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A human-powered helicopter: design considerations

by Greg Trayling

A LIGHTER CONVENTIONAL DESIGN

There is a surprising number of ways to construct a helicopter under the provisions of the Sikorsky competition. The main goal in any attempt should be to minimize the vehicle mass in the initial concept stage, rather than drilling holes and shaving parts in an unsatisfactory design. A few suggestions are offered below.

A conventional helicopter, minus the main rotor, is sketched in Figure 1. This linear-drive design reduces the vehicle mass by replacing chain with Kevlar cable, and increases the input power by using both arms and legs. A schematic of the cords' path is shown in Figure 2.

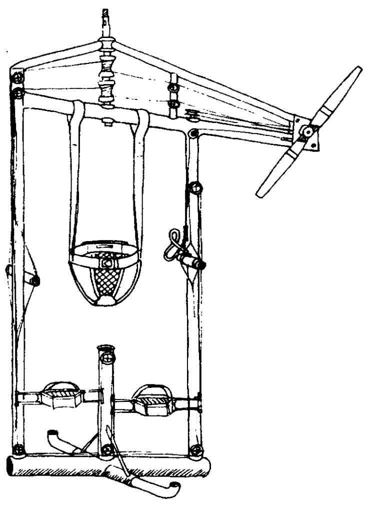

Figure 1. Linear drive helicopter

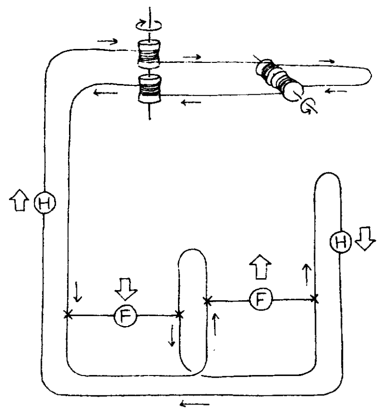

Figure 2. Schematic of cable paths

The pedals are free-standing with each side attached to the cord. Linear motion is converted to rotary motion by windings about a pair of one-way clutches on the main rotor shaft and on the stabilizing rotor shaft. Note that each element transmits or receives power on both the upstroke and downstroke. The stabilizing rotor is of variable-pitch design, controlled by twisting the left handlebar.

ROTOR ALTERNATIVES

Every attempt so far has used a rigid airfoil section. Figure 3 shows a series of kites strung in a semi-rigid circular array supporting the rider via transmission cords. This lightweight design eliminates the central rotor region where the radial velocity is too low to warrant its use. A second counter-rotating array could be placed above the first to eliminate the need for a stabilizing rotor. (This should not be done in a conventional human-powered helicopter as the long flexible rotors are likely to collide.)

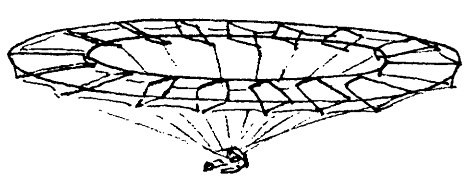

Figure 3. A circular array of kites as a rotor

Another alternative to airfoil rotors is the use of rotating cylinders. For a demonstration of how this works, take two styrofoam coffee cups and tape their bases together as in Figure 4. Tightly wrap a cut elastic band once or twice around the midsection, fastening it with your fingers. Pull back on the remaining elastic and release the cups. The device will spin as it flies and should gently float to the ground. This is caused by a greater

(continued on page 10)

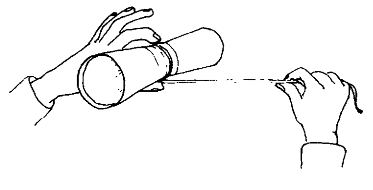

Figure 4. Rotating cylinders as a rotor

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Editorials

From famine to feast

After wondering, a few months ago, why the stream of articles requested for and submitted to *Human Power* had seemed to run almost dry, I have been happily trying to keep my head above a flood of practical, educational, stimulating and/or light-hearted pieces that have poured in, including much-appreciated short "fillers". Some authors will find that their articles have to be delayed by an issue, or possibly two. But as the supply-and-demand situation exists at present, all will get published. We are not yet having to practice triage, the selection - of those to save and those to abandon. But having too much material is a healthy state for a technical journal, so please keep the flood flowing. Write to me for guidelines on how we would like your pieces submitted if you wish (please note what should be a change to a lasting address, above). In the mean time, I will follow the editing procedure described briefly in the last issue, with the addition that I will send material in to Marti Daily and Kim Griesemer with an indication of priority that will reflect when the material arrived and what would make a good balance in the current issue.

