The HPAirship White Dwarf

Piloted by its designer, Bill Watson, the White Dwarf pedal-powered airship, conceived and owned by the popular comedian Gallagher, is filled with approximately 6000 cubic feet (170 cu. m) of helium. The 5-1/2-foot (1.7-m)-diameter propeller, mounted on a pylon behind the pilot, can have its thrust angle altered through nearly 100 degrees to allow altitude control via a lever seen in the pilot's left hand. (Thrust vector shown is approximately 25 degrees forward of vertical.) The large rear-mounted rudder, here turned to the left, is controlled by a handle to the pilot's right. Two triangular tanks, under and behind the pilot, carry water ballast. The number on the envelope, IOAYY, is an ultra-light-aircraft registration number - no licensing is required to fly the White Dwarf.

Photo by Bryan Allen, Wizard of Odd, Inc.
Editorial:

WIDENING HORIZONS FOR HUMAN POWER

The last issue of Human Power was almost entirely devoted to boats, and the exciting achievements of Alec Brooks and Allen Abbott with their Flying Fish hydrofoil, since pedalled by Steve Hegg to an unrecorded speed. We now learn that the direction of activity around the world. In this issue, John Langford tells the story of the design and development of the HPV Monarch, and the capture of the third Kremer speed prize. By now at least the second and third prizes have been claimed (that is, HPV aircraft have been flown at more than five percent faster than the previous record in each case) and I hope we can have reports from the teams involved in the next issue of HPV.

But the mind-altering contribution to this issue will be Bryan Allen's argument for non-Kremer lighter-than-air vehicles, and his description of the HPV blimp, White Dwarf. He makes a strong case for the probability of blimps becoming popular HP aircraft for clubs.

There is obviously a danger of my being branded as a dabbler by turning Human Power away from land vehicles. It is certainly true that I have solicited articles in other fields to stimulate thinking. And another strand in the wind is the article in this issue by Ray Wijewardene on human power in developing countries. In the next issue I hope to have a report from Fred Willkie on his development of a winter tricycle for use in Canada's icy conditions. Fred, who put me into the HPV business by building and redesigning my first recumbents in around 1972, has learned Bengali and, by the time you read this, should be in Bangladesh working on improving the design of rickshaws and other human-powered conveyances. The picture he drew of the human-power field, we have no record of either trials or results. He replied on December 19, 1984, with the following fascinating anecdote.

"Your comments on old ideas being reinvented reminded me of a sliding-rigger boat I persuaded Cedric Valentine to build fifty years ago. A patent search turned up a patent, not on the sliding rigger, but on improvements to the sliding rigger. The patent was issued in 1874!"

This story had force for me because I talked about our plans to make sliding-rigger shells, and our design of rickshaws and other human-powered conveyances. The picture he drew of the need for improvement in these devices was so vivid that I immediately turned to him and asked if he had any plans for future work, and he replied on December 19, 1984, with the following fascinating anecdote.

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Oars work by pushing water backward. Water pushed in this way has the momentum (mv^2) of the backward-moving water equals the momentum imparted to the boat. However, the energy (1/2 mv^2) of the moving water is always greater than the energy...
passed on to the boat. Increasing the mass (m) of the moved water improves the efficiency. The size and shape of the blade, its path through the water, and the uniformity of water velocity are important.

In the articulated oar I have been experimenting with as a retirement hobby, the blade is pivoted at the outboard end of the loom. The loom does not rotate, and feathering is produced by a slight movement of the oar handle, transmitting a rotation to a shaft running down the center of the loom.

The conventional oar, swinging through arcs of 40° to 70° degrees either side of center, becomes less efficient as the angle departs from the perpendicular. On the other hand, the articulated oar maintains efficiency and actually produces more thrust at these angles, as is illustrated by the diagrams. At present, the blade area in the experimental oar is about the same as in a conventional oar, but the greater thrust results in greater slippage. A longer blade would reduce the slip and boost the efficiency. Unlike a conventional oar where increased blade length increases speed differentials along the blade, all of the blade of the new oar moves at the same speed, and it enters and leaves the water cleanly and abruptly.

Another potential advantage of the articulated oar is reduced travel of the seat slide, and therefore reduced pitching of the shell. If feathering does not require rotating the whole oar, the oar may take the form shown. The inboard portion of the loom is angled to allow the hands to move farther out at the catch (the point at which the oar leaves the water). As a result, the initial part of the pull-through, which brings the blade to boat speed, involves a shorter travel of the slide and with it a reduction in boat check. In addition, the hands are in a more effective position at the finish.

Checking - the deceleration of the boat resulting from the acceleration of the rower - may also be reduced by storing the rower’s kinetic energy at the end of the slide and recovering it during acceleration. A possible arrangement using springs is shown. Two springs arranged to center the oar at mid-stroke run free from the washboard to a capstan at the gimbal. These springs may be contrived also to balance the oar. In the interest of lightness and corrosion resistance they may be made of graphite-fiber-reinforced resin.

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More photos on page 20.
Blimps and Human-Powered Flight

by Bryan L. Allen

SUMMARY: The Kremer Prizes for human-powered flight have led builders to design flying machines that use lighter-than-air gases in pedal-powered aircraft. The White Dwarf shows there to be many benefits if static rather than dynamic lift is used for flight. Pedal-powered blimps may be the wave of the future in the arena of pedal-flight.

The Kremer Prizes, through the inducement of cash rewards, have given us a marvelous new class of ultra-efficient human-powered airplanes. But in the five-plus years since pedal-flight appeared on the scene, the BossaBreeze Albatross, fewer than ten human-powered airplanes have been completed and flown. If pedal-planes were like the vast array of technological entities, they would be listed as an endangered species. Henry Kremer put up his generous prizes in part to encourage physical fitness through sport flying. And members of Britain's Royal Aeronautical Society, creators of the Kremer Prize rules, have always maintained that they sought to encourage "more practical" human-powered flight. Yet the recent contest, the Kremer £100,000 Speed Challenge, is resulting in craft like Monarch and Bionic Bat which compared to earlier pedal-plan designs demonstrate that Kremer Prize rules have not entirely healthy influence on what participants have created. The primary thing that has been disallowed is the use of lighter-than-air. Only the use of pedal-plan designs which encourage only certain modes of travel. Until I flew this airship, I didn't feel the Kremer Prize rules are "fair and square". But isn't that ridiculous? Aren't the esteemed gentlemen of the Royal Aeronautical Society ignoring their pledge to encourage human flight? If the true purpose of the Kremer Prizes is to popularize a sport which features people flying around the sky by their own power, why put conditions on it? It's as if someone had a literary contest which would only accept handwritten entries presented on home-made paper, or a literary contest which would only accept things written on a typewriter or word-processor as being an "unfair advantage".

The craft which makes me ask these questions is the Dunkirk Dwarf, a single-person pedal-powered blimp designed by Bill Watson of Van Nuys, California. This airship came about because the owner, Bill Gallagher, felt there should be things like it in the world. Our experience with this machine is that it deals much more effectively with the problems of cost, weather limitations, skill demands, pilot fitness, and structural complexity that have so far plagued all flyable human-powered aircraft. We have discovered that nearly any adult who weighs less than 114 kg (250 lb) can fly our pedal-powered blimp and have a lot of fun doing so. With the much simpler structure made possible by using helium instead of wings for lift, the White Dwarf is stressed for nearly five g's. This strength allows safe exploration of that third dimension, the vertical lift which makes flight different from all other modes of travel. Until I flew this airship, I didn't fully realize how constrained pedal-planes are. While testing the 60-foot span high and low, we came up against the temptation to fly hight the Icarus Syndrome. With a plane good for one and one-half g's ultimate, flying anything more than about one meter high was very foolhardy. Yet so great was the temptation to truly fly as do eagles rather than just skimming the surface like a hovercraft or a coromant that we would sometimes find myself fifteen meters in the air, a fatal height to fall if catastrophic failure were to occur. Such in-flight failures did happen several times with both the Condor and Albatross, Luckily at low altitudes. The White Dwarf allows pilots all fitness levels to safely enjoy what I call the "Stairstep Effect"; this is the feeling you get when ascending in a human-powered aircraft, the feeling as if you were walking up an invisible set of stairs into the air. Flying this blimp is truly like dream-flight. If you want to go over and check out the top of a tree, then rise up and drift meditatively in mid-air, with it you can do so. Yet even for more back-to-earth reasons, Mr. Dwarf has major advantages. When the blimp is on the ground, we have found it much less susceptible to winds than any other pedal-powered aircraft I know. Ground-handling the Dwarf in 6.2 to 7.2 m/s (twelve- to fourteen-knot) winds requires only two people. The BossaBreeze Albatross would be destroyed if taken outside in such winds, and even Bionic Bat is a handful the tailvecation. But for a gas blimp, human-powered flight is becoming an increasingly arcane discipline with but a handful of participants. I feel the Kremer Prize rules are in large part to blame for this.

