DESIGN AND DEVELOPMENT
OF A HUMAN-POWERED
HYDROFOIL

by

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Submitted to the Department of Mechanical Engineering on May 9, 1982 in partial fulfillment of the requirements for the Degree of Bachelor of Science in Mechanical Engineering

ABSTRACT

In the interest of promoting the use of human power in transportation vehicles, a human-powered hydrofoil boat was designed, and is being constructed. Hydrofoil boats are supported by hydrodynamic lift generated by submerged foil surfaces, which lifts the main hull out of the water, thereby significantly reducing drag. This allows very high speeds to be attained without requiring extra power input. The designed hydrofoil of this project should be able to attain speeds in excess of 15 mph.

The main flotation hull is a converted rowing shell, with two completely submerged foils. The foils have a 10-degree dihedral angle to provide roll stability. The forward foils have variable angle of attack, controlled by the rider with hand levers, for pitch stability and steering.

The boat is powered by pedaling from a recumbent position, and the power is transmitted to the water by a minimum-induced-loss-type propeller which was also designed and built by the author for this project.

Thesis Supervisor: Professor David Gordon Wilson

Department of Mechanical Engineering
INRODUCTION

In recent years there has been a renewed emphasis on the uses of human power. The reasons for this are numerous, ranging from the present energy crunch to a growing trend in the U.S. toward physical fitness. The most prominently displayed and useful form of the use of human power is in transportation. The modern bicycle is fast, efficient, economical, and relatively inexpensive. It is becoming a very popular method of transport in and around many cities, as well as a pleasant form of recreation.

The technology surrounding the field of human-powered transportation has grown considerably. Each year the speed records get faster, as more efficient vehicles are developed. The 55-mpg national speed limit has now been broken by a quadracycle on level ground.

The most notable advance in human-powered transportation in recent times, if not in the history of mankind, has been the successful conquest of the age-old dream of human-powered flight, with the triumphant flights of the Paul-MacCready-designed Gossamer Condor and Gossamer Albatross, two flying monuments to the advancement of modern aerodynamics and materials science. The Condor, the first of the two, won the Kremer prize (5000 English pounds) by flying a figure-eight course around two pylons placed \( \frac{1}{2} \) mile apart. The Albatross, a lightened and refined version with a more efficient propeller, flew across the English Channel under human power on her first attempt.
WATER VEHICLES

Relatively little has been accomplished in applying the modern innovations in human-powered transport to propulsion of water vehicles. This is evidenced by the fact that the fastest present-day examples are the modern racing shells, propelled by oars. Although the shell has fairly low drag due to its sleek shape, the mode of propulsion, rowing, can be classified as inefficient at best. The rowing stroke actually transmits energy to the water for only about 40% of the time of the whole stroke, with the remainder devoted to recoil and coasting. The oar also loses much energy in misdirected side force, due to its semicircular trajectory. The kinetic energies of the oar, oarsman, and boat hull are reversed in direction every half stroke because of the reciprocating motion involved. This requires additional energy expenditure by the rider. The act of rowing has other inconveniences associated with it also, including the necessary backward seating arrangement, which has obvious drawbacks in terms of vision impairment, and the annoyance of continually having one's hands occupied.

All of the most common and most efficient human-powered land vehicles and airplanes are powered by pedal-type transmissions, and there seems to be no fundamental difference between these and their water-borne cousin which would dictate that pedal drive would not be well suited for marine applications. Pedal drive has the following advantages: it
provides continuous power delivery; it utilizes the legs, which are capable of producing more power than arms; and it frees the arms for other use.

In a pedalling motion, human beings are capable of producing up to 1.75 horsepower for short durations, with this power output falling with time, to less than 1 Hp after a minute has elapsed. Output of up to ½ Hp may be sustained for several minutes by most bicycle racers in good physical condition. Figure 1 shows the power output of a test subject as a function of time.

