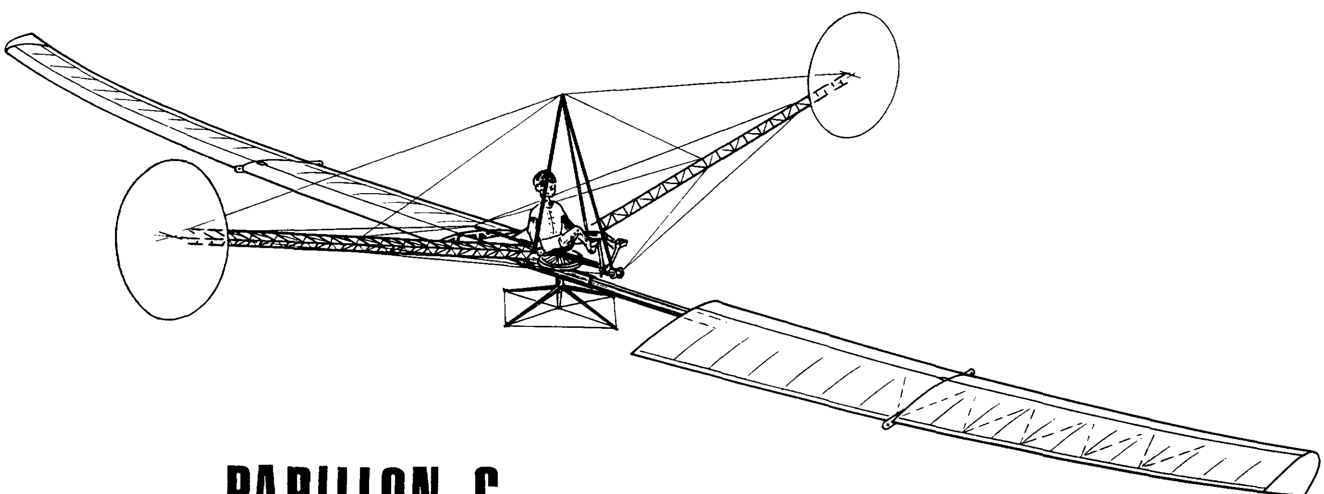
HUMAN POWER

The Technical Journal of the IHPVA

Vol. 9, No. 2 $5.00 ISSUE NO. 30 Summer 1991



PAPILLON C

Review of Developments in Human-Powered Helicopters

by Akira Naito

Summary

Many have taken up the challenge of achieving flight in a human-powered helicopter (HPH) and have not succeeded. The writer led a team that made three HPHs between 1985 and 1990. None succeeded, but several valuable lessons were learned.

Failures have been due to lack of knowledge of the fundamentals of human-powered hovering flight. The Sikorsky HPH Prize has encouraged a great deal of design activity, but, unfortunately, little actual research, especially concerning the aerodynamics of rotors very close to the ground.

The purpose of this paper is to report some basic data that we have developed, and to pass along some of our experiences to help newcomers to the HPH field.

Introduction

The dream to fly like a bird by purely human power gave birth to human-powered aircraft (HPA). The first HPA ("SUMPAC") to take off and land under human power succeeded in Britain in 1961, and in the same year the first paper on HPH was presented by Graves. He showed that an HPH was feasible.

HPA technology and achievements have been growing year by year. The MIT Daedalus HPA set the world long-distance record of 119 km in 1988. A successful HPH flight was not achieved until November 12, 1989, however, when the student team at Cal Poly, San Luis Obispo, took Da Vinci III into the air. On December 10, 1989, a flight of 7.1 seconds was demonstrated to an official witness. Although this was far less than required to win the American Helicopter Society's Sikorsky prize, it was a notable achievement. We at Nihon University have been trying since 1985, and others have made similar strenuous efforts for at least ten years, without officially observed success.

(continued on page 7...)

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International Human-Powered Vehicle
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Human Power is published quarterly by the Internat'l Human-Powered Vehicle Assoc., Inc., a non-profit organization devoted to the study & application of human muscular potential to propel craft through the air, in the water and on land. Membership information is available by sending a self-addressed, stamped business-sized envelope to:
IHPVA
P.O.Box 51255
Indianapolis, IN 46215-0255 USA

Members may purchase additional copies of Human Power for $3.50 each. Nonmembers may purchase issues for $5.00 per copy.

Special thanks to the authors, to Diane Nakashian, Linda McInnis, Marti Daily, and Carolyn Stitson, without whom this issue would not have been possible.

Editorials

Newtons, Pascals, and Pounds

Any notoriety I have in the world of HPVs owes a great deal to units. Frank Whitt hated SI units with considerable passion. He had had a manuscript on "bicycle motion" rejected in Britain, partly because it was not in SI units. He asked me to get it published in the US. After much toil and sweat The MIT Press brought it out as Bicycling Science. The publisher required that I rewrite and contribute to it - and I inserted SI units wherever possible. I am an enthusiast for a world language, and SI is just that for an important part of the discourse of science. But I know that many of you, perhaps most, don't feel comfortable with SI - yet.

A consistent unit system performs an important service besides that of enabling people in different countries to converse with one another: it removes the normal confusion between mass and force, including weight. An extreme case of woolly thinking arising from apparent total confusion about units was given to me by a bicycling friend: an advertisement for a new bicycle pedal. The blurb stated that the pedal "reduces rotating weight by over half a pound. This saves the average rider a lot of work -if you ride at 90 RPM, about 45 lbs. each minute or about 100,000 pounds every 2,500 miles!"

This is appalling nonsense. The poor old pound, which has to do duty as a unit of currency, as a verb meaning "hit forcefully", and as a unit of mass, and of weight and force, is not now a unit of work. And, since "lb" is an abbreviation for a Latin word, the plural is not "lbs" but "lb". Or, preferably, "lbm" for pounds mass and "lbf" for pounds force. The pedal reduces rotating mass, which reduces rider work only in that s/he has to put out less energy to accelerate the bike to speed, to climb hills, and to overcome rolling friction. The first of these would be identical if the rider were in a space station; the latter two depend on local gravity, and would be reduced greatly in a moon base.

European Fashions

The European HPV Championships were held in Wolverhampton, Warwickshire, UK, not far from where I first blinked and bawled into the sunlight. And there was not only the sun but the heat for which England is so famous (actually, I have never before been to Wolverhampton when it has not been under a cold rain). We were there for only the first day, occupied mainly with heats to decide the running of the races on the following days. I hope that Marti Daily or Peter Ross will give one of their fine accounts of the championships in HPV NEWS. All I want to comment on here is the vigor of European development - there was strong representation from Holland and Germany and, of course, Britain - and on the rather extraordinary lack of long-wheelbase machines. I saw only one, a Radius, similar to an Avatar 2000, used just for transportation to the site. At a time when the LWB Gold Rush is still the world's fastest HPV, and the Bluebell, based on the Avatar, was, when it was racing, still winning most European contests it entered, the apparent abandonment of this type seemed to me remarkable. But so was the profusion of alternative SWB designs. Some were of the Brummer-Lightning style, rear-wheel drive and forward handlebars. One or two had the cranks over the front wheel and front-wheel drive and steering, with the chain twisting as the wheel was steered (only a small angle was possible). And there were actual and imitation Flevos, with front-wheel drive and steering in which the whole front end pivots just forward of the seat. Michael Eliasohn's edited collection on front-wheel-drive

In this issue

recumbents in this issue is enlightening on the pros and cons of some of the variations. I wish that I could have ridden them all.

Dave Wilson

Letters to the editor

Correction to Source Guide

The entry for *Alternative Bikestyles* should have the address:

P.O. Box 1344 Bonita, CA 92002
(619) 421-5118

My apologies for this error. Please send any other corrections to the Source Guide editor at the IHPVA address -

Stephen des Jardins

Bicycle fairings and efficiency

I find particular aspects of Dave Kehoe's article (HP 8/4, winter 90-91) to be misleading. His conclusions are based upon characterization testing of only two brands of handlebar fairings: the Zzip Designs Zzipper and the National Cycle Aerosport. Perhaps if Mr. Kehoe's tests considered a more complete spectrum of aftermarket fairings, such as the Aero-Edge, his conclusions might be somewhat different.

Team Chronos' initial approach in an attempt to develop a vehicle for RAAM-HPV 1989 was to incorporate an after-market fairing for a standard bicycle. After similar exhausting coast-down tests (maximum speed measured as an indicator) Team Chronos concluded that no significant performance improvements were being achieved. Chronos' efforts then focussed on the development of an efficient alternative, the Aero-Edge fairing. At normal riding speeds, between 20-25 mph, the Aero-Edge front fairing consistently measured a 10% - 13% speed increase. In addition, contrary to Mr. Kehoe's test of the experimental Zzipper with a hot-pink Lycra wrap, the Aero-Edge fairing equipped with a full body suit consistently posted speed increases between 13% -17%.

I welcomed the thoroughness of Mr. Kehoe's tests, his Cateye Micro calibration technique, and the fact that variables such as rider position were considered. However, I disagree with Mr. Kehoe's statement that fairings will not do anything for 99% of the cyclists on the road. His statement is based on a cyclist whose average speed is between 10-15 mph. I would think that the majority of moderate cyclists would consider a 10-mph pace to be a good hill-climbing speed! The majority of cyclists that I encounter ride at an average speed between 17-20 mph. At these speeds, aftermarket fairings are undoubtedly the most cost-effective upgrade one can make for improving performance.

Brian R. Spence, Aero-Edge:
Advanced Performance Fairings,
1320 Vallecito Pl.
Carpinteria, CA 93013 USA

(We invited Dave Kehoe to respond: he said that he agreed in general with Brian Spence's letter. He believes that Aero-Edge fairings were not available when he was doing his tests.)

Foil-Propelled boat

.. I am sending you a brochure of a boat I saw at the boat show in Oslo in March.

The sales representative demonstrating it could not tell me what the practical cruising speed of the craft was. However, he hinted at a top speed of approx. 2.5 m/s (5 knots) when two people were "rowing".

The foil was an extruded aluminium section with a span of about 1.2 m and a chord of about 200 mm.

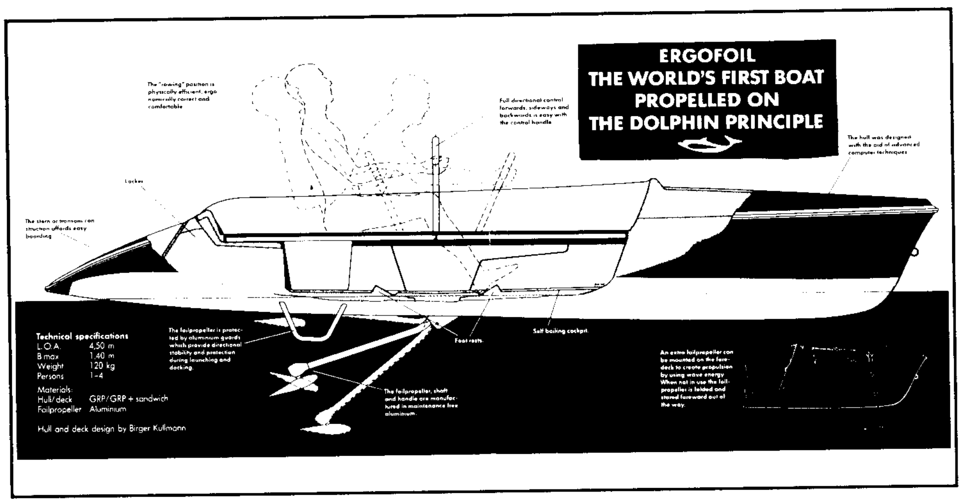
The handlebars could be turned to rotate the foil through 360 degrees for steering or propulsion in any direction.

What do [you think about the claims of invention etc.]? There must have been foil propellers prior to Einar Jacobsen's invention in 1977?

Apart from that, I'd like to thank you for inspiring and interesting publications. I've just become a member, and it's good to know that I'm not the only "laid-back" bicyclist in the world.

Trond Are Oritsland,
Oscarsgate 71,
N-0256 Oslo Norway

(Trond wrote this, he said, with a "human-powered pen". Einar Jakobsen wrote "Foil propulsion at sea" for us in HP 5/3/86, p. 7. There have indeed been earlier foil propellers -for instance, our own Calvin Gongwer - but one can be first in, and be awarded a patent for, a first application or a first type).



Linear drives

First, my very warm appreciation for the spring issue of HP, which made fascinating reading. . . On p. 18 there are two sketches of the pedal and leg positions in linear drive, as well as in rotary drive, of a reclining cyclist. Several earlier articles went to great length to suggest that (in this reclining position) rotary pedaling was no more effort than linear pedaling.

As one who has used both methods, I disagree with that view. The linear drive takes appreciable less effort for the reason that is well demonstrated in the sketches. With the rotary drive the "thrusting" leg needs to be raised (lifted) from the hip joint in order to go over TDC, and this effort of raising the weight of the leg does use a lot of effort. In the linear drive the leg is still slightly raised on the return stroke but then the thrust is directly forward, and not upwards.

The objection to most linear drives, however, is the absence of a smooth cyclic return at the end of the driving stroke. This was obviated in the fascinating drive system [shown in figure 5 of Dave Wilson's paper in the first IHPVA Scientific Symposium], which uses two short pedals each with its own short chain drive to the main drive wheel. The unique [characteristic] was that changing the ratio of the smaller chain-drive wheels to the larger would result in either pure linear pedaling (ratio 1:2) or slightly oval pedaling, or - at one-to-one - circular pedaling. Further, one could - by relocating the smaller wheels - reposition the point of the TDC for best ease of propulsion relative to the driving position. The only objection I found was the rather excessive friction in the system [because of] the several chains and wheels involved.

I feel sure that by now someone . . will have come up with a minimal friction drive of this configuration, and I [should] be most grateful for . . guidance as to how I may reproduce one here for my own recliner.

