HUMAN POWER

THE TECHNICAL JOURNAL OF THE IHPVA

Vol. 8 No. 1 $4.00 ISSUE NO. [illegible] Summer 1990

The human-powered submersible race: A review from down under

by James Osse

Last June [1989], 18 competitors from around the country assembled in West Palm Beach, Florida, to participate in the First International Human-Powered Submarine Race. The race was sponsored and promoted by the H.A. Perry Foundation and was intended to inspire student interest in ocean engineering. Those who responded represented a diverse background from large corporations to small private companies. The technologies employed in the vehicles were as diverse as their creators. Body shapes ranged from the traditional torpedo to spherical to advanced low-drag hulls. Propulsion systems ranged from the traditional screw propeller to oscillating fins mimicking fish motion. The following article discusses the various vehicles that participated and some of the lessons learned in this first race.

I led a team that designed and built an entry with the support of the University of Washington's Applied Physics Laboratory (APL). Our submarine, named the HumPSub for Human Powered Submersible, is shown in Figure 1. It was constructed using volunteer labor and materials donated by the Laboratory. This was typical of the limited financial support all the teams worked under. The body was made of strips of Sitka spruce laminated with fiberglass on both sides, a technique commonly used in boat building. This yields a strong, lightweight, monocoque hull with inherent buoyancy. The vehicle's shape was a scaled version of an advanced, laminar-flow vehicle APL developed in the early 1970s. Under ideal conditions, a hull with this shape will have less than half the drag of a traditional cylindrical submarine. It ran well at races, posting the third fastest time, and garnered the prize for the most cost-effective entry.

Race rules and course description

The race rules were fairly simple: design and construct a wet submarine capable of carrying a pilot and propulsor (the "stoker") three times around a 333-meter course in 15 to 20 feet of water in the open ocean while fully submerged. The kidney-bean-shaped course was intended to test both maneuverability

(continued on page 16)

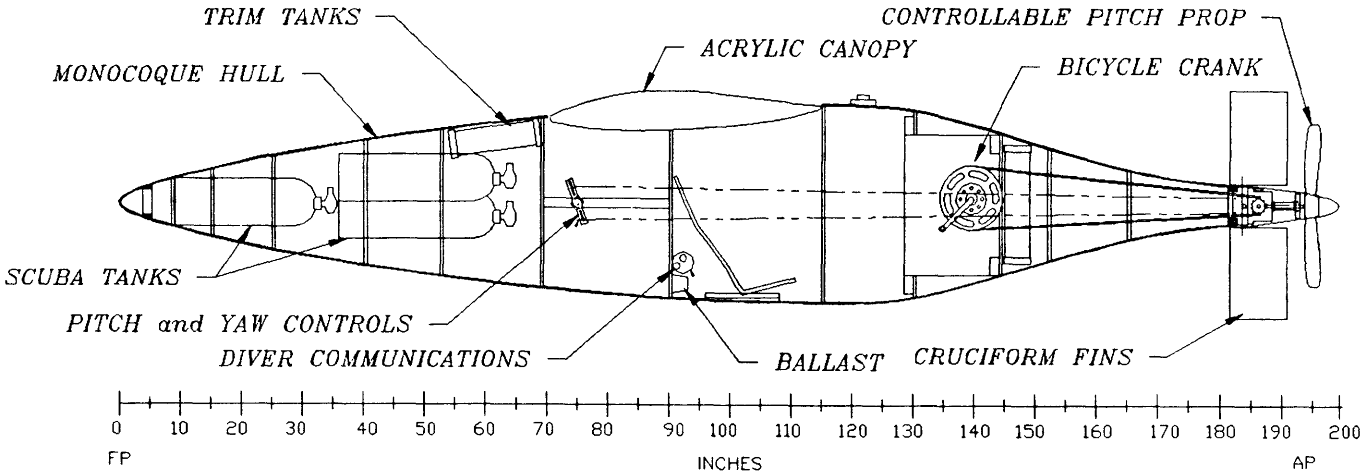


Figure 1. Applied Physics Laboratory entry, *HumPSub*.

Human Power
The Technical Journal of the
International Human-Powered
Vehicle Association
David Gordon Wilson, Editor
21 Winthrop Street
Winchester, MA 01890-2851, USA
(617) 729-2203 (home)
(617) 253-5121 (office)
Theodor Schmidt, Assoc. Editor—Europe
Rebackerweg 19
CH-4402 Frenkendorf, SWTIZERLAND
Philip Thiel, Assoc. Editor—Watercraft
4720 7th Av., NE
Seattle, WA 98105 USA
IHPVA
P.O. Box 51255
Indianapolis, IN 46251, USA
(317) 876-9478

Human Power is published quarterly by the International Human-Powered Vehicle Association, Inc., a non-profit organization devoted to the study and application of human muscular potential to propel craft through the air, in the water and on land. We invite contributions of a longer-term technical interest. Send contributions to the editor or an associate editor at the addresses above. If you would like to be sent a guide on how we prefer the articles be submitted, please write Dave Wilson.

IHPVA membership information is available by sending a self-addressed, stamped business-sized envelope to the IHPVA at the address listed above.

Members may purchase additional copies of *Human Power* for $2.50 each. Nonmembers may purchase issues for $4.00 per copy.

Special thanks to the authors, Marti Daily, Apple Press, Kim Griesemer and Carolyn Beckman Stitson, without whom this issue would not have been possible.

Editorials

This issue is devoted almost entirely to human-powered boats. It has been edited by Philip Thiel of Seattle USA and Theo Schmidt of Frenkendorf, Switzerland. I believe that you will agree that they have done a superb job of soliciting top-grade contributions from the leading people in the field. I have done the detailed editing, and should be blamed for problems in that area; Carolyn Stitson entered most of the material on to floppy disks; Marti Daily was responsible for having these converted to Macintosh diskettes; and Kim Griesemer produced the whole layout. They deserve our considerable gratitude.

If others would like to edit special issues of Human Power, please write or phone.

This issue is numbered volume 8 no. 1. It should have been 8/2, but through a typo the last issue was numbered 8/2. We decided that it would cause more confusion to renumber them than to have them numbered out of sequence. Apologies!

—Dave Wilson

Thoughts on HPBs

In this special boating issue of *Human Power*, we hope to address most of the following topics:

- sporting interest, competitions;
- environmental interests;
- technical achievements, physical knowledge;
- leisure interests;
- practical transportation;
- record-breaking; and
- historical interests.

The announcement of the Du Pont prize has resulted in increased racing and speed-related activity. We should not, however, forget the environmental advantages and implications of using human-powered and related craft, including the use of cars to transport them to the water. We will become more human-powered one way or another: either through choice, or by necessity when our civilisation collapses through the overwhelming accumulation of poisons.

—Theo Schmidt

In this issue—

Some editorial reflections

Collaborating in assembling this special watercraft edition of *Human Power* has been a rewarding learning experience. One fact that impresses me is the diversity of the contributors to this collection of papers along the several dimensions of kinds of interests, levels of technical sophistication, and areas of building and using experience. I see this variety as a great advantage to the continuing development of this nascent field, and I hope that it will continue to be encouraged and respected. The objective of this publication, I should think, is to serve as a catalyst for the growth of both scientific sophistication and the number of participants designing, building, and using HP watercraft.

To this end we should make all welcome, while doing all we can (editorially) to encourage complete and reliable presentation of data, and the development of theory and practice. This will be facilitated, I should think, by occasional articles on relevant scientific principles, eventually perhaps, constituting a sort of "layperson's guide to hydrodynamics". A parallel series might deal with principles of mechanics and materials, and even with technical case studies of marketing. By this means we may serve the interests of not only the scientifically sophisticated, but at the same time entice the backyard tinkerer to join the fun, in a democratic and pluralistic technical water-garden of many delights.

—Philip Thiel

❑

Letters to the editor

Suggestions for future HPV RAAMs

I wish to comment on your editorial about future HPV RAAMs. Top speed attained by the Lightning F-40 during the RAAM on downhills was 65 mph. This was due more to fairing design than applying the brakes. On downhills where the speed limit was 55 mph, we maintained this speed by applying more braking, as the rules prohibited exceeding the speed limit. We feel that it was not dangerous to descend hills in an HPV during this race as long as the speed limit was observed.

We also did not feel there was any problem or danger involved in riding the HPV with other traffic on the road. If anything, it was safer than a standard bike because you were really noticed by auto drivers. Many F-40s are currently being operated around the world by many people on various types of roads with no problems.

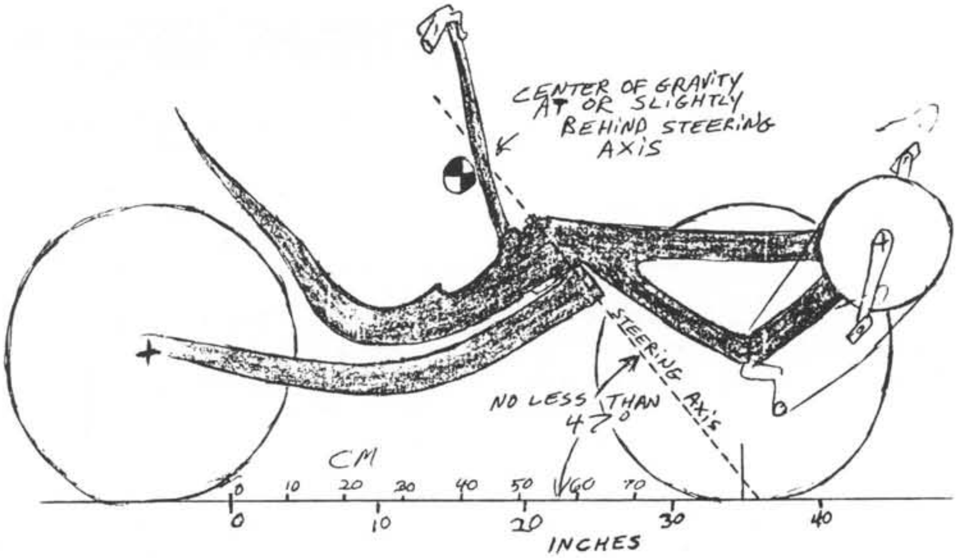
I will admit, however, that trying to keep the support vehicles up with the HPVs was a problem, and we also had our problems with navigation. Your idea of a stage race, which could be safely run even without closing the road, is well taken.

How about talking Donald Trump into having an HPV division in the Tour de Trump?

Or perhaps a "24 Hours of Sears Point" similar to the car race at LeMans, that Steve Delair is trying to put together? Or a stage race across the US in nine or ten days? You don't need to close the roads, and are we not trying to show that HPVs are street practical?

My feeling from the RAAM is that we had no vehicle problems, only format problems from riding around the clock.

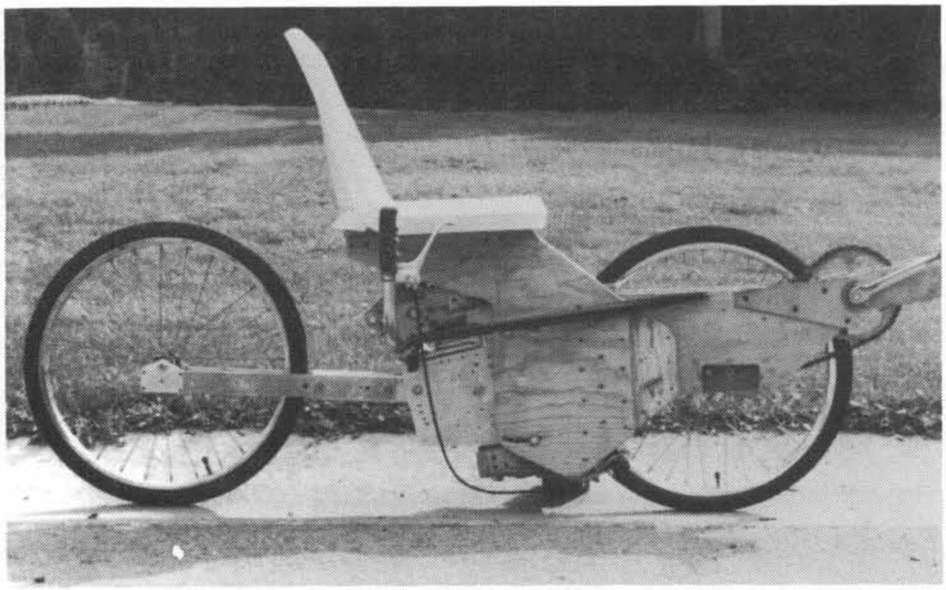
Tim Brummer
Lightning Cycle Dynamics, Inc.
1600 E. Chestnut Ct. #E
Lompoc, CA 93436



Rear-steering recumbent design by Charles Brown

Correction

We should have put the photo printed below in place of that shown on p. 17 of HP 8/1, Spring 1990 in Craig Cornelius's article on rear-steering recumbent bicycles. Apologies!



Rear-steering recumbent bicycle by Craig Cornelius

Rear-steering recumbents

After reading Craig Cornelius's fascinating account of his experiments with rear-steering recumbents (HP 8/2/90), I wondered if the following design would work. Although technically a front-steering bicycle, it would seem to meet Craig's goals, without the steering problems. Like Craig's bikes, the handlebars would turn the rear portion of the frame in the opposite direction the handlebars were turned.

Charles Brown
534 N. Main #1
Ann Arbor, MI 48104

HPV RAAM

I didn't hear of the race on the news either. I wonder if these events are "plugged" at all. We should have PR people calling the media months before a race and drumming up interest. *We* have to be the ones to push it.

I am surprised the route was not well posted with signs and direction arrows. Can signs and direction arrows be painted on the road surface? Could there be motorcycle escort teams? If we could get permission, I'm sure we could get non-police motorcycle clubs to escort HPV riders through tough areas on the freeways. I am a member of such a club. We need to blitz the media ahead of time and have public interest generated ahead of time.

Ride easy and whole Hog,
D. Douglas Meister
2520 West Avenue
Fullerton, CA 92633-3140 USA

(continued on page 5)

Creation and development of the Du Pont human-powered watercraft speed prizes

by Doug Milliken

Inventing a new sport is difficult and it doesn't happen very often! The development of the Du Pont Watercraft Prizes drew on some of the best minds of the IHPVA. Credit and thanks are due to many and I will mention the major contributors in this account.

Allan Abbott and Alec Brooks were the first to demonstrate that human-powered hydrofoils really can work. Their slide show of the development of the *Flying Fish* (Indy 1984) amazed all who were present. They have followed this with their winning performances at EXPO '86, the cover of *Scientific American,* and many subsequent successes.

My first close contact with watercraft was in 1987 at the IHPSC in Washington, D.C. I'd foolishly mentioned to then-president Marti Daily that I was going to take a year off, after racing two faired Moulton AMs at Expo '86. Marti quickly "volunteered" me to run the water event; my protests that I was a non-swimmer didn't seem to hold water... (sorry).

Following that experience, Marti asked me to chair a committee to write the rules for a watercraft contest. My first thought was "Help!", shortly followed by "Whom do I get on the committee?" The initial "Du Pont Watercraft Prize ad-hoc Committee" was made up of: Chuck Champlin, past president of the IHPVA; Marti Daily, president and wearer of many, many hats; Bill Gaines, chair of the Du Pont Prize Committee (land) and IHPVA contributor from before my time; Chet Kyle, co-founder and general source of IHPVA wisdom; Paul MacCready, the international president, introduced Du Pont to the IHPVA after they sponsored the Gossamer Albatross; and Tom McDonald, co-organizer of the IHPSC at EXPO '86 which included the biggest watercraft event to date.

Our goal was to define a contest that Richard Woodward of Du Pont would feel that the company would be willing to fund and, at the same time, was acceptable to the IHPVA as a fair test for HP watercraft. At least one meeting with Mr. Woodward occurred on the west coast before I became involved. A subsequent phone call in early 1988 indicated that he was still interested.

Several sources of starting material were discovered. Alec Brooks, as VP-Water, had written a set of draft rules. These were sent to the board and then Alec dropped out of the loop (conflict of interest). The Du Pont HP (land) Speed Prize Rules were available to follow for general format; according to Chuck Champlin, these rules were written mostly by Tom Milkie, an avid land competitor at that time. The accumulated experience on the ad-hoc committee from successfully running the land prizes would be a big help. I also dug up a set of rules for the two Kremer HP aircraft contests and the HP helicopter contest and was suitably impressed by the thoroughness of the writers.