Many pedal-driven boats exist, the most common of which are the two-seater pontoon boats which may be rented at many lake resorts. These are extremely inefficient due to the fact that they are propelled by paddlwheel, which expend most of their energy creating surface waves. They are used because of the fact that a paddlwheel may be driven by a chain in a manner similar to the transmission of a bicycle, and is simple and inexpensive to build. A more efficient device for transmitting power in fluid media is the screw propeller. Common propellers on powerboats have efficiencies in the range of 50-70%, but recent advances in the design of propellers allow efficiencies of up to 90%. There is a problem with using a screw propeller with a pedal transmission in that the direction of rotation must be turned through 90 degrees between the pedals and the prop, unless the rider sits sideways, which still would not be much more ridiculous than sitting backwards in a crew shell.
FIGURE 1

Variation in Human Power Output with Time.
(Wilson, Reference 5, page 48)
HYDROFOIL CRAFT

Hydrofoil craft fall into the classification of dynamically supported boats, and differ from displacement-hulled boats in much the same way as airplanes differ from zeppelins and other lighter-than-air flying vessels. While displacement hulls float by Archimedes' principle, displacing their own weight in water, hydrofoils displace considerably less than their own weight, and instead use hydrodynamic lift generated by the water flowing around the foils. This effect allows a large support force to be provided by a very small submerged volume.

A large part of the drag force on a boat occurs due to wave production at the air-water interface. Hydrofoils actually lift the main hull out of the water completely, while the foils remain well below the surface, leaving only support struts crossing the surface of the water. The result is a minimum of surface wave drag (hydrofoils are surpassed in this feature only by submarines), combined with a significant reduction in skin-friction drag due to the small surface area of the foils necessary to provide sufficient support for the boat.

The lift force produced by a foil is given by:

\[ L = C_L \frac{1}{2} \rho V^2 S \]  

(1)

where \( L \) is the lift force, \( \rho \) is the fluid density, \( V \) is the relative velocity between the foil and the freestream, \( S \) is the area of the foil, and \( C_L \) is the lift coefficient for the foil. Similarly, drag force is found by:
\[ D = C_d \frac{1}{2} \rho v^2 S \]  

(2)

where \( C_d \) is the drag coefficient.

The lift and drag coefficients are functions of the foil shape and angle of attack of the foil, which is the angle between the centerline of the foil and the direction of motion. See Figure 2. These coefficients have been tabulated for most common foil shapes from experimental data by Abbott and Van Doenhoff in *Theory of Wing Sections* (Reference 3). The data for the NACA 66-209 foil section is shown in Figure 3.

The reduction in drag effected by using hydrofoils may be illustrated by calculating the drag on a hydrofoil and a racing shell, carrying the same load at the same speed. For the shell, we will consider only skin-friction drag, and neglect form drag and surface-wave effects, and thereby erring in favor of the shell.

Since a shell is very long and narrow, its surface area may be approximated by that of a long cylinder, neglecting the ends. This is given by:

\[ S = \pi r L \]  

(3)

where a semicircular (hence minimum surface-area-to-displacement ratio) cross section has been assumed, with \( r \) the radius of the average section, and \( L \) is the length of the shell. Equation (2) applies to flat surfaces as well as foils. The drag coefficient may be found from the chart in Figure 4, assuming a smooth bottom, after calculating the Reynolds number of the flow as follows:
FIGURE 2

Foil Cross-section Showing Lift Force, Drag Force and Angle of Attack
Figure 3
Lift and Drag Coefficients
(From Abbott & VonDoenhoff, Reference 3)
\[ H = \frac{F V L}{\mu} \]

where \( \mu \) is the viscosity of water. Assuming a length of 25 ft., and an average radius of 3.5 inches, which would give a water displacement of 200 lb., and a velocity of 10 feet per second, the Reynolds number becomes \( 2.4 \times 10^7 \). From Figure 4 this yields \( c_d = 0.005 \). Substituting this into Equation 2 yields the drag force as:

\[ r_{d_{\text{shell}}} \approx 5.1 \text{ lb.} \]  

For the foil, we assume an area equal to that of the foils used in this project, \( S = 4.8 \text{ ft}^2 \). Assuming a load of 200 lb, at 10 feet per second, we calculate the necessary lift coefficient from Equation 1. (The lift coefficient may be varied as desired by changing the angle of attack of the foils, as will be explained in a later section.) This lift coefficient is:

\[ c_L \approx 0.43 \]  

which corresponds to an attack angle of 3 degrees, from Figure 3a. From Figure 3b, we find that the drag coefficient is:

\[ c_d \approx 0.008 \]  

Equation 2 then yields the drag force for the foil:

\[ r_{d_{\text{foil}}} \approx 3.75 \text{ lb} \]

which is about 25% less than the drag on the shell, even neglecting form and wave drag.