5

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NOTE: ALL PERFORMANCE FIGURES HAVE BEEN VERIFIED BY FLIGHT TESTING
The White Dwarf, conceived and owned by comedian Gallagher, flies against an early-morning sun near Camarillo, CA, piloted by its designer, Bill Watson.

Specifications of WHITE DWARF:

Powerplant - Human power via pedals
Length - 14.6 meters
Height - 8.2 meters
Width - 4.6 meters
Envelope volume - 176 cubic meters
Lifting gas - Helium
Seats - One
Empty mass (no ballast) - 56 kg
Gross mass - 180 kg
Pilot mass range (sea level) - 40 to 114 kg
Pilot mass range (5000 feet) - 40 to 96 kg
Minimum speed - Zero m/s
Cruise speed - 4.2 m/s
Maximum speed - 4.2 m/s
Range - Depends on physical strength and endurance of pilot
Envelope type - Raven Industries TIF-6000, modified
Fuselage materials - Aluminum tubes, mainly 2024-T3, with aluminum gussets and stainless bracing cables.
Propeller - 1.63 m diameter with ground-adjustable pitch, spruce/foam
Altitude control - Lever on left side of seat alters thrust vector through 100 degrees
Lift equilibration - gas valving and water-ballast disposal, controls on left side of seat.
Directional control - Wheel moves rear rudder through 160 degrees total travel
Fuel capacity - Zero gallons

MR PROPELLER

So far, all the human-powered vehicles that have broken records or won awards in the air or on the water have been propelled by - propellers. That is not remarkable. What is noteworthy is that every propeller, whether on aircraft or on boats, has been designed by methods that came directly from one person: Gene Larrabee, who retired recently from the faculty of the Aeronautics and Astronautics department at MIT.

His design had a dramatic debut. It was being used on a delightful but noncompetitive HPA at MIT, the Chrysalis. Paul MacCready heard that the MIT aero students had a slow biplane with a great prop, and asked if he could use the prop for his Bossler Albatross in its attempt on the Kremer cross-Channel prize. Rather than being grounded without a prop, the MIT group (in the person of Mark Drela) designed a specific propeller for its AeroVironment rivals. Paul MacCready had it made and fitted to the Albatross. The first time Bryan Allen took the plane up with the new propeller, he stayed aloft for an hour, instead of the ten minutes to which fatigue had previously limited him. The higher efficiency of Larrabee’s design approach was convincingly demonstrated. From then on, everyone had to use a so-called "minimum-induced-loss" design.

Gene Larrabee will modestly point out, as he did in his article in the last HP, that his methods are simply developments of those previously laid out by Betz, Prandtl, and Goldstein. So be it; all good ideas seem obvious once they have been proven. Gene Larrabee was nevertheless the person who enabled some significant achievements to take place when they did. If he lived in Britain he would stand a good chance of being knighted "Sir Propeller". Here he will have to make do with being Human Power’s "Mr. Propeller".

Thank you, Gene.

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This fascinating review is about one-half of a paper in a symposium at the Royal Institution of Naval Architects, London, September 9, 1964, called "HUMAN-POWERED MARINE VEHICLES: OARS, PROPELLERS, PADDLES." The complete set of the proceedings of the symposium can be had on request from the RINA, 37 Upper Belgrave Street, London SWI 8AQ, UK, for $15.00.

This paper is mostly about maximum possible speeds of some types of HPBs and the construction of one type of radical design.

RESISTANCE TO MOTION

The weight of the boat and rider can be supported by submersion or submerged buoyancy, by planing surfaces or foils, or by combinations of all these. Each method has different amounts of skin friction, pressure drag, and wave drag and offers all of which scale up differently with increasing speed.

At low speeds, surface-bouyancy hulls have very high lift-to-drag (L/D) ratios and extremely efficient craft are possible without much sophistication even using human power. A person can pull a barge weighing many tons at walking speed or propel himself slowly with a quite simple craft, using less effort than walking.

At higher speeds, all drag sources increase, but especially wave drag, which effectively limits the speeds of most surface shapes other than very long, thin ones. Modern racing shells are highly refined craft with hulls of this type optimized for minimum combined wave drag and skin friction.

Wave drag can be eliminated by using deeply submerged buoyancy hulls, which are then limited only by skin friction and some pressure drag and, of course, buoyancy.

At even higher speeds, skin friction becomes so large that less drag is incurred by supporting the boat on small hydrofoils or, ultimately, using low-aspect ratio airfoils. A separate class of vehicles has moving-skin mechanisms to reduce skin friction.

SUBMERGED-BOUYANCY HULLS

The drag of a fully submerged streamlined "torpedo" shape is predominantly skin friction with some pressure drag caused by the boundary layer separating before reaching the tail. There is also some wave drag, depending on the depth of submersion, becoming negligible when the boat is submerged more than five diameters. The skin-friction drag coefficient $C_D$ which is based on the wetted surface area of the shape, is a function of the Reynolds number $Re$ and the diameters. The skin-friction drag coefficient $C_D$ is

$$C_D = \frac{2}{Re^{0.8}}$$

where $Re$ is the Reynolds number or $Re = \frac{\rho U L}{\mu}$, with $\rho$ being the density of the water, $U$ being the velocity of the boat, $L$ being the length of the boat, and $\mu$ being the dynamic viscosity of water.

As seen in the graph, there is a region where the value of $C_D$ can lie anywhere between the two lines, depending on how far along the shape the boundary layer gets before turning turbulent.

A 3-meter-long shape going 5 m/s (10 knots) has a Reynolds number of about $2 \times 10^5$ in ordinary water. It would seem from wind-tunnel and tank tests that there is no hope of laminar flow in this region, but if the flow can be kept laminar by the use of certain tricks, $C_D$ would be very low indeed.

LAMINAR FLOW

In order to keep the boundary layer laminar as long as possible, sections are used that have their greatest thickness at the point of minimum pressure (quite far back from the nose, sometimes as much as 65%). Carmichael, Kramer, and Knoll have used shaped sections with such sections for gravity-supported underwater vehicles and report laminar flow up to $Re = 1.8 \times 10^5$ and very low values of $C_D$. This was probably possible because the tests were conducted in still water with no machinery vibrations to facilitate boundary-layer transition. Further methods to keep extensive laminar flow are the following:

The boundary layer can be sucked away by making parts of the hull porous and pumping out the water (4). This also removes pressure drag, as there is then no separation and no wake. If the suction is done correctly, drag coefficients can be halved (2).

Long-chained molecules such as polyethelene oxide can be pumped out ahead of the hull or leached out through the skin. This damps out the vibrations and eddies which are the initial cause of boundary-layer transition. These chemicals can be of low toxicity and are cheap enough for use in a speed-record attempt.

A separate class of vehicles has moving-skin mechanisms to reduce skin friction.

SUBMERGED-BOUYANCY BIG ENOUGH TO CONTAIN A PERSON

Submerged buoyancy big enough to contain a person would have at least ten times the drag of the optimum size needed for buoyancy. The rider must therefore be perched above the water on a strut, which can contribute as much drag as the hull itself. This configuration is far less stable than even a high circus unicycle, as water cannot resist a push with zero relative speed, and once the vehicle starts to tip, there is also a vertical capsizing force from the submerged buoyancy. At high speed, the submerged float could be steered with quite small control surfaces, and either produce a righting torque directly or, using a bow rudder, steer the vehicle into a fall like a bicycle, thereby causing a righting force. However, in practice, the rider must mount when the vehicle is stationary, and some static stability is needed.