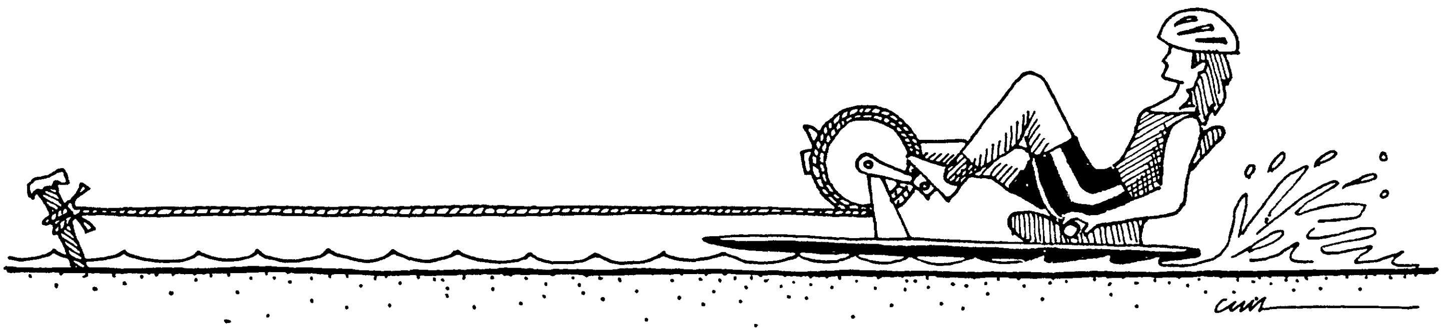
To write sensible rules for a technical contest, the subject matter must be understood. I read everything I could find on hydrofoils, from Alec's piece in *Human Power,* "The 20-Knot Human-Powered Hydrofoil" back to some history of Alexander Graham Bell's original hydrofoil experiments. Another helpful source was S. F. Hoerner's chapter on hydrodynamic lift in his book, *Fluid-Dynamic Drag.*

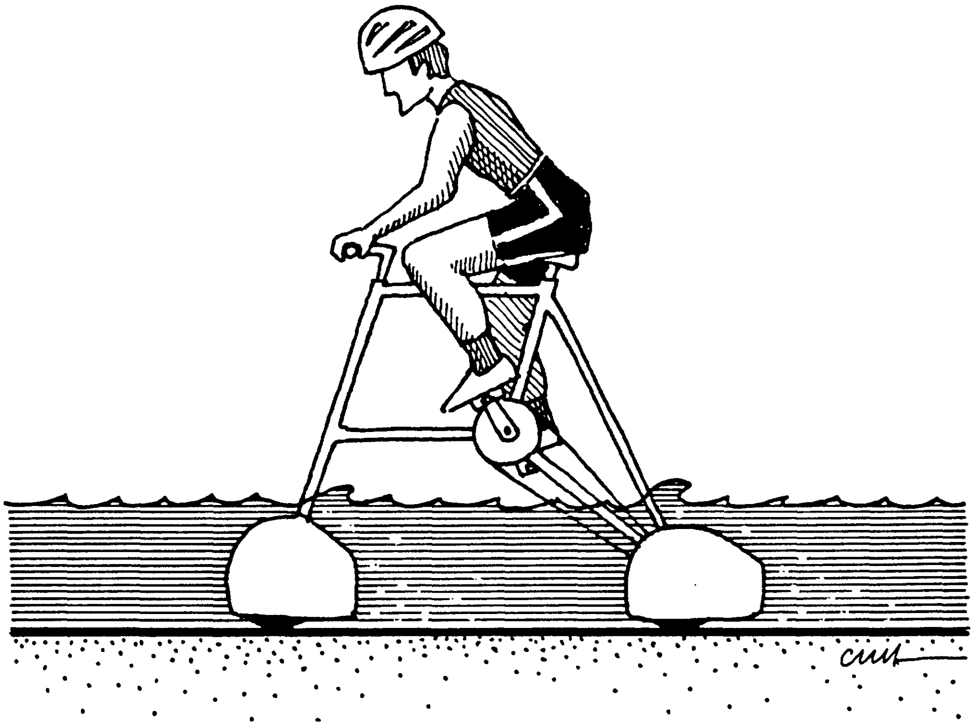
The rules were written and rewritten. This process of continual revision can be very tedious; each time a letter was sent out to the committee the responses were tallied and put into the next draft. A committee is a great way to get lots of input but I soon realized one of the unwritten rules of the IHPVA—if you want something done, eventually you just have to do it! Of course, the board of directors would have the final say if I got too far out of line.

After a few rounds, I had some great comments. The toughest problems were: distinguishing watercraft from several other related species, setting up accurate timing, and choosing the length of course and speed for the grand prize. Obviously, questions of safety (and liability) were brought up at this time as well.

The first draft of the rules that read sensibly were written on Marti's Macintosh in Jon and Carol Stinson's basement (at the time of the Michigan Chapter event, August 1988). This went out to the committee again and more good comments came back. Little tidbits (for example, not allowing ice) crept in and Adam Englund contributed his expertise on legal matters, i.e., protest procedures.

Land and air vehicles are faster than watercraft. We came to realize that any "holes" we left in the rules would result in vehicles that drew heavily on the land and air experience and might not be very convincing watercraft. Initial attempts at defining watercraft centered around





"supported by the water". My big worry came from low-flying HP seaplanes (ultimately supported by a small pressure change acting on the water surface): we assumed that these would be able to exceed 20 knots for a short distance. In a brainstorming session with my long-time friend Dave Kennedy (now president), we came up with the idea that true watercraft all derive their control from reaction against the water. We figured that an airplane with all the control surfaces in the water wasn't much of an airplane anymore! At the same time, this would allow hovercraft like Steve Ball's *Dragonfly III* (supported by a depression in the water) provided that a water rudder was used (not amphibious).

In the fall of 1988 the draft rules went to Du Pont for comment and the format of three yearly prizes and a simultaneous grand prize was suggested by Mr. Woodward. Du Pont chose to separate themselves from the administration of the prizes (for liability reasons) by making a single restricted gift of prize money to the IHPVA. Du Pont also expressed interest in finalizing the contest in time to announce it in January 1989.

In November the proposed rules were sent to the IHPVA board of directors for approval. As you know, racers are well represented on the board and racers are the experts when it comes to "creative interpretation" of rules! Mike Burrows immediately came back with the idea of winching a vehicle along on a wire or rope, thus improving rather dramatically on propeller efficiency. Someone else suggested that it wouldn't be very good if vehicles ran on wheels resting on the bottom of some sort of big swimming pool. Gardner Martin was very cagey about an idea that he and some others had come up with—luckily for us, he relented and suggested that we prevent attempts from being made in very shallow water. Gardner pointed out that shallow water (i.e., a dry lake bed after a rain) makes for a good water bearing (almost no friction) with almost no wave-making drag. A vehicle built for these conditions (with an air prop) would still float in deep water but would not be anywhere near as fast as when riding on a thin water film.

After some changes were made to cover all these tricky ideas, the regulations and conditions were approved by the board and went out to Du Pont, where Mr. Woodward had a final look and then had the text typeset. Du Pont offered the IHPVA a contract which Marti Daily signed and the prizes were official! The money was "in the bank" shortly thereafter. I kept a photocopy of the big check. Du Pont sent out a press release to over a hundred publications and organizations. Inquiries are still coming in.

Marti insisted that I set up the Du Pont Prize Committee: the members are Paul MacCready, Chet Kyle, Tom McDonald, and Theodor Schmidt, with me as chair. Our first action was to finalize a complete rules package with application forms, observer guidelines and insurance waivers. I'd be happy to send anyone interested a full set.

One last surprise occurred at the annual board meeting (15th IHPSC in Michigan, 1989); Alec Brooks (then VP of Water) quite unexpectedly nominated me as his successor. A quick look around the room showed enough nodding heads that I couldn't refuse!

Thanks again to all who helped out—the list is much longer than I could mention in this short article. Good luck to all the contestants and happy spectating to the rest of you. My prediction remains that the grand prize will be won in 1990-91!

Special thanks to Mike Lewis for the illustrations for this article.

Doug Milliken
IHPVA VP-Water
245 Brompton Road
Buffalo, NY 14221 USA ❑

Letters to the editor

(continued from page 3)

I was very excited to receive my latest issue of *Human Power*. The lead article "Riding position and speed on unfaired recumbents" was fantastic. I really enjoyed it and learned a lot. I have another non-technical viewpoint on this subject. I do not dispute one bit of the theory on seat and crankset placement. My personal opinion is that I have experienced discomfort as Charles Brown described while riding recumbents with cranksets mounted higher than the seat. I have always jumped at the opportunity to test different recumbent designs. I am interested in getting a short- or medium-wheelbase recumbent. When I ride either of my long-wheelbase bikes I am so comfortable and at peak performance because of my comfort level, compared with the discomfort that I encountered on a high-bottom-bracket/crank recumbent. Therefore, I feel that while the high-bottom-bracket bike is a faster and more efficient design, I am not as fast or efficient on this bike due to my discomfort. Regardless, I plan to continue my search for that comfortable high-bottom-bracket recumbent.

Note: My two long-wheelbase bikes are both recumbents, a Lightning Cycle "Tailwind" and an Infinity II. My previous LWB was a Tour Easy.

Robert J. Bryant
16621-123rd Ave. SE
Renton, WA 98058 USA ❑

How to win the Du Pont prize

By Theodor Schmidt

European Representative of the Du Pont Prize Committee

So you want to make $25,000? This article gives some recipes, but you may end up spending considerably more than this without necessarily succeeding. The goal—to travel 20 knots (10.4 m/s) on water with a single person's power—is sufficiently high to require an impeccable standard of fluid-dynamic understanding and mechanical engineering, as well as the determination to carry out a program every bit as ambitious as some of those to do with human-powered airplanes.

Laminar-flow hulls

It can be safely stated that 20 knots is out of reach of ordinary single-person displacement hulls. The combination of wetted-surface friction drag and wave-making drag is just too much. Wave-making can be reduced by using very long, slim hulls or completely submerged torpedo-like floats. Even here, the friction drag of a turbulent boundary layer is too great.

Only if the boundary layer (the thin layer of water effectively separating the moving hull and the mass of water at rest) can be kept substantially laminar, or otherwise controlled, e.g., by chemicals, special surfaces or active devices, is there a chance to sufficiently reduce drag. That it can be done is shown by dolphins, who have a special skin surface and use muscular control to prevent the formation of turbulent eddies, and use far less energy for locomotion than man-made bodies of the same size.

The drag of a body is very dependent on the Reynold's Number Re, which is the product of speed times a characteristic length divided by the kinematic viscosity (about 1×10^6 in SI for water).

To carry one person at 20 knots, optimal submerged-buoyancy floats would develop a Re of about 2×10^7, and something like a rowing shell 3 to 4 times this value. Well-made surfaces may keep the boundary layer laminar up to a Re of 2×10^6 giving a skin-friction drag coefficient of about 0.001. At $Re = 2 \times 10^7$, the laminar drag coefficient would be only about 0.0003, but all but the most exceptional bodies will have developed a fully turbulent boundary layer at this speed, and a drag coefficient of about 0.003. This transition can be stopped by sucking away parts of the boundary layer before it becomes turbulent, e.g., by making the hull porous and pumping out the water leaking in. Including the power for this pumping, the total drag reduction is about 2 to 3 times from turbulent, and we are back to a coefficient of about 0.001 in our example. Taking all sources of drag into account, it would take over 1000 W to propel such a craft at 20 knots, only just achievable by a super athlete for the sprint duration. See References [1] and [2].

So, unless the boundary-layer manipulation can be done more efficiently, the chance of success will be marginal with this method and, in any case, will require careful optimization of all factors.

Planing hulls

Planing lifts the hull out of the water and thus reduces wetted-surface drag and wave-making. An athlete might make a specially shaped hull plane briefly (I have seen a four-man kayak pull a water skier); however, the efficiency would be less than if using proper submerged hydrofoils.

Hydrofoils

This is the most popular line being followed at present. The main problem is getting around unfavorable surface interactions, such as drag of surface-piercing struts and induced wave-making. For information see the writings of the experts in this field, e.g., Brooks in *HP*, 6/1, Shutt in *HP*, 7/4.

It can be mentioned at this point that, although screw propellers can be designed to work at over 90% efficiency, direct "flapping" hydrofoil propulsion might exceed this, especially if the lifting foil can be used for this work [2]. Many animals of course use flapping propulsion very successfully, both in air and water.

So far, however, most man-made flapping propulsive devices have fallen far short of their expectations. Some which do work well were devised by Cal Gongwer and include the Aequeon, a set of horizontal foils for swimmer propulsion, and sets of vertical foils which propel a kayak more efficiently than paddles.

Air-lift devices

From catamarans with wing decks, on to sidewall hovercraft and ultimately flying boats and airplanes, a multitude of craft is conceivable which are more or less supported by air. In contrast to hydrofoils and submerged buoyancy, which lose efficiency near the surface, airfoils actually work better and surface-effect airplanes or flying boats have better lift/drag ratios, and thus would be faster than free-flying human-powered aircraft which can already exceed 20 knots.

If we have a craft weighing W with a ground-plane area A, this can be fully supported by a uniform air-cushion of pressure W/A. If the craft moves forward relative to the air with speed V and is shaped to allow air to enter forward below it and not let air leak out the sides or back, the resulting ram air pressure is V^2 times 1/2 the air density, or about 0.6 V^2 in SI units (Pascals). Thus the craft will be fully air-cushion supported at an air speed above $V \geq 1.3\sqrt{W/A}$ [m/s] not even yet taking into consideration lifting forces resulting from the upper surface.

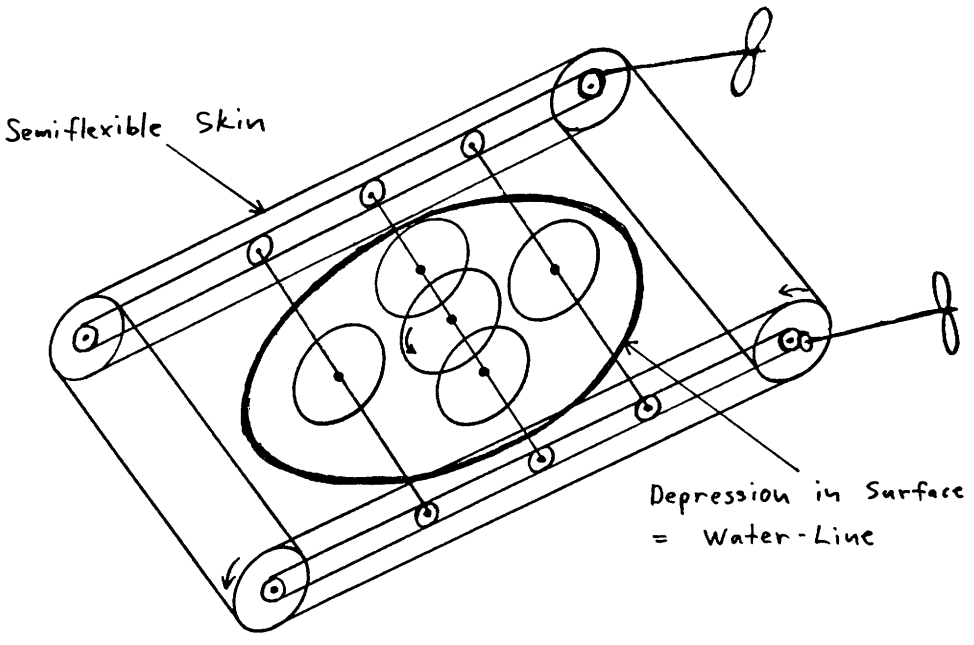
For example, a craft weighing 1000 N (~ 225 lbf) and 3-m wide and 5-m long would be fully air-cushion supported at 10.6 m/s, provided no air leaks out. In practice this can be accomplished at the sides with knife-edge side walls, just in the water but with little resistance to motion. However, the back edge would be difficult to seal off, although this might be done with a roller just touching the surface and moving at water speed.