Editorial expertise

More good news! *Human Power* has two associate editors. They have played outstanding leadership roles in the IHPVA, they believe passionately in an increasing role for human power in the world, and they have both given invaluable long-term input to HP. Philip Thiel is a professor of naval architecture at the University of Washington, Seattle, has organized the Pedal-Powered Potlatch every year since its inception, and has designed and built a series of innovative pedalled water-craft. Phil has agreed to be associate editor for watercraft. Theodor Schmidt has been involved in designing and building highly adventurous land and water vehicles, purely pedal-powered and solar-assisted, buoyancy and hydrofoil, in his native Switzerland and in Britain, for many years. He has made two or three attempts to pedal from London to Paris on an amphibious vehicle he made—a bicycle with floats and auxiliary propeller drive. Theo has accepted the post of "associate editor, Europe".

In most ways, the activities of these two great volunteers will not change, because they each regularly send to Jean Seay (HPVN) and me delightful news and contributions and other help. We hope that they may also act as foci for the special interests of members. Their addresses are listed in the editorial-page box. Possibly one or both might act as editor of an occasional special issue of HP. Welcome and thank you both!

In This Issue—

Bicycles in Japan

If this issue is a little late, it is because my spouse and I have just returned from our first visit to Japan. We expected a high density of population. The degree to which a large proportion of that population travels was higher than we expected. We travelled a great deal on the superb high-speed "Shinkansen" trains, with departures every ten or fifteen minutes, smooth and quiet and cleaner than most hospital wards. Feeding them were various types of local trains and subways, also clean and crowded and punctual. We were driven a little on the superhighways, on which traffic densities are so high, despite high tolls, that speeds are often low. We used taxis, again spotlessly clean with white linen seat covers replaced, apparently, at least daily, but usually able to make only slow progress in the clogged town traffic (one hardly ever seems to get "out of town"). And we walked a great deal. We thought of renting bicycles, but bicyclists shared the crowded sidewalks with pedestrians, and no rules as to riding or walking right or left seemed to apply—only that bicyclists should not actually hit pedestrians. So we could see that our range of exploration in our few free afternoons would not be increased much by renting bicycles, if the time taken to get through the explanations and rental agreements in our very limited Japanese were taken into account. Bicycles are used in huge numbers in Japan, but almost entirely, it seemed, as a means of getting to and from the railroad station. The bicycles are generally rather staid single- or three-speeds, left mostly along the sidewalks, often unlocked. They seemed rather old-fashioned, although shaft drives were being reintroduced in the single-speed "roadster" models. In two weeks we saw hardly any of the lightweight multispeeds that Japan is known for over here. This is not a criticism on my part. In the extraordinarily crowded conditions, the bicycles that were used were entirely appropriate.

—Dave Wilson

❑

Letters to the editor

Possible IHPSC revival?

Dr. A. A. Barry, a retired veterinarian from Lynn, MA, sent me a copy of a Barnum & Bailey poster showing a rather frightening setup for two bicycle trick riders, one of whom is looping upside down in the air while the other is right-way up directly above him. Nothing in the picture (which I hope will reproduce well enough here) indicates a structure firm enough to guarantee a safe arrival of either machine at the landing points, and how they compensated for cross, head and tail winds, burst tires and uneven ground can only be guessed at.

—Dave Wilson

Unrideable bicycles and stability

(This letter came with a piece from the ASME Dynamic Systems and Control newsletter about the course of Richard E. Klein, professor of mechanical engineering at the University of Illinois. Dick Klein has new versions of David Jones' URBs, or "unrideable bicycles" with, inter alia, counter-rotating gyroscopic-effect-cancelling wheels. He found that the only unrideable bicycles are those with rear steering.)

