THE DESIGN AND CONSTRUCTION
OF A
HUMAN-POWERED BOAT

by

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ABSTRACT

The goal and design orientation of this project was to produce the fastest possible human-powered boat within the available means. The fastest contemporary human-powered boats employ very slender displacement hulls for support, and rowing as a means of propulsion. After a thorough analysis of the alternatives available, a different support system and method of propulsion were chosen.

The support system consists of a slender displacement hull, a shell, which provides bouyant support at low velocities. This shell is lifted out of the water on tandem submerged hydrofoils at take-off speed (3 m/sec).

Side-to-side stability is achieved by a ten-degree dihedral of the foils. Front-to-back stability is achieved by active control over the front-foil angle of attack.

Propulsion is provided by a tractor screw propellor which has an estimated maximum efficiency of 87% at a design speed of 5m/sec and a rotational speed of 2000rpm.

This propellor was developed and produced by my partner Josh Lindsay (Lindsay 1980).

Steering is accomplished by a front rudder and by active variability of the orientation of the propellor's axis of rotation.

Construction is not complete at the time of this report but completion and testing are expected in the near future. A short report with test results and further recommendations will be filed at that time.

Acknowledgements

I would like to thank the following:

- Professor David Gordon Wilson for his constsnt guidance, help, and insight;
- The Wilson family for their hospitality and the use of their basement;
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I. Introduction

In an age of increasing fuel costs, popularity of physical exercise, and the amount of time spent by the average American on leisure and recreational activities, human-powered vehicles take on new importance. The ultimate goal of the current design effort would be to develop a high-speed, human-powered boat that had good market possibilities as a recreational vehicle. This vehicle would be an alternative to paddle boats which are very slow or to crew shells which are fast but inefficient both in the extraction of power from the human body and in transmitting the power to the water. A crew shell also does not allow the pilot to face in the direction of travel. Since very little previous work has been documented*, the short-term goal of this thesis project was to design, build and test a first-generation human-powered boat. The results will lead the way for further development.

The two limiting factors on the performance of any human-powered watercraft are the available power from the human body and the drag, or resistance of the water on the vessel. Any design should seek to produce and transmit the power most efficiently and to minimize the drag on the boat. The particular motion that the human body goes through to produce the power has an effect on the available

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*A review of previous work done on pedal powered water-craft is available in Bicycling Science (Whitt and Wilson, 1974) output and is a primary consideration.

A free rowing position, such as that used in crew shells, is undesirable because the body must waste considerable energy reversing its momentum twice with each cycle of motion.

Although tests have shown that a forced rowing motion is the most effecient method for a human to generate power, (Whitt and Wilson, 1974), the hardware necessary to extract this power and deliver it in a useful form is inefficient enough to render this motion inferior to that of pedalling.

The recumbent pedalling position offers the advantages of a lower center of gravity, decreased wind resistance, and increased comfort over the position one assumes on a conventional bicycle. It also allows the handlebars to be located beneath the seat, eliminating the major source of accident injuries. This could prove to be very important in a potentially unstable vessel. The use of this position also leaves the pilot's hands free to operate any steering and stability-control systems.

Of the available methods, such as paddlewheels or rowing, maximum propulsion efficiency is obtained by the use of a screw propeller (Whitt and Wilson, 1974). Rowing is inefficient because the pilot only transmits power to the water 40% of the time. Both paddle wheels and oars waste energy by transmitting power to the water in such a way that fairly large components of the resulting force are in directions other than the direction of travel and thus are wasted. Both paddle wheels and oars also go into and out of the water as they operate. Energy is lost in disturbing the water surface. A screw propeller does not have these problems and it also lends itself well to the pedalling mode of power generation because both utilize rotational motion.

A tractor propeller configuration is desirable because the screw propellor encounters only free, undisturbed water and is not exposed to turbulence or boundary layers issuing from the vessel/water interfaces or from struts, guy wires, etc. This configuration also eliminates the problem of transferring the power to a point behind the pilot as would be the case with a pusher propeller.

A remaining design consideration is that of minimizing the drag on the craft. Figure 1 shows hydrofoils to be superior to displacement vessels at high speed but inferior at low speeds. Bouyancy is necessary when the boat is at rest. A configuration that utilizes a low-resistance displacement hull, for support at low speeds, and lifts off on hydrofoils when the craft reaches the speed at which the hydrofoils produce less drag than the displacement hull, minimizes the drag on the vessel through the range of operating velocities. A planing surface, such as a surfboard, combines bouyancy and hydrodynamic lift into a single hull. This configuration has the advantage of simplicity but is only superior, in drag characteristics, to hydrofoils at speeds greater than a human-powered boat can achieve.

The drag associated with hydrofoils may be separated into four components: parasitic drag, profile drag, wave