The back edge could, however, be left slightly or fully open to allow some or all air to flow through. Although some or most of the "air cushion" lift is lost, a properly shaped upper surface will produce "suction" lift like any airfoil.

Such craft behave like a flying wing with a very high aspect ratio and a corresponding high L/D ratio. There is also some "induced wave drag" resulting from the depression in the water surface caused by the air cushion. Overall, L/D might range from 20 to 80, depending on leakage and sidewall drag. Propulsion could be by air propeller, which can work efficiently at these speeds, saving the drag from a water propeller strut or shaft. This has been demonstrated by Steve Ball.

It is only a small step to a fully-fledged flying boat: the aspect ratio of the wing is increased and the side-walls become fences or winglets. Such a craft is outside the scope of the Du Pont Prize.

In any case, the rules require control



Concept of a moving-skin platform, pedals and seat not shown.

In any case, the rules require control surfaces (e.g. rudder) to act on the water, not the air. Also, the craft must be supported by the water at all times. An air-cushion vehicle or surface-effect device can be said to be water supported, as the craft's weight is transferred to the water surface, where it displaces a certain amount of water. A proper flying boat or airplane capable of free flight would, however, be considered to be air-supported and not eligible for the prize, as useful as the craft may be. So I am afraid it's not good enough to get out your Gossamer-Daedalus-Musculaires and simply dangle a rudder [3]!

Moving-skin boat

Wave-making drag can be reduced or eliminated by using extremely long, slender hulls. There is a minimum speed below which water surface waves cannot be generated (~2.3 m/s), and it follows that, if a hull is so slender that lateral and vertical velocity components of the hull entering and leaving the water are below this figure, no waves will be generated (on smooth water), although in practice there will always be some disturbance giving rise to some waves.

Such low- or no-wash boats will, however, have considerable wetted surface and corresponding skin friction and will not reach the magic 20 knots without tricks.

Imagine the skin of the hull being spewn out the bow and gathered in at the stern, while moving at exactly water speed. Such a hull would have practically no skin-friction drag. Inventors have been trying this for over a century by using rolling floats of practically every type imaginable.

Unfortunately, small rollers generate enormous form and wave drag while rolling wheels big enough to leave only a shallow depression in the water would have tremendous air resistance and be quite impractical. Imagine, for example, a sphere of 10 m diameter with a person running or cycling inside it!

Somehow, the skin must be re-circulated without making the windage of the boat too big. Various ways are conceivable where a stiff but flexible skin or inflated sausages or rings are guided on roller bearings. Or floating tracks can be made which resemble certain land vehicles. Remember that, as the segments are to move at water speed, they need not be smooth or even flat and indeed might be used for propulsion as a high-efficiency linear paddle.

If very well engineered, the mechanical friction of the moving skins or track could be very much less than the same surface area sliding through the water. The speed of such a boat would be mainly limited by its air resistance and would require careful fairing. Note that the skin or track parts being re-circulated are moving forward at twice boat speed. Only a little power would be required to propel the skin at exactly water speed and the rest used to drive a propeller or equivalent, unless the linear paddle scheme mentioned above is used. The way to success is to find the shape and size such that combined air and wave-making resistance is minimal.

Such a project would doubtless be fun but very expensive. Just think of all those high-quality corrosion-proof ball bearings needed.

Conclusion

These ideas may be wacky, but they will work if you try hard enough and get your sums right. Besides earning Du Pont's Grand Prize, it will be a snip to win all-terrain races with some vehicles, and harassed commuters will finally leave their cars when they find that they can hop or climb over their competition with your device!

References

1. *Fluid-Dynamic Drag*, S.F. Hoerner, 1965, Brick Town, NJ.
2. *RINA Symposium Proceedings on Human-Powered Marine Vehicles*, Nov. 1984, 10 Upper Belgrave St., London SW1X, England.
3. *The Aerofoil Ram-Wing Surface Effect Vehicle*, Alexander Lippisch, Jane's Surface Skimmers.

NOTE: Almost all issues of *Human Power* and all proceedings of the IHPVA Scientific Symposia have important information on human-powered boats, with these in particular: 3/2/84, 3/3/85, 5/3/86, 6/1/87, 7/2/88, 7/3/89.

Theodor Schmidt
Rebackerweg 19
CH-4402 Frenkendorf
SWITZERLAND

Winning the Du Pont prize

by Michael Eliasohn

What will it take to win the Du Pont Prize of $25,000 for the first human-powered watercraft to exceed 20 knots (23 mph, 10.4 m/s)?

"Refinement", said the builders of the two fastest watercraft at the 15th annual International Human-Powered Speed Championships in September, 1989, in Adrian, Michigan.

As for the possibility of non-racing cyclists casually riding above the water on hydrofoils, it's not likely.

Barring someone coming up with a major breakthrough, "It's not going to be done in one jump," said Sid Shutt, builder of the *Hydropeds,* about winning the Du Pont Prize. "The next 5 miles per hour are going to be tough."

Hydroped II was pedaled by Terry Vincent to a speed of 13.8 knots at the 1988 IHPSC in Visalia, CA. Weeds apparently limited Fred Markham's top speed in *Hydroped II* at Lake Adrian to 12.85 knots (6.7 m/s). Markham holds the human-powered speed record on land, 65.48 mph (29.27 m/s).

Shutt's *Hydroped III,* with an aerodynamic cowling over the front portion of the cockpit, showed some of the needed refinement, but weeds in Lake Adrian snagged and broke the front hydrofoil, and the boat never got above the water.


Hydroped III being removed from Lake Adrian. Notice aerodynamic cowling over cockpit. Builder, Sid Shutt is at left.

Some of the refinement needed includes developing smaller underwater wings (hydrofoils) so the craft will be "cleaner" underwater, and better aerodynamically above water, according to Allan Abbott, co-developer of the *Flying Fish II.* Bobby Livingston pedaled the *Fish* to 16.23 knots (8.44 m/s) at Lake Adrian, the fastest ever, but not an official record because of the wind.

Other areas of potential improvement, according to Shutt, are more efficient drive systems and lighter weight.

As Doug Milliken, water-event chairman at Adrian, noted in his summary in the October, 1989, *HPV News,* the two fastest boats at Adrian were pedaled by top cyclists, so there is not much opportunity to increase "horsepower". With no changes in *Flying Fish II,* it would take about twice the power for it to increase its speed from 16 knots to 20, according to Milliken.

Livingston, one of the top bicycle track racers in the U.S., said after the Lake Adrian competition that pedaling the *Fish* is not like pedaling a bicycle. There's no momentum on the water, so it takes more work to go fast.

The greatest effort is needed to get the craft out of the water. Abbott noted that starting off is like starting in high gear on a regular bike. "Once you get up (on the hydrofoils), you can ease up a little bit." Abbott noted that a propeller best for high speed is not as good for acceleration.

Wouldn't gears make it easier to get a hydrofoil out of the water? No, according to *Flying Fish* co-developer Alec Brooks. A watercraft is more like a fixed-gear track bike, there are no hills to climb, and until it gets up to speed, the propeller "sort of slips". The power needed to get hydrofoils above the water and to keep them there is what eliminates their use for casual cruising. Brooks said it takes a "pretty hard sprint" to get the *Fish* onto its hydrofoils and probably the power needed to propel a road bike 20 mph (8.9 m/s) to keep it above the water "and that's barely keeping it going". Obviously, more power is needed to go fast over the water.

Shutt said that a really good cyclist has kept one of the *Hydropeds* above the water for a half-hour. "The best I can do is 2-1/2 minutes, and then I'm done."

"If you make the foils bigger, you can stay up longer," said Shutt. And larger

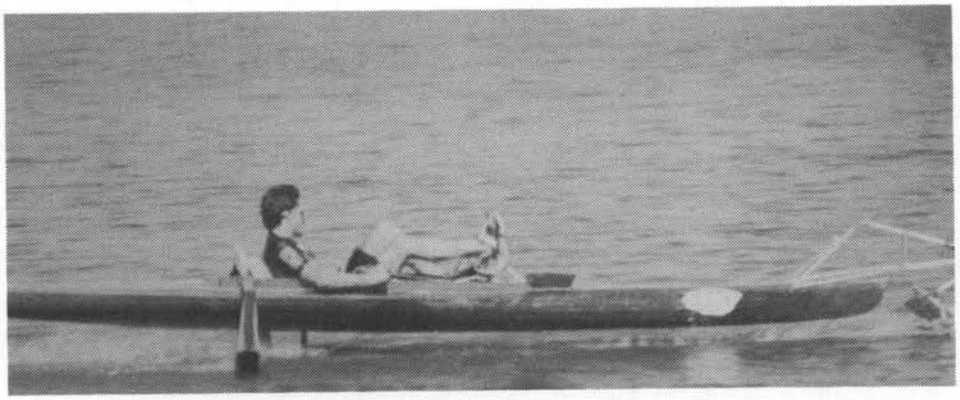
Bobby Livingston on *Flying Fish II,* Lake Adrian.

hydrofoils would make it easier to get the boat out of the water. But, said Shutt, there's a crossover point. Make the hydrofoils too big, and the rider could go faster in a displacement hull while exerting the same amount of power.

Michael Eliasohn has been president of the Michigan chapter of the IHPVA since 1984. The chapter hosted the International Human Powered Speed Championships in 1989. He is a newspaper reporter and lives in St. Joseph, Michigan.

Michael Eliasohn
2708 Lake Shore Drive , #307
St. Joseph, MI 49085 USA

☐


Fred Markham on *Hydroped II* at 15th IHPSC at Lake Adrian

Hydrofoil boats with flapping-wing propulsion

by Parker MacCready

Summary

A series of experimental human-powered hydrofoil boats with flapping-wing propulsion are described. It is found that this form of propulsion is theoretically very efficient, although difficult to implement.

Early boats

Like most human-powered vehicle enthusiasts, the roof of my car is often covered with outlandish looking contraptions (Figure 1). Once in a gas station in Chehalis, Washington on the way to EXPO '86 a man asked me what that was on my car. I told him it was a human-powered hydrofoil boat with flapping-wing propulsion. "Oh," he said casually, "I rode one of them once."

In 1984 Taras Kiceniuk and I started building a human-powered hydrofoil boat, with the intention of going very fast. We had both worked on the Gossamer human-powered aircraft so it seemed a natural next project, and one that could be done cheaply and in a small space. At the same time Alec Brooks and Allan Abbott were starting on their highly successful *Flying Fish* boat project (Brooks [1]).


Figure 1. The *Mutiny on the Boundary Layer*, on the roof, with (from the left) Lorenz Sigurdson, Taras Kiceniuck, and Dave Sivertsen. (photo by the author)

Our first boat consisted of a long, skinny hull with a tiny outrigger, the rider perched on top, and the hydrofoils on struts below in a canard configuration. We towed this craft behind a motor boat initially, to test stability and flying characteristics. At a later time we intended to add pedals and a propellor. Unfortunately, this design did little more than tip its rider into the lake and amuse those standing on shore.

Collecting data on drag, flying speed, angle of attack, height above the water, etc. can be quite difficult and inaccurate from a moving platform. Matters are made even worse by the long transverse waves and prop-wash in the tow boat's wake. I never trust my own towed data to better than about 30%. Still, towing is a valuable tool in the development of a successful boat, since it allows one to separate flying problems from propulsion problems.

Spurred on by the early success of Brooks and Abbott and using a catamaran hull arrangement, I redesigned the boat and tried more tow tests. This boat actually flew, and the tests yielded a single data point: 90 Nt (20 lbs) of drag at 3 m/sec (7 mph), measured from a spring scale and manometer aboard the tow boat. This implied an operating power not too much greater than 270 Watts (0.4 hp), well within human-powered feasibility.

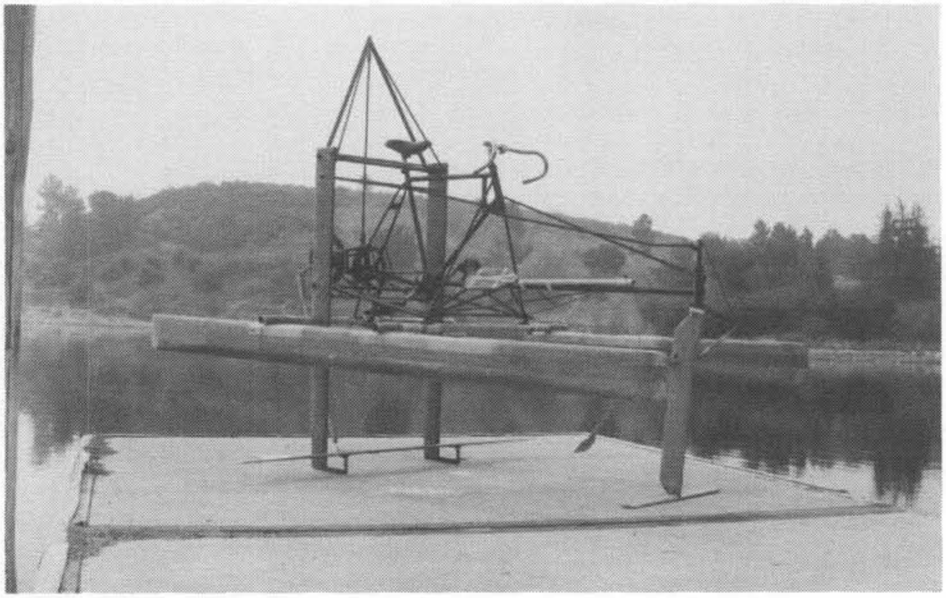


Figure 2. The *Mutiny on the Boundary Layer*, on the dock at Puddingstone Lake, CA. (photo by Dave Sivertsen)

By this time Brooks and Abbott had successfully flown the *Flying Fish* under human power. Making such a boat was thus proven feasible, but it would have required a greater sophistication than my own to go faster than the *Flying Fish.* Also they had already done the interesting part of the development; the rest would just be refinement. My work at this time was with Aerovironment, Inc., building a flying, wing-flapping model of a pterosaur; while Taras was working a lot with dolphins. Often the conversation returned to natural means of propulsion, flapping wings and tails. Flapping propulsion was claimed by some to be more efficient than a propellor.

Taras and I experimented with hydrofoil swimfins, and built a sailboard with a hydrofoil underneath that one could flap like a dolphin's tail for propulsion. We tested this boat in the ocean and it worked quite well, with speeds comparable to a kayak.

The obvious next step was to use flapping-wing propulsion for a human-powered hydrofoil boat. The idea was to use the main wing for both lift and propulsion, as birds do, by flapping it up and down. Flapping-wing propulsion is uniquely suited to such boats because of their small strong wings which can withstand the additional forces. Also the short flapping stroke required in water is relatively easy to achieve with a mechanism linked to the pilot's leg motions.

The *Mutiny on the Boundary Layer*

With visions of flapping wings, and a great deal of theoretical help from Ted Wu and George Yates at the California Institute of Technology, I went back to the workshop in 1985 to build an improved hydrofoil boat, this time with flapping-wing propulsion. The boat finally flew under human power (Figures 2 and 3) late in the summer of 1986, just in time for the IHPSC races in Vancouver, B.C.

The pilot-engine sat on a standard bike frame, with styrofoam and fiberglass catamaran hulls below for flotation before take-off. The standard bike frame allowed the rider to shift her or his weight fore and aft to facilitate take-off. The frame was extended in the front to hold a second headset to which a small, inverted-T, front hydrofoil, called the 'canard' was mounted. The rider steered by turning the handlebars which, via a rigid strut to the front headset, turned the canard assembly. The vertical foil of the canard assembly acted as a rudder, allowing sufficient directional control for the rider to keep from falling over sideways while 'flying', much like a bicycle. A rigid linkage from handlebars to the canard was important. In one tow test with a too-flexible linkage the canard started to oscillate wildly back and forth, like an aquatic form of flutter.