This can be achieved with floats on riggers; obviously the longer the outriggers, the smaller the floats can be. These must bear some proportion of the boat's displacement at rest, because when one float begins to resist a tipping torque, the opposite one is unloaded by the same amount, causing the submerged buoyancy to surface if not preloaded by at least this amount.

STABILIZATION OF SEMI-SUBMERSIBLES

Stabilization of fully submerged hulls is mostly about maximum possible speeds of some types of HPBs and the construction of one type of radical design. The rider must therefore be perched above the water on a strut, which can contribute as much drag as the hull itself. This configuration is far less stable than even a high circus unicycle, as water cannot resist a push with zero relative speed, and once the vehicle starts to tip, there is also a vertical capsizing force from the submerged buoyancy. At high speed, the submerged float could be steered with quite small control surfaces, and either produce a righting torque directly or, using a bow rudder, steer the vehicle into a fall like a bicycle, thereby causing a righting force. However, in practice, the rider must mount when the vehicle is stationary, and some static stability is needed.

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**HUMAN-POWERED BOAT**

Unlike most boats, pitch stability is completely lacking and must be carefully added as a lateral stability. This can be done with very long lateral floats or with a triscape or tetrascape arrangement. Obviously the floats will cause considerable drag, even if replaced with hydrofoils, and should be taken above the water at speed, when dynamic control must take over.

Fully submerged hydrofoil boats are not as difficult to stabilize, as at slow speeds a supporting hull is necessary anyway, and at speed the craft can be steered by moving the foils.

Static-stability problems can be mostly avoided by using three submerged hulls (or hydrofoils). They must still be carefully trimmed out at rest and steered in 3 axes at speed, but outrigger floats or mounting are not necessary. With one person on each hull, the complete vehicles would have the same top speed as a single one with no outriggers.

**SCALE EFFECTS**

Displacement hulls scale up favorably, as wetted surface increases with the power of only 2/3 of the displacement and C will decrease with speed after the rise due to boundary-layer transition. Human-powered ships could therefore be faster than HPBs, although an upper limit would eventually be set by the increased weight of ship's structure necessary per person.

Hydrofoil boats do not scale up favorably, even powered ones, as the L/D of the foils does not increase, but may decrease due to cavitation.

**MOVING-SKIN VEHICLES**

Displacement and hydrofoil boats are unlikely to ever exceed about 10 m/s (20 knots). Ground-effect devices could do better, but this would be just as much air or land vehicle as a boat.

A further class of vehicles does not appear to be intrinsically limited to these speeds. Skin friction can be eliminated almost completely by moving the hull skin at water speed. The friction of good mechanical or magnetic bearings can be extremely low, so if the skin can be adequately supported and recirculated, the overall L/D could be many times that of other systems at speed. As the amount of wetted surface does not then matter much, the hull can be extremely long and thin or wide and flat, thus nearly eliminating wave and pressure drag.

In practice, this is a daunting task. Unless it somehow floats on air or magnetic bearing, the skin must be supported by rollers and will sag between them, creating drag. If the skin is stiff enough to resist sagging, it is likely to suffer considerable hysteresis losses in bending it around. The mechanisms must be supercritical to give any benefit.

**PROPULSION**

All vehicles propel themselves by imparting momentum to some medium, this being water for most boats.

The Rankine/Froude momentum theory of propulsion gives as the ideal limiting (Froude) efficiency of any propulsor:

\[
\eta_f = \frac{1}{4} \frac{v}{V}
\]

where \(V\) is the fluid speed at the ideal propulsor, and \(v\) the speed increase behind it. (The total speed increase between some distance upstream and downstream is taken to be \(2v\)).

In the case of propellers, this can be written as:

\[
\eta_f = \frac{C_T}{1 + \frac{2}{C_T} + \frac{C_T}{C_p}}
\]

where \(C_T\) is the thrust coefficient where \(F\) is the thrust, \(\rho\) the density, and \(A\) the swept area of the propeller.

It is seen that in order to obtain a high Froude efficiency, a relatively large mass of water must be accelerated by only a small amount, i.e., for a given thrust, the larger propeller is the more efficient. Fast vehicles can have reasonable effectiveness with small, highly loaded propellers, or even jets or airfoils, but slow boats need relatively large propellers to perform efficiently.

Propellers have other losses than the ones implied by the above; energy is lost in the tip vortices of the blades and in the rotation of the wake. The latter can be counteracted by the use of counterrotating, coaxial propellers and tip losses can be reduced by using high-aspect-ratio blades, but there is a structural limit to this.

Betz and Goldstein worked out a theory for radial distribution of thrust along the blade which gives minimum possible induced drag. This has been refined by Larrabee at MIT and used to design propellers for human-powered airplanes and more recently HPBs. These propellers can just exceed 90% total maximum efficiency in contrast, motor-boat propellers might have only 50 to 70%. This is because these are often too small, have highly loaded blades which must then be of a small aspect ratio for structural reasons, and too cavitate.

There are many other propulsors utilizing lifting surfaces, but these are usually quite complex. Nature has provided marine creatures with highly efficient and practical bodies and tails for propulsion, but these are very difficult to imitate successfully.

Thrust can also be obtained by using surfaces providing pure drag, such as sails and paddle wheels. It is not very difficult to work out the total efficiency of drag devices.
SUBMERGED-HOYANCY
HUMAN-POWERED BOAT

Consider a hull with drag coefficient of \( C_D \) and related area \( A_D \) travelling at speed \( V \) and pulling with force \( F \) against a drag device with \( C_D \) and \( A_D \) which is slipping in the water with speed \( v \). Then power used for propulsion is \( FV \) minus work input is \( F(v + V) \).

\[
\eta_{\text{efficiency}} = \frac{FV}{F(V+v)} = \frac{1}{1 + v/V}
\]

A similar expression as for the Froude efficiency, but here it is the total one. As \( V^2 = F/2C_D A_D \) and \( S = F/2C_D A_D \).

Comparing the efficiencies of propellers (total efficiencies of minimum-loss propellers are perhaps 5 to 15% less than their Froude efficiencies) with those of drag devices (see table), it is seen that at ordinary sizes, propellers and the like can be far better than drag devices, which are limited by the fact that pure drag coefficients in water do not exceed about 1.5.

At extremely low loadings, a drag device can, however, reach any desired efficiency by making it big enough, whereas propellers of any size are limited by the finite L/D ratios obtainable by foils. The maximum blade efficiency of a pure foil (i.e. assuming no tip and swirl losses) can be shown to be approximately: \( \eta_b = 1 - 2(0/L) \). As foils probably cannot exceed an L/D ratio of 100 in practice, 98% appears to be the limit for propellers. In reality 95% is probably the maximum figure even for very well-designed and constructed ones.

Drag devices must by their very nature operate intermittently, and it is the cost of recycling the rather large surfaces that limits their efficiencies in practice, even if there appears to be no well-defined theoretical limit.

For example, winching one's boat up to a large parachute deployed in the water could achieve over 99% momentary efficiency, but the energy cost of periodical redeployment makes this method impractical, although it has been suggested by Job (12) for moving icebergs. He has calculated that even with redeployment, total efficiency is higher in this application than using tugboats.

DESIGN AND CONSTRUCTION OF A SEMI-SUBMERSIBLE HPB

First, the section of revolution had to be chosen. A laminar-flow section is preferable. The ideal 1/d ratio of about 4 for a deeply submerged hull is too small for a shape operating near the surface, as this would have more wave drag than a thinner hull at the same depth. Therefore the section chosen was the NACA 0010-35, which has a 1/d ratio of 10 and is nearly symmetrical fore and aft with the maximum diameter exactly in the middle chordwise. This is easier to make than the NACA 66 family of sections with their tricky concave curves, and also appears to have the lowest two-dimensional drag coefficient (at zero lift) in the book (5).

A short computer program was used to work out the necessary dimensions given data from (5), resulting in these formulae:

\[
V = 0.004695 \sqrt{A}, \quad 1 = \sqrt{213} V
\]

For ellipsoid with \( a = 10b = 10c \):

\[
A = 0.2273 \pi^2, \quad 1 = \sqrt{191} V
\]

Target volume was 95 liters, giving the required length \( L = 2.72 \text{ m} \) and the resulting wetted area \( A = 1.68 \text{ m}^2 \).