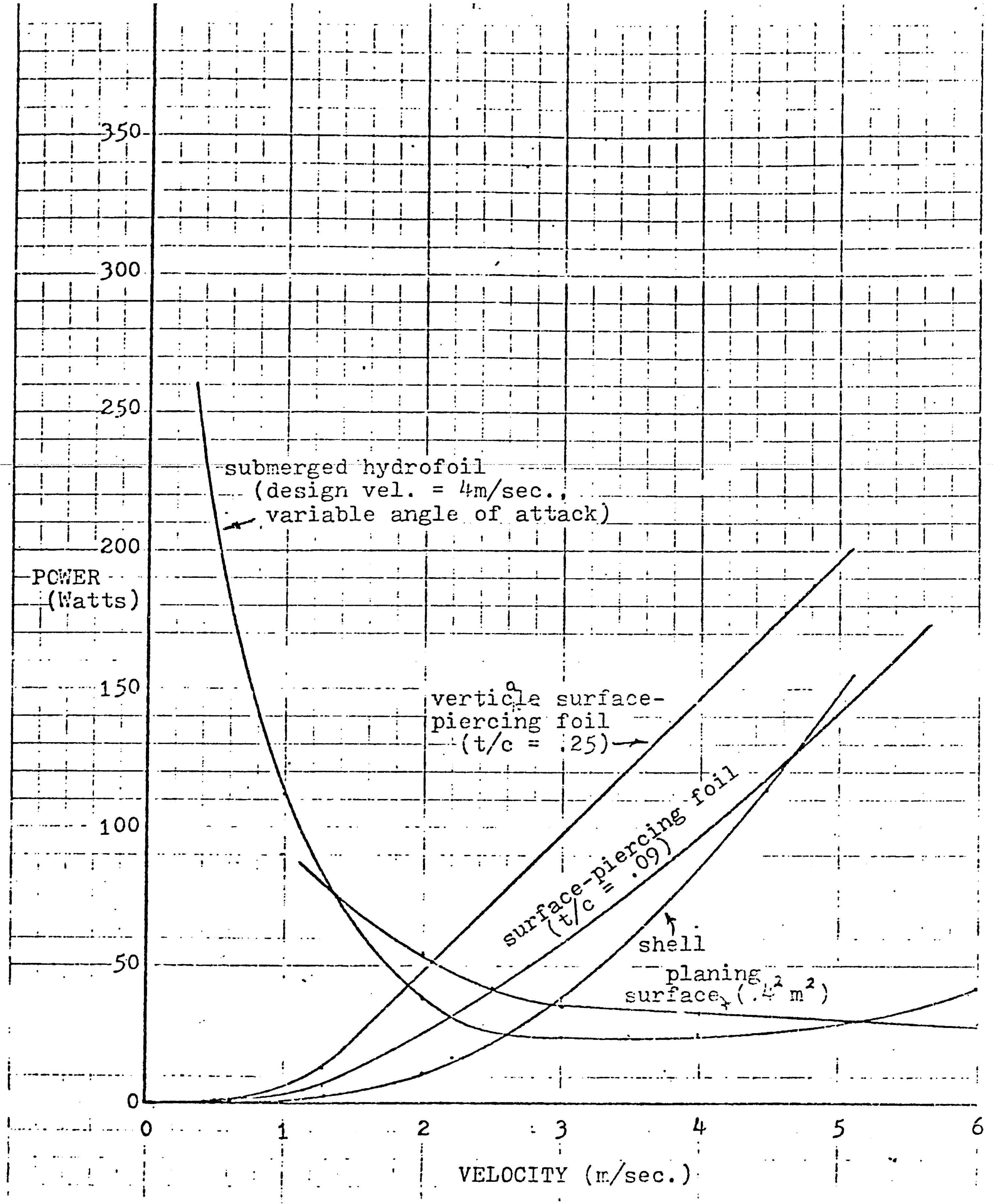


FIGURE 1. COMPARISON OF THE SPEED-VARYING POWER REQUIREMENTS FOR AN ASSORTMENT OF VARIOUS SUPPLEMENTARY SUPPORT STRUCTURES. Each structure supports 20 kg.

(Brewster, 1979, p. 13)

drag, and induced drag. Parasitic drag is caused by the support structure piercing the surface of the water and creating spray and small waves. In a well-designed system this factor should be negligible compared with the other terms.

Profile drag arises from two components: pressure drag and skin friction. Although a submerged hydrofoil is about one-half as efficient as a submerged torpedo or a shell, as measured by their drag coefficients, a foil, that has equal lift characteristics, requires only one-tenth the wetted surface area. The resulting reduction in skin friction makes the wing far superior to displacement vessels in the area of profile drag.

Wave drag, as the term implies, is caused by the boat's producing waves on the surface of the water. In hydrofoil craft wave drag can be eliminated by positioning the foils at least one chord length beneath the surface. This component of the drag is maximum at a low Froude number and falls to a negligible quantity as speed increases.

Induced drag is a direct result of hydrodynamic lift and therefore is characteristic of lifting surfaces. This drag exists because the resultant hydrodynamic lift on the wing is not perpendicular to the direction in which the craft is traveling (Figure 2). Induced drag is inversely proportional to the aspect ratio (span/chord length) and directly proportional to the angle of attack of the foil. This phenomenon is the reason why submerged-foil craft, with a variable angle of attack, exhibit decreasing induced

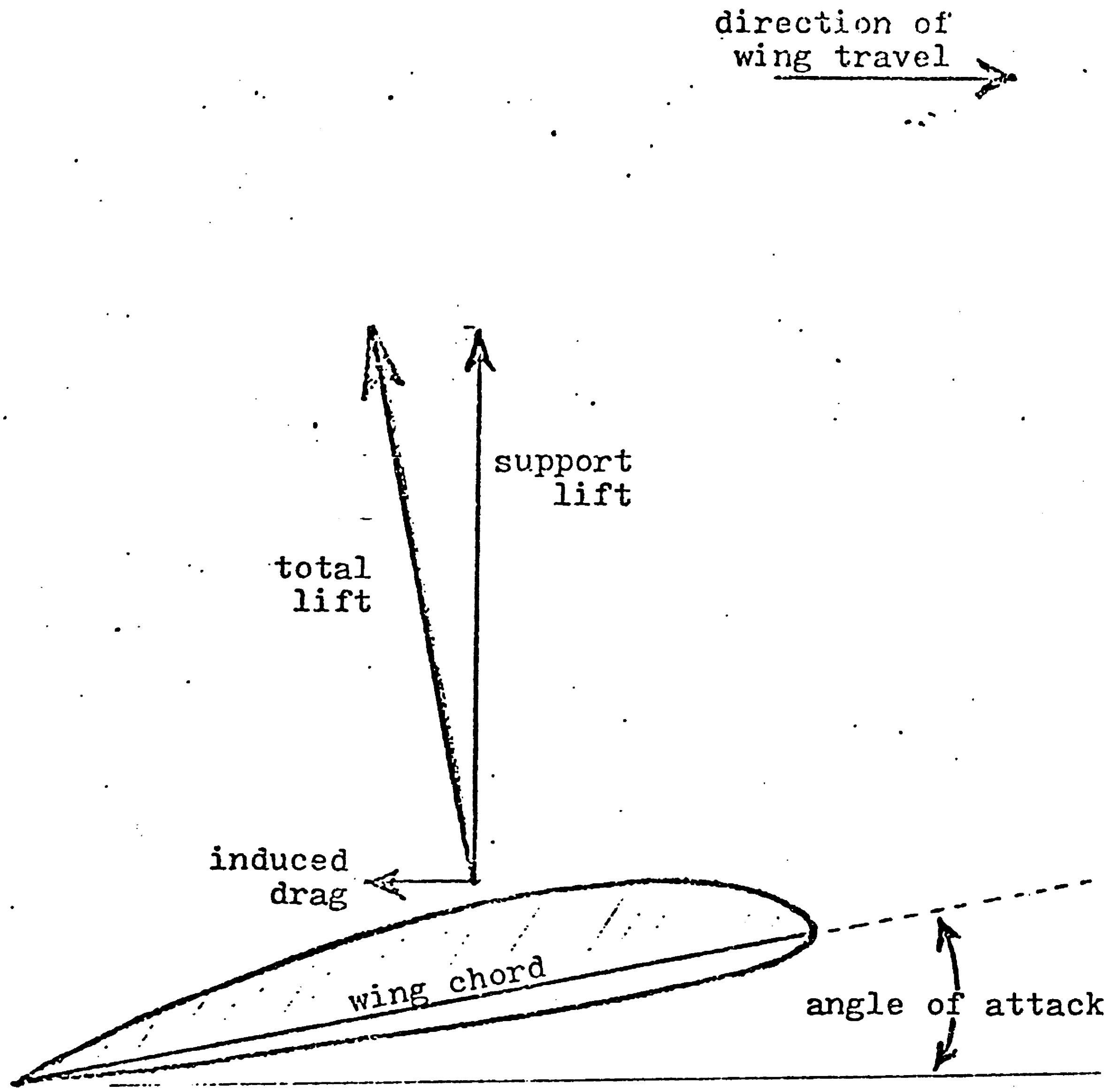


FIGURE 2 INDUCED DRAG OF A WING.
(From Brewster, 1979, p. 17)

drag with increasing speed. That is, as speed increases, the angle of attack required to maintain a constant lift decreases and the induced drag decreases as the angle of attack is lessened.