Ray Wijewardene,
133 Dharmapala Mawatha,
Colombo 7, Sri Lanka.

The Most Significant Invention. .

". . . We often ignore the fact that the most significant invention certainly in recent human history, maybe in human history, is the bicycle. The bicycle has had a major impact on the population structure of humans. Before the invention of the bicycle, most people married someone who was born no more than ten miles from where they were born. Now the average marriage distance for the vast majority of people around the world who still ride on bicycles and don't drive around in BMWs or Mercedes is more like a hundred miles. That means the average breeding population is radically expanded so that the degree of genetic outbreeding as opposed to relative inbreeding has changed very significantly and this is already having an effect on the genetic structure of populations, on the physical structure of populations. That still has a way to work its way through and it is changing the effects of natural selection in ways that are simply not estimable at the moment."

From "a conversation with David Pilbeam (director of the Peabody Museum of Architecture and Ethnology)" in the Harvard Gazette, May 24, 1991. It was sent in by John Sweeney of The Charles Stark Draper Lab., Cambridge, MA 02139, USA.

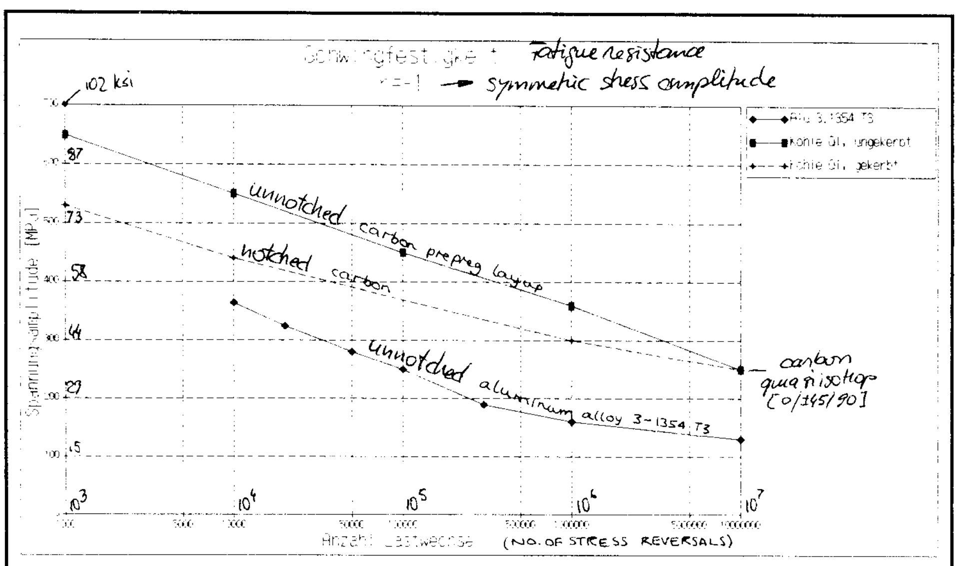
Fatigue Data, Aluminum and Composites

[Here are] some data about a standard aircraft aluminum alloy and a standard carbon-prepreg lay-up. You will see the difference in allowable dynamic stresses which also depends on the stress amplitude/ frequency/symmetry, specimen design, and temperature/moisture. The difference [in favor of the carbon lay-up] increases when notched specimens are considered. A rule of thumb for this (notched) case is that the allowable stress is three times higher for carbon than for aluminum at a million cycles - but I'm not a metallurgist. I often hear that an aluminum structure must fail sooner or later however low the stresses. The data I have do not exactly reflect this though the allowable stress is low. But the long lifetime of aircraft - often incredibly exceeding twenty years - shows that aluminum cannot be totally bad.

Another example of a good aluminum structure is the Vitus bicycle frame, which I have been riding for eleven years - including five years of hard competition, and now exceeding 53,000 miles - with no problems. Unfortunately I can't tell anything about the stress levels, but the weight is slightly lower than a good steel frame (1700 gm for the 420-mm frame). This would imply a stress level approx. 36% of the level in the steel frame. A good diffusion of the load is important: it is not surprising that it has bonded joints. I guess that the joint problem with its complicated three-dimensional stresses is the reason why good carbon frames are not lighter than this aluminum frame. (The diagram is for only simple loading of the specimens and cannot be extrapolated for complex joints).

I have also seen catastrophic aluminum crank designs where the crank arm was lightened by a milled sharp-edged groove exactly where you want to have the most undisturbed material. The best cranks have, besides good materials, smooth or even polished surfaces and generous material around the high-stress areas around the pedal threads and around the square tapered axle socket. Forging improves the properties because of the favorable grain alignment.

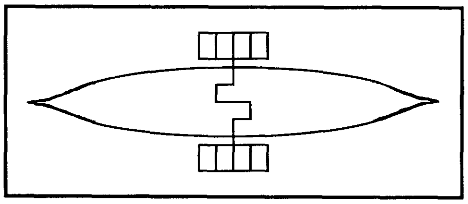
Peer Frank,
103 Skyhill Rd.,
Alexandria, VA 22314, USA.



Tandem Pedaling Paddlewheels

Some time ago I considered that high performance could be obtained with two recumbent people facing each other in a narrow boat, with feet on opposite sides of a single pair of pedals, to minimize the number of parts. One person would be pedaling backwards, but this might seem natural for the person who is travelling backwards. Now, the papers in the spring HP (9/1/91) have made it clear that paddlewheels would be ideally suited to transmit the power directly to the water (see sketch). Socializing may be more difficult than with a side-by-side configuration, but easier than in a narrow boat tandem configuration. The entire drive unit could be assembled separately and installed on a conventional vessel, if it is desired to minimize cost and fabrication time.

John Whitehead,
JCW Engineering,
3322 Biscayne Bay,
Davis, CA 95616, USA



News From the VP-Air

Bryn Bird decided to resize his ornithopter before quite completing the current hardware. I feel that he overestimates the likely performance, but that something may be learned about ornithopters if he persists.

Wayne Bliesner is expected to be speaking to the Royal Aeronautical Society in November 1991.

There are rumours that a university group may be considering a water take-off HPA.

Chris Roper,
19 Stirling, 29 Tavistock Street,
Covent Garden
London WC2E 7NU UK

Recumbents And the UCI

I've been re-reading some old books and articles about recumbents. I would like to challenge two fairly common assumptions about recumbents typically made in such articles. It is fairly typical to cite the incident where the Velocar's record was not allowed by the UCI as the reason recumbents were not heard from between WW II and the start of the IHPVA (or perhaps until the engineering competition you started). It probably did not help, but I wonder how big of a cause the UCI decision was.

Certainly competition improves the breed and calls attention to the winning designs, but the example of mountain bikes would seem to show that it is not necessarily essential. Competition is playing a role in their refinement, but had nothing to do with their initial appearance and rapid rise.

But for the sake of this discussion, let us assume that competition is desirable and helpful. I think the reason that there were no recumbents in competition after the war was not because of the UCI decision. The UCI decision did not block the formation of an IHPVA-type organization. According to a recent article about the Velocar in Cycling Science, Charles Mochet did the obvious thing and created a trophy cup for the fastest hour, regardless of type of machine. The record was challenged by Marcel Berthet in a streamliner. Berthet won the record, and in 1938, Francis Faure and Georges Mochet put streamlining on the Velocar and won it back. It seems to me that what Charles Mochet had done was not unlike what the IHPVA did much later. Additionally, had the UCI allowed recumbents, conventional bike racers may have bolted the organization, formed a new sanctioning organization, and the UCI and recumbents may have disappeared together.

Basically, my theory is that recumbents (at least for racing) did not reappear after the war for other reasons. There was much rebuilding to be done in Europe. The U.S. became the dominant nation in the west. And the U.S. prospered in the postwar years. Gas was cheap and there seemed to be no limit to the expansion of car use for transportation. As an example of the low esteem in which bicycles were held, Dan Henry, then an airline pilot, says that on several occasions his job was threatened simply because he brought a bicycle with him on flights. The U.S. embraced the automobile totally, and everybody else seemed to long for the day when they could do the same. Even now, developing countries are struggling to repeat this mistake. In Bicycling Science, you [Dave Wilson] go on from the issue of the UCI decision to discuss public fascination with other transportation modes as an inhibitor of bicycle progress. I think this is more to the point.

Now cut to 1974 and the IHPVA. By the time the IHPVA was formed, society had changed again. Remember the sixties? Flower power, back to the land, Woodstock? There was a bicycle boom in the U.S. in 1970, and a world—wide energy crisis in 1973. Now people were ready to consider alternatives, recumbents included. So the success of the IHPVA in bringing unconventional machines once more to the fore may have been less about the IHPVA correcting the UCI "wrong," than about the times being right. The design competition you [DGW] started in 1967 spurred some activity, but I think many more people were ready to get involved by the time the IHPVA got organized in the seventies. Also by the seventies, I think there was much more willingness on the part of the general-interest press to cover HPVs. So my first point is that the UCI did not cause the disappearance of recumbents, but rather that it was the fascination with the automobile that reduced interest in bicycles and bicycle innovation, including recumbents.

My second contention is that they may not have entirely disappeared, but that what activity there was received little attention. There is some evidence that they continued to be built. One of the things I re-read was a Dan Henry article from a 1970 (the year the bicycle boom started) compilation of articles from Bicycling magazine. Henry starts this 1968 article about his recumbent by talking about previous recumbent designs, including prone bikes. In a recent phone conversation, Henry said that he did not save his information, but that he used to subscribe to a British cycling magazine and that recumbents would appear there from time to time.

Presumably pedal-car racing continued in England, though I must admit I know little about this activity and how it might fit into this discussion. I believe the Kingsburys, builders of the hour-record Bean, have built pedal cars for many years. In your [DGW] paper detailing the history of the Avatar, you mentioned a clip someone sent you telling of two brothers from Denmark touring on recumbents in the 50s. By the mid-sixties, besides the designs for your competition, other machines were starting to turn up in the U.S. press. There were plans in Popular Mechanics in April 1969. My hunch is that people continued to build recumbents and various other types of unconventional bicycles (Alex Moulton, for example), but that they never achieved much notoriety because people simply were not that interested.

And here is Chet Kyle in Bicycling May 1982: "After the trauma of World War II, The Europeans' work in streamlining continued. Oscar Egg made a teardrop shaped bicycle and called it Sputnik. In 1961, John Carline, an Englishman, rode the Sputnik at 37.3 mph over a one mile course, or about five mph faster than the fastest standard bicycle of the day." By the way, Roy Barrett, apparently the current owner of the English Sputnik, says that the magazine *Cycling* still promoted recumbents in the 30s after the UCI ban. He attributes the waning of interest in them to their "impracticality." (*Bicycling*, June, 1973)

The Sputnik was not a recumbent, but it was a non-UCI approved bike, so I think it supports my two points that the UCI ban may not have had a total chilling effect and that there may have been more activity than is commonly acknowledged.

My reason for bringing this up is not to defend the UCI or its decision, but to remind those who would promote bicycle research and usage of what I believe to be yet another example of the almost overwhelming cultural influence of the automobile. I think this is the primary reason for whatever lack of activity and attention there was in the postwar years.

John Riley,
150 Gough Avenue,
Toronto, ONT M4K 3P1,
Canada

Land-Skates in China

Are there any successors to the bicycle that have matured? There seems little hope that there could be "the son of bicycle" because it is two-hundred years old.

As a successor to the bicycle I've made a skate for use on dry land. With it the skater steers in the same way as a bicyclist steering "no hands". The land-skates are stable and steering is also accomplished at will and without manipulative input. This protects the beginner from falling and helps an old hand to play new tricks.

There are many theoretical and practical needs to bring the land-skate to maturity. I have too few resources to do as much as I would wish. I would welcome letters from people who may be able to help me with this development.

Yangben Guo,
10 Lingxiaoli,
Guangzhou, P.B. 510030,
China.

(I have edited Yangben Guo's letter rather freely and hope that I have correctly interpreted his meaning - Dave Wilson)

Conversion Factors

MASS	1 lbm	=0.4536 kg(kilogram)
FORCE	1 lbf	=4.448 N (newton)
LENGTH	1 inch	=25.4 mm (millimeters)
	1 foot	=304.8 mm
	1 mile	=1.609 km(kilometers)
AREA	1 sq.ft.	=0.0929 sq.m.
VOLUME	1 cu.ft.	=0.02832 cu.m.
PRESSURE,	1 lbf/sq.in.	=6.895 kPa(kilopascals)
STRESS	1 Pa	=1 N/sq.m.
	100 kPa	=1 bar = 14.503 lbf/sq-.in.
DENSITY	1 lbm/cu.ft.	=16.017 kg/cu.m.
VELOCITY		
	1 mile/h	=0.447 m/s(meters/second)
		=1.609 km/h
	1 knot	=0.52 m/s
TORQUE	1 lbf-ft=1.356 N-m	
ENERGY	1 ft-lbf=1.356 J	(joules)
	1 Btu	=1054.9 J
	1 kcal	=4.186 J
	1 kWh	=3.6 MJ (mega-joules)
POWER	1 hp	=746 W =746 J/s (watts)
	1 kcal/min	=69.78 W
	1 ft-lbf/s	=1.356 W
SPECIFIC HEAT		1 Btu/lbm-degR =4.187 Jkg-degK
HEAT FLUX		1 Btu/sq.ft.-h=3.154 Wsq.m.
	1 kcal/sq.m.-h=1.163 W/sq.m.	

Kremer Prizes

In 1988 Mr. Henry Kremer offered, through the (British) Royal Aeronautical Society, two additional prizes for human-powered flight. We know of no attempts having been made on them as yet. The following is a brief summary.