The hull was made from Styrofoam discs cut out on a hot-wire jig to the correct diameters and angles, glued together, lightly sanded and filled, covered with a layer of lacquer both in epoxy, with some carbon fiber near the central hole for housing the bevel-gear box which connects the propeller shaft to the upper drive system. This is a simple bicycle chain drive, with the chain passing through the strut. Also incorporated in the foam were forward and aft buoyancy trim tanks with control tubes going up the strut. Further tubes were put in for rudder and elevator control, for a pitot speed gauge, and for releasing polymers from the nose.

Four stabilizing floats were made in the form of buoyant triangular surface-piercing foils which are connected to the top structure with a framework of metal tubing.

PRELIMINARY RESULTS

Numerous tests in a swimming pool showed the problem of static stability to be a difficult one, and with hindsight, the chosen buoyancy of 95 kg was too high, even for the 73-kg author, and the trim tanks always had to be completely flooded.

Two outings in the sea revealed that the test boat suffered from insufficient stiffness of the outrigger structure, and the and the ensuing balancing act detracted from pedaling power. This wasn't great anyway, as a calculation error resulted in a wrongly pitched propeller, and the vehicle didn't manage over 4 knots.

HISTORY OF THE SEMI-SUBMERSIBLE IDEA

This is not a new concept; it was proposed by Morwood in 1961, examined by Brewster (11) in 1979, and suggested to me by Sanderson. Huppes also built a similar vehicle in Amsterdam some years ago.
This would be stable, increase drive efficiency, and avoid submerged bouyancy by itself.

Total efficiency of a hypothetical propulsor with ideal blades of L/D = 50, no tip or swirl losses:

- 500 mm: 94.5%
- 400 mm: 98%
- 300 mm: 96.5%
- 200 mm: 93%
- 100 mm: 80%

Total predicted efficiency of typical Larrabee propeller:

- 500 mm: 88%

Total momentary efficiencies of drag devices with $C_D = 1$ at optimum angle:

- Cars: $0.1 \text{ m}^2$, 76%
- parachute: $20 \text{ m}^2$, 98%

**REFERENCES**

7. AVRS Publication No. 100, article on propellers by R. Frank
GARY HELFRICH: MASTER FRAMEBUILDER

DW: Very similar to Shawn Buckley's experience at MIT. His seminars on building aluminum bicycle frames were always over-subscribed — often 50 at a time. Gary Klein was one of his students.

GH: One of my students, Larry Dumont, became a framebuilder for Jim Desilva at Laughing Alley. He still races the stainless-steel bike he made in my class.

DW: I'd be worried about the fatigue resistance of stainless steel.

GH: Agreed. But he used commercial Reynolds 531 forks.

DW: Other than the forks, I'm scared about fatigue failures near the joints of top and down tubes with the head tube, especially with small frames when the head tube is very short. Then the twisting torque from pulling on the handlebars to counteract pedal forces seems to produce high local stresses.

GH: Don't agree: I've found just the opposite. It's the frames with a long head tube, and therefore a trapezoidal rather than a triangular frame, that seem to have more failures there.

DW: I hope that we can encourage some analysis. But to get back to your story — did you go full time on frame building then?

GH: No, I hadn't enough experience. I learned most of what I know from Prof. Dick Murphy of Northeastern. Wayne Kirk was the leader of the HPV project, which developed from an earlier ASME go-cart type of project. The Northeasterners were unfortunately influenced by a group of MIT students led by Rondo Mepham, who wanted to make a long-cigar with a huge number of peddlers. I became an expert at welding bike wheels into pairs for both groups. Prof. Murphy's grounding led me to studying more about welding for myself, and I persuaded Chris Chance to switch from brazing to welding his frames.

DW: So you really believe that welding is better than brazing for bicycle frames. Why?

GH: Well, those beautifully hand-welded BMX competition bikes took a beating and never came apart. During the time we were making both brazed and welded frames, we had far more trouble with the brazed frames.

DW: But brazing doesn't affect the properties of the steel, while in the heat-affected zone near the weld in welded frames, the properties must change for the worse?

GH: You would think so, but we have made several-hundred welded-frame bikes, and we have never had a weld failure or a failure of a tube near the weld. At first we had a combination of both — a welded frame with brazed-on reinforcements — but we had cracks near the brace and not near the weld. So now we make the head tube, for instance, machined from a single piece and welded, and have had no troubles.

DW: What tubes do you use?

GH: Aircraft-grade chrome-moly. We find it much better than bicycle tubing. But Tange is making a big effort to produce top-quality bicycle tubing. Tange himself, the president of a large Japanese steel company, appeared right here in our workshop. We have a set of his new tubes to evaluate. We feel that there is a stigma against Japanese tubes, and that the only people who would be willing to experiment would be mountain-bike builders, because they are not bound by tradition. Our tubes are 1-1/4-inch (32mm) diameter, and Tange has given us some 4140 tubes that are 0.015-inch (0.38mm) thick at the center and 0.022-inch (0.55mm) at the ends, with the yield improved to 175 ksi (1.21 GPa). Fatigue strength increased by 50 percent through cold working and quality control. You had convinced me during our trip to New York that we should design to fatigue limit rather than yield point or ultimate.

DW: All your welding is TIG (tungsten inert gas). Tell us something about that.

GH: It's the same as Heli-Arc. It was invented by Linde, and used helium at first, because helium was a by-product of natural-gas production and pretty cheap. Now a cylinder is $100. It doesn't live to stay on the work (as a shield) so you have to use a huge flow. So argon which used to be more expensive is now cheaper (about $40 a cylinder), and you can use about a tenth of the flow. It really sits down on the work. We use helium only for welding aluminum.

DW: Why?

GH: Because aluminum conducts heat away so fast we really have to dump in the power. TIG welding is pretty well a constant-current operation. Argon has a low ionization voltage — 12-20 volts — so the power level is moderate. Helium has an ionization voltage of around 35 volts, so we can get much more heat into the aluminum and get the job done faster.

DW: So for the chrome-moly frames you stick to argon?

GH: Actually we use a mixture of argon and hydrogen. Wayne Kirk kept hammering away that high-tech people must know more about welding than the bicycle builders. So I talked with people at the GE jet-engine plant at Lynn, and 2-percent hydrogen, just enough to wipe off the oxide layer and turn it into steam. So we have a spotlessly clean surface to work with. More hydrogen and we would have the danger of hydrogen embrittlement.

DW: How do you get that close a mixture? Is that the mixer there?

GH: No, that's the glycol heat exchanger — I use a glycol-cooled torch body. I bought the same equipment that GE uses (indicating an impressive-looking welding device covered with dials and controls, a Miller Synchrowave 300). We buy the pre-mixed argon-hydrogen mixture from Airco.

DW: Are you willing to say what the future holds for materials, designs, and you yourself?

GH: Well, as for materials, I think that we should stay away from aluminum, particularly welded aluminum. Titanium has gotten much less expensive than it was. For a frame set the tubes might cost $65 versus $30 for a steel frame. Pure titanium has superb fatigue and corrosion resistance. I can TIG-weld it and it doesn't need heat treating. I can save a hundred bucks on painting needed for the
DEVELOPMENT OF A HUMAN-POWERED RACING HYDROFOIL

by David J. Owers

SUMMARY

A human-powered racing hydrofoil craft has been designed, built, tested and developed over a period of one year. At speeds above 4 m/s (9 mph) the craft requires less than half the power normally required in a conventional sailboat. An athlete should be able to power such a craft through its take-off speed of about 3.5 m/s (7.8 mph) to speeds approaching 6 m/s (13.5 mph) in foilborne mode. This is approximately the speed of Olympic rowing eights over 2000m.

The first prototype required 287 W of effective power for take-off, which occurred at 3.6 m/s. Due to low transmission efficiency and excess weight, however, the cyclist was able to power the boat to only 3.5 m/s, at which point the hydrofoil supported only 80% of the total craft weight.

It was with this average speed over 200m that the craft won the first European competition for such craft at the Thamesmead Festival of Human Power in July, 1984.

Developments have been made in propeller design which proved successful in tests during September, 1984. These, plus the use of composite materials, will ensure the success of such craft over the coming year. Already a human-powered hydrofoil designed by Alec Brooks and Allan Abbott and powered by Steve Hegg is claimed to have reached 15 mph.