The boat's flying angle and elevation above the water surface were controlled by a flap at the rear of the canard, which was linked to a small paddle on a lever arm. The paddle rode along the surface of the water. If the canard sank too low the paddle was forced up by the water surface. The linkage from paddle to flap then increased the lift on the canard, causing it to rise back up. This design, developed early in the history of hydrofoils, keeps the foil a set distance below the water surface.

The main wing 2 m (6 ft) in span and about 0.12 m (5 in) in chord at the center, was mounted nearly below the center of

(continued on page 13)

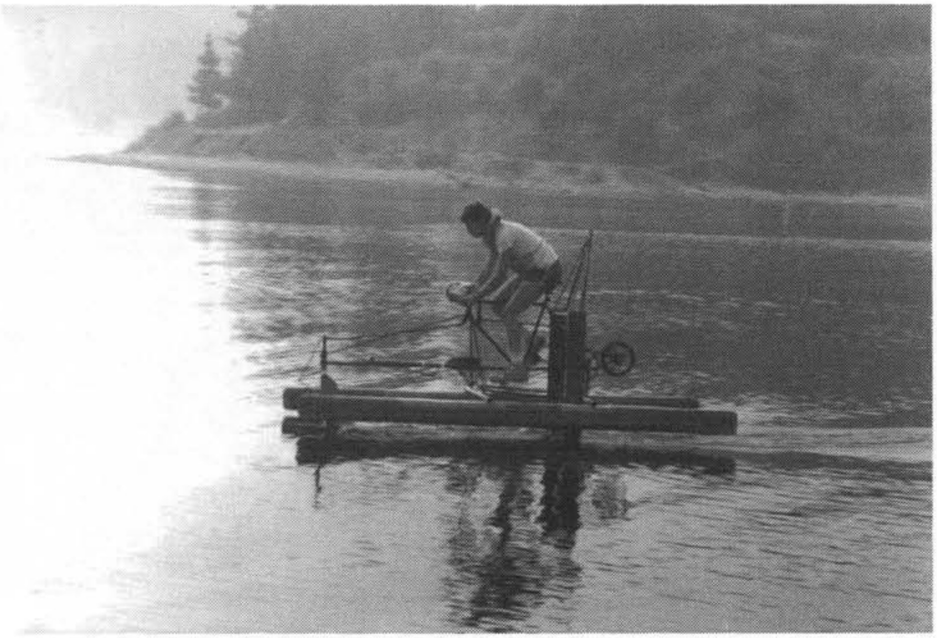


Figure 3. The *Mutiny on the Boundary Layer*, foilborne, ridden by the author. (photo by Dave Sivertsen)

Measurement of propeller efficiency

by Sid Shutt

Abstract

A method for measuring human-powered-boat propeller efficiency is given that requires no special equipment and gives sufficiently accurate results to be useful.

Introduction

High efficiency of all parts of a human-powered boat is very important to acheive satisfying results since available human power is so limited. A propeller is a useful device to drive a boat since it can be made very efficient, more than 90%. Propellers of high efficiency, matched to power of humans, can be designed using theoretical approaches that are to be used in the calculations. It is desirable to have a test that can measure the efficiency of a propeller under actual operating conditions so that test results can be compared to theoretical predictions to refine the value of these coefficients and thus add confidence to a propeller design. This report describes such a test.

Definitions

1. *Efficiency*

Efficiency of a device is usually defined as the output power Po the device delivers divided by the input power Pi needed to produce that output. The output of a propeller is given by the product of the force F it generates and the velocity υ of the boat. The input is the product of the torque T needed to rotate the propeller and the angular velocity ω of the propeller shaft. This is expressed as: *Equation 1*

$$\eta \equiv \frac{Po}{Pi} = \frac{F\upsilon}{T\omega}$$

where

η is propeller efficiency
F generated force (N)
υ boat velocity (m/s)
T propeller shaft torque (Nm)
ω shaft angular velocity (rad/s)

Any consistent set of units can be used.

The parameters of equation 1 could be measured directly and the efficiency determined, but these measurements are normally not conveniently made. An alternative approach is given using propeller slip to measure propeller efficiency.

2. *Slip*

If a propeller had no slip the water velocity passing the propeller would be the same as the boat velocity and the water left behind the propeller would not be rotating. Since a propeller has some energy loss the water passing through the propeller is $\Delta\upsilon$ larger than the boat velocity and the water left behind the propeller would be rotating $\Delta\omega$ relative to the water ahead of the propeller. The change in components of velocity $\Delta\upsilon$ and $\Delta\omega r$ cause slip to occur. Because of slip the propeller must be rotated further and faster than would be required if no slip existed to go the same boat distance and speed.

Analysis

1. *Efficiency related to slip*

Consider the diagram shown in Figure 1 that represents a propeller blade moving through the water at velocity μ. A lift L is generated normal to μ and a drag D is produced parallel to μ in the direction to resist rotation. The velocity μ is the vector sum of the boat velocity υ and the angular velocity ωr of the propeller rotating at shaft angular velocity ω. The velocity μ' is that of water passing across the propeller blades and is the vector sum of $\upsilon + \Delta\upsilon$ and $(\omega - \Delta\omega)r$ and has the same magnitude as μ. Either the drag or the slip can be used to express propeller efficiency.

The lift L and the drag D can be used to express the force F and the torque T. From figure 1 it is observed that

$$F = L\cos\phi - D\sin\phi \qquad \textit{Equation 2}$$
$$T = r(L\sin\phi + D\cos\phi)$$

Also L' can be used to express F and T. Again from figure 1 it is observed that

$$F = L'\cos(\phi + \varepsilon) \qquad \textit{Equation 3}$$
$$T = rL'\sin(\phi + \varepsilon)$$

Equation 3 can be expanded to be equal to

Equation 4

$$F = L'\cos\varepsilon\cos\phi - L'\sin\varepsilon\sin\phi$$
$$T = rL'\cos\varepsilon\sin\phi + rL'\sin\varepsilon\cos\phi$$

But $D = L'\sin\varepsilon$ and $L = L'\cos\varepsilon$ and substituting these into equation 4 the result is identical to equation 2. Therefore, it is recognized that the components of slip $\Delta\upsilon$ and $\Delta\omega$ produce the same result as the drag in determining propeller efficiency.

From Figure 1 *Equation 5*

$$\tan(\phi + \varepsilon) = \frac{T/r}{F} = \frac{\upsilon + \Delta\upsilon}{(\omega - \Delta\omega)r} = \frac{\upsilon}{\omega r}\left(\frac{1 + \frac{\Delta\upsilon}{\upsilon}}{1 - \frac{\Delta\omega}{\omega}}\right)$$

then

$$\frac{F\upsilon}{T\omega} = \frac{1 - \frac{\Delta\omega}{\omega}}{1 + \frac{\Delta\upsilon}{\upsilon}}$$

Propeller efficiency η can be related to slip by combining equation 1 and 5. *Equation 6*

$$\eta = \frac{1 - \frac{\Delta\omega}{\omega}}{1 + \frac{\Delta\upsilon}{\upsilon}}$$

where $\frac{\Delta\omega}{\omega}$ is the rotational slip and $\frac{\Delta\upsilon}{\upsilon}$ is the translational slip. If the drag D is zero then $\frac{\Delta\omega}{\omega} = \frac{\Delta\upsilon}{\upsilon} = 0$, there is no

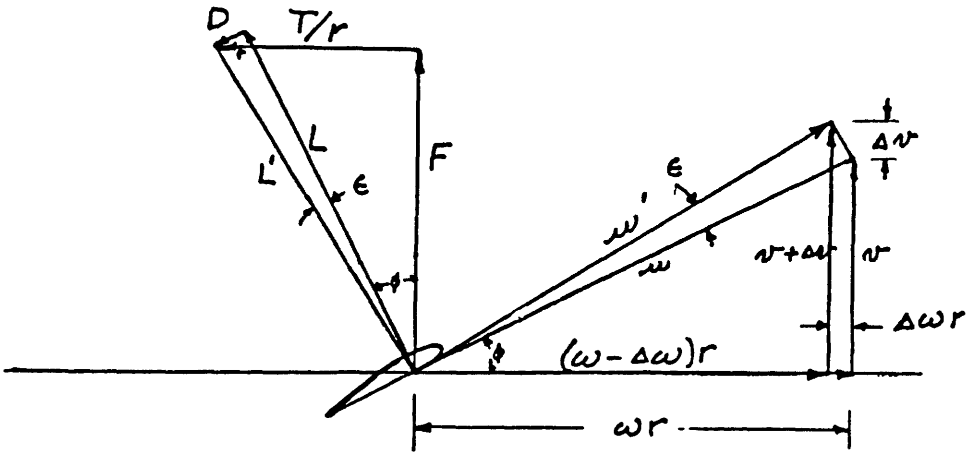


Figure 1. Diagram of propeller parameters

slip and the propeller is 100% efficient. However, there is always some drag that causes slip which reduces efficiency to something less than 100% or 1.0.

An alternative derivation of equation 6 is given that does not use the propeller diagram shown in figure 1 and adds confidence and insight into the determination of propeller efficiency.

Consider a propeller with no slip and 1.0 efficiency. Equation 1 would be

$$\eta = \frac{F'\upsilon}{T'\omega} = 1.0$$

Now consider the conditions with slip to produce the same boat velocity υ. The water passing the propeller must increase by $\Delta\upsilon$ accompanied by a reduction of generated force ΔF and a decrease in the angular velocity of the water relative to the propeller of $\Delta\omega$ accompanied by an increase in torque ΔT. The result is then

$$1 = \frac{(F' - \Delta F)(\upsilon + \Delta\upsilon)}{(T' + \Delta T)(\omega - \Delta\omega)}$$

and

$$\eta = \frac{(F' - \Delta F)\upsilon}{(T' + \Delta T)\omega} = \frac{F\upsilon}{T\omega} = \frac{1 - \frac{\Delta\omega}{\omega}}{1 + \frac{\Delta\upsilon}{\upsilon}}$$

the same as equation 1. This alternative approach makes no assumption relative to the propeller-blade shape or to the boat-hull form and suggests that equation 1 is valid over a wide range of conditions. This result also shows that a lower propeller efficiency requires more input torque to produce less output force, and that the propeller efficiency is directly a function of propeller slip.

2. *Slip related to propeller rotation*

Slip is measured by observing the difference in propeller revolutions while pulling the boat with the propeller rotating freely, then pedalling the boat the same distance. Consider two buoys A and B separated by a distance H as shown in Figure 2.

If the boat is pulled the distance H while the propeller is free to spin the number of propeller revolutions in going from A to B is given by

Equation 7

$$N_1 = \frac{\omega H}{2\pi\upsilon}$$

Equation 7 is the combination of $N = nt$, $H = \upsilon t$, and $\omega = 2\pi n$ where n is the propeller revolutions per second and t is the time to travel between A and B.

If the boat is pedalled between A and B, ω will increase by $\Delta\omega$ and υ will decrease by $\Delta\upsilon$ so that the number of propeller revolutions in going the distance H is given by

Equation 8

$$N_2 = \frac{(\omega + \Delta\omega)H}{(\upsilon - \Delta\upsilon)2\pi} = \frac{\omega H}{2\pi\upsilon}\left(\frac{1 + \frac{\Delta\omega}{\omega}}{1 - \frac{\Delta\upsilon}{\upsilon}}\right)$$

By combining equation 7 and 8 the slip is related to the rotations.

Equation 9

$$\frac{N_2 - N_1}{N_1} = \frac{\frac{\Delta\omega}{\omega} + \frac{\Delta\upsilon}{\upsilon}}{1 - \frac{\Delta\upsilon}{\upsilon}}$$

The relative size of $\frac{\Delta\upsilon}{\upsilon}$ and $\frac{\Delta\omega}{\omega}$ are defined by equation 10 and when substituted into equation 9 give equation 11. The two components of slip are given by

Equation 10

rotational slip $\frac{\Delta\omega}{\omega} = k\frac{\Delta\upsilon}{\upsilon}$

Equation 11

translational slip $\frac{\Delta\upsilon}{\upsilon} = \frac{N_2 - N_1}{N_2 + kN_1}$

3. *Significance of k*

The relative size of rotational slip and translational slip is expressed by k as given in equation 10. The slip, given by equation 9, can be caused entirely by rotational slip ($k = \infty$) or entirely by translational slip ($k = 0$) or by a combination of both with k between zero and infinity. An accurate value of k is not needed to give reasonably accurate results; this will be illustrated by examining three cases.

Case 1: *Equation 12*

$$k = \infty, \frac{\Delta\upsilon}{\upsilon} = 0, \frac{\Delta\omega}{\omega} = \frac{N_2 - N_1}{N_1}$$

$$\eta = 1 - \frac{N_2 - N_1}{N_1} = 1 - \text{slip}$$

Case 2: *Equation 13*

$$k = 0, \frac{\Delta\omega}{\omega} = 0, \frac{\Delta\upsilon}{\upsilon} = \frac{N_2 - N_1}{N_2}$$

$$\eta = \frac{1}{1 + \frac{N_2 - N_1}{N_2}} \cong 1 - \frac{N_2 - N_1}{N_2}$$

Case 3: *Equation 14*

$$k = 1, \frac{\Delta\omega}{\omega} = \frac{\Delta\upsilon}{\upsilon} = \frac{N_2 - N_1}{N_2 + N_1}$$

$$\eta = \frac{N_1}{N_2} = 1 - \frac{N_2 - N_1}{N_2}$$

It is observed since N_1 and N_2 are nearly equal in a highly efficient propeller, that any value of k gives nearly the same result; however, accuracy can be improved if k is known. An estimate of k from theoretical propeller design indicates that k is between 0.2 and 0.6; a value of $k = 0.4$ is typical.

Measurements

1. *Slip*

Figure 2 shows a buoy at A and one at B with a distance between them of H. First the boat is pulled between A and B and the number of propeller rotations is recorded. The propeller revolutions can be recorded by counting the pedal revolutions and multiplying by the gear ratio between the pedals and propeller. Then the boat is pedalled between H and B at nearly the same speed and again the number of propeller rotations is recorded. These data are used to determine the propeller efficiency for the conditioning the test. The components of slip are computed using equation 10 and 11.

where N_1 is the number of rotations pulled between A and B
N_2 is the number of rotations pedalled between A and B
k is a selected constant

N_1 and N_2 can be either for propeller or pedal revolutions counted. Let k equal 0.4.

2. *Efficiency calculated*

The values of the components of slip given by equation 10 and 11 are used in equation 6 to calculate the propeller efficiency. The rotation measurements N_1 and N_2 can also be used, with no knowledge of k, in equations 12, 13 and 14, to estimate propeller efficiency.

3. *Sample calculation*

Measured pedal revolutions travelling between A and B

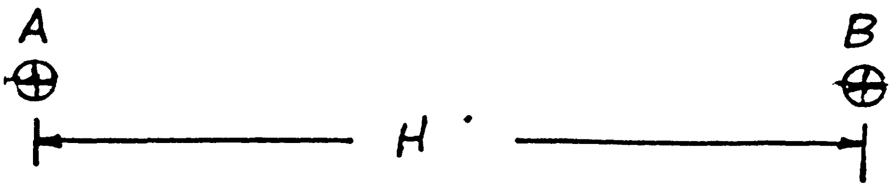


Figure 2. Buoys A and B at test site

Pulled $N_1 = 51.0$
Pedalled $N_2 = 57.5$
Assume $k = 0.4$

SLIP CALCULATIONS,

Equation 11

$$\frac{\Delta\upsilon}{\upsilon} = \frac{57.5 - 51.0}{57.5 + 0.4 \times 51.0} = 0.0834$$

Equation 10

$$\frac{\Delta\omega}{\omega} = 0.4 \times 0.0834 = 0.0334$$

PROPELLER EFFICIENCY CALCULATION,

Equation 6

$$\eta = \frac{1 - 0.0334}{1 + 0.0834} = 0.892$$

SIMPLIFIED FORMS,

Equation 12

$$\eta = 1 - \frac{57.5 - 51}{51} = 0.873$$

a difference of 2.1% from the more accurate calculation.

Equation 13

$$\eta = \frac{1}{1 + \frac{57.5 - 51}{57.5}} = 0.898$$

a difference of 0.7% high.

Equation 14

$$\eta = \frac{51.0}{57.5} = 0.887$$

a difference of 0.6% low.