(A simple calculation of a bicycle ridden along a curved path so that the angle of lean would be 20 degrees and using typical values for wheel and tire size and mass distribution showed that the gyroscopic torque on the front wheel would be very small—equivalent to about one-third of one percent of the horizontal force on the center of gravity.—editor's summary of calculation.)

How about starting with a single wheel rolling and without torque except from gravitational and centrifugal forces, and then looking at bicycles with

1. vertical steering axis;
2. offset vertical steering axis;
3. inclined steering axis; and
4. inclined and offset steering axis (as on a bicycle)?

The last three would be tried with and without a balance weight. Stability should be examined without a rider; with someone riding "no hands"; and with a hands-on rider.

Didn't someone at MIT master the rear-steering bicycle? I have a memory that he took a long time to learn, but did it.

Edward S. Taylor
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Lee Laiterman built a rear-steering recumbent in response to my 1975 challenge to improve the long-chain transmission of my SWB recumbent. Eddie Taylor founded the Gas Turbine Lab. at MIT in around 1946—ed.

An overlooked issue?

Dan Hofstetter here (Steve Ball's partner). I just finished absorbing the latest issue of HUMAN POWER. It was outstanding! . . .

However, I have a question. It doesn't concern the quality of journalism—that's top drawer—but rather the system for logging the issues. . . . I have a fall 1979 HP that does not appear on your list. You have v1/3 (summer '79) and v1/4 (spring '80). Is my fall '79 issue v1/3.5?

Daniel K. Hostetter
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San Diego, CA 92111
USA

(I don't have that issue, and it wasn't on the master list I acquired when I took over editorship in 1984. I've asked Dan to send me a copy, and will publish a revision-apology in the next issue—ed).

Will speed limits be lowered?

Despite all of the wonderful reasons city speed limits should be lowered, it is unlikely they ever will be. Here in the U.S. merely enforcing the existing speed limits would bring many of the benefits mentioned by Riess & Pivit (v7/1/88/1). Unfortunately, our "free" society seems unwilling to pay for either the added enforcement costs or the additional travel time taken by slower-speed transportation. Look at the history of the 55-mph speed law if you need convincing that good engineering is only a small part of the solution here. Perhaps the West Germans will have better luck with the politics than we did.

Tom Feledy
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In defence of the Moulton

I showed Dr. Alex Moulton Rainer Pivit's article on vibrational stress on cyclists; he was [puzzled]. For one thing, the weight of the AM7 is 10.9 kg, not 14 kg; what on earth was loaded on it?

Having ridden the AM7, albeit only since my cycling powers have been considerably on the wane, I find Pivit's report hard to take. Once I had the AM I did not want to use any of my other bikes; in fact I have now sold them and am in the process of selling my tricycle. Only three veterans remain in the stable. What Pivit means by "the highly damped rear suspension is especially troublesome" I cannot make out—what trouble is there? "Swinging of the rear suspension in reaction to pedal forces" . . . bunkum!

The paper reads to me as though Pivit set out to prove something and allowed nothing to come between him and his goal!

Derek Roberts, Honorary Editor
The Fellowship of Cycling Old-Timers
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(A response from Rainer Pivit will have to wait for his return from a three-month bicycling tour of New Zealand on his home-built Moulton-inspired "Spyder". This photo and report were sent by Rainer's senior collaborator, Falk Riess—ed.)

Hydrofoil progress

HPV News Nov/Dec '88: I was delighted to see Sid Shutt's Hydroped II faring so well at the Visalia championships. He has obviously overcome the stability problems I encountered with Foiled Again, which you featured in HP 5/1/85/16. I'd be surprised if the 20-mph [mark] is not broken before long, now that the Flying Fish has some real competition. Will this provoke an explosion of interest in HP hydrofoils, with new clubs and events springing up around the world? I would certainly hope so, but the experience with HPVs suggests that until we get the economics and practicality issues right, Mister Joe Public will continue to file our efforts in the "Gizmo" category.

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Recumbent seat height—an update

In HP 5/2/86/3 I reported discomfort pedalling semi-supine recumbents when the bottom bracket was higher than the seat. Perhaps this was due to the flexibility of the wooden frames being tested. I now pedal steel bikes that have the bottom bracket 3-5" (80-130 mm) higher than the seat bottom with good comfort.