Since the metacenter of a hydrofoil craft is well below the vessel's center of gravity, a major concern in the utilization of hydrofoils is stability. There are four basic foil configurations that address this issue. They are as follows: "tandem submerged foils, surface-piercing ladder foils, surface-piercing V-foils, and submerged after foil plus surface skids (Grunberg Configuration)" (Buermann, Leehey, and Stillwell, 1953, pp. 243-244). These configurations are shown in Figure 3.

In the case of tandem-submerged foils variable angles of attack and large aspect ratios are obtainable. These two factors help make this configuration very efficient. This efficiency is offset, to some degree, by fairly serious stability problems. This configuration is unstable, both front-to-back and side-to-side. An active and complex control system is often required. A 20° or less dihedral on the foils is often employed to achieve side-to-side stability (Figure 4). As the vessel rolls to one side the lift component from that half of the foil increases as the lift component from the other side decreases. This acts to right the boat. The use of a dihedral decreases the lift:drag ratio slightly because only projected length of the foil produces lift while the entire length contributes to the drag.

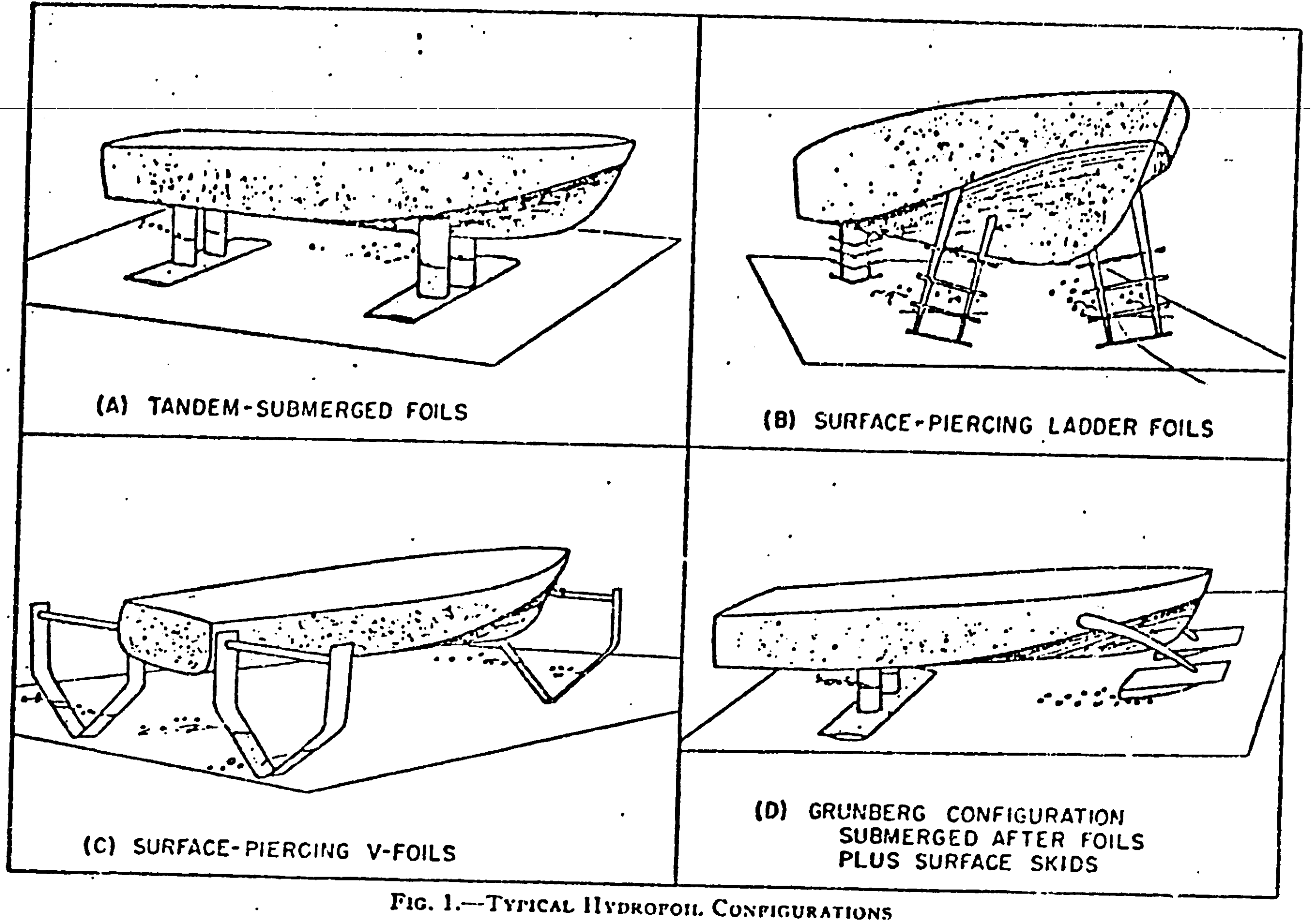


FIG. 1.—TYPICAL HYDROFOIL CONFIGURATIONS

From Buermann, Leehey, and Stillwell, 1953, p. 244. Used with permission.

FIGURE 3. FOUR KINDS OF HYDROFOIL CONFIGURATIONS.