Kremer International Marathon Competition

A human-powered heavier-than-air plane is to cover, in under one hour, the following course. Two turning-point markers are fixed 4051 metres apart. The aircraft is to complete two "outer" circuits around the markers, a figure-of-eight circuit around the markers, and two final "outer" circuits. The prize is fifty-thousand pounds sterling.

Kremer International Seaplane Competition

A human-powered heavier-than-air seaplane is to cover, in six minutes or less, the following course. Two turning-point markers are established 805 metres apart in a body of water. The craft shall take off from the water, complete two figure-of-eight circuits around the two markers, and land. The prize is ten-thousand pounds sterling.

Both courses must be set up within the United Kingdom. Full details are obtainable from the R.Aero.Soc., 4 Hamilton Place, London W1V 0BQ, UK.

continued from p. 1

Why is success so difficult? What factors prevent so many HPH from hovering? I hope to shed some light on these problems in this paper.

Power Required For Hovering Flight

The power (watts) that a HPH requires for hovering flight was given by Sherwin in "Man-powered flight" (with his equation converted to SI units):

$$P = 1.3\ K.W \sqrt{\frac{2W}{p\pi R^2}} + 0.78\ W.V \left(\frac{Cd}{CL} \right)$$

where the factor 1.3 is the hovering-efficiency factor; K the ground-effect factor; W the all-up weight in newtons; R the rotor radius in meters; and V is the rotor-tip velocity in m/s. Other symbols will be defined below.

The first term is the power lost in induced drag, and the second term is the power required to overcome airfoil drag.

Ground effect is a function of the ratio of the rotor radius to the mean height, h, of the rotor above the ground. Sherwin showed that K varied with h/R as line 1 of figure 1.

While this simple equation is basically correct there are considerable uncertainties regarding the ground-effect factor K and the airfoil drag coefficient Cd. The most optimistic assumptions for K are obtained by modelling the rotor as a thin disk that produces an instantaneous change in the momentum of the flow ("actuator-disk theory"). Such models lead to lines 1, 2 and 4 in figure 1, and give very favorable (low) values for K. Another model is to consider the ground as the line between the rotor and a mirror image of the rotor, in which case K becomes high, line 3. (Lines 2 and 3 are from Mouritsen, Arizona State University).

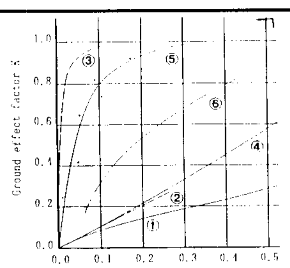


Figure 1. Comparison of K

Until recently no one has succeeded in measuring K experimentally. Using models presents difficulties because of the very low Reynolds numbers and the relative inaccuracies in the configuration. Measuring from full-scale HPH is difficult because of the fragility of the whole structure and particularly of its rotor blades. We at Nihon University have been collaborating with Akira Azuma (emeritus professor at Tokyo University) in research into airfoil characteristics at ultra-low Reynolds numbers, producing the data shown in figure 2.

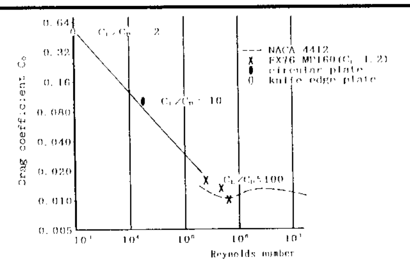


Figure 2. Drag coefficient in Ultra-low Reynolds numbers

With these data and the lift coefficient, C_L, we at Nihon University have been able to calculate the second term of the above power equation.

And in August 1990 we successfully measured the hovering power of small rotorcraft models, enabling us to calculate the first term of the power equation, and to produce an empirical value of K: line 5 in figure 1. This shows, disappointingly, that the rotor blades have to operate extremely close to the ground to realize any worthwhile reduction of the induced drag.

In September 1990 at Nihon University we made one-twentieth-scale models of Da Vinci III (USA), Vertigo (UK), A Day Fly (Japan) and Papillon A & C (Japan). The hover power, P, and lift, T, were measured to produce the efficiency represented by T/P (newtons per watt) and are shown in figure 3. While these values from models should not be extrapolated directly to full-scale HPH, the relative values are instructive. In particular, the value for the one machine that has actually hovered, Da Vinci III, is seen to be the highest, and must be taken to be the starting point for all future efforts.

Figure 3 also shows that a single-rotor HPH has a higher T/P ratio than a double-rotor HPH. But a single-rotor HPH must have a reverse-torque system such as a tail rotor or a deflector, which can result in a 15-20 percent loss, to balance against the major advantage of the lower weight of a single-rotor system.

These considerations were used at Nihon University in the design and construction of our fourth HPH, Papillon C in May 1991. This is now being tested.

Human Power Available

The power requirement discussed above is for smooth input power. The power required will be larger if the input torque fluctuates. There is also the possibility that a varying torque will set up vibrational instabilities in the rotor blades. But human power delivered by the legs does fluctuate, approximately as shown in figure 4.

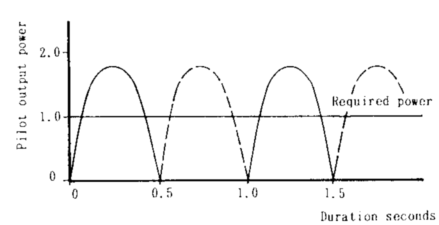


Figure 4. Pattern of pilot power

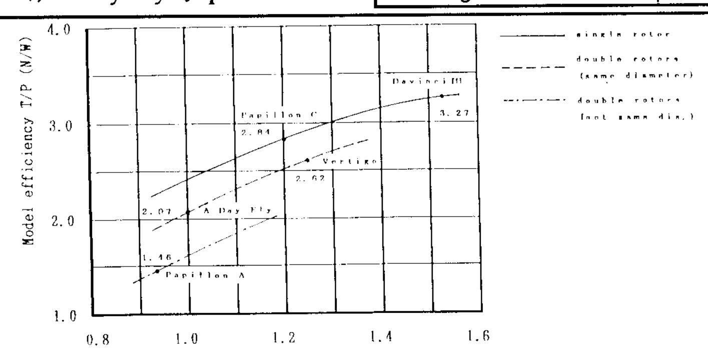


Figure 3. Comparison between 1/20 models

At Nihon university we used three countermeasures.

One was the use of an oval gear (figure 5) tailored to each individual pilot. The high-torque parts of a pilot's pedaling cycle could thereby be smoothed. However, the oval gear could not produce output power where there was no input power: the dead points could not be cancelled.

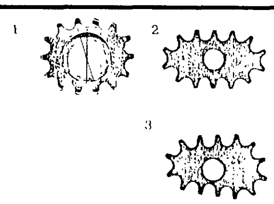


Figure 5. Alteration of the oval gear design

The second countermeasure was to use a camspring system of energy storage. The stored energy could then be released at the dead points. After lengthy tests on a bicycle we employed this system on Papillon A. It was effective in reducing the superimposed oscillations of the rotor blades.

The third measure was to use two pairs of one-way clutches. The pilot pushes the crank bars with the feet alternately instead of rotating the cranks. There are, therefore, no dead points in this system, and it was applied to Papillon B and C.

Da Vinci III has an entirely different - and much-admired - driving system. Each rotor blade is pulled around by a propeller turned by a light cable that is winched in by the pilot's pedaling. A flywheel is used to even the power input.

Other HPH Problems

There are other unsolved problems with HPH. Here we will discuss what we believe are the most important.

Slipstream near the ground.

The flow around the rotating blades is entirely unknown. The stream is too complex to solve by the momentum theory and to model as an actuator disk. This is the case for a single rotor: for counter-rotating rotors we have even less insight.

Change of airfoil characteristics near the ground.

An airfoil moving near a ground plane suffers considerable modification of its free-air pressure distribution. The negative pressure decreases on the upper surface and the positive pressure increases on the lower surface. The flexibility of HPH rotor blades makes the proximity to the ground uncertain even for a known pilot position.

Flow conditions in the test space

Tests of HPH have been conducted principally indoors, usually in

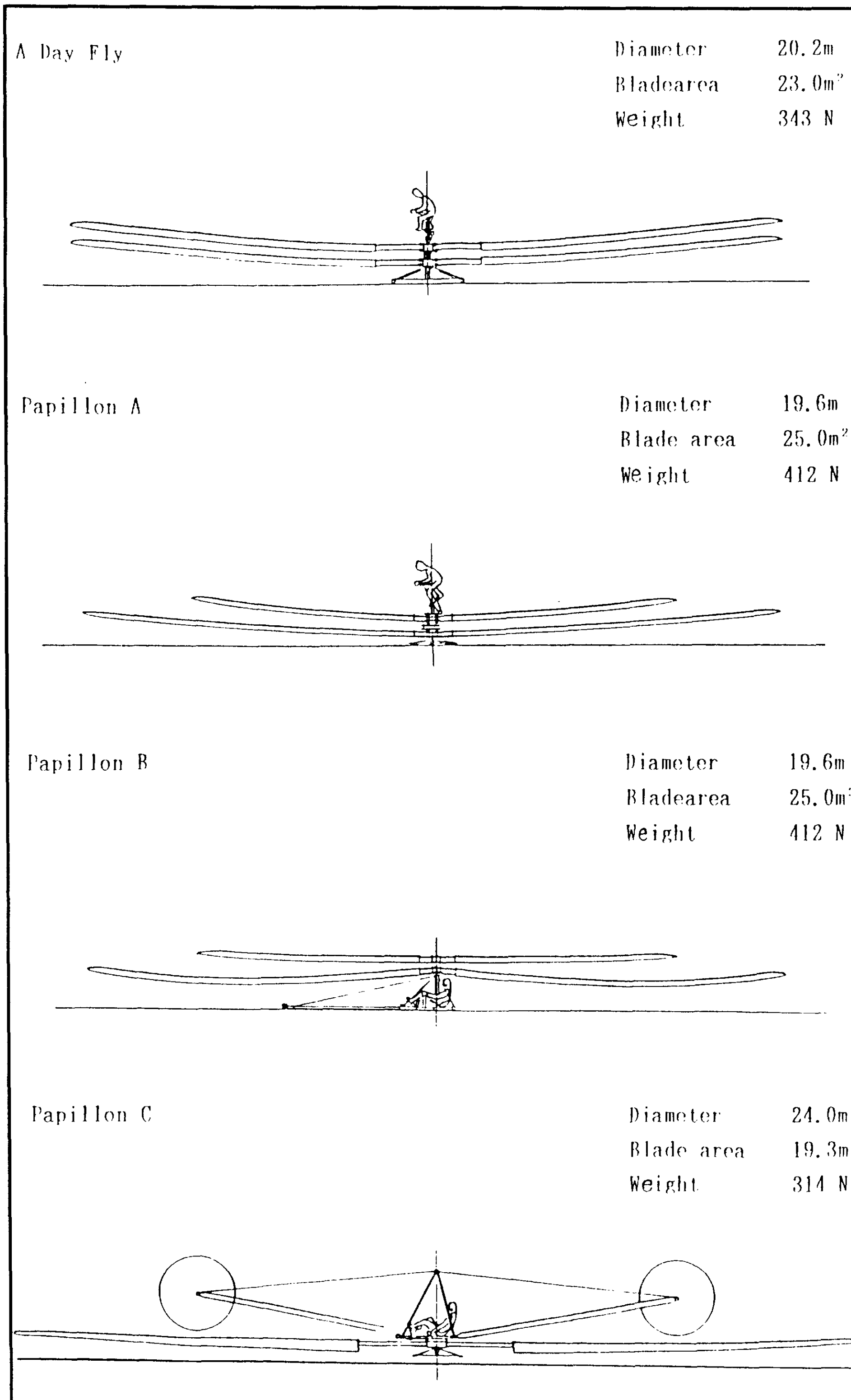


Figure 6. HPH Series of Nihon University

athletic facilities, because even very low wind would have a strong effect on performance. But as a test run in a large enclosed space proceeds, the rotor reaction can set the whole air mass rotating. Soon a large vortex ring is formed that acts to decrease the HPH lift. The volume of the air in the Nihon University dome is 23,000 cu m. It is insufficient to provide relatively undisturbed conditions for an HPH flight.

Structural problems

In contrast to the load on an aircraft wing, the load on a helicopter rotor rises strongly towards the tip. This produces a very high bending moment at the blade root. The pilot's pedal force also produces a high stress at the blade root.

In counter-rotating HPH rotors, large torsional stresses occur on the blades as they pass each other.

All these large but somewhat uncertain loads make the design of the blade spar very difficult.

Dynamic stability

When Da Vinci III succeeded in hovering the problems of dynamic stability of HPH began. The dynamic stability is affected by the position of the center of gravity relative to the rotor disk. These problems were discussed fifty years ago in the early days of so-called "flying platforms" that led among other things to the Harrier jump-jet. The conclusions were that the vehicle is dynamically stable with the CG just above the rotor disk, and unstable with the CG just under the disk. However, the conditions of "flying platforms" were very different to those for an HPH, in which, for instance, the rotor blades rotate extremely slowly. Further study is required.

Conclusions

The problems of human-powered hovering flight have been discussed with the aim of giving some guidance to newcomers to the field to avoid some of the problems experienced by the author.

To design a successful HPH demands new approaches in aerodynamics, structures, mechanics and physics, all virtually virgin fields in the unusual constraints of this endeavor. There are few reports and no manuals. Learning is largely through trial and error. The only way to shorten the road to success is to learn from the failures of others and to listen to the advice of experts in all the fields just listed.

Over-enthusiasm to have the dreams of HPH flight come true can lead to repeating past failures. We should learn from experience and avoid repeating mistakes.

Acknowledgments

The author would like to thank Professor Munekazu Kanno and undergraduate students who assisted in the Papillon A-C projects. Thanks also to Miss Tomoko Mizoguchi and Editor Dave Wilson who assisted the author in preparing this paper.