1. INTRODUCTION

Everybody wants to fly. However most of the airborne goals of man have now been achieved: powered flight, human-powered flight, even human-powered airships. Tremendous effort has gone into this sphere of activity and the rewards have been well deserved. Similarly, the development of the humble bicycle, though not so rapid, is now racing ahead. However, progress in human-powered-boat design has been very slow. Racing shells dominate the scene today as they did in 1890.

2. THEORETICAL DISCUSSION

The intuitive reaction of most engineers to the suggestion of a human-powered hydrofoil is that insufficient power is available for "take-off". This is not so. The engineers may well prefer to be convinced by the test results given later in this paper. A theoretical analysis does, however, predict the test results with reasonable accuracy, although a caveat must be expressed regarding hydrofoil performance data.

The analysis proceeds upon the following lines:

- We assume that, if the boat will "take-off", then it can continue to travel in foilborne mode, and we judge its operation feasible.
- We assume that it will take off at 3.5 m/s.
- By researching the literature we attempt to predict the drags associated with the following components as accurately as possible:

  1) the hull (in displacement mode);

As we walked out of Gary's cluttered but effective workshop, talking about the 1 importance of youth, he indicated a miller set up to alter tubes. Last year he slipped on something which was on automatic feed. His right hand went through the feed handle, which was rotating, breaking his arm and wrist in several places. The stop switch was on just out of reach. Gary is a powerful guy, and he managed to kick the transmission out before his arm was torn off altogether. He said that he learned that he was not immortal. His arm will always hurt, and he has limitations in movement, but it's working pretty well. He got a wry grin, and said that it was a way of teaching us to work our stop buttons around power equipment.

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Fig. 1. The Effective Power Requirements for...
Development of a Human-Powered Racing Hydrofoil

iii) hydrofoil profile drag; and

iii) hydrofoil induced drag.

- Parasitic drag is ignored.
- Knowing the speed, we calculate the aggregate power requirement to overcome these drag forces.
- Making assumptions about the various components of the transmission system, we arrive at a human-power requirement.

2.1 Symbols

Throughout the analysis, the following symbols are used.

\( A_{ws} \) Wetted surface area of the hull \( \text{m}^2 \)

\( c \) Chord of the hydrofoil \( \text{m} \)

\( C_D, C_L \) Drag and lift coefficients respectively for the hydrofoil immersed in, and moving relatively to, the water

\( s \) Span of the hydrofoil \( \text{m} \)

\( V \) Relative velocity of the craft \( \text{m/s} \) passing through the water

\( \rho \) Density of water \( \text{kg/m}^3 \)

2.2 Analysis

Hull drag: a summary of literature relevant to this calculation may be found in Owers (3). The formula that emerged as best explaining the the drag of a vee-hulled racing kayak was

\[ \text{Hull drag} = 1.27 A_{ws} V \]

Hydrofoil profile drag: classic aerodynamics defines the drag coefficient by

\[ \text{Profile drag} = C_D \frac{1}{2} s c \]

Hydrofoil induced drag: again from aerodynamic theory:

\[ \text{Induced drag} = \frac{2 C_L}{\pi} \frac{1}{2} s c \]

Hydrofoil wave drag is assumed to be negligible, following the conclusions of Sakic (9) and also Buermann et al (10) that it represented less than 1% of the drag of a small craft.

Putting numbers to these drags we need, in effect, to design a boat. We shall use one in which:

\( A_{ws} = 0.6 \text{ m}^2 \)

\( c = 0.102 \text{ m} \)

\( s = 1.524 \text{ m} \)

and we shall further assume that the density

\( \rho = 1000 \text{ kg/m}^3 \)

The most difficult numbers to find are the hydrofoil lift and drag coefficients. Many references do not cover the Reynolds-number range \( 1.0 \times 10^6 \) encountered by this craft. Of those that do, three are listed in table I for a NACA 4412 aerofoil. It will be seen that they are by no means identical. Ramadan's figures (6), obtained from a questionable experiment, give far lower lift-to-drag ratios than the others. However, we will take his results for the purposes of this analysis. Assuming an angle of attack \( \alpha \) of 7,

we have

\( C_D = 0.04 \)

\( C_L = 0.76 \)

Substituting these numbers we obtain:

\[ \text{Hull drag} = 61.12 \text{ N} \]

\[ \text{Profile drag} = 37.98 \text{ N} \]

\[ \text{Induced drag} = 23.39 \text{ N} \]

Total drag \( 122.57 \text{ N} \)

The power requirement is thus:

\[ 3.5 \times 122.57 = 429 \text{ W} \]

2.2.1 Transmission-system Efficiency

Figure 2 shows the transmission system. The efficiencies are as follows.

Drive chain plus derailleur mechanism 96 %
Crankshaft bearings 99%
Bevel gears and bearings 95.5%
Propeller-shaft bearings 98%
Propeller 68 %
Overall efficiency 60.5%

Fig. 2 Transmission System

Fig.7 Propeller Slip - vs - Thrust Relationship
Note that the propeller efficiency is the critical factor. This will doubtless be the subject of some discussion.

Using this efficiency, which is by no means optimistic, we obtain a human-power requirement of

\[ 429 \times 100 = 709 \text{ W} \]

Figure 3 shows a good summary of human power capability from Whitt and Wilson's *Bicycling Science* (1982, ref. 5). From it we see that an athlete could indeed develop 709 W, but only for twenty or thirty seconds. It was for this reason that the author did not favor the "jettisoned hull" design proposed in the U.S.

One check remains to be carried out on the hydrofoil analysis, and that is to ensure that enough lift is developed by the hydrofoil to support the total weight of the craft. The lift achieved is

\[ \frac{CL \cdot \rho \cdot V^2}{2} \cdot S_c = \text{722 N} \]

Since it is possible to conceive of a pilot weighing, say, 620 N (10 stone) and a craft weighing 100 N (a Kevlar craft weighs about 30 N), the particular example under analysis supports the feasibility of a human-powered hydrofoil.

The foregoing example is a very crude simulation of what actually happens. Although it ignores parasitic and wave drag, and postulates a quite impossible single hydrofoil, it is in fact a pessimistic model, for the following reasons.

In the analysis we assumed that the hull drag at 3.5 m/s would be given by the displacement-mode equation, using the wetted-surface area 0.6 m². This is, however, the area at rest when the hull supports the entire craft weight of 720 N. By the time 3.5 m/s is reached, the hull is nearly out of the water and the hull drag is dramatically less than the 61 N allowed for in the example.

A desk-top-computer program to try to simulate this effect was written, employing an iterative technique to try to optimize the foil shape for given craft weights and foil-performance data. It was thus possible to test the sensitivity of the power requirement to these factors. The results are shown in figures 4a and 4b.

These predictions have the pessimism of the first example removed and may be truly said to be "idealized". They are useful for comparison, however. Figure 4a shows how a high-aspect-ratio (s/c) hydrofoil will be easier to power to take-off but will make it harder to achieve high speeds. Figure 4b illustrates how the data source affects the predicted power, and why there is really no substitute for building a boat and measuring the drag!

The curve for Ramadan's data (fig. 4b) is the equivalent to the example studied above. We see that take-off is predicted to occur at c. 4 m/s and the power requirement is two-thirds that which we calculated, due to our "double-counting" of hull and hydrofoil drags.

---

**Fig. 3 Summary of Human-Power Capability Data (Whitt & Wilson, ref. 5)**
It is interesting to compare these performances with conventionally-hulled boats. Brewster (2) conveniently did this, although postulating a slightly different design of hydrofoil boat in his 1979 thesis. His results are shown in figure 1. His analysis did not allow for a combined shell/hydrofoil craft, but it can be seen that the critical speed where the hydrofoil becomes superior to a shell is about 3.5 m/s, while it outperforms even a submerged torpedo (W.B. Theodore Schmidt article) beyond 4.0 m/s.

I have tried to combine these two sets of predictions in figure 6 to show the whole gamut of predicted power requirements from pessimistic to ideal: see how much better we are likely to be able to achieve 6.0 m/s with an effective power of c. 300 W — well within human capability for extended periods — with other sets of results suggesting we can take off at this power level, and soon encounter a "wall", making speeds of 5 m/s or above impossible.