Accuracy

Any measurement will contain errors which can be determined to estimate the error in the result. If in the sample calculation an error in determining N_1 and N_2 is 0.5 revolutions then η could be calculated to be in error of less than 1%. If k is assumed to be 0.5 the calculated efficiency would be 0.891, a difference of less than 0.2% from the sample calculation. Random errors can be reduced by repeated measurements and averaging results. Measured propeller efficiencies of near 90% have been made with total estimated error of less than 0.4%. These measurements have agreed well with theoretical calculated efficiency using blade-element theory as described in reference 1.

The largest inaccuracy could be in the assumption that the propeller diagram shown in figure 1, that is rigorous at a particular propeller radius, can be used to represent the characteristic of the whole propeller. However, this may not be so bad since $\frac{\Delta\omega}{\omega}$ and $\frac{\Delta\upsilon}{\upsilon}$ are used in both equation 6 and equation 9 in the same way, to represent the average effect for the entire propeller. Also, by obtaining the same equation relating efficiency to slip by an alternative approach using different assumptions without the need for figure 1 suggests that the equation used to determine propeller efficiency from slip measurements is reliable.

Conclusion

It is important in the process of improving a device to be able to measure the quality of operation that it is desired to improve. In the case of a human-powered-boat propeller it is important to develop the propeller to produce the required force at the desired shaft speed with a minimum energy loss or the highest propeller efficiency. A convenient method for measuring propeller efficiency is given with acceptably small error to produce useful results. This method can be a significant help in developing a highly efficient human-powered-boat propeller.

References

1. Richard Von Mises, *Theory of Flight*, 1945, Dover Publishing, Inc., New York, N.Y.
2. Sid Shutt, "Some Ideas Used on Hydro-'ed—a Hydrofoil Pedal Boat," *Human Power*, Summer 1989, vol. 7, no. 4.

Sid Shutt is an engineer interested in human-powered boats. He operates an engineering company specializing in new-product development.

Sid Shutt
612 Briarwood Drive
Brea, CA 92621 USA

❑

Flapping wing propulsion

(continued from page 9)

gravity of the boat. It had a constant-chord midsection and tapered in the outer two-thirds of its span, with an aspect ratio of 20. The airfoil section was a NACA 4415, chosen because of its fairly rounded leading edge, which I hoped would not be too inclined to boundary-layer separation during the flapping motion. The wing was made of solid epoxy and unidirectional graphite laid up in a styrofoam mold cut out on a hotwire. This was the same technique used by Brooks and Abbott for the *Flying Fish* wing.

The wing had two pivot points (Figure 4) on the bottom about one-third of the way in from either tip. These attached to a vertical streamlined strut assembly. This wing/strut assembly was joined to the bicycle frame by a parallelograming frame which allowed it to move vertically relative to the bike frame and floats. If you are having trouble understanding how this all works, don't worry, the mechanism was fairly incomprehensible even when you looked at it up close.

The pedals turned a crank arm which pushed the wing/strut assembly up and down at 200 rpm, as the rider pedalled at 100 rpm. While flying, the main wing carried on average 90% of the weight of the craft, and the canard carried the rest. To create thrust the lift of the wing varied from average by about ±20% during a flapping cycle. The wing oscillated vertically 20 cm (8 in) in full, while the rider had a much smaller excursion of about 2 cm (1 in).

On the downstroke the rider was pushing the wing down, but during the upstroke the loads in the drive train reversed and tried to accelerate the rider's legs. To keep the flapping stroke close to sinusoidal I found it necessary to use a rather substantial flywheel in the system. I ended up using a Volkswagen flywheel spinning at 1000 rpm. It weighed 5 kg (10 lbs) but made a great improvement to the craft's performance, and kept the variation in flapping frequency to about ±20% over a cycle. One problem was that it added so much weight to the rear of the boat that if the rider leaned back for more than a few seconds the whole craft would capsize backwards. The final weight of the boat (without the rider) was a staggering 490 N (110 lbs), plus about 45 N (10 lbs) of water that the floats would soak up while it was floating.

The most crucial part of flapping-wing propulsion proved to be controlling the main wing angle of attack during the flapping cycle. The main wing had a lever arm off the back which attached, via a small streamlined strut, to an arm which came off the crank assembly. By varying the attachment point of the streamlined strut to this crank arm one could vary both the amplitude of the wing 'pitch' (angle of attack), as well as the phasing of the pitch relative to the 'heave' (vertical wing motion).

Final touches were a life vest and a paddle, the latter of which was useful

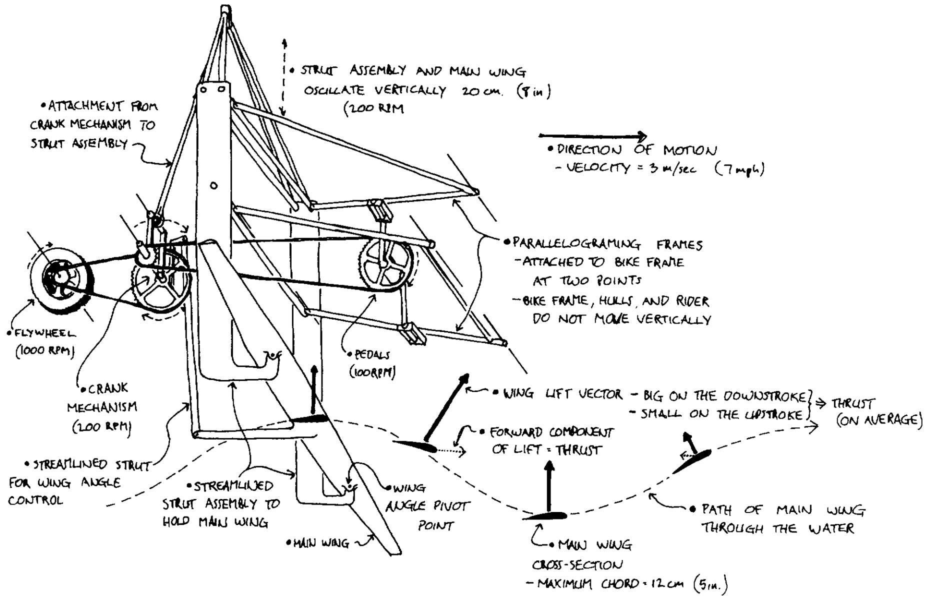


Figure 4. Schematic drawing of the drive mechanism for the *Mutiny on the Boundary Layer*, including wing motion and lift forces used to generate thrust.

once when a small mechanical failure caused the flywheel to vent its considerable destructive energy on the rest of the drive train, leaving me adrift in the lake.

The craft was christened *The Mutiny on the Boundary Layer* (a name Martin Cowley had suggested some time earlier) just before a race at the 1986 IHPSC, when an official came by asking what the boat should be called. In general I would call this type of vehicle an 'ichthyopter', that being the fishy version of an ornithopter.

Take-off on the *Mutiny* was fairly quick; one could be foilborne in 5-10 sec. It was maneuverable enough to make 180° turns. The horsepower required was high, though, perhaps 400 Watts (0.5 hp) based on ergometer calibrations of the pilot, while cruising at 3.2 m/sec (7 mph). Hence flying time was limited to about 100 sec before the pilot was exhausted.

Tow tests indicated that less than half this power was required to fly the craft. Clearly the propulsive efficiency of the flapping wing and drive train was more like 40% instead of the 90% predicted by calculation (MacCready [2]). I think about half of the problem was that the wing angle was not what it should have been at each point during the flapping cycle. The other half of the inefficiency was probably due to mechanical friction in moving parts.

The *Mutiny on the Boundary Layer* was difficult to fly but it did accomplish its goal, which was to fly using flapping-wing propulsion. As far as I know only one other human-powered (or human-carrying) watercraft has ever done this. In a movie called *Gizmo* there is a black and white clip of an inventor who has a set of hydrofoil stilts which he somehow managed to hop onto and fly away on. It remains a strong challenge to the hydrofoil builder to match the simplicity and cleverness of this early invention.

Theory and experiment with flapping-wing propulsion

The propeller has hundreds of years of scientific innovation behind it, yet only recently have we begun to see 85% propulsive efficiencies. Flapping-wing propulsion, ubiquitous in the natural world, is only in the infancy of its development in human engineering.

Like propeller design, the analysis of flapping-wing propulsion can be extraordinarily complicated. It is simplest at the start to make the 'quasi-steady' approximation (see MacCready [2]). Here the forces on the wing are assumed to be those given by the usual steady formulas for the wing's instantaneous angle of attack and velocity. If, however, the wing travels less than about 30 chord lengths forward during a flapping cycle, the quasi-steady analysis begins to have significant (say 10%) errors. In this case the variability of the wing's wake modifies the flow that the wing encounters, and the analysis is called 'unsteady'.

Von Karman and Sears [3] give an introduction to unsteady airfoil theory, although it is probably only accessible to those with a background in fluid mechanics. Their theory is for a two-dimensional, flat-plate airfoil with small-amplitude pitching and heaving in an inviscid fluid. Sears [4] extends the theory to a wing of finite span. Garrick [5] gives equations for more general two-dimensional flapping which include a phase shift between pitch and heave, as well as the effects of an oscillating aileron. His results include expressions for the thrust gained from flapping, and so are particularly useful to the designer. Wu [6] utilizes the results of unsteady theory to find the optimum motion of a two-dimensional airfoil in order to maximize its propulsive efficiency.

The *Mutiny* made direct use of Wu's theory. I could easily vary both the amplitude of the main foil's pitching motion, and the phase shift between pitching and heaving, achieving theoretically optimal motion. I found that while the best flapping motion was similar to Wu's prediction, the propulsive efficiency was quite a bit lower than the 90%+ his theory gives. I still believe the theory, but think that the translation from theory to actual propulsion system needed to be much more refined than what the *Mutiny* could offer.

Some researchers have done careful studies of flapping-wing propulsion. Bennett et al [7] experimented with an oscillating 'two-dimensional' airfoil in a wind tunnel, and came up with results for the lift very similar to the predictions of unsteady theory. Archer et al [8] experimented with a bird's wing type of flapping arrangement. They never measured the propulsive efficiency above 50%. DeLaurier and Harris [9] did flapping experiments with a wing of finite span. Interestingly they also never measured a propulsive efficiency above 50%. Clearly it would be nice to see some experimental verification of the high propulsive efficiencies predicted by theory.

Cal Gongwer [10] has done much to bring flapping wings toward practicality. In particular his *Aqueon* hydrofoil swimming device is a clever use of flapping-wing ideas. Also the University of Goteborg (Thiel [11]) has used counter-oscillating hydrofoils to propel a human-powered boat, although it does not fly on the foils.

Obviously some very fundamental challenges remain in the process of creating a high-efficiency flapping-wing propulsion system: What airfoil section to use? What flapping motion to use (birds vary widely from a sinusoidal stroke)? How to control the motion mechanically? What is the optimum heaving amplitude and frequency? etc. . . .

The *Preposterous Pogo Foil*

For the past three years I have been experimenting with a boat similar to the *Mutiny on the Boundary Layer*, but much simpler, which I call the *Preposterous Pogo Foil* (Figure 5). The design philosophy of the *Pogo Foil* is that, by giving the pilot some measure of control over the flapping motion and some form of feedback about the forces on the wing, she or he should be able to develop an efficient flapping motion. That is, by trial and error, the pilot will 'learn how to fly.'

Without knowing precisely how to do this, I built the boat, saving the foil angle actuation system for last. The *Pogo Foil* has a lightweight pyramidal superstructure above the hulls, and the pilot stands on a tube which forms the aft base of the pyramid. The peak of the pyramid holds the main headset and handlebars.

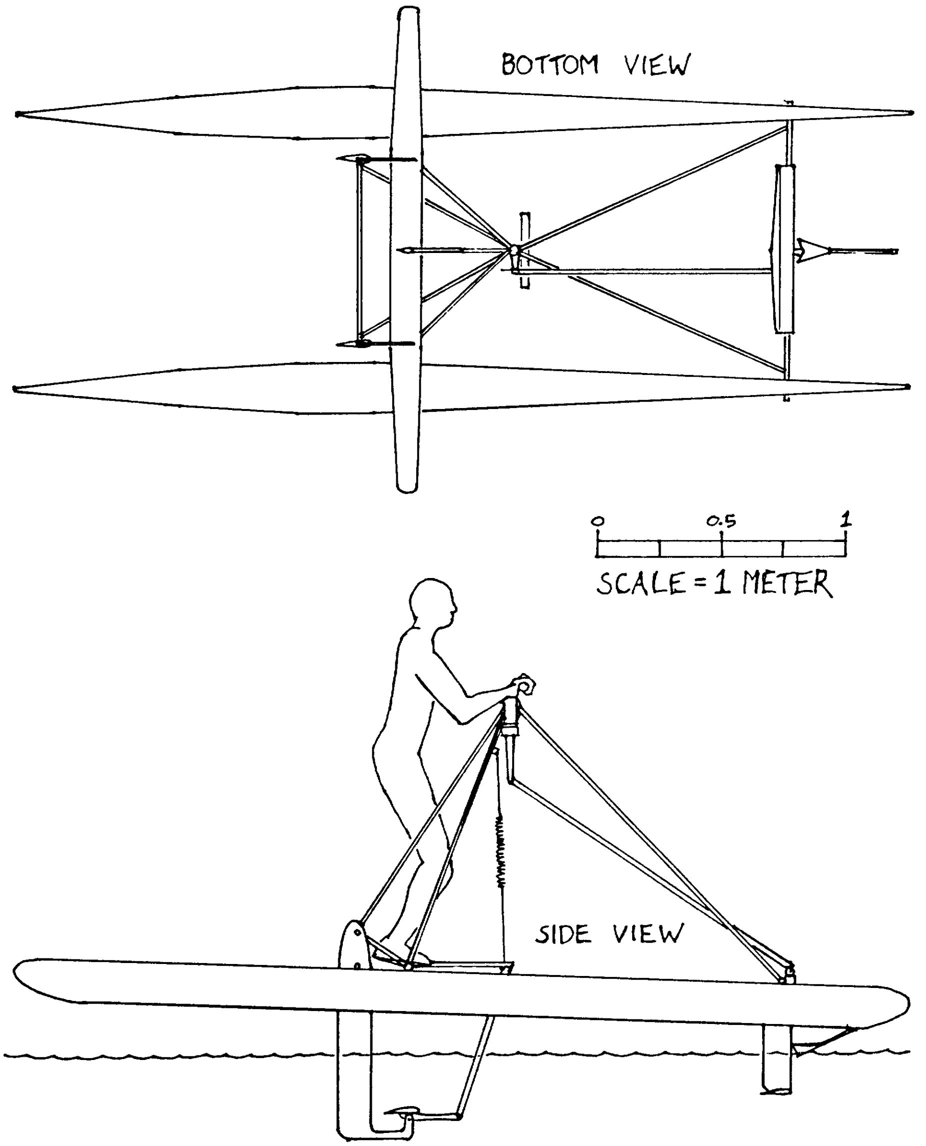


Figure 5. Two-view of the *Preposterous Pogo Foil.*

The heaving motion is accomplished by the pilot bending at the knees to raise and lower their mass relative to the rest of the boat. Unlike the *Mutiny*, the *Pogo Foil* is all one piece, so when the rider pushes the main foil up and down, the hulls and superstructure move with it. The boat weighs 200 N (45 lbs), less than half the *Mutiny*, and flies at about the same speed because the main wing is the same.

I have tried many foil-angle actuation systems. Initially the thought was that the pilot could directly control the wing angle by twisting the handlebars, but this proved very difficult and the boat barely moved forward. The main problem was that, while the average lift force acts through the quarter chord of the wing, which is just aft of the pivot point, the unsteady force (the 'apparent mass') acts through the half chord, placing large torques on the control system. These forces appear explicitly in Garrick's [5] expressions. Later I tried attaching a fixed stabilizer off the back of the main wing. Such a system can inherently give the angular change and phase shift one desires. This system at least made the boat go forward rapidly. I also tried a stabilizer in conjunction with some springs which held the foil near its average angle. The most successful system so far has been a combination of springs with brake levers which allow the pilot to control the wing angle directly. It is easier for the pilot to be precise with a brake-lever arrangement opposed by spring tension, since people are very aware of the position of their fingers relative to the rest of their hand. The pilot gets feedback on the wing lift force directly through her or his legs, and the pressure required on the brake levers gives an indication of the wing angle of attack during the flapping cycle.