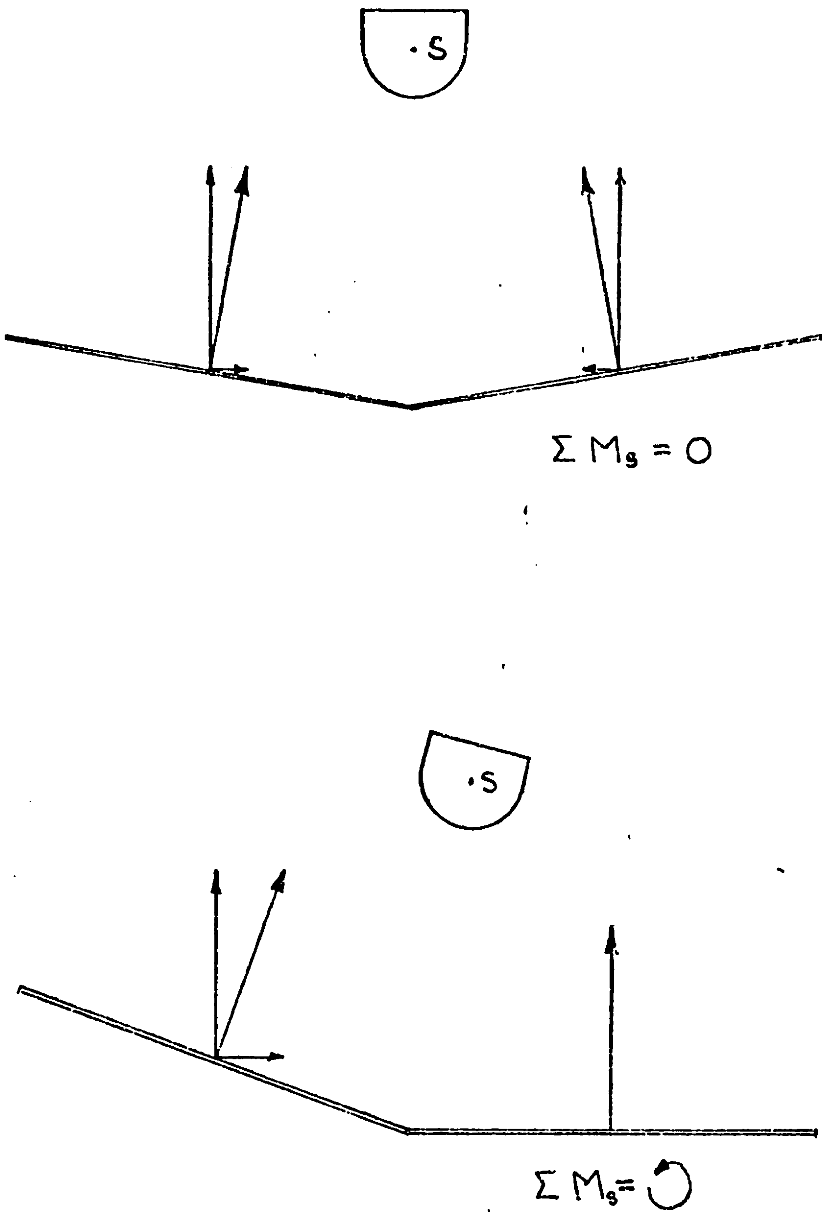


FIGURE 4 - STABILITY RESULTING FROM A DIHEDRAL

Ladder and V-foils both embody a passive stabilization system. As the vessel rolls or pitches onto a particular foil, more foil area is submerged. This increased lifting area provides more lift and rights the boat.

Although stability control is greatly simplified, wave drag and induced drag are greatly increased using this system. In both cases some portion of the foil is less than one chord length beneath the surface of the water which causes increased wave drag. Induced drag is also greater because high aspect ratios are difficult to achieve with both ladder and V-foils. V-foils must have a fairly large chord to provide enough lifting surface on a steep piercing angle. Also, since the angle of attack is fixed, the aspect ratio decreases as velocity increases and less of the foil is in the water. In the case of ladder foils, the low aspect ratio results from the fact that the total foil area is divided among so many wings. Drag is also high for V-foils because only the projected foil span contributes to lift while the entire span produces drag. Low lift:drag ratios are characteristic of V-foils for this reason.

The Grunberg System of submerged after foils plus surface skids also lends itself to stability. The front surface skids define the height above the water that the craft will fly. The rear foils, which support the majority of the load, will reach an equilibrium height defined by the front skids. For a given skid height, the angle of attack, and consequently the lift characteristics, of the rear foil changes with its depth below the surface. Although the system has good stability control, the front skids produce high wave drag and induced drag.

For an up-to-date review of commercial hydrofoil vessels, consult Jane's Surface Skimmers: Hovercraft and Hydrofoils 1978 (McLeavy, editor, 1978).

II. Design

The goal of this design was to create a human-powered watercycle that embodies simplicity of construction and operation and optimum performance. The design was a team effort. My area of concentration was the transmission and control systems while my partner, Josh Lindsay, designed the propeller, foils, and support configuration. Much overlapping of responsibility existed both in the design and construction of the boat.

An overall layout of the design is shown in Figure 5. The general features and design parameters are as follows:

Design speed - 5 m/sec (3 m/sec take off)
Support structure - displacement hull supported by tandem submerged hydrofoils
Power source - human, recumbent pedalling position
Propulsion - tractor screw propeller (Lindsay, 1980)
Transmission - three stage 1:27 step up
Steering - steerable front rudder and propeller

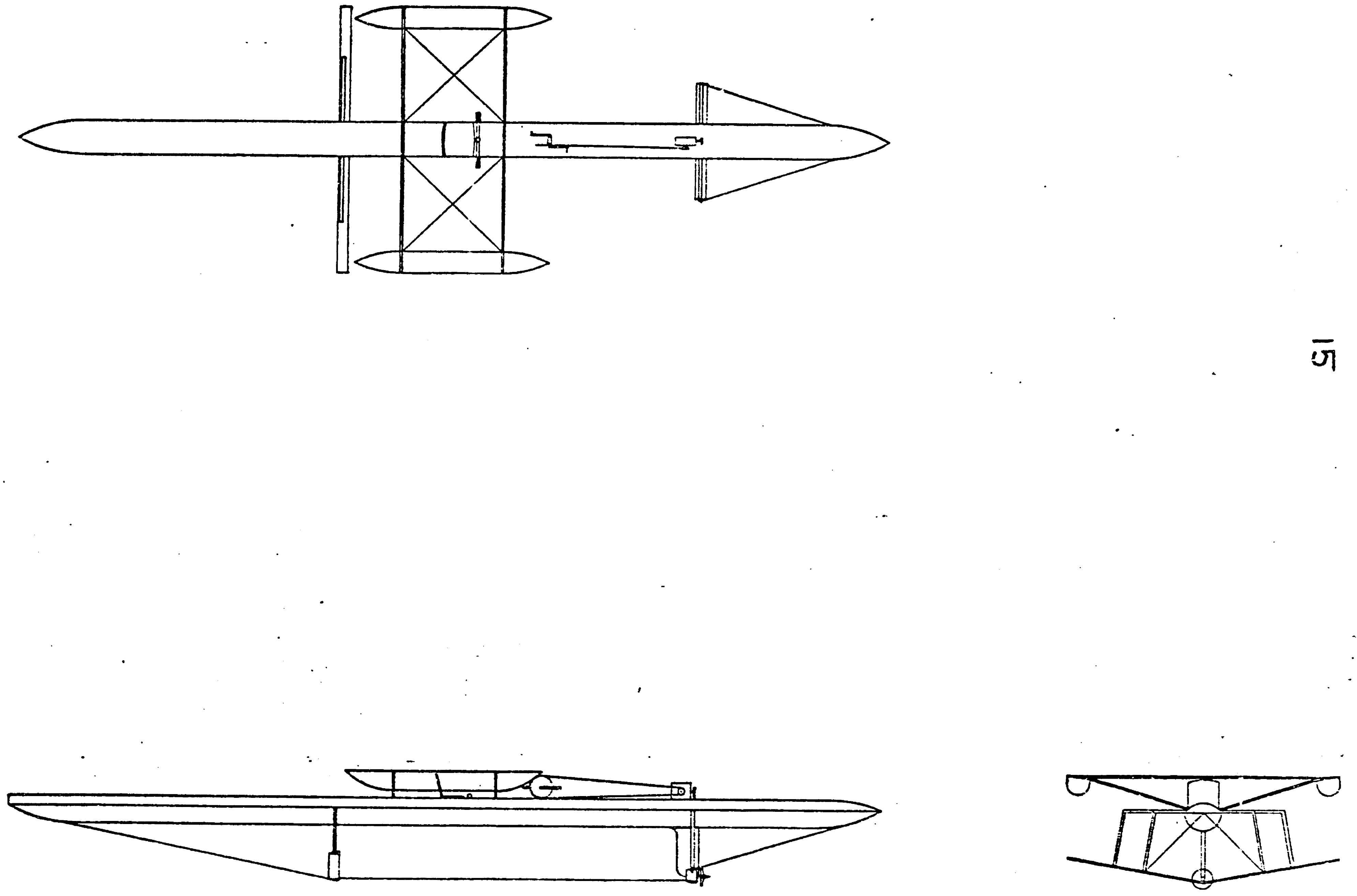


FIGURE 5 - OVERALL LAYOUT OF CRAFT

Stability and control - handle bar with twist-grip cable controls to vary angle of attack on each side of front foil. Outriggers for static side-to-side stability

The hull is a single shell of the following dimensions: length - 7.62 m., width - 0.28 m., draught - 0.20 m. The shell serves only as bouyant support for the weight of the other hardware and the pilot. It is not meant to absorb any stresses resulting from the large pedalling forces and torques. A support frame to which the foils, the transmission, the handlebar headset, and the seat attach is to absorb all of these stresses. The shell is hung from this frame.