This analysis was done assuming that the foil has already succeeded in lifting the hull out of the water. In practice, the hydrofoil must start out with the hull in the
FIGURE 4

Variation of Drag Coefficient with Reynolds Number for a Smooth Plate parallel to Flow (Fox & McDonald, Reference 6)

FIGURE 5

Qualitative Shape of Drag vs. Speed showing Liftoff at 2 m/sec
water, and thus until liftoff, must overcome the drag of both the hull and the foils. Both of these drag forces will be proportional to the square of the velocity, so that the drag force will look qualitatively like the curve shown in Figure 5. Note the significant reduction in drag at liftoff.

The data in Figure 4 is strictly valid for Reynolds numbers starting at $3.0 \times 10^6$ and higher. For this foil, that would correspond to a velocity of 14 meters per second, or 32 M$\text{p}h$, which is, unfortunately, out of the range of possible operating speeds for this craft. However, through the range of attack angle between about $-6$ degrees and $+6$ degrees there is almost negligible difference in the lift coefficient as Reynolds number is varied by a factor of three. Since the Reynolds number of this foil is $5 \times 10^5$ at a velocity of 3 m/sec, which is only a factor of six below the minimum tabulated, and the variation of $C_L$ is so small with varying Reynolds number, the data is assumed valid within this limited range of attack angle. Through a similar argument, the drag coefficients may be extrapolated from the given data for this lower Reynolds number. The dotted line in Figure 3b shows approximate drag coefficients for $R = 5 \times 10^5$. 
STABILITY

There are two types of basic stability problems associated with hydrofoil design. The first to be considered is resistance to roll, or tipping to the side. In displacement hulls, the designer must be sure that the metacenter is above the center of gravity. The metacenter is the point through which the buoyancy force acts, and is the same point regardless of the angular deflection. Figure 6 shows this for a displacement hull. Maintaining the metacenter above the center of gravity ensures that the restoring torque will always be in such a direction that it will tend to return the boat to an upright position. In a displacement boat, this problem is easily handled by keeping the center of gravity low, as by filling the keel with lead.

In a hydrofoil, the center of gravity is generally above the water's surface, so that attention must be paid to keeping the metacenter high. For a hydrofoil, the metacenter is located at the point through which the lift forces act. Figure 7 shows three possible locations of metacenter position for a hydrofoil. The first is an unstable configuration, with the metacenter below the center of gravity. The second is neutrally stable, since the lift force lines do not converge, except at infinity. The third is stable, as long as the dihedral angle is small enough that the metacenter remains above the center of gravity.
FIGURE 6

Metacenter of Displacement Hull
Dotted Line Shows Locus of Center of Bouyancy
7a) Unstable Configuration

Note that the metacenter is below the center of gravity, and therefore the net moment about the center of gravity tends to topple the craft.

7b) Neutrally Stable Configuration

Net lift force always points through the Center of gravity, so there is no net moment about that point.

7c) Stable Configuration

Net moment tends to return craft to its upright position.

FIGURE 7

Hydrofoil Stability
The second type of stability problem is associated with balancing the lift force against the weight of the craft. As velocity increases, it is seen from Equation (1) that the lift force varies as the square of the velocity, with all other factors held constant. This clearly will present a problem, since when the velocity becomes great enough that the lift exceeds the weight of the craft, the boat will rise until surface effects interfere with the flow over the foils. This is likely to cause cavitation or ventilation, with an accompanying sudden loss of lift, soon followed, no doubt, by a crash. Fortunately, this problem may be handled by allowing either the surface area or the lift coefficient to vary, enabling the lift force to be held constant and equal to the weight of the boat.

There are several methods which may be employed to vary the surface area of the foils, including surface-piercing V-foils and ladder-foil configurations. Both of these types have disadvantages associated with surface effects, since they require some foil area at or near the surface at all times.