Presently the *Pogo Foil* has flown only about five 'flaps' in a row with the hulls fully out of the water, still far from the performance of its predecessor, but its flight seems limited more by control problems than by excessive power requirements. In the future I hope to improve the handling of the boat to the point where it can serve as a reliable testbed for different ideas about controlling the wing motion.

Conclusion

Over the years my purpose for building human-powered hydrofoil boats has changed greatly. Initially I wanted to go fast. Now my goal is a little less rational: I want to know what it feels like for a bird to fly by flapping its own wings. I want to learn how to fly that way. This is now an endeavor somewhere between aeronautical engineering and biology, between human design and natural experience.

Acknowledgements

Many thanks to Allan Abbott, Michael Blatt, Keith Brainerd, Alec Brooks, Tara Kiceniuck, Molly Knox, Peter Kaczkowski, Kirke Leonard, Paul MacCready, Tyler MacCready, Ray Morgan and the crew at Simi Valley, Dave Sivertsen, Ted Wu, George Yates, and the famous tow-boat operators Jim Burke and Dale West.

References

1. Brooks, A.N. (1984) The Flying Fish hydrofoil, *Human Power*, vol. 3, no. 2, pp. 1-8.
2. MacCready, P. (1986) Features of flapping-wing propulsion, *Third Int'nl H.P.V. Sci. Sym. Proc.*, A. Abbott, ed., IHPVA, Seal Beach, USA, pp. 45-52.
3. Von Karman, Th., and W. R. Sears, (1939), Airfoil theory of non-uniform motion, *J. Aero Sci.*, vol. 5, no. 10, pp. 379-390.
4. Sears, W.R. (1938) A contribution to the airfoil theory of non-uniform motion, *Proc. Fifth Int'nl. Congress A. Math.*, pp. 483-487.
5. Garrick, I.E. (1937) Propulsion of a flapping wing and oscillating airfoil, *NACA T.R. 567*, pp. 1-9.
6. Wu, T. Y.-T. (1971) Hydromechanics of swimming propulsion, part 2., *J. Fluid Mech.*, vol. 46, pt. 3, pp. 521-544.
7. Bennett, A.G., et al. (1975) Ornithopter aerodynamic experiments, *Swimming and Flying in Nature*, vol. 2, T. Y.-T. Wu et al., eds., Plenum Press, New York, pp. 985-1000.
8. Archer, R.D., et al. (1979) Propulsion characteristics of flapping wings, *Aero J.*, pp. 355-371.
9. DeLaurier, J.D. and J. M. Harris. (1982) Experimental study of oscillating-wing propulsion, AIAA 82-4107, New York, *J. Aircraft*, vol. 19, no. 5, pp. 368-373.
10. Gongwer, C. (1986), Letter to *Human Power*, vol. 5, no. 4, pp. 7.
11. Thiel, P. (1989) The 1989 Delft waterbike regatta, *Human Power*, vol. 7, no. 3, pp. 11-14.

Parker MacCready is presently in graduate school at the University of Washington, studying Physical Oceanography. He piloted the Bionic Bat *human-powered airplane to win second prize in the Kremer World Speed Competition, and worked as a test-pilot and builder on the Gossamer Condor and Gossamer Albatross projects.*

Parker MacCready
12017 Bartlett Ave. NE
Seattle, WA 98125 USA

The human-powered submersible race

(continued from page 1)

and straight line speed. Three prizes were awarded: for the most innovative design, for the most cost effective design and construction, and for the fastest time around the course. A $5000 grand prize was awarded to the best all-around entry.

The rules were stringent with regard to the safety of the two occupants but were intentionally lax in other aspects to foster innovation in submarine design. The two occupants, who breathed from a standard SCUBA system, had to have an air reserve equal to 50% of that required to run the course. Most vehicles carried between 150 and 300 cubic feet of air. Ease of egress for both pilot and stoker was an important safety issue. In addition, the submarine had to tow a surface float, be completely free flooding, and be 2 lb positively buoyant in its heaviest condition.

The actual race was an example of how the best laid plans can go awry. The competition was to consist of a 100 meter sprint to determine seeding, followed by a series of 1000 meter sub-to-sub elimination races. These plans were upset by unseasonable weather and unexpected delays. Stormy seas, high currents, and low visibility made just getting to the starting line a challenge. In the end, each entry was given the opportunity to complete a single 100 meter timed sprint. Of the 18 vehicles entered, 9 managed to complete the sprint in less than the mandated 10 minutes. The teams that entered and their speeds are listed in Table 1.

Description of Entries

Given the limited power that can be generated by a fit human being, and the loss in power due to working in a fully flooded environment, submarine designers focused on vehicle drag and propulsive efficiency. Because water is about 1000 times denser than air, drag reduction was a key element in the design of a fast submersible. Overall, speeds were less than many had estimated: as seen in Table 1, all were less than 5 feet/second.

Drag of a hydrospace vehicle is a function of several variables. Primarily they are the wetted area, which determines the amount of drag due to skin friction, and the frontal area (or prismatic coefficient), which determines the pressure drag. The submarine designer minimizes the wetted area by designing the smallest submarine capable of enclosing the occupants and equipment. Pressure drag is minimized by a small frontal area and by the design of the

Vehicle No.	Name	Affiliation	Award	Speed (ft/sec)
1	*Nicole's Nickel*	Tennessee Tech. Imagineering Inc.		--
2	*SPUDS*	Univ. of New Hampshire		2.53
3[a]	*DaVinci*	Will Forman		--
4	*Gossamer Albacore*	Lockheed Advanced Marine Systems	Innovation	1.72
5	*Sub Human*	Sub-Human Project		--
6	*Subasaurus*	Benthos, Inc.		--
7	*Knuckleball*	Innerspace Corp.		--
8	*SQUID*	U.S. Naval Academy	Overall Performance	4.47
9	*Icarus*	Massachusetts Institute of Technology		--
10	*Sea Panther*	Florida Institute of Technology		3.92
11	*Centipede*	Sea Scapes Aquariums		1.16
12	*Turtle*	David Taylor Research Center		--
13	*HumPSub*	Applied Physics Laboratory, University of Washington	Cost Effectiveness	4.32
14	*FAUtilus*	Florida Atlantic Univ.		2.31
15	*Honeysub*	Univ. Calif. Santa Barbara		--
16	*Superfluke*	Cal. Poly., San Luis Obispo		--
17	*Subversion*	Cal. Poly., San Luis Obispo	Speed	4.46
18	*Speedstick*	Cal. Poly., San Luis Obispo		2.77
19[a]	*Barracuda*	Florida International Univ.		--

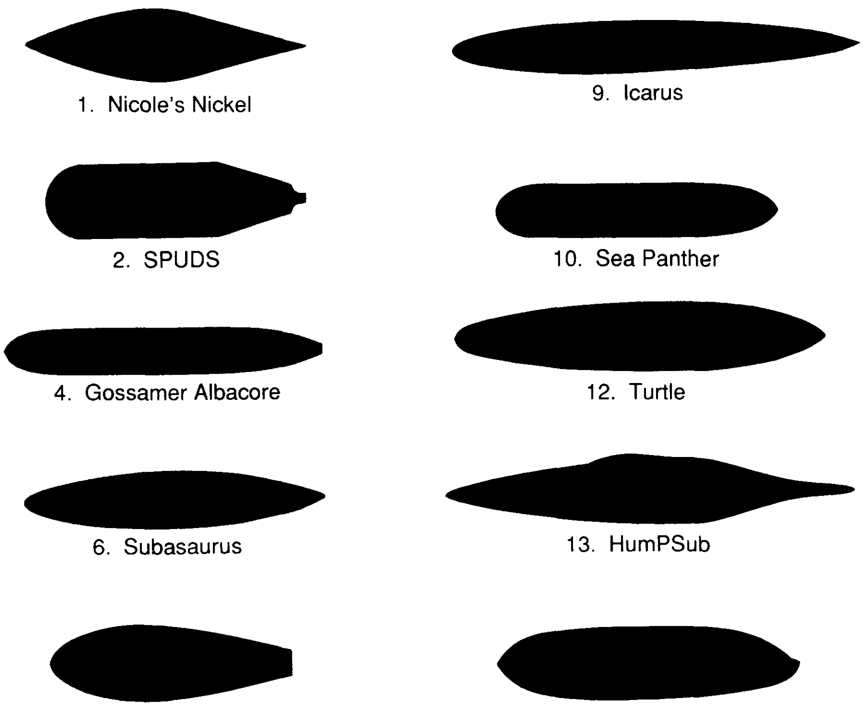
a. Withdrawn.

Table 1. Entrants and posted speeds

Table 2. Principal characteristics of the 18 entries.

No.	Affiliation	Diam. (in.)	Length (in.)	L/D	Wetted Surface Area, S_{wet} (sq. ft.)	Vol. (cu. ft.)	Vol./S_{wet}
1	Tenn. Tech.	36	138	3.8	62	35	0.56
2	UNH	36x48	216	5.1	153[d]	113[d]	0.74
4	Lockheed	23	162	7.0	86	28	0.33
5	Sub-Human[a]	--	--	--	--	--	--
6	Benthos	28	148	5.3	67.1	31.8	0.474
7	Innerspace	60[b]	60	1	78.5	65.5	0.83
8	Naval Acad.	38[c]	120	3.1	69.1	36.6	0.53
9	MIT	28.5	200	7.0	91	44.5	0.49
10	FIT	22x26	138	5.7	62.1	23.6	0.038
11	Sea Scapes[a]	--	--	--	--	--	--
12	DTRC	37	184	5.0	111	68.7	0.62
13	APL	32	192	6.0	88	45	0.511
14	FAU	24x36	144	4.5	135	45	0.333
15	UCSB[a]	--	--	--	--	--	--
16	Cal. Poly.[a]	--	--	--	--	--	--
17	Cal. Poly.[a]	--	--	--	--	--	--
18	Cal. Poly.[a]	--	--	--	--	--	--

a. Data not available.
b. Hull is spherical.
c. Hull is asymmetrical, maximum diameter shown.
d. Estimated.



1. Nicole's Nickel

2. SPUDS

4. Gossamer Albacore

6. Subasaurus

8. SQUID

9. Icarus

10. Sea Panther

12. Turtle

13. HumPSub

14. FAUtilus

Figure 2. Scaled profile view of various hull shapes.

body, primarily the shape of the afterbody.

A wide variety of hull forms were used in the Florida race. Figure 2 shows scaled profile views of several of them, and Table 2 lists their principal characteristics. The shapes ranged from advanced laminar-flow designs to what can best be describe as the "Cadillacs of the submarines." The APL entry was perhaps one of the lowest-drag shapes to compete. Low drag was achieved through maximizing the extent of laminar flow in the boundary layer, which intrinsically produces less skin-friction drag than turbulent flow does. Equally important is the shape of the afterbody; how rapidly it is closed off influences the degree of pressure drag, as well as preventing separation of the boundary layer. Afterbody separation increases vehicle drag tremendously and must be avoided.

Several methods are used in advanced submersible design to reduce drag. They range from active techniques such as boundary-layer suction or polymer injection to passive techniques such as laminar-flow bodies or drag-reducing riblet tapes. A few entrants, in particular APL and Tennessee Tech., made concerted efforts at employing advanced drag-reduction techniques.[1] It is not possible to state how effective they were owing to the abbreviated race and/or technical difficulties with the vehicles.

Figure 3 plots length vs. diameter for several entries, from the high length-to-diameter ratio of the Lockheed vehicle to the spherical *Knuckleball*. Figure 4 shows wetted area vs. enclosed volume for the same entries. These two graphs indicate what is possible in designing a two-man wet sub for minimum wetted area, minimum enclosed volume, and minimum frontal area. The numbers by each data point correspond to the vehicle numbers listed in Table 1.

Several factors enter into the optimal position for the pilot and stoker. Maximum efficiency of the stoker's power output and visibility of the pilot were two of the more crucial ones. Many designers opted for fully prone positions for both the pilot and stoker. The pilot and stoker were usually face down but occasionally the stoker was face up. This positioning produces the smallest frontal area but can decrease the pilot's range of vision. A prone position reduces the pressure differential between the diver's mouthpiece, where the air pressure is equalized, and the diver's lungs. There is some speculation that this improves the power output of a diver, but this is unproved.[2] Our entry had the two divers back-to-back in a recumbent position. This design, like others, tried to reduce claustrophobic feelings in the stoker. A single hatch made for easier fabrication of the hull and effortless loading of the pilot and stoker. The recumbent position also provided more restraint against unnecessary movement than a prone position. In air, a bicyclist can work against his or her own weight. A neutrally buoyant bicyclist has no weight and must minimize the energy spent to accelerate his own mass. Many subs used multipoint, quick-release restraints to keep a stoker from unnecessary movement.

Power transmission

Several approaches were taken by the entrants to extract power from the human body. The rules did not restrict how the power could be extracted, but it is evident that human's legs have the most muscle mass. Because the stoker would be working in water, a traditional rotary bicycle power transmission might not be optimum.

Because of its simplicity and the large number of components available, most of the designers chose to use a standard, rotary bicycle-crank mechanism to extract power from the stokers. There were some exceptions though. The unusual *Knuckleball* used arm power alone, the arms turning a crank mechanism coupled directly to the propeller. The Cal. Poly. *Superfluke* and the Lockheed entry used a leg-powered linear drive system, with the stoker's legs pumping in straight strokes. An improvement in efficiency would be expected, since a linear drive reduces the swept area about 30% compared with a rotary drive. Several teams considered using both arm and leg power, but rejected this idea because of the additional mechanical complexity and limited endurance of arm power.

One obvious benefit of a linear drive is the reduction in space required for the stoker's leg motion. This space requirement dictated the minimum hull diameter, and many vehicles were designed

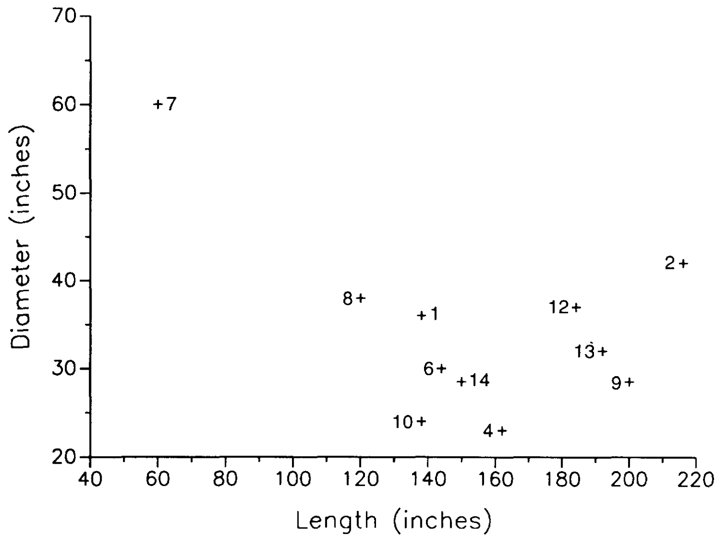


Figure 3. Submarine hull length versus diameter.

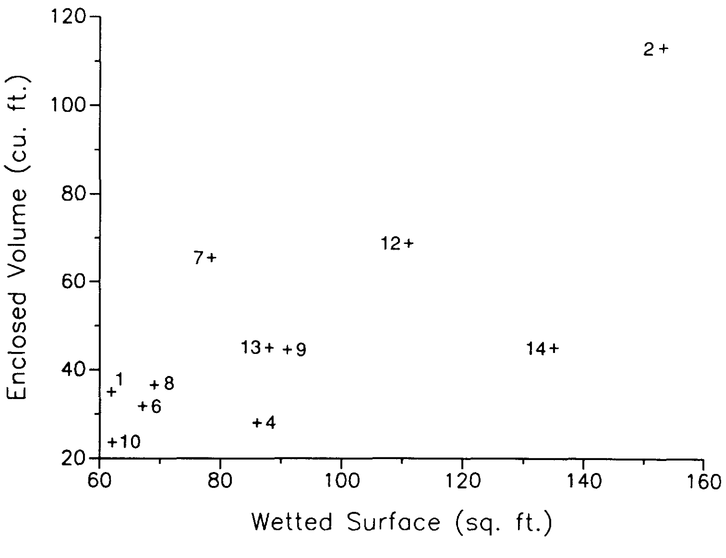


Figure 4. Submarine wetted surface area versus volume.

around this dimension.