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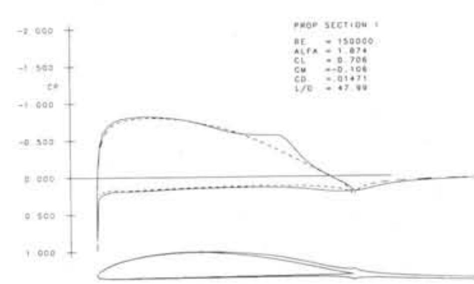
The pursuit of a better slide has always inspired innovation: witness these bicyclists on sled runners.
From *The Smithsonian*, December 1987.

Aerofoil section used over the outer blade, (for r/R > 0.2).



One of the modified sections used at the blade root.

Propeller-airfoil-section pressure distributions.
Figure 6, McIntyre, P. 22
(We apologize for the scattered illustrations for the Airglow paper. We could just squeeze it in this way.)

Book Reviews

Form & Function of the Baidarka

by George B. Dyson

The word "baidarka" applies to a form of Aleut kayak that has a horizontally cleft bow, that is constructed of seal-skin stretched over a framework, and that has astonished non-Eskimos because of its speed (sustained speeds of 10 knots, 5 m/s, have been recorded) and seaworthiness in calms and storms.

This small book, described as no. 2 of "occasional papers of the Baidarka Historical Society" (P.O.Box 5454, Bellingham, WA USA 98227-5454), reviews the known history of this ancient craft, and discusses the hydrodynamics of flexible-skin and bifurcated-bow vessels. It is not yet conclusively known whether or not the flexible seal-skin allows laminar flow to persist longer in the hull's boundary layers, or how other aspects of the boat's construction, including the bow, contribute to what appears to be a low drag coefficient. While the author would like to see more research, his tone throughout is of great respect for the creators of a beautiful and highly effective design. His final quote is from Ivan Veniaminov, 1840:

"It seems to me that the Aleut baidarka is so perfect of its kind, that even a mathematician could add very little if anything to improve its seaworthy qualities."

It's a pity that his judgement should be so flawed as to include mathematicians in the same category as the builders of this remarkable boat: maybe he was mistranslated.

Fluid mechanicians and boat builders, particularly, will find this booklet intriguing.

Dave Wilson

Bicycle Technology

by Rob van der Plas

This is a book of 255 pages, published in 1991 by Bicycle Books, P.O.Box 2038, Mill Valley, CA 94941, $16.95 US. It is also available in Canada and the United Kingdom, and, translated into Flemish, in The Netherlands.

This book is subtitled "understanding, selecting, and maintaining the modern bicycle and its components." In addition to all the stuff on regular bicycles and components, there's much of interest to HPVers and much other oddball stuff. (Some items may be "oddball" only to readers in the United States: for instance, a discussion of hub brakes.)

For example, there are CHAPTERS devoted to hub gears, hub brakes, accessories such as lights and chain guards, special bicycles for short and tall riders, and tandems. There's also information on unusual transmission designs, a useful chart on tire-size-designation equivalents, and quite a bit on HPVs.

Unfortunately, Van der Plas has a very low opinion of recumbents, HPVs in general, and most innovations. He argues that recumbents are not more aerodynamic than regular bikes with dropped handlebars and are less comfortable. For instance, he writes, "...in races between enclosed recumbents and normal bikes, the normal machines often enough run away from the recumbents." HPVers know that this is not true.

Van der Plas even ignores the facts to "prove" his contention that regular bikes are superior in every way to recumbents. For instance, he claims that speeds reached by some streamlined human-powered vehicles aren't "really all that impressive when you realize that regular bicycles in competition reach speeds of 50 mph over similar distances [200 meters]... So far they have not improved on the records established on regular machines by more than 10 percent..."

When Fred Markham set the 200-meter speed record of 65.484 mph (105.387 kph) in the streamlined recumbent Gold Rush in 1986, the record over the same distance on a regular bicycle was 43.9 mph, set by East German Lutz Hesslich. Markham's speed was 49.2 percent faster.

The world's hour record for a streamlined HPV is 46.96 mph (20.99 m/s), set by Pat Kinch in the Bean in Great Britain in 1990. That's 47.7 percent faster than the record on a regular bike of 31.78 mph (14.21 m/s), set by Francesco Moser in 1984.

There are also some glaring errors. For instance, the caption under a photo of the Bowden Spacelander bicycle states: "Dream bike of the fifties. This American-designed plastic-framed bike never did go into production." The Spacelander was designed by Briton Benjamin Bowden (who moved to the United States after World War II). 1,200 Spacelanders were manufactured in Michigan, USA, in 1960, and the bikes are now prized by collectors.

Even with the errors, Bicycle Technology is worth having by those people interested in the subject. There's a wealth of useful and interesting information, and the book is written simply enough that one doesn't have to be an engineer or real technically-minded to understand it.

Van der Plas in the preface promises the next printing of the book will correct errors found by readers. The writer of this review sent three typed pages to the publisher listing distortions and mistakes. Van der Plas wrote me back and said he would "try to incorporate as many corrections as possible in the next printing of the book, which is due to appear later this year [1991]."

I suggest readers of this review who want to buy Bicycle Technology wait until the second edition is available.

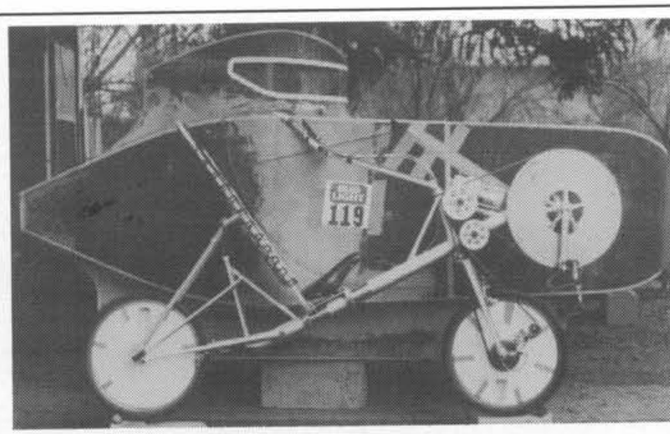
Michael Eliasohn

Front-Wheel-Drive Recumbent Bicycles

by Michael Eliasohn

Front-wheel drive works very well on cars. Some HPV builders say FWD works just as well on recumbent bicycles. The advantages, according to one builder, John Stegmann, Newlands, South Africa, "are the compact overall size with maximum wheelbase, the load-carrying potential, the compact 'workings' (short chain, short cables) and the possibility of folding.

For purposes of simplicity, this article is restricted to FWD, front-steering, leg-powered recumbent bicycles. Rear-steering FWD bicycles were written about in the spring, 1990, issue of Human Power. Some other examples of FWDs were shown in HPV News in June-July, 1989 (the arm and leg-powered Manuped), March-April, 1990, and December, 1990, and in Human Power in summer, 1989, and summer, 1990 (and written about in winter, 1991). Most of the information for this article was gathered by writing to builders of FWD recumbents. I obtained information on the Dutch-manufactured Flevo Bike from several sources. I've seen enough photos to know that numerous other FWDs have been built in Europe. I hope that someone in Europe will write an article for a future Human Power on some of them.



Jon Lebsack's faired FWD.

There are two ways to build an FWD, both of which have their advocates. One is to attach the bottom bracket to the forks, so that as the front wheel turns, the bottom bracket/crank/pedals move with the wheel. The other way is to mount the bottom bracket to the frame, then run the chain to the front wheel, usually over idlers or via use of a crossover drive, to change direction of the chain from horizontal coming off the chain ring to vertical as it runs to the wheel sprocket(s). The vertical portion of the chain twists as the wheel turns. Presumably a third way would be to use a center-pivot drive hub like that on a front-wheel-drive car, but such a hub would be complicated to build and I don't know of anyone who has tried it on a bicycle. A motivation of all the FWD builders appears to be to eliminate the long chain required by conventional rear-wheel-drive recumbents. Presumably it requires more of the rider's energy to "propel" a long chain than does a short one. A long chain obviously weighs more than a short one and on a short-wheelbase rear-drive recumbent requires use of an idler to get the chain over the front wheel. And cleaning a long chain is twice as messy as cleaning a short one. Also, as Tom Traylor in the accompanying article and John Stegmann elsewhere point out, not having a chain running under the seat provides space to carry cargo. Stegmann's FWD can carry a saddlebag behind the seat "which weighs very little and is large enough to take a crate of 24 cans of beer".

John Stegmann's 1988 FWD experiment.

FWDs are obviously more compact. W.A. Harper, Redding, Calif., U.S.A., who sells plans for his FWD design, wrote that there are "no problems with long cables. Everything is right there on the front fork. I kept the overall length at 6 feet (1.8 m) so it fits nicely crosswise on the rear of a car. "Although Traylor says in his article that climbing hills on his FWD isn't a problem, opinion by the other builders varied concerning hill-climbing ability. Of 36 entries in the Midwest HPV Rally in Michigan, U.S.A., in August 1990, the FWD of Michael Bledow, Plymouth, Mich., U.S.A., was fifth in the hill climb (ridden by Tom Caldwell). That's despite the fact the bike weighs 36 pounds (16.3 kg) and has only five speeds. "There is no problem with traction because the rider is practically sitting on the front wheel of the bike, with the weight of the legs in front of the wheel," Bledow wrote.

In contrast, Jon Lebsack, Fort Collins, Colorado, U.S.A., wrote that smooth pedallers could ride his FWDs up hills of up to 16-percent grade, "Jerky riders have trouble at 8-percent grade. Any strong rider can break the wheel loose at most speeds if s/he wants to, even on clean dry pavement."

Lebsack notes that "hill-climbing ability and traction under acceleration are determined by the weight distribution and the height of the center of gravity. The weight distribution of my FWD bicycle is 47 percent (on the) front wheel. The center of gravity is located 32.75 inches (832 mm) above the ground with 700c wheels."

In contrast, 55-60 percent of the weight is on the front wheel in Traylor's design.

But Stegmann notes, "The rider's center of gravity has to be sufficiently behind the front wheel for safe braking. I experience rear-wheel lifting when braking as well as front-wheel tire slip when setting off on an incline which is in any way slippery. Once moving, it is difficult to induce wheelslip."

Put all the builders of FWD recumbents in one room, and no doubt a debate would break out between those who mount the bottom bracket to the forks and those who feel it should be mounted to the frame: that is, in a fixed position.

Mounting the bottom bracket to the forks seems to defy all "cycle logic," since the distance from seat to pedal, which should be fixed, is going to be constantly changing. But, Stegmann writes, "There is no problem with varying leg length as the cranks swing from side-to-side with the steered front wheel. The big adjust-ment which the rider needs to make is that of constantly adjusting the direction of thrust to have the reaction on a line from the steering axis and not to apply torque which has to be resisted by pulling on the handlebars.

"I subsequently found that hands-off steering is an additional advantage, useful for peeling bananas, putting on gloves, [or] resting one's arms by interlocking fingers over one's belly."

Harper spoke of what he calls "torque steering" from attaching the bottom bracket to the forks: "I don't really find it to be much of a problem. It seems to happen only at low speeds" and "if I shift into too high a gear for conditions. This tends to make the bike unruly in heavy traffic, so I avoid heavy traffic."

"I believe the cause of torque steer is simply overpowering your arms' ability to steer with your legs," Harper continued. "The pull and push (of your arms and legs) have to be equal. I find you have to stay in lower gears than normal and gradually increase speed."

Presumably the big disadvantage to attaching the bottom bracket to the forks is learning to ride the bike. "It requires practice to learn to ride," Stegmann said, though "I'm not sure if this is true for all similar machines and I think kids would learn fast. Experienced cyclists need to make too many adjustments to their established habits."

In fact, Stegmann notes "my FWD was at first virtually unridable, and now I ride hands off, uphill, and round corners."

"The bike takes a little getting used to," Harper said "but I have never had anyone who couldn't ride it on the first try."

Stegmann notes another disadvantage: "the relatively large mass of the cranks, bottom bracket, framing and chain, all above the steering axis has a horribly unbalancing effect on the steering. This is worst when wheeling (pushing) and parking and is somehow manageable when one has learned to ride it. Not a nice feature. If these masses were below the steering axis, I'm sure it would be better. Impossible?"

Jon Lebsack's unfaired FWD.

Mike Bledow's drive system.