The shell will be supported, at high speeds, by a hydrofoil system. This system consists of tandem submerged hydrofoils of 0.09 m chord length. Each wing has a 10° dihedral to provide side-to-side stability. Front-to-back stability is achieved by means of an active control system. The front foils will carry only 35% of the load and will have a variable angle of attack, controlled through two cables (one for each side) running to twist grips on the handlebar. This system also facilitates turning by allowing the pilot, through the use of the twist grips, to lean the craft into the turn as one would on a bicycle. At low speed (prior to lift off) side-to-side stability is provided by the outriggers which were designed to support the full weight of the pilot 0.50 m laterally from the center of the shell. The outriggers are supported by the rear hydrofoil struts.

The propeller was designed by Josh Lindsay in conjunction with Professor E. Eugene Larrabee. It was designed to have an efficiency of 87% at the design speed of 5m/sec. The rotational speed of the propeller is 2000 rpm when the boat reaches this velocity. The overall diameter (tip-to-tip) of the propeller is 0.18 m. It is used in a tractor configuration and is steerable. A rudder is attached to the timing-belt housing (Figure 6). By allowing control over the propeller's orientation, the boat is always being pulled in the desired direction of travel. This feature minimizes the loss of propulsion efficiency while turning and may allow the craft to remain supported on the hydrofoils while maneuvering.

Steering is actuated through handlebars located beneath the seat. A bicycle-type headset, secured to the support frame, provides a pivot for the handlebars. Two cables form a complete loop as each runs between the same sides of the handle bars and the timing-belt housing. The system is shown in Figure 7.

The power transmission is shown by Figure 8. From the recumbent pedaling position the pilot rotates a 52-tooth bicycle-type chainwheel. This chainwheel drives a 14-tooth sprocket through a standard one-half-inch-pitch bicycle chain. The sprocket is mounted on a right-angle bevel-gear drive that has a 3:1 gear ratio. Mounted on the output shaft of the gear drive is a 24-tooth timing-belt pulley.