This allows me to tilt the seat back a little farther without the rider's torso bouncing up and down when climbing hills. This new position allows at least 5% higher speeds; in crude coast-down tests with friends, my unfaired bike can at least match Tour-Easys with the Super-Zzipper fairing.

Charles Brown
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Rear-wheel-steered tricycles

I have a question that needs to be answered. I am a new member, so the answer may be well known, but here it is.

Why do I never see any rear-wheel-steered tricycles with one or both of the front wheels driven? This would seem to be a superior configuration to the standard rear-wheel-driven trike with the long chain. (Maybe I'm biased, but I don't like the long chain). Has there been a comprehensive study that shows an unsolvable instability with a rear-steered trike? For all headset angles?

I, like many others apparently, am looking for an elegant solution for a safe, fast, lightweight, rain-proof commuting vehicle with good wet-weather braking. There has to be a large market for such a vehicle, especially if priced below $500.

Am I asking too much? Currently I commute ten miles a day on my Infinity; I've logged over 3000 miles on it. I enjoy this very much, but I want to go faster with protection from the rain and cold.

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Visions and campaigns

Thank you for your article on propeller performance prediction. However, for a very simple drive system for HP kayaks, I have found a direct air drive the simplest.

The design is old: it involves forcing air through a set of fine nozzles beneath the central one third of the hull roughly one third of the way back from the bow. The nozzles must all point towards the stern of the boat, and there has to be a set of shallow parallel keels on either side of each nozzle running from just in front of the nozzles all the way to the stern.

The air pressure source has to come from a set of rather large-capacity bellows, made to fit inside the hull, one for the left foot and the other for the right, both exhausting into a central pressure chamber before being forced out the nozzles. A set of pulleys and a cord to expand one bellows as the other is exhausted is about all that is left. This drive system operates on the venturi effect of the nozzles, and the "surface effect" function of the air beneath the hull significantly reducing drag. Flow restrictors on opposing sides of the nozzles can steer the craft.

Now, my real chief concern is this. The flight of the "Daedalus" has impressed me with the conviction that much more down-to-earth HPVs should be able to go faster than 100 mph for more than 100 miles. The motivation to build such HPVs is the problem. United Technologies poured $1.5 million into the "Daedalus" project, or roughly $38/foot of the flight. If we were to raise prizes of that sort for record-setting performances with HPVs, we would soon have HPVs that could go 100 mph for 100 miles.

I have been proposing that we do just that. I believe that we should try to raise funding for at least six annual events, three high-speed events with 100 mph as the qualifying speed, and three very-long-endurance events. . . . .

Mark J. J. Offenbach
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San Francisco, CA 94122-1557
USA

(Mark Offenbach has written rather similar letters, about a half of one of which I have given here, to many contributors to HP and to IHPVA officers—ed.)

□

Daedalus—the aircraft

Mark Drela talked about the details of the Daedalus aircraft at an October MIT seminar. Mark has been the aeronautical genius behind all the modern MIT HPAs: the Chrysalis, Monarchs I & II, and the three aircraft that culminated in Daedalus. For the first he was a student and for the last he is an assistant professor. He is also a superb and demanding craftsman, and made many of the crucial prototype components. He has taken over the leadership of propeller design from former MIT faculty member Gene Larrabee, whom the IHPVA designated "Mr. Propeller" from his many contributions to HPAs and HPBs.

The technological challenge in designing the Daedalus aircraft, once the goal of a flight distance of about 120 km was set, was to choose a combination of aircraft speed and power requirements that was within the capabilities of an athlete-pilot. Extensive weather studies for that area of the Aegean showed that occasionally a maximum of six hours would be available, giving a usable flying time of five hours. The minimum flight speed was, therefore, 24 km/h or 6.7 m/s (15 mile/h). This was between that of the Gossamer aircraft (HP vol. 1/2), about a third lower, and the Musculair (HP vol. 5/2), about a third higher. Both these demanded 3.5 - 4 watts per kg of pilot mass. The goal for Daedalus was to demand only 3 W/kg, a level that could be maintained by good athletes for five hours (from tests conducted by Steve Bussolari—HP v5/4) and that was achieved.