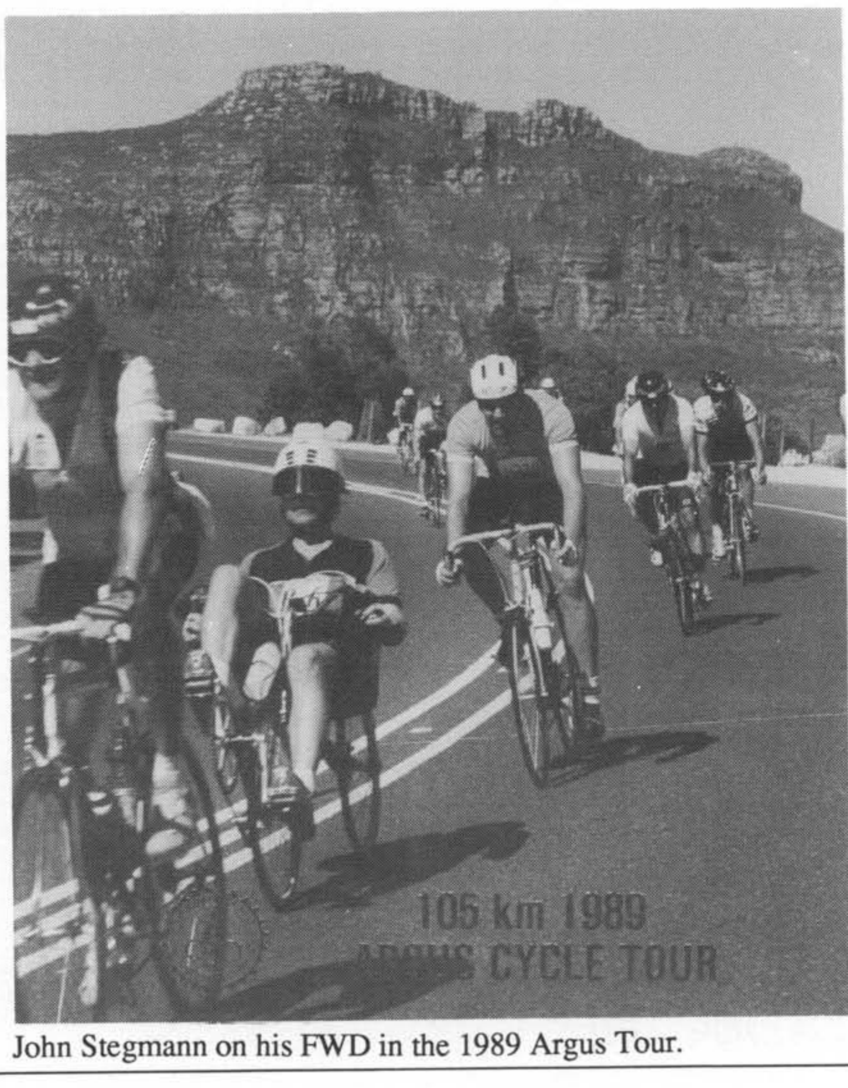
It should be noted that Stegmann built what he calls his experimental FWD in 1987, has made some improvements since, but doesn't recommend copying it. He plans some day to build his "dream" machine, which will be FWD.

Bledow said he chose to build an FWD with bottom bracket attached to the frame because, "I personally do not feel that the crank assembly should be attached to the front fork, where it will be moving about as the bike is maneuvered.

"Twisting the chain to allow the front fork to turn has proven to be no problem at all, provided that some sort of chain-tensioning device be included in the assembly to pick up the slack in the drive chain while pedaling straight ahead," Bledow said. (Bledow's FWD initially used a Sturmey-Archer five-speed hub, making addition of a chain-tensioning device necessary. Obviously, using a rear derailleur with a freewheel would serve the same function. The distance from bottom bracket to the front-wheel center on Bledow's bike is 15 inches (381 mm), long enough for use of derailleur gears, he feels.) Lebsack, who built several FWDs (as opposed to Bledow's one, as of when research was done for this article), reports he had "no drive train problems" with his twisting chain. Although his design could be refined, he said, his original machines "handled well and the feedback through the handlebars was very slight. It could be ridden 'no hands'.

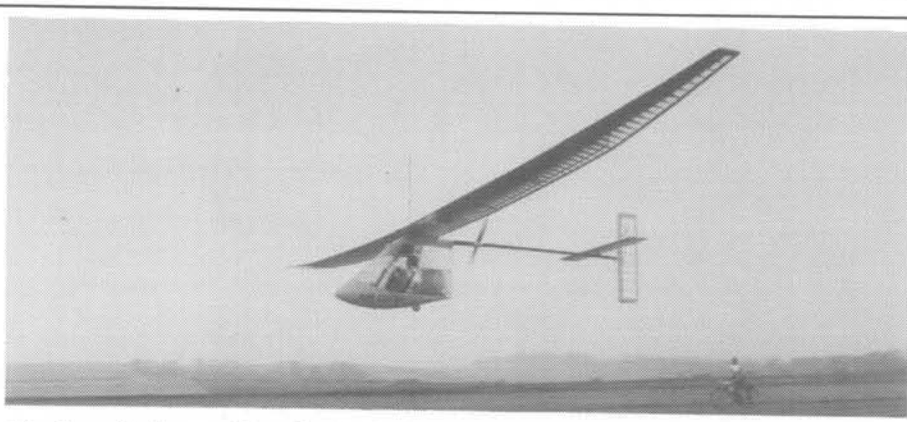
Mike Bledow's FWD in action.

"Incidentally, the fixed-bottom bracket design would be ideal for anyone who wants to build a two-wheel-drive bicycle - though I'm not sure why anyone would want to. Lebsack constructed a two-wheel-drive, all-terrain (mountain) bike, that is, with upright riding position. He described it as "great for riding up stairs." (Lebsack now manufactures Vertebra all-terrain, bikes - rear-wheel drive only.) Lebsack was the only builder to mention that "the fork on an FWD recumbent must be stronger than on a conventional fork. The cyclic pedaling forces require that the fork be rigid also. The side effect of this is a rough ride."



John Stegmann on his FWD in the 1989 Argus Tour.

Both Traylor's and Harper's designs, for which they sell plans, require modifying standard forks, which become triangulated when the bottom bracket and braces are added. The need to extensively modify standard forks or to build ones from scratch is a disadvantage of building an FWD, as opposed to being able to use a standard, unmodified fork on a rear-wheel-drive recumbent. Short riders have a problem with short-wheelbase recumbents in that in order to get enough clearance between the heels/pedals and the front wheel, they have to sit far forward, which makes the ride uncomfortable, since they end up sitting very close to the front wheel. That can also be a



Airglow flying at Duxford Airfield, September 1990.
Figure 1, McIntyre, P. 20. Photo: Mark McIntyre. Pilot: Nick Weston

problem with FWDs, according to Stegmann. "I think that short people do have a problem with FWD bikes in that their mass gets to be too far forward for safety and comfort. My FWD experiment(al bike) has a fixed bottom bracket and moveable seat, but the seat cannot be brought far enough forward for a short rider."

Apparently the only production FWD recumbent bicycle is the Flevo, manufactured in the Netherlands by Johan Vrielink. In addition to the FWD, it features 20-inch wheels, hydraulic brakes, front and rear suspension, can easily be taken apart into two pieces, and the rear wheel subframe is interchangeable with a two-wheels-in-back subframe, making it into a tricycle. It's available with 3, 5, 10 or 12 speeds, according to Vrielink and is adjustable to fit riders from 5.1-6.5 feet (1.56-1.98 m). Reportedly it weighs 45 pounds (20.4 kg). There is also an aluminum version that weighs only 15.9 pounds (7.2 kg), but Vrielink, in his letter to the author, didn't say if he's producing it for sale.

How good the Flevo is apparently depends on whom you ask. IHPVA executive vice president Marti Daily, writing in Bicycle Guide (December, 1990) about the 1990 European HPV Championships, said of the Flevo: "When mastered, both the two- and three-wheel versions can turn on a dime and either [of them] will blow most other vehicles away in a slalom test." In contrast, Flevo owner Li Hock Hung of Singapore in Recumbent Cyclist (January-February, 1991) says, "maneuverability is limited to large turning circles or [the rider must] watch out for instability. Because of this handling characteristic, speed has to be sacrificed." Ton ten Brinke, in writing about the Flevo in The Netherlands IHPVA chapter newsletter wrote: "The learning process to ride it is not ordinary. It takes a little bit to become accustomed to it." (English translation).

Opinion also isn't unanimous among FWD builders on how good such machines are. Lebsack also built rear-wheel-drive versions of his recumbents before going into the all-terrain-bike business. He writes: "My FWD recumbents were not faster than the RWD models. My FWD recumbents were not lighter than my RWD recumbents. My RWD recumbent has a better chain line, fewer bearings, lighter weight, and a more pleasant ride quality than my FWD recumbent." But, as noted earlier, Lebsack feels his FWD design could be refined.

There are three sources of plans for constructing a FWD recumbent bicycle.

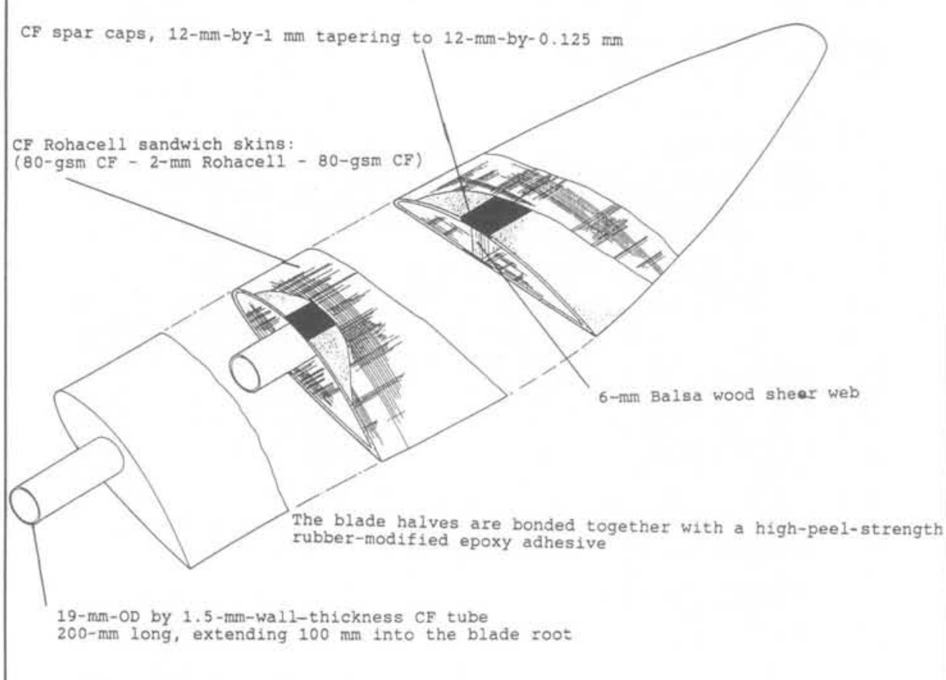
1. W.A. Harper, P.0. Box 491871, Redding, CA 96049, USA. Information, $2; plans and information, $10.

2. Tom Traylor, 22407 Warmside Ave., Torrance ,CA 90605, USA, plans $12. Self-addressed stamped envelope for information.

3. Plans for an early version of the Flevo, not the production version, are available from the Netherlands chapter of the IHPVA: NVHPV, Ton ten Brinke, Postbus 10075, 1301 AB Almere, The Netherlands. The address for Flevo Bike is: de Morinel 55, 8251 HT Dronten, The Netherlands; telephone: 03210-12027.

According to *Recumbent Cyclist*, the price of the Flevo plans is $15 U.S. and the Flevo bike, $1,000 U.S. for the 5-speed version, plus shipping. If you are interested in the bike or plans, I suggest that you send an inquiry first, and, if you don't live in the Netherlands, that you enclose an international postal reply coupon.

Michael Eliasohn
2708 Lake Shore Dr., apt 307
St. Joseph, MI 49085, USA.



Airglow propeller construction.
Figure 5, McIntyre, p. 22

Front-Wheel-Drive Bicycles
by Marek Utkin

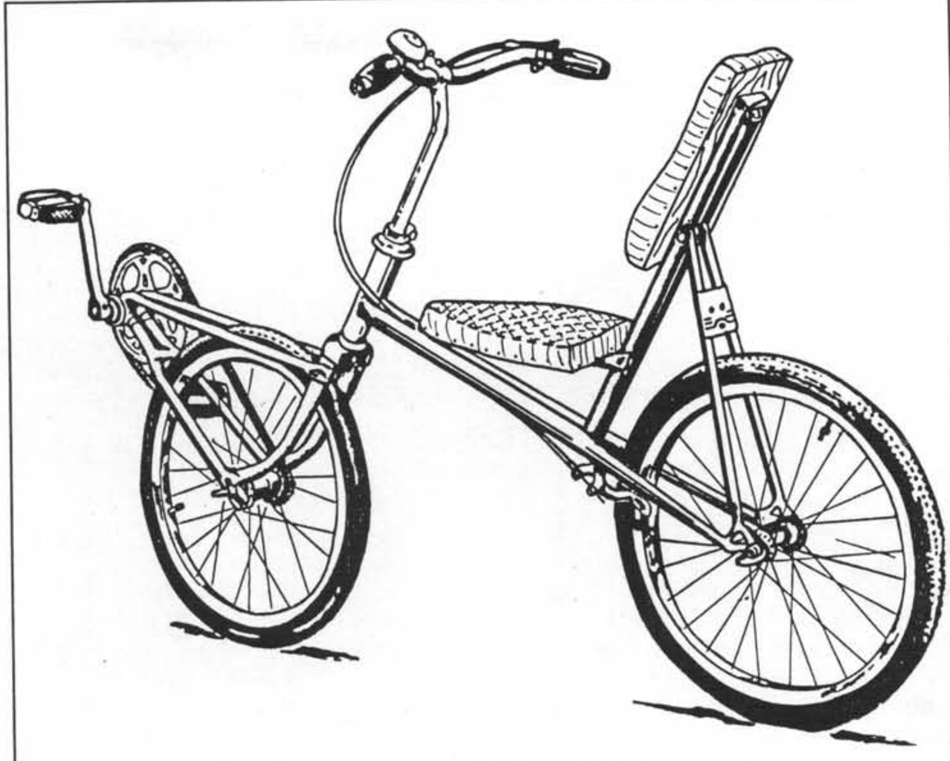
Drawbacks of front-wheel-drive bicycles with the bottom bracket attached to the forks are that extra hand force is required for straight riding in high gears (during 200 meter sprints, weaving of these bikes is visible); and high skill is needed when making small radius turns. Pedaling during such turns is very difficult, sometimes impossible.

The simplicity of construction offers advantages in weight, compared with a normal rear-wheel-drive recumbent. However, rather adventurous geometry is required. A popular fork angle is 45 degrees.

For propulsion, the ideal fork angle would be parallel to the ground; for steering, 70 degrees, so 45 degrees is a compromise. The smaller the angle between the propelling force and the fork angle, the less the steering is affected. Also, the greater the distance between the fork axis and the bottom-bracket axle, the less the steering is affected.