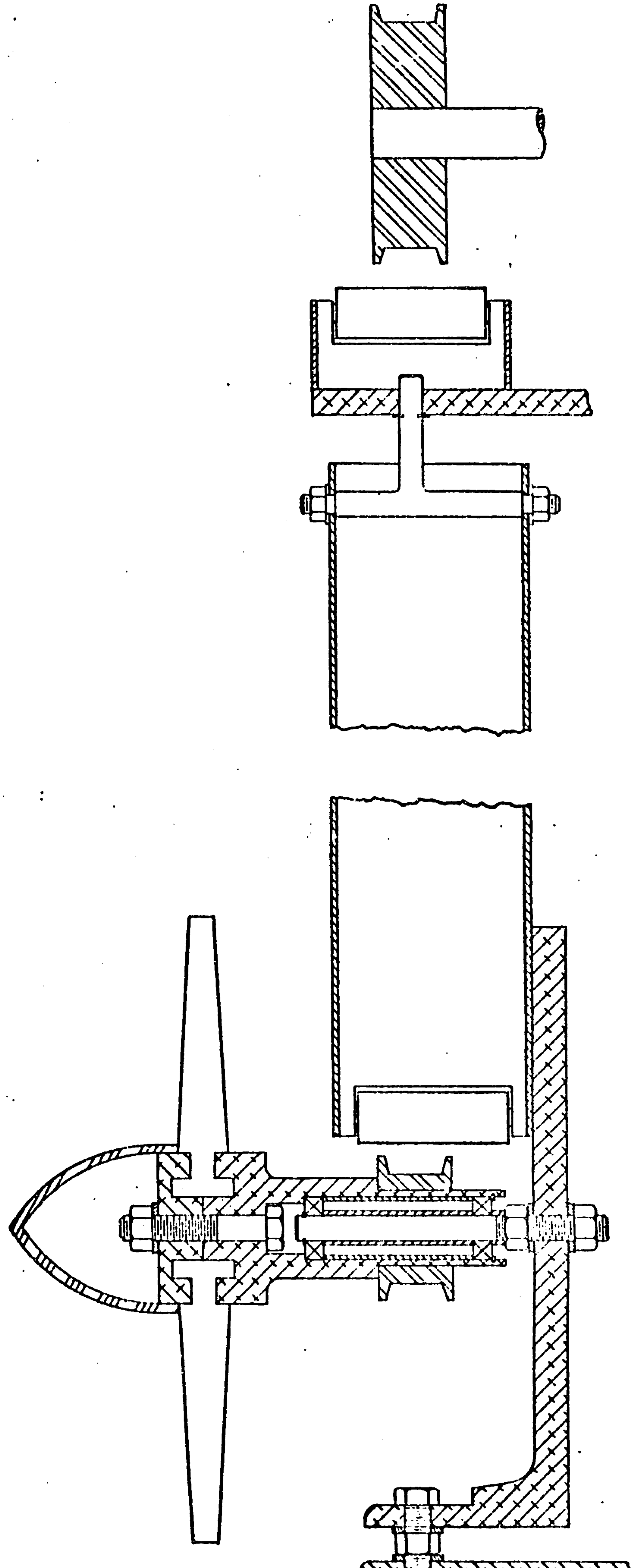


FIGURE 6 -
PROPULSION SYSTEM

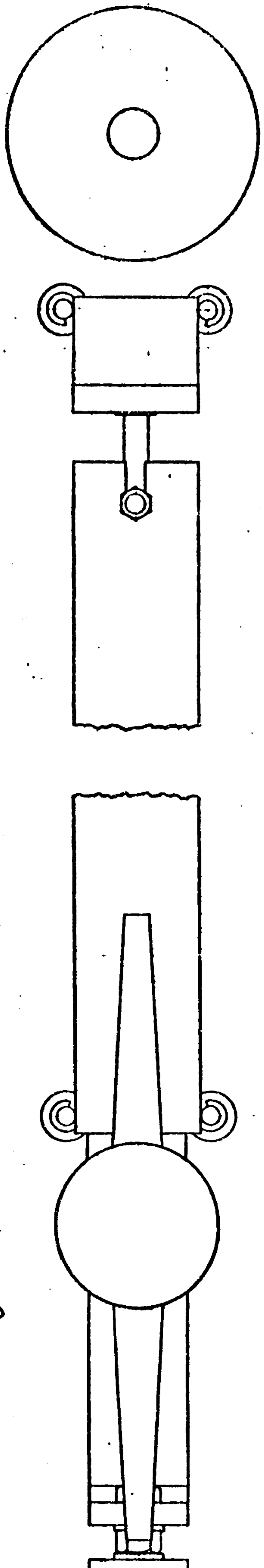


FIGURE 6 - CONTINUED

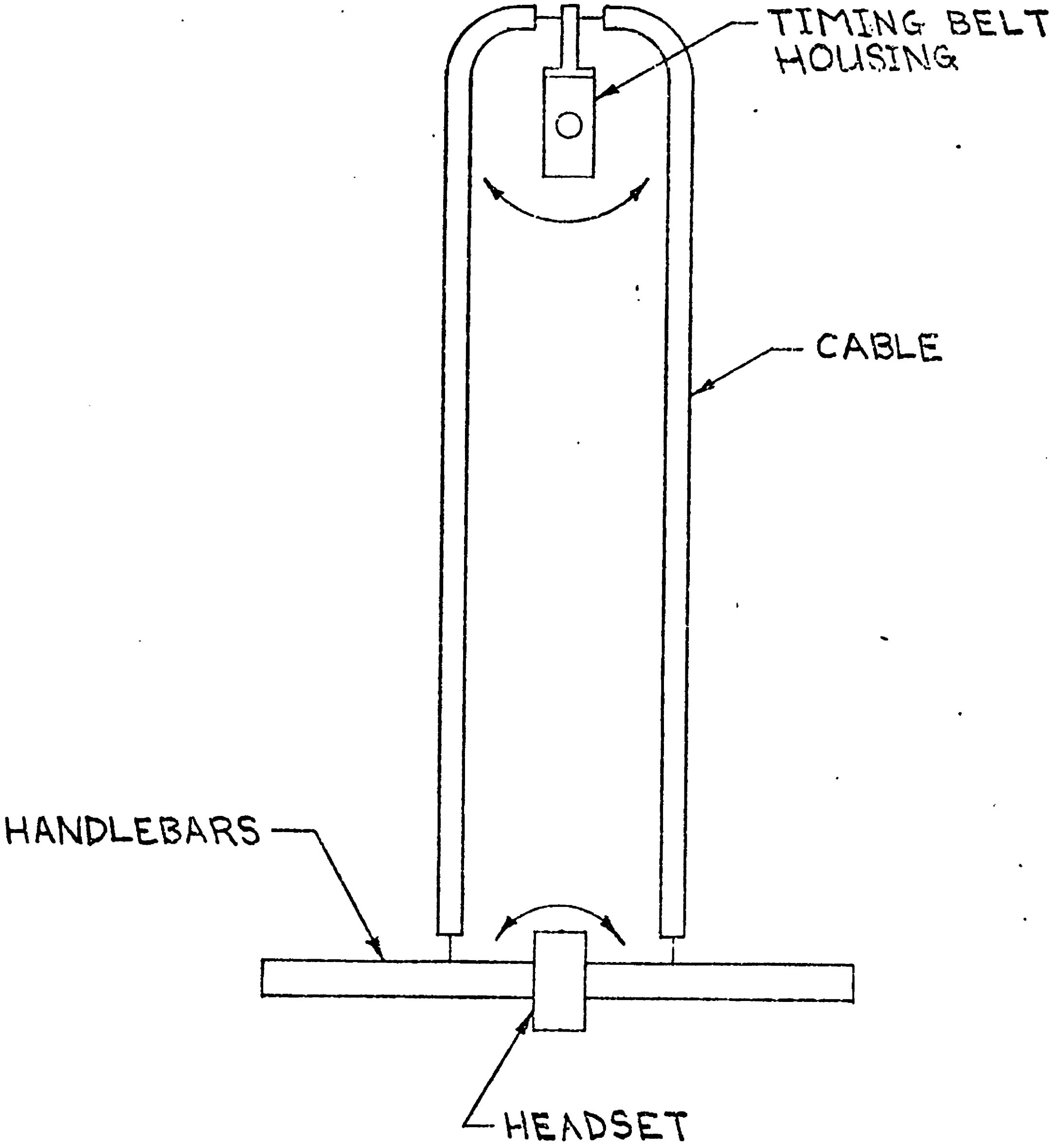


FIGURE 7 - STEERING SYSTEM

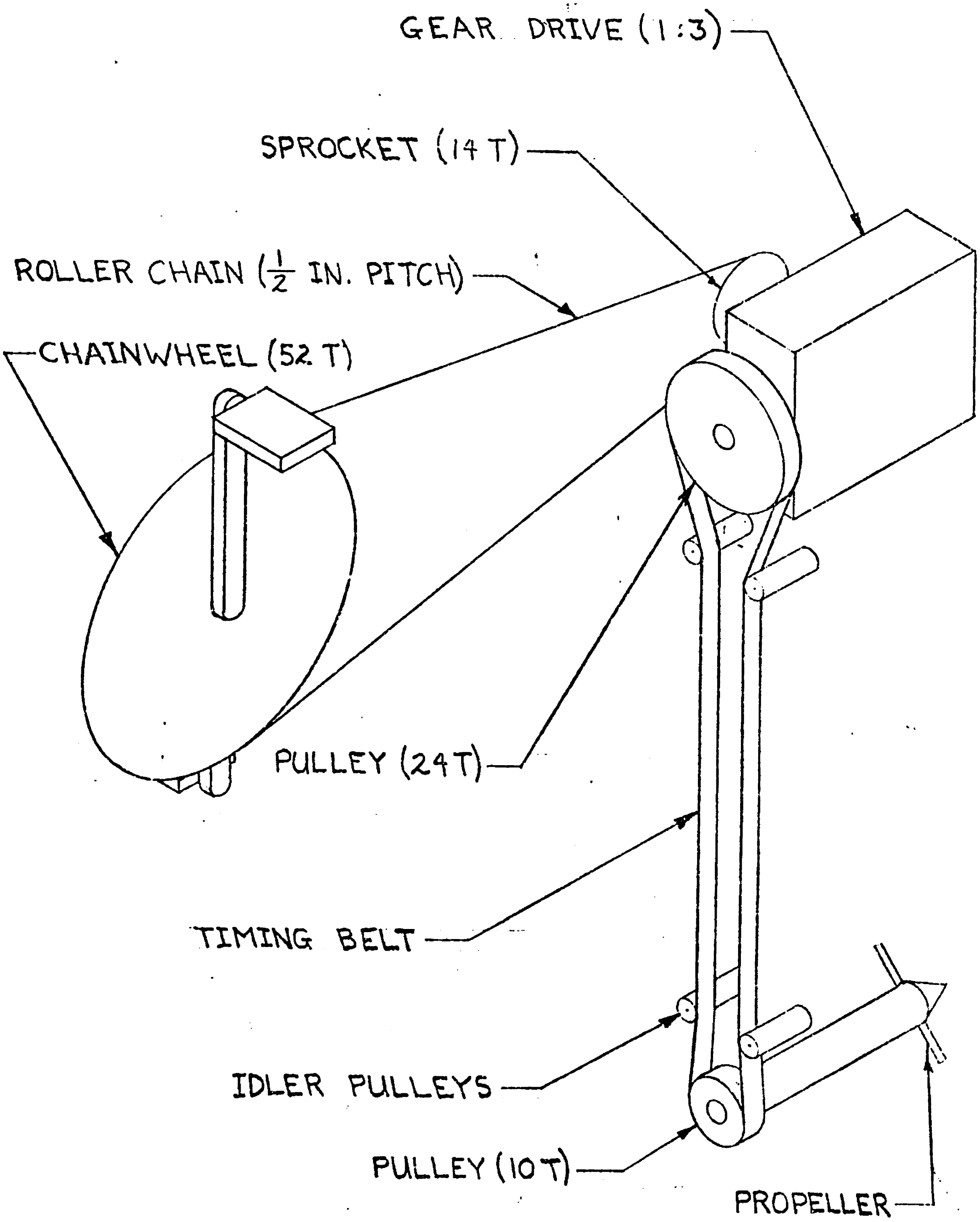


FIGURE 8 - TRANSMISSION LAYOUT

This drives a 10-tooth timing-belt pulley by a one-half-inch-wide three-eighths-inch-pitch timing belt. The ten-tooth pulley is mounted on the propeller. The total step-up ratio is 1:27 for an input of 75 rpm (pedalling) to an output of 2000 rpm (propeller speed). The timing belt is allowed to twist as the pilot turns the boat 45° in either direction. The belt is kept on track by two pairs of idler pulleys. These pulleys also keep the belt profile as thin as possible to reduce drag. The top pair of pulleys is fixed to the support frame and the bottom pair is fixed to the belt housing.

The crankset is supported well above the support frame by a partial bicycle frame. It must be supported high enough so that the shell and the support frame do not interfere with the pilot's heels as he or she pedals.

The seat is made of canvas stretched over an aluminum-tube frame. The frame is attached to runners on the support frame which provide adjustability for the seat and clearance for the handlebars.

III. Construction

The construction of the boat was partially dictated by the available materials and components. Available to us were some partially constructed hydrofoils, a 3:1 right-angle gear drive, and a shell. The foils were built by Brad Brewster for his thesis in 1979. The vehicle to which these foils were to be fitted used a V-foil support system. As a result, these foils have a 0.20 m chord length whereas the design chord length, for the current craft, is 0.09 m. Instead of compensating for this increased chord by decreasing the span of the foils to maintain the design foil area, the span was kept the same. The reason for this was to facilitate retrofitting of foils, with the design profile, in the future and also to keep the aspect ratio as high as possible. This change will have an effect on the performance of the boat. There will be more drag and it will lift off at 2.1 m/sec instead of 3 m/sec.

