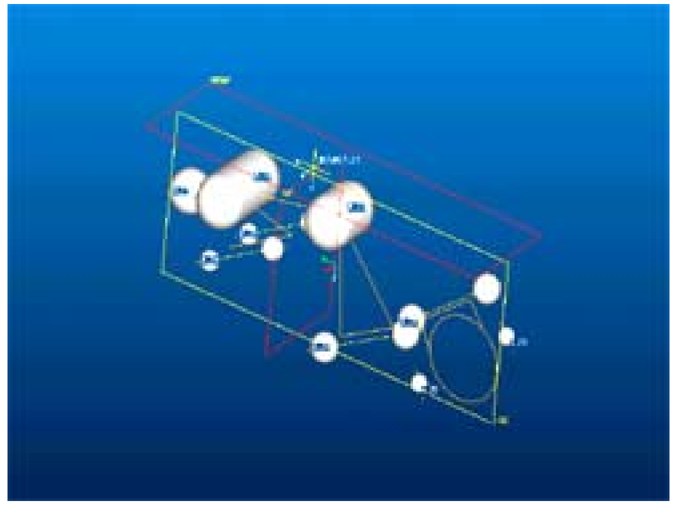

Fig. 1 Model pilot used to determine required volume for pedaling in the prone position. The head is the sphere to the left. The two cylinders are from left to right, the shoulders and hips. The heels are to right where they are swept through their 360° pedaling motion.

The model was a simplified skeleton, consisting of lines connected at points representing the pilot's limbs and joints. The degrees of freedom and rotational limits of the model joints were constrained as in an Inverse Kinematics (IK) bone chain to accurately represent the pedaling motion of the pilot. An end effecter was attached to the model's toe and was swept through a circle. The circle represented the path of the drive system pedals as they run through their full 360 degrees of motion. Pro Engineer then solved for the positions of the model's heels and knees, thus yielding the required clearances for the knees, toes, and heels.

With the motion of the pilot fully defined, the hull shape directly surrounding the pilot was created by encapsulating all but the model pilot's legs within two ellipses in three-dimensional space as shown in Fig 2. To accommodate the pedaling motion, the curves swept out by the pilot's knees, toes, and heels were added to the elliptical sections as shown in Fig 3. The curves were added to the hull shape rather than increasing the width of the primary ellipses because this would have dramatically increased the submarine's cross-sectional area, thus producing significant drag forces.

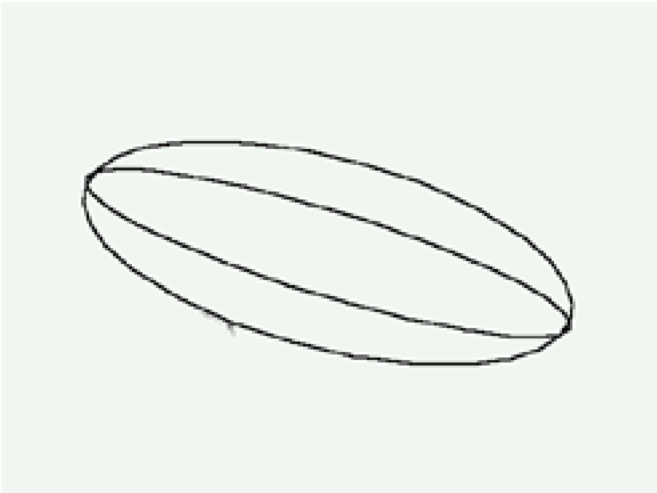

Fig. 2 3D ellipses. These encapsulate the static components of the pilot's body.

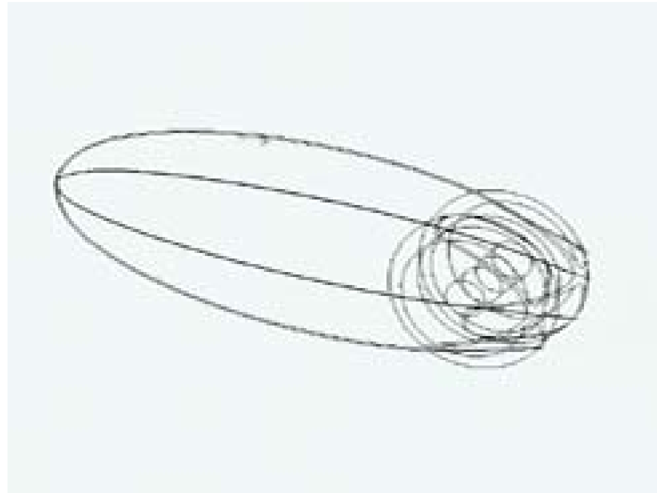

Fig. 3 The two circular paths swept out by the pedaling motion, in place with the 3D elipses.

From a wide range of literature it was determined that a length to width ratio of about four to one would yield a hull shape with sufficiently minimized drag. In order to achieve this ratio, the rear part of the hull was extended approximately three feet from the vertex formed by the intersection of the two ellipses, as shown in Fig. 4. The conical extension had a 15° taper angle. This particular taper angle was chosen based on research described in [2], which discusses the relationship between tailcone angle, propeller diameter, max hull diameter, and the corresponding thrust deduction value. Based on [2], we theorized that our propeller diameter to hull diameter ratio of .92, using a 15 degree tailcone angle should result in a near zero thrust deduction for propeller thrust offset due to propeller diameter – hull diameter aspect ratio interaction.

Ideally, the team would have used a computational fluid dynamics (CFD) software package to verify that the final hull design would yield low drag values. However, such resources were not available to the designers at the time. The UCSD Human-Powered Submarine team is currently using CFD to investigate new hull designs and components, e.g. control surfaces and propeller blades.

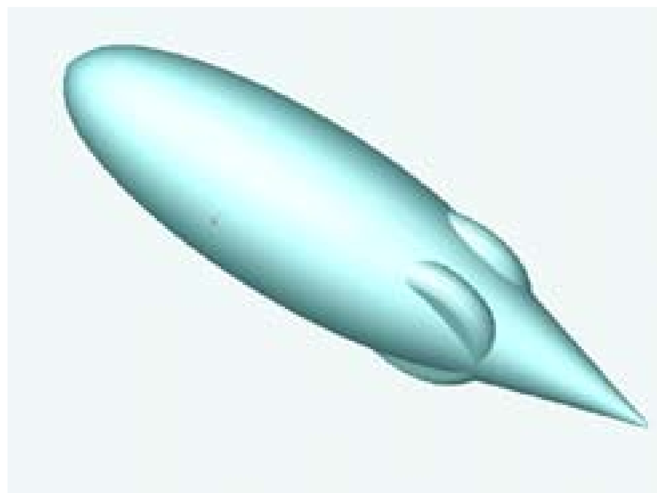

Figure 4 The finished hull design with 3D ellipses, pedaling curves, and conical extension.

References

[1] R. Fox and A. McDonald, *Introduction to Fluid Dynamics*, John Wiley & Sons, Inc., 1998.

[2] R. Burcher and L. Rydill, *Concepts in Submarine Design,* Cambridge University Press, 1998, pp.116.