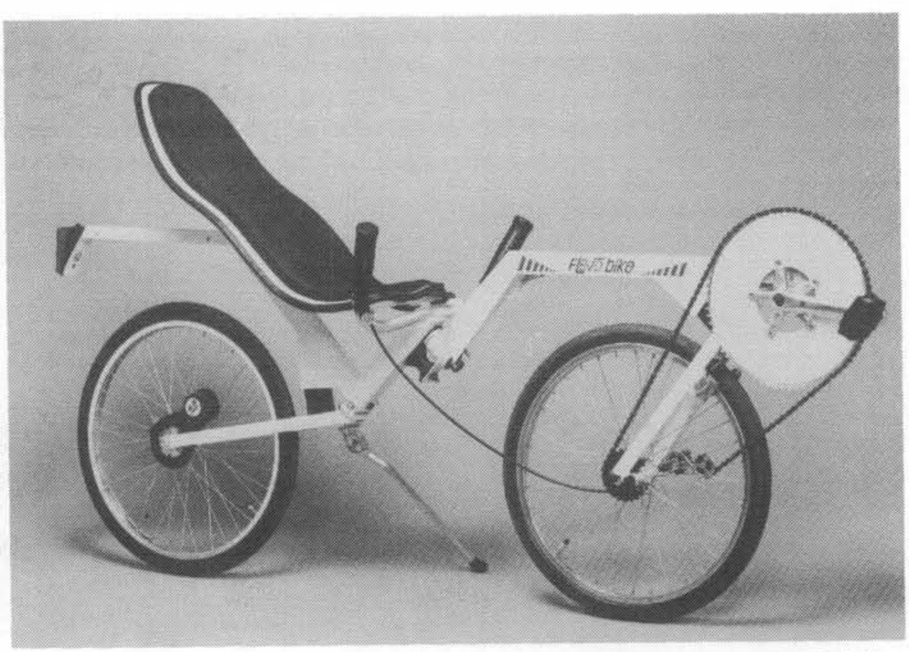
The chain wears only when bending, so if there are no idlers, sprockets and tensioners, I see no difference between a long-wheelbase recumbent and a regular 10-speed bicycle. In theory the long chain on a rear-wheel-drive recumbent could be replaced by stiff rods and the work would not be affected: the friction would not be increased.

Marek Utkin,
Warszawa, Poland



Dariusz Pajorek's FWD, drawn by Marek Utkin for his book.

[The following are translations of Netherlands HPV News articles on Flevo and Cha-Cha Bike front-wheel-drive bicycles, courtesy of Peter DeGroot, Coloma, MI. This translation is a paraphrase. Mr. DeGroot gave a rough translation orally, while I (Eliasohn) took notes. As a result, some portions may be inexact.]



Johan Vrielink's Flevo FWD bike.

Johan Vrielink and the Flevo Bike
by Ton ten Brinke

The bicycle is named after the Flevo Polder in the Netherlands, a polder being somewhat equivalent to a county in the U.S. The Flevo bike is built and designed by Johan Vrielink in the town of Dronten, in the polder of Flevo.

Vrielink is an entrepreneur who has built sailboards, ice boats, land sailers and cars. "What I (ten Brinke) saw, his hands made." Vrielink operates under the motto, "I want to make it myself."

Vrielink has built a tricycle similar to the Wind-cheetah (Speedy), using square tubing. He builds the Flevos out of square tubing. Why does he use square tubing? "Why do it the difficulty way when you can do

The Flevo conversion to a load-carrying tricycle.

it the easy way?" The motto (I think unofficial) of the Netherlands HPV Association is, "Nothing is impossible and everything can be done differently."

Vrielink teaches metallurgy in the capital of Flevo Polder. He had an accident while riding a moped on a bike way, which required a long period of recovery. (I didn't write down the significance of that—I recall something like, the recovery period gave him a lot of time to think.)

He originally built a long-wheelbase recumbent out of an old bike and square tubing.

The Cha-Cha Bike was the inspiration for the front-wheel-drive Flevo because of the Cha-Cha's short chain, compactness, and because it absorbs shock.

The Flevo was born in the spring of 1988. Originally, only the rear wheel was suspended. Eventually the front wheel also was suspended. The front and rear wheels are interchangeable, as on a car.

The bike can be taken apart with one move of the hands.

Interchangeable parts enable the Flevo to be converted into a tricycle (two wheels in back) for carrying groceries, a passenger, [or] camping equipment.

Construction drawings are available by writing to the Netherlands HPV Association. (The address for the NVHPV is: Ton ten Brinke; Postbus 10075; 1301 AB Almere; The Netherlands.)

Anyone wanting to build a Flevo should realize that the design requires some machining and the drive system has the turning axis in the middle.

Learning to ride it is not a matter of course. It takes effort to become accustomed to it.

NOTE: Marti Daily told me (Eliasohn) that she tried riding the tricycle version and found it very difficult to ride. Apparently, the two rear wheels don't keep the rider/front part of the bike upright. Keeping it upright depends on riding it like the two-wheel version. She didn't try riding the two-wheel version.

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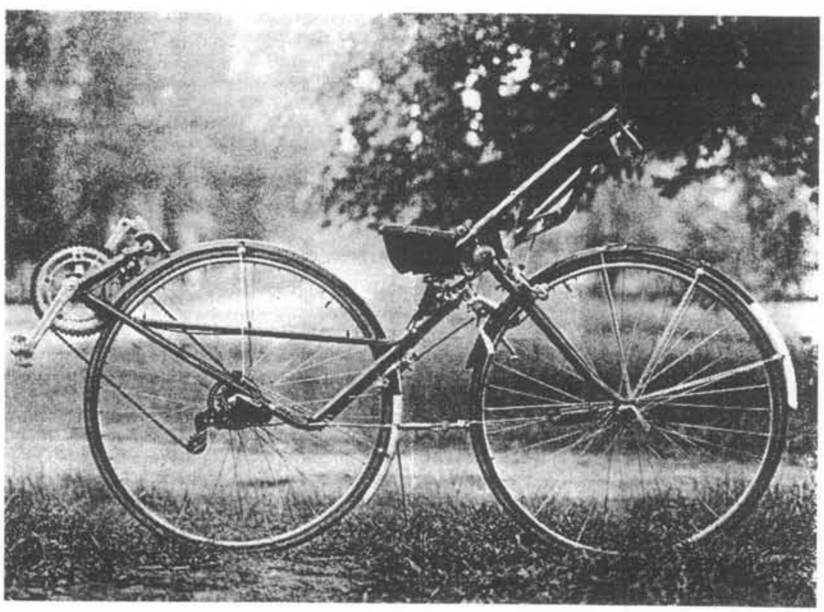
Cha-Cha Bike
by Bernd Zwikker and Bram Moens

Once in a while there is a design that is different from the ordinary. Wim van Wijnen is the designer of a bicycle that fits this category.

Cha-Cha II is a very compact bicycle with big (27-inch or thereabouts) wheels. The rider sits in a semi-reclining position. It has front-wheel drive.

The unique setup has a frame of two parts. The seat, which has shock absorbers, is kept together with cables. (Looking at the photo, it appears the Cha-Cha may have a



The Cha-Cha bike.

horizontal pivot in the middle. Cables at wheel-center level hold the front and back together. The cables are attached to springs at the rear. As the bike flexes in the middle as it is ridden, the cables and springs provide a springing action.)

The bike offers tremendous visibility (presumably because of the very high seating position). The bike is unique and comfortable, "but it's a question of personal taste."

The design is effective, although some riders question this because of the light construction of the seat. When climbing hills, the seat flexes to the extent that the rider (presumably one of the authors, not van Wijnen) is afraid of it breaking. There's a lot of pressure on the seat.

How does it ride and steer? After 10 minutes, an inexperienced rider could ride it pretty well. Maneuvers can result in some unexpected problems and situations, but overall, the bicycle is very stable and roadworthy.

After riding 25-30 kilometers, the rider could ride it with folded arms. (I'm finding this is "common" with FWD recumbents where the bottom bracket is attached to the forks. What happens is that the rider learns to steer with his legs—I assume only when riding in a straight line—while pedaling.)

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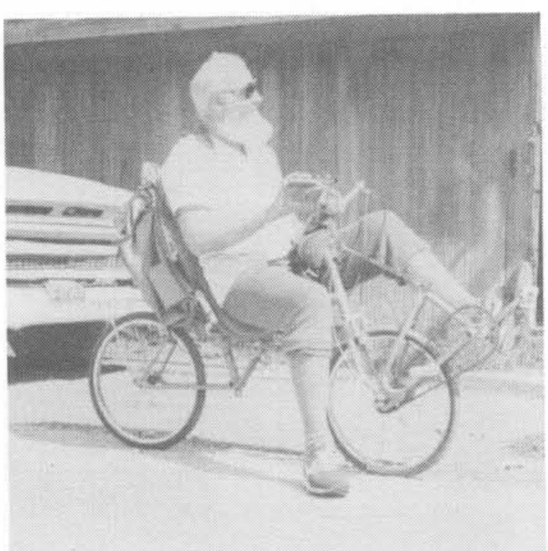
(Bernd Zwikker is a member of the board of directors of the Dutch HPV Association, NVHPV, and is editor of its journal HPV Nieuws. He spends much of his spare time either riding recumbents or writing about them).

Olon Belcher's FWD

by Michael Eliasohn and Randy Gilmore

If the other articles about front-wheel-drive recumbent bicycles in this issue of Human Power have you intrigued with the idea, but you are hesitant about spending a lot of time building your own to decide if you like FWD or not, here is a simple FWD design that can be built quickly.

The design was the idea of Olon Belcher, who was living in California, U.S.A., when Randy Gilmore wrote about his machine for Gilmore's Ecomotion newsletter. Portions of this article within quotation marks are taken from Gilmore's article, which appeared in the August, 1982 issue of Ecomotion, the last issue.



Olon Belcher on his "bocy" (short for "body cycle").

What Belcher named the Bocy was "converted from a Raleigh Twenty 20-inch-wheel utility bicycle, with the addition of the rear half of a BMX racing frame. As such, it is surely the easiest-made recumbent today, needing no brazing, welding, or major frame alterations."

"On this particular machine (Olon has made several), 20x1.75 skinside tires on alloy-rimmed wheels are used, swapped end-for-end from their usual positions."

"The BMX frame, complete with crankset, extends forward from the front wheel's axle, and is cable-braced (in this case with rawhide cord) to the handle-bar stem. The normal handlebars and brakes are used, and the drive wheel is equipped with a Sturmey-Archer three-speed hub."

As can possibly be seen in the photo, Belcher bolted the drive wheel into the dropouts of the BMX rear frame. The front forks were then bolted to holes in the dropouts (not the dropout slots). Presumably that would require spreading the fork ends apart, which might be done simply by tightening the bolts fastening the fork ends to the BMX frame dropouts.

The seat consisted of a backpack frame, with padding added, covered with sheepskin.

"Being front-wheel-driven, the crankset moves as one with the front fork during steering. Consequently, hard pedal pressure can throw off the steering for an inexperienced rider such as myself. Olon, however, can start from a complete stop without using his hands to steer." (In a letter to me (Eliasohn), Gilmore wrote that, "Once going, however, the bike wasn't hard to handle.")

"In my limited riding experience with the Bocy, I found it comfortable to ride and maneuverable, due to its short wheelbase. I am sure that with more practice I would have no difficulty starting smoothly. Part of my trouble was due to the bike being stuck in top gear."

"Olan is quite a bit taller than my 6 feet, and I had some trouble reaching the pedals correctly. Anyone thinking of building a similar machine would do well to look for a short-chainstay (BMX) frame for the crankset-mounting, or consider shortening the chain-stays even though this increases the construction work."

Obviously, 20-inch-wheel utility bikes, such as Belcher used for the main part of his bike, are rare in the United States, but a BMX frame could be substituted. Doing so, however, would add two complications. A BMX front fork could not be spread apart to be bolted to the rear half of the BMX frame used to "support" the pedals, plus due to its design, a BMX fork probably would not fit between the dropouts of the subframe. The easy solution would be to substitute a "regular" 20-inch fork with tapered blades.

Also, the long head tube and stem of Belcher's bike fit between his legs. But the short head tube and stem and U-shaped lower section of handlebars on BMX bikes will not provide such clearance, so a different setup will be needed.

Those people building a FWD recumbent frame of their own design from scratch who are seeking simplicity might consider using a regular front fork in the rear to hold the back wheel—which is normally a front wheel. That is what Michael Bledow used on his FWD. (See photo.)

Front-Wheel-Drive Recumbents

by Tom Traylor

It's about time HPV enthusiasts realize there are alternatives to the now entrenched short- and long-wheelbase rear-wheel-drive recumbents.

I built my first front-wheel-drive recumbent bicycle about 11-12 years ago from two old bike frames. That bike worked so well that I have been modifying and refining the same basic design since. I still have the original bike, and it is the basis for the plans I have been selling for many years.

Since I built that first bike, I have built several more. They include three tandem recumbents which feature two-wheel drive with independent shifting and back-to-back seating. Three single-seaters featured monocoque construction in sheet aluminum.

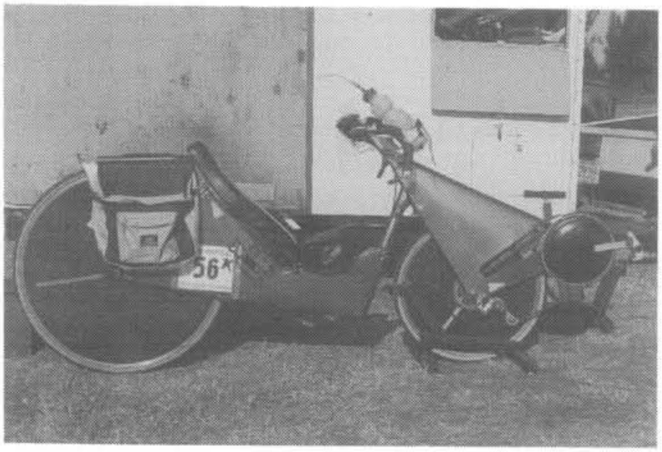
The most-often-asked question concerns having the bottom bracket and pedals mounted to the forks. People will ask, "Doesn't pedaling interfere with steering and don't you have to constantly exert pressure on the handlebars to keep from swerving all over?"