The actual profile of the hydrofoils used in construction is shown by Figure 9. The foils were constructed of polyester resin and fiberglass. The foils were obtained in very rough condition. They were cut to length and fitted with mounting hardware. Then the ends and surfaces were filled with auto-body filler and sanded. This was repeated several times to create a smooth and uniform surface. Finally, they were painted and sealed with varnish.

The shell that was used was 7.62 m long and 0.28 m wide and had a maximum draught of 0.20 m. It was made of gel-coat fiber glass backed with urethane foam and supported by a tubular aluminum frame. The oarlocks, stretchers, and seat slider were removed before construction.

Some aspects of the original design were changed during construction. Originally the shell was to be hung from a frame that supported the foils, the transmission, theseat,

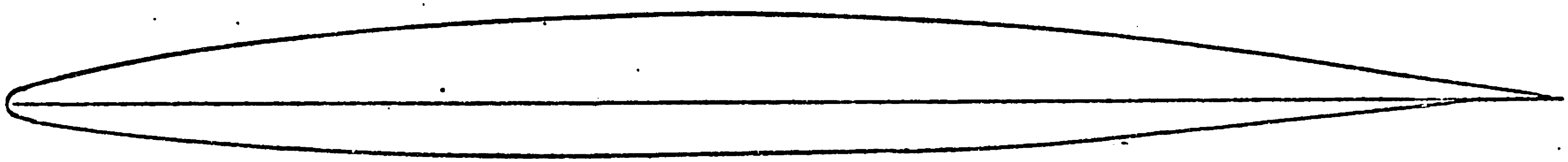


FIGURE 9. ACTUAL SIZE AND CROSS SECTION SHAPE OF V-FOIL WING, THE NACA 66-209. Re = $5x10^5$ at 3m/sec.

(From Brewster, 1979, p. 30)

and the steering and stability controls. When it became apparent, after construction began, that the shell was sufficiently stiff, it was decided that the rear foils could be attached directly to the shell. This eliminated a rear frame extension.

Another aspect of the design that was changed is that bicycle brake levers were substituted for the twist grips on the handlebars for varying the angle of attack of the front foils. This was done for ease of construction and for availability.

The base of the support frame was made of 3/4-inch plywood and was attached to the shell by hose clamps (Figure 10). To this base the partial bicycle frame, which includes the bottom bracket for the crankset, was attached by U-bolts. Also attached to this base were the gear-drive extension, the seat runners, and the headset. The gear-drive extension was made of 3/4-inch plywood and bolted directly to the base where the two pieces overlap. The seat runners were made of plywood with aluminum tube along one edge. The opposite edge was attached to the base using aluminum angle and bolts.

The propeller hub, drive mechanism and housing, steering headset, and miscellaneous hardware and fixtures were machined out of 2024-aluminum stack. Photographs of the partially completed craft are shown in Figure 11.