The lift coefficient of the foils may be varied by changing the angle of attack of the foil, or by using control flaps like those on airplane wings. Many sophisticated hydrofoil powerboats use automatic control systems to vary the lift coefficients of their foils.
PREVIOUS WORK

There have recently been two human-powered boats designed as bachelor's theses at M.I.T. Robert Emerson designed a pedal-driven, displacement-hulled boat which had sliding pedals which drove a propeller. M. Bradham Brewster investigated three different configurations, all propeller driven. One was a catamaran with the rider seated between the hulls. Catamarans provide good lateral stability, and are therefore useful on sailing boats, since a tall sail rig may be used. They are of questionable value in applications where a large righting moment is unnecessary. Another configuration he investigated employed the use of a bouyant, submerged torpedo for flotation with outriggers for stability. The third configuration, which he chose to develop for his thesis, was a hydrofoil. It used three V-foils which pierced the surface. As the boat lifts off, the ends of the foils come out of the water, thereby reducing the area of foil in the water, and the boat will maintain a force balance between the weight of the boat and the lift of the foils. See Figure 6.

As mentioned in the previous section, the surface-piercing foils have several disadvantages. The wave drag produced at the surface interface is a major contributor to the total drag, so it is undesirable to have foils at the surface. Also, since the foils are positioned at a rather steep angle to the horizontal, their lift has a large (In Brewster's configuration 30% of the total) compo-
FIGURE 8

Design Proposed by M. Kredhem, Engineer.
ment in the horizontal direction, which does nothing useful, but is responsible for a similar proportion of drag. Finally, the reduction in foil area is accomplished by a reduction in only the length of the foil submerged, and therefore the aspect ratio of the foils is reduced proportionally. A high aspect ratio is desirable, since it reduces the relative induced drag.

As a result of these and other considerations, Brewster concluded that "further effort...should be focused on the tandem submerged-hydrofoil configuration," rather than on the surface-piercing type. However, he also points out that such a configuration would have stability problems, but also that "the superior drag efficiency of the tandem submerged-foil configuration more than outweighs its complex stability problems for those designers who are seriously interested in developing a low-drag high-speed water vehicle." It is the belief of this author that the lateral (roll) stability of submerged hydrofoils is not as severe a problem as Brewster seemed to think. In his section on hydrofoils, on page 18 of his thesis, he says "...the meta-centers of these craft, on the level of the submerged lifting surfaces, is well below the vessel's center of gravity." This misconception is at the root of his confusion, as may be seen by referring back to figure 7. Any small dihedral in the lifting surface makes for a stable configuration.
The design which is under construction for this project employs two fully submerged foils, with a human control system to provide stability. One of the foils, the forward set, is hinged so that the angle of attack of either or both sides can be varied, controlled by brake levers on handlebars which also serve to steer the propeller. The basic layout is shown in Figure 9.

The foils' shape is the NACA 66-209, chosen because of the availability of the foils built by Brad Brewer originally for use on his surface-piercing hydrofoil, which was never completed. The foils are made of reasonably stiff fiberglass which allow the use of high aspect ratios. The foils have a chord length of 8 inches.

The weight distribution places 40% of the weight of the boat and rider on the forward foil when both foils are operating at the same angle of attack. This was accomplished by arranging the areas of the stern and forward foils to be in 60:40 proportions. The total foil area is 4.8 ft², with the rear foil having a 54" span, and the forward foil having a 36" span.

Both foils are arranged with a 10-degree dihedral. Ignoring end effects, this gives metacentric heights of 77" and 51" for aft and forward foils, respectively, with the resultant metacentric height being 67" at the center of mass fore and aft. The center of gravity of the boat is located at approximately 30" above the foils. This should ensure proper stability in roll.
Designed Hydrofoil of this Project

Transmission of Craft

Flexible Rubber seal
Minimum induced loss Prop
Forward foil
Sealed Bearings
Belt Housing

52-Tooth Sprocket
Chain
3:1 Bevel Gearbox
12-tooth sprocket

Figure 9

Figure 10
The main hull is a converted rowing shell, which has been generously donated for this project by Prof. David Wilson. This hull will provide flotation at speeds below takeoff, while creating relatively low drag. The hull should lift completely out of the water after takeoff.

The craft will be driven by a rider in the recumbent position, wherein the rider is sitting back in a seat with a back on it against which he can push, so that he is not limited by his weight in how much force he can transmit to the pedals, or required to counteract pedal forces with arm restraint, as he is on a conventional bicycle seat.