Various methods were employed to convert the rotary athwartship pedal shaft motion to the longitudinal shaft of the aft-mounted propeller. The natural design goal was to reduce the mechanical losses in bearing and gear assemblies to yield the highest possible mechanical efficiency. Some form of gearing was required, as the typical propeller speed was approximately 125 to 150 rpm. The optimal cadence of the stoker was found to be 40 to 50 rpm,[3] much slower than a typical cadence of 80 to 100 rpm in air. Some entries used twisted chain drives, eliminating the usual bevel-gear set, while others placed the gear set at the crank mechanism and ran the propeller shaft from there. Precision bearing assemblies could reduce mechanical losses here as they do in land human-powered vehicles, but the complication of being immersed in salt water produced designs using synthetic bearings or bevel gears.

Propulsion systems

The standard marine screw propeller was by far the choice of the majority of entrants, with only two entrants trying a novel oscillating-fin approach. The Lockheed entry had two fins of equal area driven in opposite directions similar to fish fin propulsion and was ideally suited to their linear drive method of power extraction. Given the novelty of their system, their eighth-place finish was indeed respectable.

While the technology for designing efficient marine propellers exists, there is a dearth of design information at the speeds and power outputs typical of a human-powered submersible. It has been found that the typical fit male under water can produce less than 0.2 hp when coupled to a standard bicycle mechanism.[2] Most teams had no means of testing the candidate stokers for output. Another problem was the lack of data about the drag of a given submarine design over the range of anticipated speeds. Both of these problems produced considerable uncertainty about the speed of advance of the propeller.

Many teams designed their own propellers using computer programs that range from elementary to advanced. Building a propeller to the fine tolerances required of an advanced design can present a fabrication problem that exceeds the design challenge. But conducting experimental runs to determine optimum pitch was difficult because of the lack of controlled test facilities available to most teams. Some entrants used the best available commercial propellers, while others fabricated theirs from wood or fiberglass over foam cores; we used a cast aluminum fan blade. Some teams, notably Benthos and MIT, had beautifully crafted propellers.

Two teams entered submersibles with ducted propellers. In general, such propellers must be carefully designed if they are to provide a sufficient increase in thrust to offset their additional drag. They are often used in designs where there is a limitation on the allowable propeller diameter. A properly designed ducted propeller minimizes the tip losses of a standard propeller, as well as accelerating the flow into the propeller. In this race their use may have been warranted because of the protection the ducting would have afforded a fragile propeller during the less-than-controlled launch and recovery.

Several teams had articulated tails that enabled the entire propeller to rotate around a vertical axis for improved maneuvering. It is questionable whether such added complexity was needed to maneuver through the 18-meter-radius turns of the race course. Experience proved our vehicle had a sufficiently small turn radius to run the course, and others reported turn radii as small as 8 meters.

The Naval Academy's *SQUID* and the Sub-Human entry were equipped with counter-rotating props. If they are designed properly, such propellers can improve efficiency by eliminating residual vorticity in the propeller race. In addition, they eliminate the propeller-induced roll. The latter can be minimized with sufficient vertical separation between the centers of buoyancy and gravity. Most single-prop vehicles apparently had little problem with excessive roll. The design of counter-rotating propellers is a complicated undertaking and probably beyond the volunteer resources available to most teams.

Perhaps the most advanced design belonged to the cycloidal propeller used on Tennessee Tech.'s *Nicole's Nickle*. This fairly complicated system permitted the pilot to vary the pitch of each blade as it rotated, allowing the generation of side forces as well as longitudinal thrust. It is similar to the collective pitch control of a helicopter and allows the vehicle to be maneuvered without the aid of control fins. The concept has been proved in previous submersibles, but the complexity of the design induces fabrication problems. At the race this relatively complicated system proved to be unreliable. The lack of testing facilities (common to most teams) was a particular disadvantage to complicated entries, allowing little time for debugging mechanical problems.

Lessons learned

All the teams who participated in the first human-powered submarine race came away with some valuable experience and some hard-learned lessons. It was evident that building a reliable vehicle is equally important to having an advanced design. Of the original 18 entries, only 9 managed to finish a greatly abbreviated course. Many had simple mechanical failures, such as broken drive chains or sheared propeller pins. Others had precision systems fouled by grains of sand. This was the fundamental lesson learned from this first race: Reliability is of paramount importance.

Many of the subs had no provision for entry into or out of the surf zone. The submarines weighed well in excess of 1500 lb when flooded, and their inertia when tossed by waves caused damage to many. Some sort of handling system should be considered for future entries.

Perhaps the most common flaw was lack of trim and ballast control. When moving at such slow speeds, dynamic stability can be easily overcome by static instability, which many entries suffered from. Once again, the difficulty in testing these designs from a logistics standpoint prevented fine tuning the static trim of the vehicles. Several vehicles had fore-and-aft trim tanks under the control of the pilot, which allowed achieving neutral buoyancy and level trim just prior to the start of the race. Our entry had two simple tanks yielding 13 lb of buoyancy located as far apart as feasible. These were immensely valuable in every open-water exercise.

Another often overlooked design requirement was adequate visibility for the pilot. The usually calm, clear waters found in Florida in June were replaced by stormy conditions and 10-to-20-foot visibility. Several vehicles, because of a design goal of minimal frontal area or structural requirements, had pilots looking through poorly sized or placed windows. As a result, some pilots either could not keep on course, could not find the course markers when driven off course by sizable currents, or could not see the start or finish markers.

A design that allows quick exits from the vehicle is desirable. Some of the entries had tortuous loading sequences for the pilot and stoker that hampered their readiness at the start of the race. Fast and fail-safe egress was a definite requirement of the judges, and as a stoker I emphatically endorse this.

Communication systems were present on a few of the vehicles, ours included. Allowing the pilot to communicate with the stoker during the race was definitely a competitive asset, as well as a safety feature.

Several of the entries incorporated an automatic buoyancy-compensation system to offset the increase in buoyancy as air was consumed from the SCUBA tanks. These systems took the form of a bladder whose volume decreased with the SCUBA air pressure, or a hard tank that slowly flooded through a precisely set orifice. This change in buoyancy would be approximately 8 to 12 lb. Without such compensation, it is prudent to position the tanks at the center of the vehicle to minimize trim changes as a result of buoyancy changes.

Summary

This article was meant to provide a simple, objective review of the numerous designs that raced. Because of the minimum number of race times recorded, little can be said definitively about what technology worked and what didn't. Despite the limited competition, all the entrants enjoyed the challenge, as well as the camaraderie of the race. It is sufficient to say many teams will race again in June 1991, some with new vehicles and some with the same.

References

1. J. Osse, 1989: "Low drag technology applied to human powered vehicles," *OCEANS '89 Proceedings*, Vol. 6, Human Powered Submersibles, IEEE Pub. 89CH2780-5, pp. 7-11.
2. M.L. Nuckols, P.K. Poole, R.M. Price, and J. Mandaichak, 1989: "Project SQUID, a lesson in design simplicity," *OCEANS '89 Proceedings*, Vol. 6, Human Powered Submersibles, IEEE Pub. 89CH2780-5, pp. 38-42.
3. S.L. Merry, S.L. Sendlein, and A.P. Jenkin, 1988: "Human power generation in the underwater environment," *OCEANS '88 Proceedings*, Vol. 4, IEEE Pub. 88CH2585.8, pp. 1315-1320.

James Osse obtained his Bachelor's and Master's degrees in Ocean Engineering from University of Washington. Since then he has been employed at APL working on the development of various subsea instruments, including towed arrays, small autonomous vehicles and oceanographic sensors. His professional interests center around hydrodynamics and his personal achievements include an around-the-world bicycle trip and long experience in sport and scientific diving. The combination of these talents made the Human-Powered Submarine a natural challenge.

James Osse
Applied Physics Laboratory
College of Ocean and Fishery Sciences
University of Washington
Seattle, WA 98105-6698 USA

❑

Information gathered through experience

by Shields Bishop

The simplest way to propel a boat in deep water (where you can't use a pole to push on the bottom) is by means of a paddle (very popular). The next simplest way is by means of oars or sculls from sides or stern (pretty popular). The next simplest way is by foot- or arm-powered paddlewheels (hardly popular). The next simplest way is by foot- or arm-powered screw propellers, either in the water or (almost unheard of) in the air.

The above listing indicates that the human race thinks rationally, which is heartening. Now, if only this trend could be carried over into other activities, the troubles of the world would be over in a generation or two.

But I find myself mesmerized by the marvelous action of the screw propeller. Here is a surprisingly small, compact, deceptively simple-looking device which can develop much thrust. Think of all the things it has made possible, both good and bad, over the oceans of the world.

And I find myself mesmerized by the marvelous action of the human leg. The legs perform a function far beyond the capabilities of the arms—supporting and moving the human body, almost effortlessly, for hours at a time.

And so, to combine the action of the human leg with the action of the screw propeller has been the object of most of my recreation for almost 18 years. All other concerns in life have been secondary. It's been a lot of fun.

First, arrange the linkage between the legs and the propeller so that the least effort is lost to friction. Luckily, the bicycle technology which is available gives us lots of help here. Chains, sprockets, ball bearings and structural parts from old bicycles are cheap. The biggest problem in the linkage is the right-angle drive between pedals and propeller shaft. Many people have suggested that I "just sit sideways." It's a possibility, but inappropriate. If you want to, go ahead and build a pedalboat where you sit sideways. It's only half as ridiculous as sitting backwards, as in rowing, but somehow it seems non-symmetrical. It would always feel uncomfortable for most of us.

So we come to a right-angle gear drive. I have experimented with cardan-joints, friction drives and timing belts. A twisted timing belt works well and is very quiet compared to chains and gear. But, for the home-builder, a good right-angle gearbox[1] combined with bicycle chain and sprocket drive will serve best, and it's the quickest way to get on the water with an effective mechanical linkage.

Next is the propeller and shaft. Remember that there isn't much power involved, so a small shaft will do. Believe it or not, I have used a 1/4-inch- (6-mm-) diameter shaft on a boat pedaled by four *strong* cyclists. Of course, it was 17-4 PH stainless steel temepered as hard as spring steel.[2] But even so, remember that a 3/8-inch- (9-mm-) diameter steel shaft would be plenty strong enough for one or two strong pedallers. The reason I use a very-high-strength shaft is so that I can bend it to an arc for retraction of the shaft and prop. I have used small bendy shafts for both pulling (tractor) and pushing props. In all my boats the prop thrust is taken by a small thrust bearing (ball or plain) located near the prop on the mounting strut, which I make retractable. The small bendy shaft is better than cardan/universal joints because the power transmission is smoother and absolutely silent. The stress is figured to be a compromise between the radius of the bend and the allowable torsion. One more point: another purpose of the bendy shaft is to get the prop operating so that it is rotating perpendicular to the forward motion, rather than at an angle, as in many boats.

Now comes the prop. The various literature on propellers shows that at the speeds we have in mind for comfortable non-Olympic athletic effort (5-10 mph)(2-4 m/s) we need a prop about 12 to 18 inches (300-450 mm) in diameter with a pitch-to-diameter ratio of about 1.5 to 1. A prop having two blades is the simplest layout and more efficient than three or four blades for the same power output. The material should have a high strength-to-weight ratio in order to keep the blades *thin*. Fiberglass composite is very good, but there may be an advantage in aluminum, 17-4 PH stainless, carbon-epoxy or other exotic materials. The advantage of metals for propellers is that damage can be more easily repaired. And propellers *do get damaged*. The best compromise blade shape is elliptical with a small ratio of width to length. Typically, a blade 8 inches (200 mm) long (16-inch-diameter prop) (400-mm) should be about 2-inches (50-mm) wide at the hub and taper in an elliptical plan form to the tip. This results in a prop that looks more like an airplane propeller, but that is what works best (most drive for least effort). Keep the blade thickness below about .05 times the blade width, and finish it to a good airfoil shape as shown in NACA literature at the library.[3] To get a good approximation to the proper twist in the blade (helix), make a "pitch block" by fanning out thin material (1/8" or 1/4" plywood) (3 or 6 mm) so that the angle between each lamination is proportaional to the helix angle. That is, 360° = the pitch length. For example in a group with 24-inch (610-mm) pitch, each inch means 15° (360/24 = 15) so that each 1/8" (3 mm) lamination would be rotated 15/8 = 1-7/8° from its neighbor. Once you have the pitch block, twist and hammer the blade to conform to the block. Then weld or screw the blade to the hub. Remember, the hub needn't be much bigger in diameter than the shaft because of the low power and thrust.

The drive speed ratio between pedal shaft and prop can be adjusted by means of appropriate sprocket sizes. If you choose a 24-inch- (610-mm-) pitch prop for a boat which you want to pedal 6 mph (2.7 m/s) and you want to pedal at 60 rpm, do the following arithmetic:

6 mph= 528 feet per minute (2.7 m/s)
24-inch pitch = 2 feet (610 mm), but most good props "slip" about 15%, so each prop revolution will move the boat 1.7 feet (520 mm) (2 x .85 = 1.7). So prop rpm is 528/1.7 = 311 rpm.

$$\left[\frac{2{:}7 \text{x} 1000}{520} \text{ x } 60\right]$$

For 60 rpm pedal speed 311/60 = about 5, so use a right-angle gear and pedal shaft-sprocket size to give 5 to 1. For example, if you use a 2:1 right-angle gear, then use a 40-tooth chain wheel (sprocket) and a 16-tooth sprocket on your input to the 2:1 gear.

Next is the boat layout. If you use the conventional bike seat and frame which is the simplest way to get started in pedal-boating, you will sit so high that you will need outriggers on your boat or, better, a catamaran with two hulls. With the catamaran layout it is easier to put the prop shaft into the water (without piercing the hulls).

You will need a frame to suspend all this above the water so that your feet will remain dry.

If there is sufficient interest, I will contributed future write-ups on *how to* (real how-to) make props, rudders, seats, shaft linkages, hulls, etc., but in the above you have the bare bones of it. From there on it's a matter of taste if you want to sit recumbent or conventional, super safe and seaworthy or all-out speed. Day-trippers should be built differently from dockside boats for the kids to race around in. And there are other compromises. For example, the fastest straight-ahead boat is not as much fun as one that is more easily turned. I can offer other suggestions on hull design and construction methods. Want to win the Du Pont prize? I'll tell you how to do that too.

Notes

1. Sources of right-angle gear boxes:
   Adantex, Inc. 1705 Valley Road, Wanamassa, NJ 07712 (201) 493-2612
   Mitrpak Division of Johnson and Bassett, Inc., Box 278, Worcester, MA, 01613 (508) 835-4155
   Boston Gear, 14 Hayward Street, Quincy, MA, 02171 (617) 328-3300
2. The 17-4PH (or UNS S17400) type 630 are martensitic precipitation-hardening stainless steels.
3. Eastman N. Jacobs and Raymond F. Anderson, *Large-scale aerodynamic characteristics of airfoils tested in the variable density wind tunnel* T.R. 352, NACA, 1929.

Shields Bishop has worked as a metallurgist for many years, and as an avocation has acquired extensive experience in designing and buiding a variety of pedal-powered watercraft.

Bishop Pedalcraft Company
103 Sunnyside Road
Scotia, NY 12302 USA

❑

Human-powered boat race at Lauwersoog, June 1989

by Marten Gerristen and Marinus Meijers

In cooperation with the yacht club Lauwerszee and the Dutch International Moth Association, a human-powered boat rate was held at Lauwersoog on June 10, 1989. Boats were invited from the human-power movement (through their organizations, such as IHPVA, NVHPV, BHPC and DHPV) and from the Waterbike regatta, which is an annual event organized by technical universities.