The answer in both cases is "no." The pedals are in front of the wheel and therefore in front of the steering head and almost in line with it. Applying pressure to the pedals tends to pull the wheel toward the center, not away from it. When cruising, that is, not accelerating or climbing, no pressure on the handlebars is needed. Hands-off riding is easy, and I do it all the time on long rides when I want to relax.

When accelerating or climbing, the pressure needed on the handlebars is an asset. It allows the rider to use his/her arms, back and legs in an action that is very much like riding a standard bike "out of the saddle". Being able to use your whole body instead of just your legs makes FWD bikes very good climbers.

Even though the weight shift is away from the drive wheel on a steep hill, traction has never been a problem. This is because 55-60 percent of the weight is on the front wheel to start with. I have raced in hill climbs with grades of more than 20 percent without losing traction.

I am often asked about pedaling around a corner, because it appears that the pedals would be at different distances from the rider. The steering head is near the rider's crotch, therefore close to the pivot point of



Tom Traylor's monocoque FWD recumbent.

Tom Traylor on his original FWD bike (c. 1981).

the hips. As the front wheel swings through its arc, the radius of the pedal swing doesn't change much in relationship to the hips. In normal riding, even around 90-degree corners, the difference in pedal reach is virtually undetectable. Only when you make a very slow, tight turn do you have to reach for the outside pedal.

All of my bikes have the bottom bracket mounted to the forks (or what passes for forks on my monocoque bikes), so the distance between the bottom bracket and the freewheel is shorter than on a standard bike. This causes an exaggerated chain angle between the chainwheel and the freewheel. This means more care is needed to align and adjust the derailleur, but after it is set up, it works just fine. Most of my bikes have 18 speeds, so that even with the short chain stays a full range of gears is possible. I use a standard-length chain minus six or seven links.

Most recumbents look the way they do because you cannot let pedals overlap the front wheel. The result is a very long or very short wheelbase, or is having the crank above the wheel. With the cranks and wheel turning together as it does on a FWD, overlap doesn't matter. You can have any combination of bottom bracket and seat height or wheelbase you want. Most of my bikes have a bottom bracket height of 16 inches (406 mm) and seat height of 17 inches (432 mm), with a wheelbase of 43-44 inches (1092-1116 mm).

This puts me several inches lower than most recumbents, and my tandem is even lower. This not only gives me a small frontal area, but even a short rider can easily reach the ground with both feet when stopping, something many recumbent riders cannot do.

I am 5 feet, 8 inches (1.7 m) tall, and I do not have any problem with sitting close to the front wheel. Even the 24-inch (610 mm) wheel gives me plenty of room. My kids were riding these bikes when they were well under 5 feet (1.5 m) tall. The bottom-bracket spindle is about 14.5 inches (368 mm) in front of the front-wheel axle. By reducing or extending this distance, you can accommodate almost any size rider without changing the seating position. As for heel clearance, if the spindle is at least 16 inches (406 mm) above the ground, the pedals should not hit the ground when cornering.

Compared to conventional recumbents, the FWD is just as fast on the level and downhill and much faster on hills. Compared to standard upright bikes, it's just as fast on hills and faster on the level and downhill. It handles well at speeds from a few miles per hour to 60 m.p.h. (27 m/s) downhill.

If you corner too fast on a wet or sandy road, the rear wheel tends to break loose first, making it possible to recover from the slide.

I have raced my three monocoque bikes and tandem at the International Human-Powered-Speed Championships, in the unfaired, partially faired, multirider and GT classes. At Vancouver in 1986, I had a second and third, respectively, in the 20-mile (32.2k) and 10-mile criteriums, unfaired class. At Visalia in 1988, I finished second in the 200-meter sprints multirider class and third in the partially faired class. I also had firsts in the one-hour time trial and 20-mile criterium, in the partially faired class. In Portland in 1990, I had a first in the GT-class 20-mile criterium.

I also have raced against standard bikes with my unfaired bikes at the Great Western Bicycle Rally over the last four years. I have had two second and two thirds in the 100-meter drag races; two fourths and a third in the 10-mile time trial. The performances would have been better if I had a younger, stronger rider. I am 55.

Another advantage of this design is that it is small enough to be carried on a standard auto bike rack. Take the rear wheel off and it will fit in the trunk of most cars. The hollow body of the monocoque bikes have room inside for a pump, spare tubes and tools. If you go bike camping, you can carry an enormous amount of gear, not only over and around the rear wheel, but under the seat because there isn't a chain going to the rear wheel.

There are drawbacks to the FWD bike. The biggest is learning to ride it. This is definitely not a bike you will appreciate the first time you try it. It has a different feel than a bike with a frame-mounted bottom bracket. It takes time to feel comfortable on it. Most of the problem lies with getting used to letting your legs swing with the front wheel when steering. This bike is steered with arms and legs. In fact, when you get used to it, you can steer with your legs only.

Oddly, people who don't ride bicycles very much have the least trouble learning to ride it. People who ride standard bikes have a little more trouble, but the people who really have a difficult time riding this bike are HPV people who are used to riding regular short- or long-wheelbase recumbents. Anyone can master this bike, but s/he will be discouraged at first.

I think the difficulty in learning to ride an FWD of this type, along with the fact the design doesn't look as if it would work, has discouraged a lot of people from trying it.

Another problem I have had with these bikes is gearing. Most of my bikes use a 20-inch (508 mm) drive wheel, which lowers the gear ratio quite a bit. My unfaired bikes have a 60-tooth chainwheel. The smallest freewheel sprocket has 12 teeth and that gives me a high gear of only 100 inches. That is okay most of the time, but it's too low with a tailwind or downhill. On my GT bike, I have 64-tooth chainring and 11-tooth freewheel, for a high of 116 and that is definitely not high enough. A similar (rear-wheel drive) bike, the Lightning F-40 has a high of 136. The trouble is finding a chainring larger than 64 teeth or a freewheel smaller than 11 teeth, which is almost impossible.

My original design uses a 24-inch front wheel, but when I was designing my monocoque bikes, the only 24-inch wheel available was one with a steel rim for low-pressure, 1-3/8-inch (35 mm) tires. Today, 24-inch, high-pressure, narrow rims and tires are readily available. When I get around to redesigning my bikes, I will go to a 24-inch drive wheel, and that will solve my gearing problems.

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Design and Flight Testing of the Airglow Human-Powered Aircraft

by J. McIntyre

(From: Human-Powered-Aircraft Group Conference on Technologies for Human-Powered Flight, The Royal Aeronautical Society January 30th 1991).

Summary

In early 1987 we set out to design a human-powered aircraft suitable to be used as a flight research vehicle. Sponsorship was obtained from the RAeS Kremer fund in late 1987. Design, testing and construction proceeded as time and funding permitted. The aircraft was completed in June 1990 and made its first flight on July 21st. This paper describes the important facts and lessons learnt during the project. A previous paper by McIntyre [16], describes many of the construction methods used in detail.

Introduction

Airglow is one of a number of HPAs built outside the rules of the Kremer competitions in recent years to investigate and extend the technology of such energy-efficient aircraft. It was foreseen that involvement in such a project would bring diverse educational rewards to those contributing to it. In the past aircraft have been constructed to win prizes or because human-powered flight represented an engineering and athletic challenge. While these are still strong motives it has become apparent that the technology used and the lessons learnt can be applied to some important problems. An example is the design and construction of high-altitude long-endurance aircraft, to be used in the planetary sciences as remote sensing platforms or for atmospheric sampling.

Aircraft Description

The aircraft is optimized to fly at a speed of 7.8 m/s for a power input of 234 W (3.9 W/kg of the pilot's body weight). The pilot is housed in a fairing hung under the wing. He sits recumbent and spins a standard pair of bicycle cranks driving a 1:2-ratio spiral-bevel gear box that delivers power to the rear-mounted co-axial pusher propeller through a mixed shaft-chain drive. Overall transmission efficiency is of the order of 86%, (propeller efficiency 90% and transmission efficiency 95%).

The 25m-span wing is stressed to an ultimate limit load of 2g and has a single bracing wire out to half the span to reduce the bending load. An advantage of this arrangement is that it results in a rugged structure. The aircraft survived a high-speed ground loop that occurred after one of the ground crew hit and damaged the rudder at take off. The fuselage structure is stressed for high stiffness to prevent binding in the drivetrain and to protect the pilot in the event of a 4g yawed landing.

A drawing of the Airglow aircraft is shown in figure 1.

Airframe and Structures

The aircraft's primary structure is assembled from 25-to-86-mm-diameter thin-walled carbon-fibre tubes. It was assumed throughout the structural design that the primary structure alone carries all the main loads, while the secondary structure serves to maintain the desired aerodynamic profile. The tubes were made by a hand-layup process. Strips of carbon fibre pre-preg were spiral-wrapped around waxed aluminium mandrels in carefully calculated orientations; a layer of peel-ply was added in order to create a rough surface finish for subsequent bonding operations. The whole mandrel plus spar was then tightly bound in two layers of high-shrink tape and oven cured at 120C. After cooling, the mandrel was pulled from the finished carbon-fibre tube. This could sometimes be accomplished by hand whilst in other cases a winch, lashed to the tube with Kevlar rovings, was needed. In this way it was possible to make tubes up to 8m long.

Detailed analysis determined the loads carried by each structural member. The laminate geometry was then tailored to meet this requirement with the minimum weight of material. For example the wingspar has a 0.56-mm, 4-ply, wall thickness. Design trade off using laminate analysis [23] gave an optimum ply angle of 40 degrees to the tube axis for the basic shear/torsion tube. This choice of ply orientation yields a 27% improvement in bending/axial stiffness for only a 3% loss in torsional stiffness compared with a tube fabricated from 45-degree plies. Additional zero-degree plies are added top and bottom to carry the bending and compression loads.

The graphs generated for this trade-off study are shown in figure 2. Torsional stiffness drivesthe wing-spar design. Approximately 70% of its weight is accounted for in the basic shear/torsion tube element of the spar. Additional shear plies were incorporated at local stress concentrations, e.g. at the lift-wire attach point. A number of tests where made to investigate buckling of the 0.56-mm-wall tubes. It was found that at this wall thickness buckling was not a problem and that the tubes did not require internal bulkheads to stabilize them. However bulkheads were used at points of stress concentration e.g. at the wire-attach and transport joints and at the fuselage/wing joint.

The need to be able to disassemble the aircraft for transport and storage led to the wing being made in five sections. Plug-together joints provide continuity for bending and shear transfer. The smaller-diameter tube extends into the larger-diameter tube for a distance equal to four times the large-tube diameter. Torsion and compression loads are transferred across the joint by means of bonded-on aluminium fittings. A single 2.5-mm-diameter steel wire out to half the span relieves the main bending loads, its length being chosen to give the desired dihedral dictated by stability requirements.

The lift wire has Cda = 0.035 and accounts for about 5% of the total drag.

An 18mm-diameter carbon-fibre rear spar and Kevlar 'X' bracing forms a lightweight truss with the main spar to provide in-plane stiffness. Figure 3 shows the bending moment in the wing spar at 1.1 g in level flight.

Wing ribs are cut from 5mm styrofoam (this material has a density of 27 kg/m3). They are locally reinforced where penetrated by the spar with 1/64" (0.4mm) plywood. Strips of 0.8mm-by-6mm plywood bonded to the top and bottom edges of the ribs carry the chordwise loading and form an attachment point for the covering. End ribs made from a sandwich of 0.8-mm birch plywood and 10-mm Rohacell (an acrylic foam with a density of 50 kg/m3) act as compression members in the 'in-plane truss', carry the main spanwise covering loads and provide a strong area for handling the wings during transport and assembly.

The leading edge is sheeted with a 3mm glass-styrofoam laminate that extends back to 60% of the upper surface and to 15% on the lower surface to maintain the accurate profile needed to ensure the required laminar flow. The trailing edge is a Kevlar Rohacell sandwich sized to deal with the large loads produced when the Melinex covering is shrunk. Covering is 12-micron Melinex type 'S' and is attached to the trailing edge and ribs with a heat-activated adhesive and Sellotape. The covering is then shrunk tight with a hot-air gun.

The tail-boom, rudder and elevator are stressed for full control deflection at Vne.

The fuselage is assembled from 25-76-mm-diameter carbon-fibre tubes, of 0.28-1.12-mm wall thickness, butt-jointed and reinforced with layers of carbon-fibre cloth.

Aircraft Performance

It is difficult to predict the performance of HPAs with the high degree of accuracy that is desirable, and obtaining good performance data from flight tests is surrounded by many practical problems, see for example Bussolari [4]. The data presented here for Airglow were calculated. A lifting-line model was used to obtain the drag of the wing and tails. Trim drag was calculated from the known flight conditions and other drag components were calculated using Hoerner [11] as a guide. The predicted power was factored by 10% to take account of imperfections in construction and miscellaneous efficiency and interference losses. Ground effect was assumed to reduce the power required by 11%. This is consistent with the experimental data presented by Langford [14]. It is hoped that planned future flight tests will provide more reliable data.

The aircraft's power polar is shown in figure 4 plotted with some other HPAs for comparison. Table 1 summarizes some of this information for aircraft for which reliable data are available. Data for Gossamer Albatross, Michelob Light Eagle and Vélair are taken from Frank [10] and Langford [14].