It is almost a matter of faith as to which of these analyses you prefer. The author's experiences have "converted" his firmly to the optimistic end of the spectrum. The rest of this paper, on the more practical aspects of this art, aims to preach this gospel.

3. DEVELOPMENT OF A PRACTICAL CRAFT

Encouraged by the foregoing analysis and by James Grogano, who lent me his sailing/sculling hydrofoils, I designed and built a plywood kayak and fitted it with an efficient transmission from pedals to propeller. The craft was designed for 90% of its weight to be supported by the fully-submerged main foil. The small vee-foil at the bows doubled as a rudder, and it took the remaining 10% load. The main foil was of solid aluminum, but could be twisted elastically by hand. It proved to be ideal for controlling the roll of the boat — by far the most unstable mode. The pilot was able to control the angle of attack of the foil on both sides. Thus, if the boat rolled to port, he could increase the angle of attack on that side, generating more lift and righting the boat. In eight weeks of tests up to 20 mph the boat never capsized!

3.1 Towing Tests

Shoe-horned into this odd craft at the start of an evening's towing tests, the pilot could have been forgiven for questioning his sanity. The lake is highly exposed, and windsurfers and waterskiers do not look as if they are going to make way for you even if you have their peers' permission. Your motor-boat driver is very well-meaning and helpful but may not realize just how precarious this strange boat feels. Your colleague in the motorboat, whom you pressurized into taking an evening off by offering liquid refreshment at the close, has the speed and tow-rope force measurements as well as making qualitative observations and instructing the motor-boat driver. Will he notice if you fall out? It really doesn't feel very stable at all. Musing along these lines, I cheerfully gave the "OK" signal to the motor-boat, and we began to thread our way out to the calmer side of the clay-pit lake. Up till then we had tested the boat without foils to validate the hull-drag expression used in the theory. (It was accurate to within 5% up to 6.0 m/s.) The tests so far with foils had been disastrous. First, the support mechanism had broken, then control had been such a problem that the whole system had to be re-designed. It was a much firmer and sturdier system that now challenged the waves.

The waves were getting ominously large. from such a low level you need a swell of only a foot or so to obscure everything but Concorde from view. The observer would try to adjust the tow-rope length so that the front foil of the boat did not coincide with a trough in the motor-boat's wake, as this led to "crashes": the small vee-foil, having no water to support it, crashing back into the foam.

Nevertheless, all seemed as stable as I knew it could be. I signalled for the start of a test-run once we arrived at the calmer, less-populated far side of the lake. As 3 m/s (6.7 mph) was approached, control became trickier. Later we found this was almost entirely due to the towing mode — under human power all is more predictable. Spray from the motorboat, together with the new controls, made an interesting ride. At this point, too, on all previous runs, something had broken and we had had to limp home despondently.

This time, however, we carried on up to 3.5 m/s. All was well, if wet, but then I saw the front foil dip down. This had happened before and meant we were about to "crash". Nothing happened, though. Through the spray I could see my colleague pointing excitedly towards me and shouting at the motor-boat helmsman. Snatching a glance to one side I understood why. The bow foil had not dipped as I had thought — the main foil had lifted. The hull was three inches clear of the water.

Then, of course, it did crash. The boat had taken off at a speed of 3.6 m/s with a tow-rope force of 83 N. Hence an effective power of 300 W was necessary to achieve take-off. Although this is slightly higher than the computer predictions, it is of the same order, and within human-power capability. Once foilborne, the tow-rope force dropped, confirming the "power hump" shape of the predictions (fig. 6).

These results were encouraging, and I went ahead and completed the fitting of the transmission and the propeller in order to test the characteristics of the craft in human-powered operation.
3.2 Human-powered Operation

Availability of lakes, personnel, and motor boat had severely restricted the possibilities for towing tests. Human-powered trials were less demanding. Two men could handle the whole outing, which could be completed within four hours.

Measurements, however, became more difficult to take. The speed had been measured electronically on the motor boat in towing trials. This arrangement was too cumbersome to consider attaching to the craft itself. We resorted to (distance/time) measurements taken off shore, but accuracy suffered and instantaneous readings became impossible. The thrust, which had been measured by tow-rope tension, now had to be estimated from the propeller slip characteristic, which was assumed to be linear.

The only points on the curve which we could check were the zero- and 100%-slip conditions. At 100% slip, we were able to measure thrust forces in the propeller shaft when measurements were made of the transmission, assuming the design pedal rotation of 120 rpm of the motor boat in towing trials. This enabled us to calculate the effective thrust from the propeller rpm and speed.

We then optimized the trim of the boat by conducting a series of trials with varying angles of attack of the small bow foil. As expected, an optimum angle emerged (1-1/2°), which gave minimum drag at 3.5 m/s.

We were then able to optimize the crucial operation of the main foil. It was hoped, at this point, that the pilot would be able to power up the boat to say, 2.5 m/s comfortably with the foil at minimum-drag angle (about 1°). Then with a burst of power he should take the craft up to 3.5 m/s and raise the angle of attack into the maximum-lift (3°). The momentum of the boat, plus pilot, would then help him over the "power hump" and into foilborne mode, at which point the foil could be returned to a low-drag angle (4°) while power requirement would be within aerobic capability.

This did not happen.

For two weeks we tried various modifications and methods of "take-off" control. There is no doubt that the ability of the pilot to control the boat confidently and effectively is as important as pure power input. This was found with the Boston whaler Abbatross. However, inexperience at controlling the new boat did not explain the disappointing performance entirely.

The cyclist acting as pilot was fit and strong. We knew from the color of his face that he was putting at least 275 W into the transmission for short intervals. Yet we knew from the towing tests that the effective power from the propeller was less than 300 W (or it would have taken off). Where was all that power going?

3.3 Analysis of Power Shortfall

Plainly the power was being lost in the transmission somewhere and yet I had been quietly congratulating myself on how efficiently and reliably it had all appeared to work. People had commented on how well-made the propeller looked.

However, my suspicions lay with the propeller. I lacked the facilities to test its efficiency under comparable conditions, so I had to work "backwards" to estimate its efficiency. Already, with the help of Theodore Schmidt, I have made progress in this area.

After meeting at the recent Thamesead Festival in London, Theodore Schmidt (a fellow HPB builder and consulting engineer on kite systems) offered to make a two-blade propeller to my basic requirements (pitch, diameter, and hub design) using ideas promulgated by Gene Larrabee of MIT. In fact, he made two such propellers, both of which were considerably lighter than my aluminum three-blade propeller, and both of his out-performed mine. On a bitter evening on the Thames at Putney we lacked the equipment to make any more than slight estimates of the efficiency improvement, but we think even these first attempts give us 10-20% better efficiencies. Gene Larrabee's computer program "Helice" gives efficiencies as high as 92% for similar propellers and his Boston whaler Abbatross propeller indeed achieved high efficiencies in the high 80s.

The second Owers 4rk now being constructed has a similar hull and lighter mainframe. Many hydrofoils and propellers will be made for it in order to compare performances of different configurations. Although the design is not yet finalized and I am open to ideas, I am confident that it already incorporates enough improvements to become the first practical human-powered hydrofoil - if I have not already been beaten to it by Allen Abbott and Alec Brooks, and other rivals in the United States.

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David's new boat is being sponsored by BOC Ltd., and is being built at British Aerospace, Neybridge, UK.

REFERENCES

TABLE 1

* Ramadan measured the total drag coefficient C_d.
Since the two-dimensional coefficient C_D has been used in the calculations shown in this article, the figures have been corrected, in the right-hand column, using the formula:

\[ C_D = C_{D_0} + \frac{2 C_L c}{s} \]

where:
- \( C_L \) = lift coefficient
- \( c \) = chord length (m)
- \( s \) = span length (m)

Comparison of lift and drag coefficients for the NACA 4412 foil used.

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Another of David Owens’ HPB designs is pictured on page 7.