The transmission consists of a conventional crankset and chain assembly, which provides approximately a 4:1 gearing stepup. This turns the input side of a 90-degree 3:1-ratio bevel gear box, which was constructed by Robert Emerson as part of his thesis. The output shaft from this box drives a belt which drives the propeller with another 2.4:1 stepup. The transmission is shown in Figure 10.

The propeller is a minimum-induced-loss-type propeller, designed according to a method developed by Prof. E. Eugene Larrabee of M.I.T.'s Aero and Astro department. This design method is described in his Design of Propellers for Motorsoarers 1979. Professor Larrabee designed the propeller for the Gossamer Albatross using this method. The basic idea behind the method is to give the slipstream of the prop an axial velocity which is constant across its area, except at the center, where the shaft makes this impossible. This constancy eliminates internal shearing
of fluid and the resulting dissipation of heat into the fluid.

The author developed a computer program which provides all critical dimensions and pitch angles of the prop as functions of power input, desired velocity, fluid properties, and the lift coefficient of the chosen foil section for the propeller. It also computes theoretical efficiency and design speed in RPMs. The propeller being used in this project is designed to operate at a speed of 5 m/sec, and a power input of 350 watts (\(\frac{1}{2}\) HP). It will be driven at a speed of 2000 RPM, through a total gearing stepup of 28:1 requiring a 75 RPM input by the rider. The propeller is theoretically 87% efficient.
CONSTRUCTION

The hydrofoil is presently under construction, with a considerable, but by no means insurmountable, amount of work yet to be done.

To date, the following has been done: The foils, which were badly pitted and rough, have been cut to the right lengths and putted and sanded; mounting brackets and hinges were made from aluminum sheet metal and bar stock; the support struts were made from 3/4" aluminum tube, and attached to the foils in a manner which makes them easily adjustable; the support frame was built from plywood, and partially installed in the shell. The foil-mounting assembly is shown in Figure 11.

The propeller was made from aluminum on a machine in the aerophysics-laboratory machine shop. See photos in Figure 12. The machine cuts the propeller blades with two milling cutters which are guided through linkages to a cam which must be made for each blade shape desired. The cam was made by taking the calculated dimensions of the propeller, multiplying by 4 and adding $\frac{\pi}{8}$ all the way around, and making a template at each 10% of the radius. These are sandwiched between pieces of wood of the proper thickness, and the wood is sanded smooth to the shape of the templates. The cam is shown in Figure 13, and the template layouts shown in Figure 14. The drive motor on the fine cutter had bearing problems, and caused a lot of chatter, which caused excessive surface roughness, so the
FIGURE 11
Foil-Mounting Assembly
FIGURE 12a

Installation Detail Showing Con Rollers and Overriding Gear

FIGURE 12b

Showing Killing Cutters and Linkage.
**Figure 13**

Can for Propeller Blade
machine was adjusted so that the workpiece came out a couple thousandths oversize, and the blades were hand sanded.

The hub of the propeller was machined out of aluminum, and the blades mounted in it. The bearings were fitted for the propeller shaft. The housing for the belt is being made from an aluminum extrusion, with idler rollers at each end to ensure that the belt will not contact the housing. A hinge arrangement is being built to facilitate the turning of the belt housing for prop steerage. The mounting bracket for the bevel gearbox is also under construction.

Final assembly is not far off, and will be followed by fiberglassing over the parts of the hull which had to be torn up to facilitate installation of the mounting frame and belt housing. Evaluation of the necessity for guywire support of the foils will follow final assembly.
CONCLUSIONS & RECOMMENDATIONS

The hydrofoil has a very good chance of success. If the design has a weak point which stands out it would be the propeller, which seems too small for one's intuition to imagine it pushing a boat. The mathematics say that it should work, and so it awaits a road test. It should have no trouble operating at its design speed, but may tend to "spin its wheels" at speeds below the design. It is possible that it may need a tow to get it up to operating speed. Also, the decision to make the propeller steerable introduced some severe complications in the construction of the hydrofoil, with questionable marginal returns.

Overall, the progress in recent weeks has been encouraging and inspiring, and the boat should be ready for launching within three weeks.
REFERENCES