Aerofoils

The DAI1335, DAI1336 and DAI1238 aerofoils were designed by Mark Drela for the Michelob Light Eagle HPA. The DAI1335, used over the centre panel of the wing, has a two-dimensional L/D of 110 at a Reynolds number of 500,000. These sections have a 60%-laminar upper surface designed to minimize transition-bubble losses. The lower surface is fully laminar. Details of the methods and philosophy used by Drela in their design can be found in reference [6]. Fuselage sections were designed to fit around the pilot and to have a wide,low drag bucket, necessary because HPAs commonly fly with quite large amounts of sideslip. The tails use the Wortman FX 76 100-MP aerofoil [23].

Weights

There is a complicated trade-off between structure weight, aerodynamic refinement, performance and longevity. It would not be hard to build an aircraft of this size down to an empty weight of 28 kg, but such an aircraft would be fragile and would possibly not have survived the mishandling we subjected Airglow to during the early test flights. As the primary structure accounts for only 43% of the empty weight it is probably best to seek weight reductions by lightening the secondary structure.

Table 1 Comparison of Human-Powered-Aircraft Data

	Gossamer Albatross	Michelob Light Eagle	Airglow	Vélair
Span (m)	29.00	37.40	25.00	23.20
Area (m2)	49.80	31.00	22.50	16.90
AR	19.00	38.84	27.78	32.00
Weights (kg)				
Empty	33.00	42.00	35.66	30.50
Pilot	61.00	68.50	57.50	59.00
Misc. (Drink etc..)	2.00	4.00	—	—
Gross	96.50	114.50	93.16	89.50
Cruise conditions				
Pilot specific power (W/kg)	3.60	3.30	3.91	3.81
Absolute power(W)	221.40	226.05	234.00	225.00
V (m/sec)	5.43	7.33	7.76	8.61
q (Nt/m2)	18.09	32.91	36.90	45.40
Aero Coefficients				
CL	1.05	1.10	1.10	1.20
Cd0	0.014	0.010	0.010	0.011
L/D (2-D)	75.00	110.00	110.00	109.84
L/D (3-D)	25.79	40.43	35.60	33.59
Drag (N) Induced	18.48	11.24	11.60	
Profile	12.61	10.20	8.30	
Parasite	5.58	6.32	6.27	
Total	36.67	27.76	26.17	

A summary of the aircraft weight breakdown and some areas where savings could be made is shown in table 2.

Propulsion

Human-powered aircraft already operate perilously close to the pilot's maximum sustainable power output of 4 W/kg for an endurance-trained athlete, so only a small loss in efficiency would be sufficient to reduce flight duration from hours to minutes!

The 3.1-m-diameter propeller was designed using a procedure for minimum induced loss [2]. At the design point it has an efficiency of 90.5%. The propeller blades are hollow carbon-fibre-Rohacell sandwich shells, with an integral I-beam spar, structurally similar to a modern glass glider wing. They were constructed in a glass-epoxy mould. A drawing of the propeller structure is shown in fig 5.

The blade section was designed using Mark Drela's XFOIL code [6]. The root sections had their chord and thickness increased to meet structural constraints. Camber was then modified to maintain the designed blade-loading distribution. Two of the propeller aerofoil sections with their pressure distributions are shown in fig 6.

The pilot/engine spins a standard pair of bicycle cranks on a 1:2-ratio spiral-bevel gear box that turns a 38-mm internal-diameter C.F. shaft running inside the lower fuselage spaceframe tube. A 6-mm-pitch roller chain then drives a second parallel 100-mm-ID co-axial torque tube on the tail boom.

A roller clutch on the lower drive shaft allows the propeller to free-wheel, protecting the drivetrain from snatch loads. Binding of the drivetrain as the structure flexed in response to control inputs had been a problem on earlier aircraft employing this arrangement, which we eliminated by the simple expedient of making the propeller-drive-shaft bearings a loose fit on the tail boom, allowing it to float freely.

Cooling

Working as an aero-engine the pilot operates with a efficiency of only about 25%: thus in generating the 250 watts of power needed to keep the aircraft flying 750 W of waste heat must be removed. Pilot rationality degrades as comfort deteriorates, though some body temperature rise can be tolerated before power output starts to fall. Preventing overheating therefore assumes major importance. An airscoop with an inlet area of 125 cm2, Cda=0.0125, is provided to direct cooling air over the upper body and head. Experiments carried out during the Daedalus project [18] show that this provides the most effective cooling. Most of the fuselage fairing is covered in aluminized Mylar to reduce solar heating to a minimum.

Table 2 Summary of Airglow Components Weights (kg)

	Actual	possible	comments
Wing Primary structure	10.352		
Ribs	4.193		
Trailing edge	1.021		
Leading-edge sheeting	4.276	2.65	Change to hot-wire cut
Covering	.775		polystyrene
Wing miscellaneous	.061		bead board
Wing total	20.858	19.23	
Rudder	.526	0.35	
			Lighter spars and
Elevator	.898	0.68	trailing edges
Fuselage Primary structure	3.639	2.75	Lighter spaceframe
Landing gear	1.032		
Drivetrain	3.361	2.80	
Propeller	.924		
Fairing	2.806	0.91	Change to styrofoam
Seat	.484		glass laminate
Control System	1.098		
Fuselage total	14.768	11.03	
Aircraft empty weight	35.625	30.26	
Pilot weight (Nick Weston)	57.50	57.50	
Gross take-off weight	93.126	87.76	

Controls

The aircraft has a 3-axis fly-by-wire control system. The all-flying rudder, elevator and ailerons are actuated by model-aircraft servos. A 450-mAh nicad pack provides power. Bryan Gostlow, who designed and built the fly-by-wire system, gave some consideration during the design phase to the use of a fly-by-light system, but this was not implemented on account of its higher weight and complexity. Control surfaces are moved by Futaba S-134 model-aircraft servo motors. These are protected from internally generated noise by optical isolators. The wires delivering the control signal and power are run inside the aircraft's tubular structure. The pilot controls the aircraft with a small joystick in the cockpit.

The rudder and elevator are spring balanced and pivot on their spars. The servo motors driving them are buried in the tubular tail-boom and connected to control horns projecting from the spars by quick-connect linkages. The outermost 2m panels of the wing are operated as all-flying wing-tip ailerons. The aileron spar is fitted with ball-races so that the aileron can pivot. Major advantages of this system are its simplicity and that it allows a reduction in wingspar torsional stiffness. The pitching moment of the modified DAI1238 aerofoil used over this panel of the wing changes little with angle of attack so the inner wing spar sees only a change in bending moment when the ailerons are used. Strip ailerons would generate additional torsional loads that would require an increase in spar torsional stiffness and weight. Initial fears about the ability of the small servos to handle the large control loads led to a series of tests. The whole tail-boom and tail assembly was set up on a car-mounted test rig and driven at a speed 20% above the designed Vne. This system has proved simple, light and rugged, completely eliminating the problems associated with the installation of cable-operated controls in a highly flexible aircraft.

Flying

The aircraft is transported in a specially constructed trailer. It can be rigged for flying by four people in about 15 minutes.

During the initial stages of take off the aircraft is pushed by a ground handler who holds the tail boom. A second handler runs with the wing tip until sufficient speed has been built up for the pilot to have control authority. The power required for take off is high; this is a result of the high rolling resistance of the small 200-mm-diameter main wheel and the low efficiency of the fixed-pitch propeller at low speed. Once airborne the power drops significantly. Our current estimates for the pilot's specific-power requirement are in the range of 3.8 - 4.0 W/kg. The longest flights to date have been about 1600 m, and have been limited by the length of the available runway.

The landing roll is long, typically 50-100 m, and it is clearly desirable to fit brakes. The aircraft has run off the end of the runway, and on one occasion came close to hitting the perimeter fence. A larger-diameter driven wheel would reduce the take-off power and is probably essential for faster aircraft having higher specific-power requirements.

Pitch response is fast, but pitch damping is good and the aircraft has a large static stability margin so this does not lead to difficulties. Other aspects of the aircraft's flight dynamics have not yet been fully investigated.

Conclusions

The project's goals were primarily educational bringing together knowledge from fields as diverse as aeronautics, human physiology, composites design and meteorology. Certainly it is these educational benefits that are repeatedly cited (often retrospectively) as the major rewards and justification for involvement in human-powered-aircraft projects. Although the project's most apparent achievements are technological, its lasting value lies elsewhere in changing our ideas about where the limits lie.

The main accomplishments of the project include:

a. demonstrating that a small and marginally funded team of dedicated individuals can realize a technically demanding goal;

b. construction of a rugged transportable highly energy-efficient aircraft well suited to its intended use as a flight-research vehicle; and

c. development of a lightweight (about 1-kg) fly-by-wire control system.

Planned future flight research includes:

a. direct measurement of flight power by:

i. strain gauging the drive shaft;

ii. Removing the propeller and flying the aircraft with a small model-aircraft engine (probably electric) to allow measurement of thrust and speed for level flight to obtain the power polar;

b. investigation of the 'inverse ground effect' observed during flight research carried out by other groups (see Sullivan [21]);

c. in-flight measurement of stress in the structure; and

d. investigation of the aircraft's flight dynamics.

Acknowledgements

Roughly half the direct material costs were met by a R. Ae. S. Kremer fund grant.

Alan Maltpress, Managing director of Ciba-Geigy Plastics and Wilf Bishop of Aero-Consultants authorized material support, without which the project would have been impossible.

The Imperial War Museum at Duxford gave permission to use the airfield and were tolerant of our early-morning 4-am arrivals at the site. Many individuals gave their time and expertise to help make the aircraft a success. In particular my brother, Mark McIntyre, spent many hours building the aircraft and made significant contributions to its detail design. Bryan Gostlow developed the avionics. Nick Weston trained to be the pilot/engine and assisted with construction. Other individuals who gave important support were Norman Brain, Mike Wigg and Brian Homes of Ciba-Geigy; Allan Organ of Cambridge University; Mark Drela, Bob Parks, Harold Youngren and the other members of the Daedalus team from MIT; and the members of the HPAG of the R. Ae. S.

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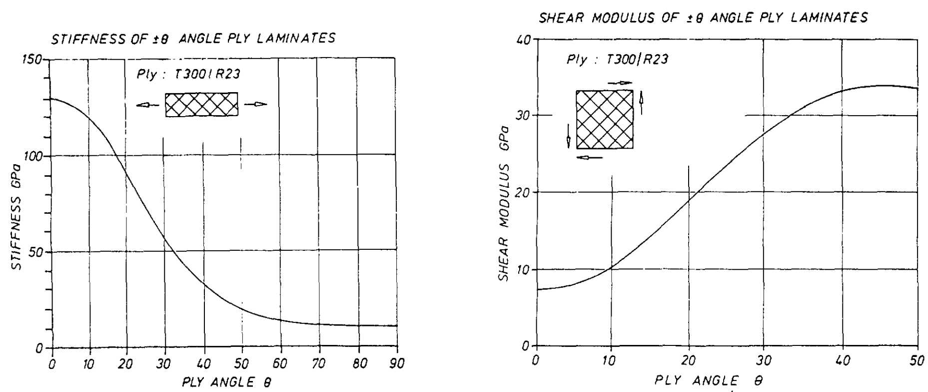

Figure 2. Wing-spar-tube torsion/bending ply-angle trade-off.
The carbon fibre used was Torayca T300-B high-tensile fibre.

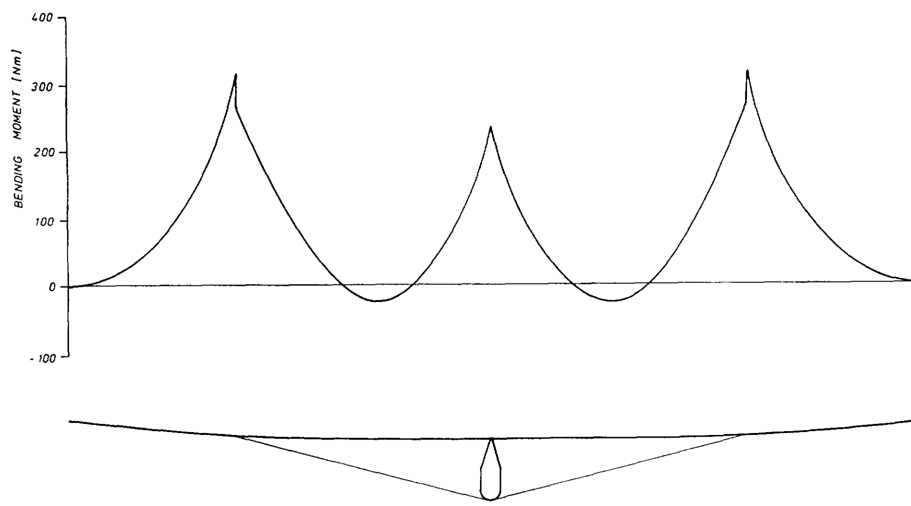

Figure 3. Bending moment in the wing spar in a 1.1g pull-up.

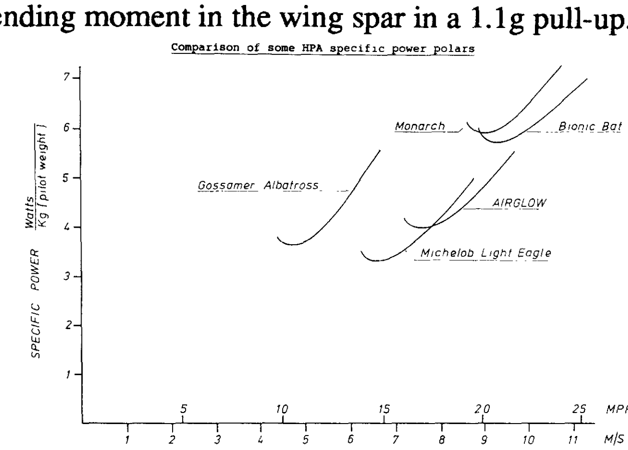

Figure 4. Comparison of some HPA specific-power polars.