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In the last issue of HUMAN POWER, a discussion of the paddle-HPB Madeleine was published without the accompanying illustration, due in part to lack of space, and in part to the poor reproducibility of the drawings supplied. A better copy has been obtained for this volume. Our apologies if the labels are still unreadable — the reader who desires a clear brochure may write to:

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TEL. 207-594-7587

About seven knots at full foot power.
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HUMAN POWER: A VALUABLE RESOURCE

by Ray Wijewardene

Editor's Notes: Ray Wijewardene's article came about because he was rash enough to write a complimentary letter to the paper in November '84, which started: "This is a note of many appreciation for the continued excellence of HUMAN POWER and the winter 1984 issue was a record-breaker! A small group of us here - right on the other side of the world - are deeply grateful to you and your team at the IHPPA for the opportunity you provide in HUMAN POWER to share with us your happenings in this fascinating field, your experiences and experiments." With that sort of accolade I had to write back to ask Ray to share some of his experiences as an agricultural engineer in Sri Lanka. We sent this article and a book he co-authored that I hope is required reading at the Peace Corps called CONSERVATION FARMING. I hope that we hear more from Ray later.

It was only a decade or two ago that anything hand-made was considered inferior - or else "cute" or "crafty"! Perhaps we need to thank OPEC for bringing us all to our senses. We have been made to realize the prolific self-indulgent waste of natural resources: first wood and then petroleum exploited as substitutes for muscle sources of power. I view with alarm a tendency for "energy-engineers" to search for alternative fuels for those same indulgences in the use of energy, and see in the efforts of the human power group one of the few sensible re-directions into the economic and efficient use of small energy sources. And what better start than the small-energy source of human beings and the new "respectability" that is now emerging for human-powered machines through the efforts of such groups as the IHPPA? The achievement of higher speeds through new designs of human-powered vehicles is one, very constructive, line of challenge. The development of faster human-powered craft on the water is another. Likewise the tremendous challenge of human power in flight, the exercise of superb skills in design, in engineering, and in aerodynamics that enabled the achievement of new horizons and concepts.

The optimization of the efficiency of human-powered operations requires three stages of development.

First, the fine-tuning of the source of power: the training of racing cyclists is an excellent example of this, as also the training of oarsmen. Perhaps the culmination of such training occurred in the training of aviator-cyclist Bryan Allen for his epoch-making human-powered flight over the English Channel.

Second, the development of the mechanism for translating that power, that source of energy, into a form where it could efficiently and conservatively be exploited by the objective in mind. The bicycle pedal-and-chain drive still performs as one of the most efficient of such translational mechanisms.

And third, the vehicle which utilizes that translated energy with still further efficiency and economy of the original energy source.

I believe that the achievement of still further excellence in the optimization of human-powered systems will depend on dedicated and individual effort in these three areas of development. I will first describe our own efforts to improve the economy of human power and facilitate its use, starting with two techniques used traditionally in the developing, tropical regions that bear considerable study.

The long-handed hoe in Figure 1 has proved in many studies its ability to dig, lift and turn a sod, or even to dig a pit or a drain, with greater economy of energy and time than use of the spade. The hoe efficiently utilizes gravity in the downward swing of the hoe to penetrate deeply. The pull thereafter to raise and invert over the sod is much easier than pushing and lifting as with a spade. As any golfer will confirm, the skill that goes into the swing contributes greatly to the impact and power of the ball, and this relates to the efficiency with which the golfer harmonizes muscle power with gravity to direct the force of momentum optimally.

Figure 2 illustrates the "kandang" or carrying pole (bamboo, usually) as used by hawkers all over the tropics when transporting loads of up to 60 kilogrammes over level roads. The excellent analysis of the ergonomics of the carrying pole by Oliver F. Campbell of Cornell (1) shows that the shock loading upon the shoulder of a person carrying a 54-kg (120-lb) load with a bamboo carrying pole and strapping along at about 3 steps a second in harmony with the "bounce" of the suspended loads is only about 1/3 the shock loading which would be experienced were a rigid steel pipe used as the carrier.

1 - Using the long-handed hoe, the tropical farmer uses only about half the energy he would with a spade to dig, lift, and turn a given volume of soil in the same time.

2 - The bamboo carrying pole enables a hawker to carry reduced "peak loads" on his shoulder while trotting in harmony with the bounce of the equally balanced suspensions.

3 - The solar-photo voltaic panel, batteries, and motor are a non-essential sophistication on this independently-three-wheel suspended recumbent trike for town running. It is convertible in about half an hour into an out-of-town commuter bike, still with independent wheel suspension.
IN THE DEVELOPING COUNTRIES

V. A. Tucker (1) in a paper on The Energetic Cost of Moving About analyses how greater efficiency is achieved by birds, fish and bicyclists than walking or running in animal locomotion. The book Mechanics and Energetics of Animal Locomotion (3) is further fascinating reading for those interested in achieving greater efficiency in the translation of human power into locomotion — whether on land, sea, or in the air. It would appear that springs and similar energy-converting devices will come into much greater use in the future to convert the cyclic retardation of body masses in reciprocating motion for the subsequent acceleration process. As an oarsman it always worried me that the aquatic pedaller using only his legs could propel himself as fast over the water (perhaps faster) as the oarsman using arms, legs, and body! The deceleration at the end of each stroke and energy absorbing coil-up for the next stroke was inadequately re-converted into drive despite the efforts of the oarsman toward rhythmic motion. Our efforts (in Sri Lanka) to design a reciprocating pedal drive more efficient than the rotating pedal achieved very smooth and sustained transmission of the thrust of the (reclining) pedaller's legs (figure 3), but did not provide the dramatic improvement we expected. This disappointing result may have been partially because the cyclist was very unused to the reciprocating pedal, but more because we failed to devise a system for cyclic absorption of the deceleration that occurs at the end of a stroke and the conversion of this energy into the subsequent driving stroke. Back to the drawing board! Incidentally, simple measurement of the energy used by the cyclist was achieved through measurement of the carbon dioxide exhaled over a fixed distance. For the present, and until we better achieve harmonic movement of the (reciprocating) masses in a re-cycling of the energies of deceleration, the rotating pedal still reigns!

Our studies into facilitating the effort of pedalled transport naturally led us toward recumbents, and we quickly concluded that most of the commercially available designs for recumbent bikes erred in not lowering the cyclist sufficiently to achieve a substantial reduction in both frontal area as well as in coefficient of drag. Lacking a wind tunnel for quantifying our results, we resorted to towing the bikes behind a vehicle at calibrated ground-speeds along the airport runway in various head as well as following winds, the relative air-speed being measured by a pre-calibrated air-speed indicator mounted on the bike. The "pull" of the bike was initially measured by a sensitive (pre-calibrated) "fish-scale" mounted on the rear of the towing vehicle and linked to the

3 - The "bike-trike" in two-wheeled configuration, here undergoing trials of the reciprocating pedal drive system. Good "drive" but not all that much of an improvement on the standard pedal!

6 - The rear-wheel fork is hinged to the main backbone of the bi-trike, and hard rubber balls inside the wedge-shaped box above the hinge provide excellent "damped" springing. Inset shows the box open. The transfer-sprocket drive also operates on the same axial pin of the hinge.

7 - Haven cane is used in the shaped reclining seat of the bike-trike to enable the skin of the cyclist to "breathe" better in the hot climate, and thus afford better cooling.

5 - The front-wheel suspension uses rubber shock-cord suspension in a "heel-type" joint. Very necessary on heavily rutted roads in most developing countries.
HUMAN POWER IN THE DEVELOPING COUNTRIES

bike being towed by a 60-m (200-ft) cable. The fish-scale was later replaced by a recording strain-gauge, and correlated with the ground speed and air speed to enable accurate measurement of rolling resistance as well as air resistance at the various speeds. It was interesting that the fiberglass streamlined cow we built around the bike proved impractical in our tropical (damp humid) environment. Ventilation is essential here, and plenty of it is. A further observation was that while the recumbent bike was fine when used for speed runs or for commuting to town, it was not too easy in the continuous stop-and-go traffic in town, and here the conversion to the trike configuration proved essential for comfort, thus the name "bike-trike". It could then start and stop with the other heavy traffic without wobble.