Four teams appeared on race day, all with very different boats and in a very friendly atmosphere.

At the university regatta only two-man boats can compete, and a variety of tests are run. Handling, practicality and speed are all important, and this we find in the designs. In the human-powered competitions, anything goes, so here we find more variation, as exemplified by the four-man speedster and the single tourer.


Some of the Lauwersoog entries (Photograph by B. Sprenger DeRoover)

Participants

Present were:

- The Clementine, of the Hamburg student group H.F. Latte. The Clementine is a two-man-powered trimaran with paddle drive. The boat is 6 m long, 3.4 m wide and has a very shallow draft (0.4 m).
- The Delft Blue, of the student group William Froude. The Delft Blue is a 5.5-m trimaran, powered by two persons sitting in tandem, driving a propeller. The hull shape is said to plane at speed.
- The Fast Waterbike by the association 'de snelle waterfiets' of Amsterdam. This tried-and-tested design features a decked wooden hull with a four-person drive. 15 m of bicycle chain transfers the power to a tractor propeller. The propeller drive is mounted on a hinge, reducing the risk of damage when inadvertently hitting some obstacle under water. The hull is 8.8 m long and total weight hovers around the 130 kg mark. Design speed of the hull is 6.7 m/s. Despite the length, maneuverability is very good, thanks to the 'Schottel' (swivelling) propeller mounting.
- The Nat Moth by Barry Sprenger de Roover. This was a combination of an International-Moth hull with a drive mechanism that is being developed to power a touring catamaran. The drive mechanism is a linear design with sliding pedals. The reciprocating movement is transferred to Kevlar wires to a system of pulleys and clutches into rotary motion. The propeller swivels through a large arc, making for a very maneuverable boat.

Competition

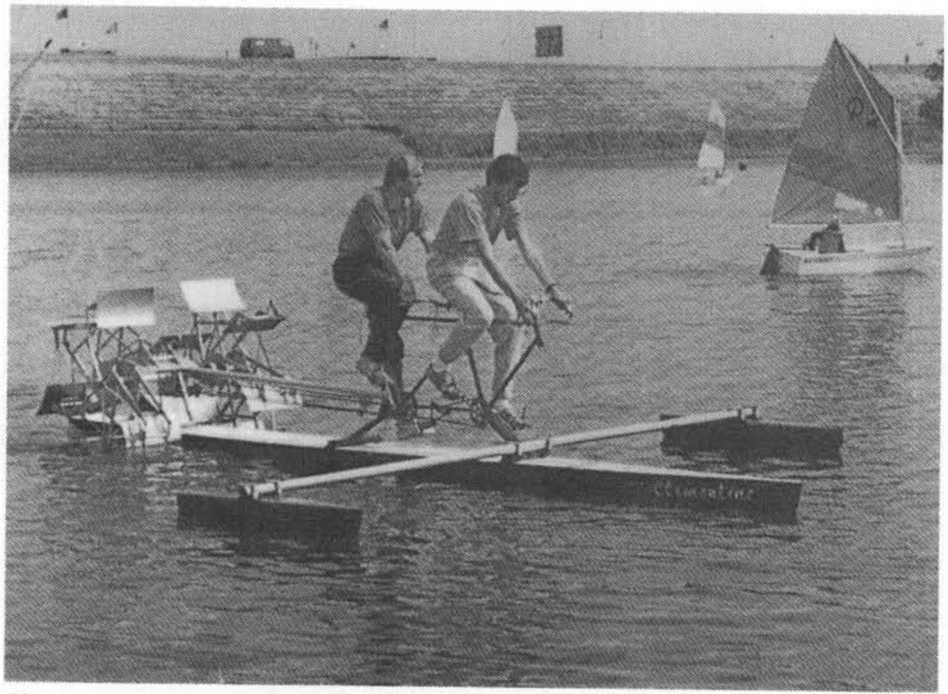
The competition consisted of two parts: a speed trial in three heats on a course round two buoys in the Lauwersoog harbor; and the completion of a questionnaire on the good and bad points of fellow competitors' designs.

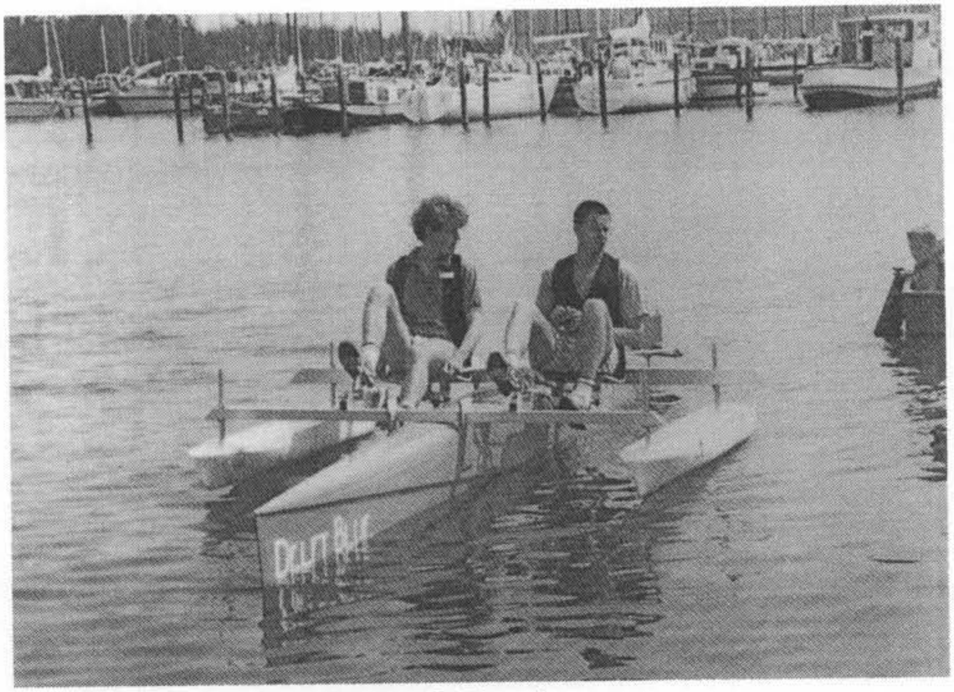
For the speed trials a handicap system was used. Final winner was the Fast Waterbike which had a decisive advantage in the last heat when wind and waves increased. Clementine and Delft Blue were well matched, the paddle boat just beating the Delft competition. Nat Moth had to give up in the last heat, the drive efficiency being a notable candidate for improvement.

The large crowd of spectators (thousands manned the quays) were able to get a good impression of the speed potential of a proper waterbike. To see a waterbike keeping up with a fishing cutter entering the harbor is an impressive sight indeed.

In the questionnaire participants were asked to judge their fellow competitors' boats on subjects such as design, user friendliness, quality, degree of innovation and potential for development. The last question concerned the 'ideal boat'.

It became very clear that all competitors used their own designs as yardsticks when judging other designs. For example, the Nat Moth team (4 m, 30 kg) found all other boats very awkward to transport, while the Snelle Waterfiets team (9 m, 130 kg) found no such problems with the other designs. We will present the results per boat below.


Clementine (Photograph by B. Sprenger DeRoover)



Delft Blue (Photograph by B. Sprenger DeRoover)

Fast Waterbike

Design: the hull shape meets wide approval, and the chain drive and the tilting propeller are other points in its favor. The heavy and dirty construction (the boat could shed 50 kg in weight), the pedals (no toe-clips) and the side pontoons are minus points.

User friendliness: the teams differ on the subject of transportability: one team praises the trailer, in which the boat has a load-bearing function; other teams think the boat too large. The tilting prop interferes with braking and reversing (in which the Clementine shines) but the reclining seating position and the good visibility it affords are well liked.

On the subject of quality, the visual design meets with approval and disapproval (side pontoons). Speed is another point of disagreement: some think the boat fast, others not fast enough for a foursome.

The degree of innovation is thought to be low: the design is called proven (as the boat is six years old). This perhaps shows how fast developments go. The reliability is impressive.

Delft Blue

The side-by-side seating position has social advantages but will result in an unequal trim of the hulls with unmatched (in weight) cyclists. The drive is very simple, and the prop looks good. Other plus points are the rudder, adjustable for reversing, and the speed of the boat.

The imperfect shape the hull (flat stern) and the large draft are points of criticism.

On practicality, it does not score very well. The transportability is not good with lots of spanner work required, and getting in/on the boat is tough as well. Once seated, most criticism ceases: one can even carry a crate of beer!

Clementine

The paddle concept, the exceptional maneuverability, the standard-bicycle seating position and the craftsmanship are all appreciated. However, the paddles are very vulnerable, and this was unfortunately proven in a collision after the speed trials when everyone was trying out each others' boats. The collision left a lot of Clementine fans without a ride. The high seating position has a high wind resistance.

The view from Clementine is very good but not totally dry due to the paddles. The paddles are also awkward to transport.

On performance, it gets full marks: fast, maneuverable and fun. The high seating position could prove to be a handicap when passing low bridges.

Paddles are not considered an innovation, but everybody is surprised by the potential. Considering the accident, it is not surprising to see everybody recommending some sort of guard to protect the drive.

Nat Moth

Nat Moth was specially concocted for the trials by combining an existing hull with a drive mechanism. To improve trim, the boat was lengthened with a block of styrofoam and tape. All teams who have spent many hours building their hulls, appreciated this fast solution. But they also commented on the hull shape, which is far from optimum. The drive system with a hammock seat is nicely designed, but the very small propeller, the linear drive and the schottel propeller that will not turn completely around are points of criticism.

The seating position looks and is comfortable, but getting in requires the skill of an acrobat. Transportability is very good due to the low weight, but the speed is also very low. (All other boats needed about 4.5 - 5 mins. to complete a heat, but Nat Moth took nearly twice as long with 9 mins.)

Durability scores low as well. Not surprising considering all the pieces of string, foam and tape to enforce the marriage between hull and drive.

For speed, the boat is considered too slow, and for touring too tiring.

Future fun

The last page of the questionnaire was devoted to the ideal boat.

The Clementine crew would like to go high-tech: a hydrofoil on a single strut with automatic leveling system, adjustable prop and streamlined form above water are the ingredients to make the Clementine IX.

Team Nat Moth is not quite so much attracted to speed: a two-person catamaran with linear drive and a Darieu-rotor connected to a propeller to make use of the wind point to a recreational vehicle. But a boat with an almost submersible hull and a flapping wing could be fun too.

The Delft Blue team has no ready concept for the future. But innovation, low resistance and maneuverability will be important.

The Fast Waterbike team too are still thinking. But they have learned from their present boat: the next one is going to be lighter, cheaper, faster to assemble and easier to transport—and, of course, more maneuverable.

Marten Gerritsen
Marinus Meijers

The *Spinsurfer* Story

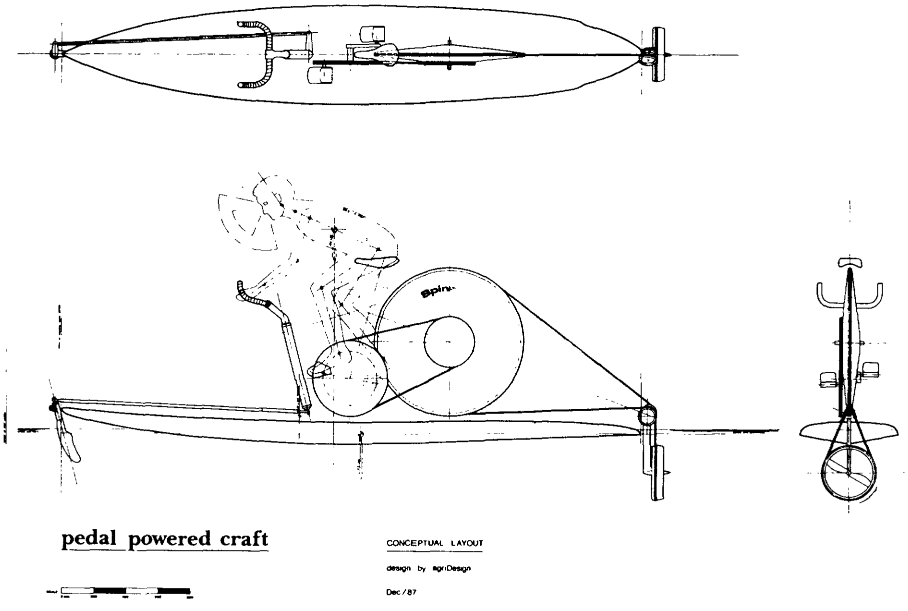
by Bruce Stewart

My colleague Jim Kor, P.Eng., and I of Man Design, Inc. have been active in developing human-powered watercraft for three years, and what follows is the story of our experience to date.

The initial concept of cycling on the water led to the development of the first *Spinsurfer*, based on a CRIT 630 windsurfer hull. A prone position was used, with steering supposedly performed by leaning. The drive train combined an industrial chain much like that used in a bicycle, with a "Berg" chain (by Winfred M. Berg) similar to the one employed in the *Gossamer Albatross*. The plastic Berg chain was twisted 90 degrees to turn a propeller purchased from Emprise Inc. of Methuen, Massachusetts. This first prototype did move through the water, but had problems turning, and failures in the drive train, most notably with the Berg chain. We added a side rudder, but soon decided that the prone position was too uncomfortable to be practical.

The second prototype employed a standard bicycle frame, with the front forks linked to a front rudder, and the tire-less rear rim driving a v-belt that we twisted over pulleys at the rear of the board to drive the propeller. This was a dramatic improvement over the first attempt, and we actually pedalled for many hours on the water with this version. The drive train was not very efficient, but we were insired to build the third prototype of the *Spinsurfer* in spite of this; cycling on the water had proved to be both feasible and a lot of fun.

The third prototype also uses the CRIT 630 windsurfer hull, a very efficient low-speed design. It was completed in the summer of 1988, and was entered in the IHPSC in Visalia, California. The speed increase from pedal shaft to propeller shaft is about 4:1. The purpose of developing this prototype was to test the feasibility of an "add on" unit for a windsurfer hull. For this reason, we routed the drive train over the rear of the hull as shown. The large wheel serves the purpose of reducing belt tension to the point where we were able to use a round polyurethane belt that handles the multidirectional twists of such a drive path.



The *Spinsurfer*

The shrouded propeller has advantages of safety and performance. As mentioned above, the belt-tension consideration made it seem desirable to utilize the shroud as the driver for the propeller. Jim designed and built a new propeller for this version. As a pre-production prototype, it was designed with a number of considerations, including speed, in mind. It performed reliably, and we had a lot of fun in the competition. Its performance was another dramatic improvement over the previous version, and the *Spinsurfer* is a joy to ride—smooth, reasonably fast (3 m/s, 6 knots), and quiet.

The *Spinsurfer* is designed to feel as much like a bicycle as possible. Like a bicycle, speed provides stability. If you stop pedalling the *Spinsurfer*, it becomes very difficult to keep balanced while remaining seated. It is, however, easy to stand on the board. The transition from standing to pedalling is the most difficult part of "spinsurfing". I have learned to do it repeatedly, with virtually 100% success. Once in motion, the *Spinsurfer* is very stable—even to the point of being rideable "no hands"! If the rider should fall, no injury results—he or she just gets wet. The opening in the frame in front of the seat post allows the swimmer to climb onto the hull and become a rider once more. The *Spinsurfer* is easily righted, and has been designed with both fun and safety in mind. As an experienced windsurfer, I can say with authority that learning to ride a *Spinsurfer* is much easier than learning to windsurf.

Subsequent market studies have led ManDesign Inc. to continue development of the *Spinsurfer* with an integrated frame and hull, rather than as an accessory to a windsurfer hull. The restrictions on the drive train are therefore largely removed, so the next (4th) prototype will be quite different in appearance. The next prototype will still have a shrouded propeller, but will probably be shaft driven rather than shroud driven, so the shroud need not turn.

Bruce Stewart is a partner in Man Design, Inc., and plans to attend the Speed Championships in Portland, Oregon, USA this summer with his associate Jim Kor.

Bruce Stewart
Man Design, Inc.
618B Erin Street
Winnipeg MB, R3G 2V9, CANADA ❑