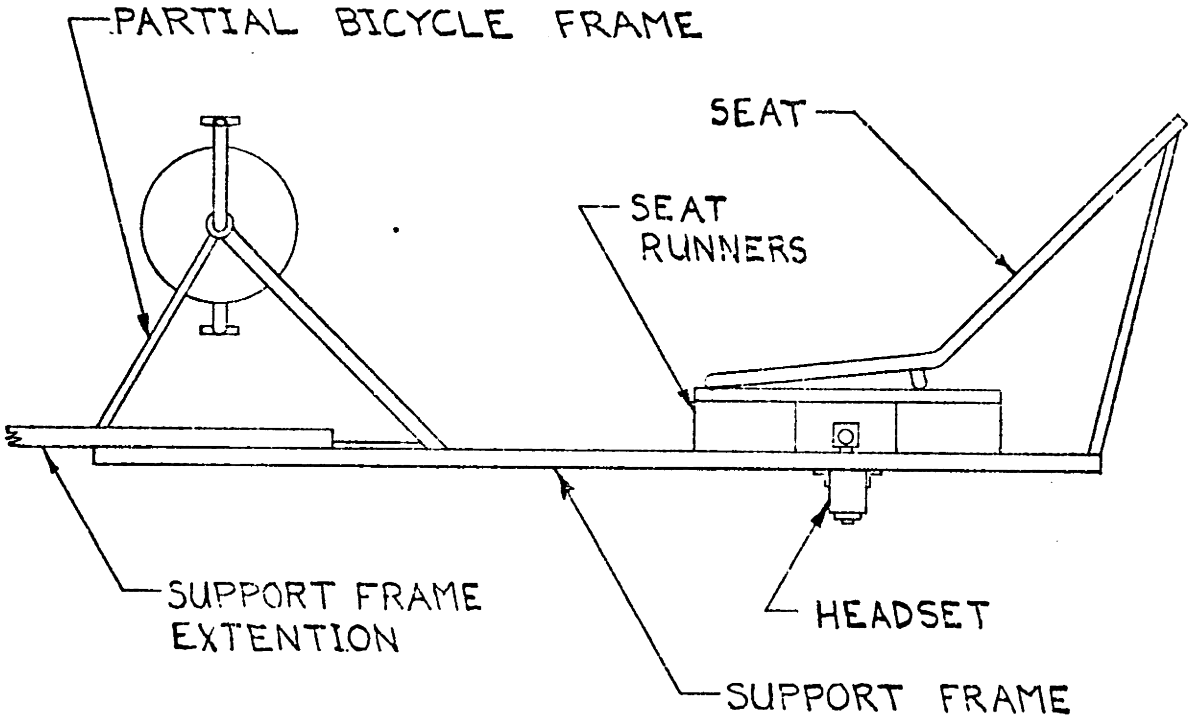
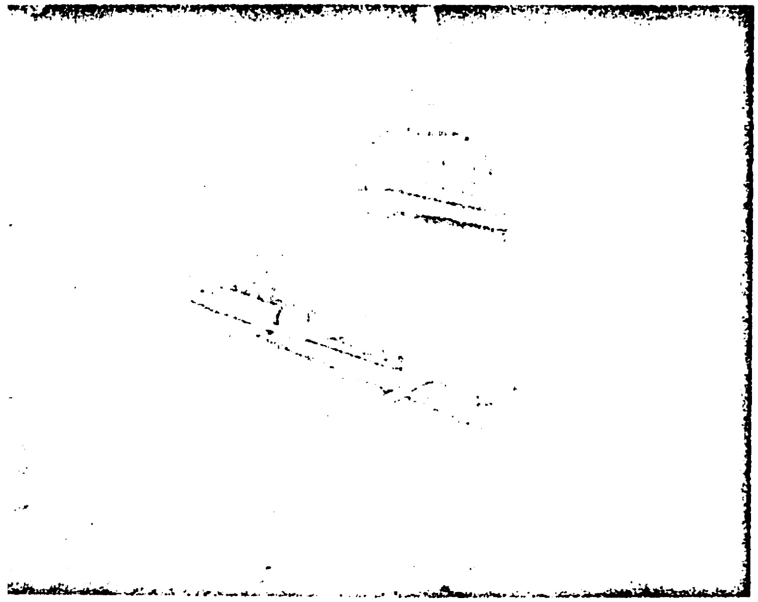
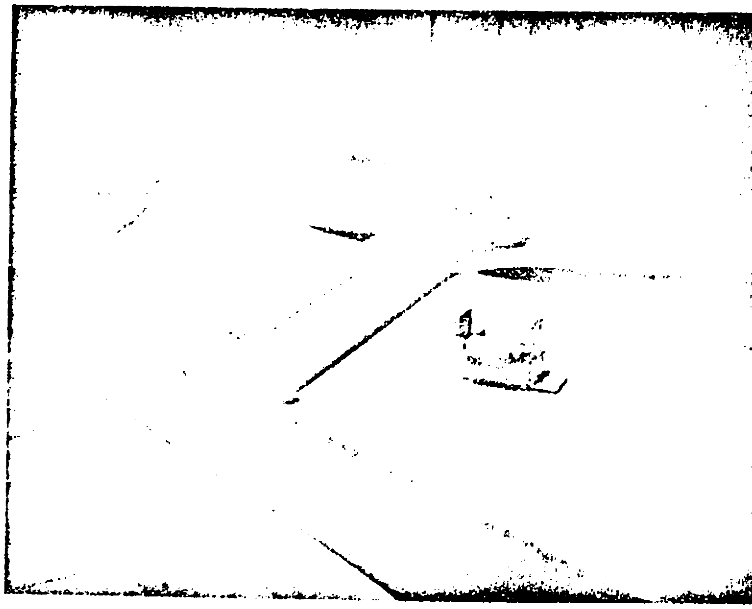


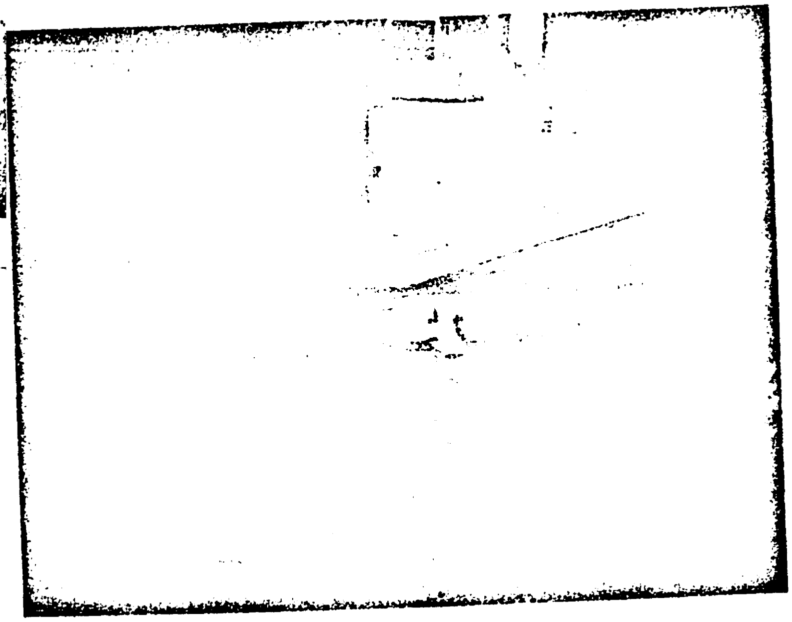
FIGURE 10 - SUPPORT-FRAME LAYOUT



SHELL



BELT HOUSING



FOILS

FIGURE 11 - Photographs

IV. Future Work

Future work on this craft falls into two categories. The first is to complete the construction and testing of the current craft. My partner and I plan to complete this work in the near future. After construction is complete the craft will be tested in the water. If lift off cannot be achieved under the power of the pilot alone, a tow test will be performed. In this test the boat would be towed until it reaches lift off and the pilot will then attempt to keep it "flying" under his own power. A speedometer should be used to determine the critical speeds. These would then be compared with the theoretical values used in the design.

The second category of future work is that of a second-generation design. This could consist of a radical design change or small improvements to the existing vessel. One such improvement would be to retrofit foils that correspond to the original design. This would create better performance from the hydrofoils by increasing the aspect ratio and therefore decreasing the drag. The originally chosen profiles are better suited for this application due to a better lift-to-drag ratio.

Another possible improvement is to use a shell that is shorter in length and hence lighter than the existing one. The reason that a shorter shell could be used in this case but not with rowing is that a certain portion of the shell's length is necessary to provide front-to-back stability as the rower slides his or her center of gravity back and forth on the seat slider; This length could be eliminated in the case of pedalling since the pilot's center of gravity remains stationary with respect to the boat.

Other such improvements would come out of the testing of the first generation craft which has yet to be completed. Even if the hydrofoils proved to be undesirable for this application, the shell with just the propeller should perform significantly better than a conventional single shell that uses rowing as a means of propulsion.

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