In the developing world, most of the roads are terrible! Pot-holes and ripples everywhere make standard cycling unpleasant. So we investigated various forms of suspensions, and these are illustrated in photographs 4, 5, and 6. Rubber shock-cords and balls (made locally from our own rubber trees) were the media of suspension used, and they performed delightfully. In figure 7 you will note the ventilated woven-cane contoured seat we used to help dissipate sweat and body heat quickly. Does the suspension really help? Yes it not only greatly helps smooth the ride for the rider; it also clearly reduces the energy inputs into propulsion of the vehicle over rutty and potholed roads. This we measured by towing the vehicle at rated speeds over smooth and rutted roads, both with the suspension locked and the suspension operative. Depending on the depth of the potholes, the suspension afforded a reduction in the energy of propulsion of up to 20%. This is substantial! And how? We conclude that the independent wheel suspension greatly reduces the energy lost in vertical acceleration of the bike and cyclist. Seems to make sense.

Where do we go from here? Well, we've learned a lot about improving efficiency in human muscle power. This is particularly vital in our part of the world where muscle power provides 90 to 100 percent of the energy needs for agriculture and also for transport. A soft sack draped over a draught-animal's shoulders, in front of his hump, provided greater comfort than the solid yoke, and increased work output by 20%. While this is not great, it points the direction for future efforts in design (figure 8). We've also learned to think holistically and synergetically. Our studies have emphasized the truth behind the contention (perhaps a "law") that for a given system, the product of energy and duration remains constant. In other words, the impact of "mechanization" has mainly been to impose higher energy use with shorter durations in place of the lower energy use but longer durations of manual systems. What we really need, however, is to devise short-duration, low-energy systems to achieve the same end objective. For example, in farming, when replacing the bullock in front of the plow with a tractor, did we mechanize agriculture — or did we mechanize the bullock? Had we really studied our objective more deeply, we would have realized that the fundamental purpose of tillage was weed control. We do not need to cut, lift, and turn soil, and precipitate erosion and compact the soil any more, just to control weeds. Alternative methods for control of weeds now use very little energy and achieve great savings in time and cost, and these are being further developed into very practical tools for the small farmer in the tropics (4).

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B — A sack draped in front of the draught-animal's hump made it very much easier for the bull and greatly reduced fatigue. A considerable improvement on the solid wooden yoke used earlier — and more simple!

Mr. Holfre rows his articulated-oar equipped shell.
THE MIT MONARCH B1 First-Prize Winner in the Kremer World Speed Competition

by John Langford and Mark Drela, MIT

Abstract

This paper provides an overview of the Monarch, MIT's human-powered aircraft that on May 11, 1984, won first prize in the Kremer World Speed Competition. Designed and built by an all-volunteer team in 88 days during the summer of 1983, the Monarch made 29 flights before it was disassembled and stored for the winter. During the spring of 1984, a revised and improved version known as the Monarch B made 35 flights culminating in the record flight. This paper details some of the design considerations and construction details behind the Monarch, with particular attention to the aircraft's propulsion system and advanced avionics.

I. Introduction

In May of 1983, Britain's Royal Aeronautical Society (RAeS) announced the third in its series of human-powered aircraft (HPA) competitions. Known as the Kremer World Speed Competition, this new contest offered a £20,000 prize to the first entrant to fly a 1500m closed course in less than 180 seconds (requiring a speed of roughly 20 mph). In a significant departure from the previous Figure-Eight and Cross-Channel prizes, the Speed Prize allowed the use of energy storage. During a ten-minute period before the flight the pilot(s) could store his own energy via whatever means the contestants could devise. The rules also included provisions for official observation, minimum and maximum altitudes, a qualifying flight, and follow-on prizes (£5000 each) each time the record is broken (1).

Upon announcement of the competition, a small group of students at MIT (including the authors, Juan Cruz, and Steve Finberg) began to examine the feasibility of transferring from that experience into a project by John Langford and Mark Drela, MIT

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THE MIT MONARCH B

carried the main lift loads. A single wire from the top mast was designed for 1.5 g downloads. The trailing-edge wire was sized to carry the forward loading concentrated at high lift. Each joint was machined to fit and then lashed with Kevlar. The landing gear and main lift wire together carried aft bending loads. The wing was originally warped for roll control, but in the “B” version recumbent seating was allowed with 4.7-mm (3/16-in) plywood. Special angled ribs at the panel joints took compression and covering sheeted with 0.75 oz fiberglass cloth. The leading edge was provided with 0.75-inch thick foam. The ribs were reinforced near the spar with 0.4-mm (1/64-in) plywood. Special angled ribs at the panel joints took both compression and covering loads. The wings were covered with half-millennium Mylar, donated by DuPont.

Construction of the all-flying rudder and stabilizer was similar except that these surfaces were fully cantilevered. The tail surfaces had 2.54 cm (1.0-in) diameter spars and were covered with third-mill Mylar.

IV. Fuselage

The fuselage was built of aluminum tubing, with each joint machined to fit and then lashed with Kevlar roving. In the initial design the pilot was seated vertically, but in the “B” version recumbent seating was allowed. The seat itself was Kevlar cloth stretched over an aluminum frame. The pilot grasped a three-axis stick, with toggle switches on the stick for motor on/off and throttle control, and hand grips for radio mike and manual control of prop pitch. The aircraft had a main landing gear beneath the pilot and a small wheel beneath the nose. The main landing gear was covered and shock-absorbing. A brake was included on the “B” version.

V. Propulsion System

After briefly considering flywheels (too complicated) and rubber (too heavy), we elected to develop an electronic energy-storage system. In our judgment the relatively low efficiency (about 33%) was more than offset by the low development time and cost. The final system (shown in detail in Figure 1) consisted of: 1) standard bicycle cranks, driving a flexible chain; 2) a minimum-induced-loss tractor propeller, disconnected via a clutch during charging; 3) a 62:1 worm-gear motor (Geist type 60/28) normally used for electric model aircraft; 4) a power controller; 5) a battery; and 6) a servopushrod, and control logic to vary the pitch of the propeller.

The key concept in this system was the idea of splitting the battery pack, automatically cycling between two subsystems every ten seconds during charging. This allowed us to unload the flight motor as the generator, and to do so without changing the gearing between charging and flying (the conversion could be accomplished in less than 10 seconds). We used mechanical complexity for electronic simplicity: a key element in the system was the power controller. Designed and built by Steve Finberg, the controller performed a variety of functions, including: 1) splitting the battery pack, automatically cycling between two subpacks every ten seconds during charging; 2) providing visual confirmation of charge cycling via LEDs; 3) providing a direct current between the batteries and the motor (the pilot “tapped” the motor on and off via a relay, and the amperage readings were taken via a Hall-Effect device, without the losses of a shunt); 4) use of a current-sensing system to act as a no-loss diode; and 5) performing battery pack voltage and providing an audible low-voltage alarm.

Figure 2 - Operating map of the Monarch propulsion system for a flight speed of 22 m/s. Solid curves represent motor performance; dotted lines, prop performance.
MIT Monarch team posed in front of the record-setting human-powered machine. Left to right are: John Langford, Jim Hilkerson, Tidhar Shalon, Mark Brehla (holding glass), Steve Finberg, and Frank Scarabino.

1984. On July 20, 1984, the Bionic Rat team filed a claim for the 5000 second prize in the Kremer Speed Competition, although at the time of this writing (10/84) that claim has not been approved. In addition, a team in Germany built an aircraft known as the Musculaire. In June, 1984, the Musculaire claimed a £10,000 prize offered by the RAES to the first non-American entry to fly the Figure-Eight course, and later in the summer (with an energy-storage system added) filed a claim for the third prize in the Kremer World Speed Competition. Even after the first three prizes have been awarded, some £70,000 will remain in the Speed Prize fund, although it remains to be seen whether the plans to disburse it in £5000 increments will attract additional competitors.

VIII. Conclusions

The Monarch is clearly a transitional aircraft. It is no longer a fragile gargantuan and yet neither is it a "practical" ultralight aircraft in any sense of the concept. Using nearly two orders of magnitude less power than present-day ultralights, Monarch illustrates the potential efficiencies that may be gained through technical sophistication.

The two great strengths of the Monarch design were its sizing and its propulsion system. From the beginning, the aircraft was properly sized to the task at hand. The propulsion system marked the first real use of advanced avionics on an HPA, and conclusively demonstrated the potential reductions in pilot workload and increases in system efficiency.

The Monarch was an educational experience for all those involved with it. It showed once again how well-matched human-powered aircraft are to the university environment: small enough to be manageable and yet sufficiently complex to test all aspects of an engineering education.

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