New airfoil sections for the wings and propeller were devised using computational fluid dynamics, optimized for structural considerations—eg for reduced torsional loading and optimized span loading (for 1.5 g). Only one external bracing wire was fitted. There were no rivets: every member was lashed and glued. The propeller was the largest that could be fitted, to give the maximum propulsive efficiency. A conventional layout was used with a small unloaded tail surface, in contrast to the "canard" ("tail-first") design of the Gossamers. The first planes had ailerons, which made them more manoeverable but a little heavier and less reliable than the final aircraft, which relied on the wing dihedral and the rudder for steering ("trim centering"). The total drag broke down approximately as follows.

DAEDALUS DRAG BREAKDOWN

Profile drag	45 percent
Induced drag	35 percent
Fuselage drag	10 percent
Miscellaneous	10 percent

The weight breakdown of the plane and supplies (no pilot) was:

wing	50 percent
fuselage	25 percent
water	12 percent
drivetrain	7 percent
tail	3 percent
miscellaneous	3 percent

The primary structure was 33 percent of the total, and was principally high-modulus carbon-fiber-epoxy. The secondary structure was 53 percent, and was carbon, Kevlar, foam, wood and aluminum. The nonstructural items—water, radio, instruments, etc.—were 14 percent.

Some special features were designed to reduce the load on the pilot: aluminized cockpit skin to reflect away the sun; good cooling-air flow; in-flight heart-rate monitoring; in-flight adjustment of the propeller pitch for pedal-cadence selection; short-term hands-off control ability; and a comfortable recumbent seat. In fact, there were two recumbent seats, each fitting two of the four pilots.

(continued on page 8)

Overview of a method that can help select and refine the optimum human-powered vehicle frame design

by Hei Wei (Don) Chan

INTRODUCTION

A human-powered-vehicle designer is often faced with the challenge of designing a vehicle frame from scratch, with little or nothing existing previously to draw as a reference. To have to actually build everything that looks suitable may be prohibitively expensive and very time consuming. What is needed is a "quick and dirty" method to compare frames with different geometries and dimensions to help refine and select the optimum design.

The following is an overview of one "quick and dirty" method called formally, "matrix structural analysis using the displacement method" or more simply, the "finite-element method (FEM)". The method described here is a particular subset of finite-element analysis where the elements are *complete beams, struts or tubes* instead of small but finite pieces in continua. It is particularly suitable for use on a microcomputer and the computing time of the program is usually less than a minute after all the inputs are keyed in.

MODELING OF THE VEHICLE FRAME

To use the program, one needs to establish a "matchbox" model of the vehicle frame and to determine the loading conditions. A "matchbox" model is one consisting solely of uniform beams, struts or tubes as elements, set in between load-bearing nodes. For this FEM program, elements have to have equal bending stiffness in all directions. In addition, the torsional stiffness of each element is expressed in terms of GI_p for a circular section and, therefore, non circular sections will have to use an"equivalent" GI_p. G is the shear elastic modulus and I_p is the polar moment of inertia.

WHAT THE PROGRAM LOOKS LIKE TO THE USER

Once activated, the FEM program will ask as inputs the number of nodes and elements. For every node, it will ask whether each of the six degrees of freedom (DOF) is active or inactive. Active means the node can be moved along that DOF and inactive means the node is fixed in that DOF. The six DOF are the orthogonal axes x, y, z and the three rotational axes about these orthogonal axes. The program will also ask for the external forces applied in the x, y, and z directions and the external moments about the three orthogonal axes. Finally, it will ask for the coordinates of the node.

For every element, the program will ask between which two nodes the element is situated and the EA, EI and GI_p of the element. E stands for the elastic modulus, A the cross-sectional area, I the bending moment of inertia, I_p the polar moment of inertia and G, the shear elastic modulus.

To accomodate situations where some of the elements are force fitted or heated or cooled to be fitted onto the frame, the program will ask for the initial mechanical and thermal strain.

After all the above information is obtained, the program calculates the displacements of the six DOF of each node. The forces and moments at the two ends of each element are also calculated and displayed.

If the same loading conditions are used to test several frame designs, the stiffer one is simply the one with the least linear or angular displacements in the various degrees of freedom at the nodes of concern. Besides comparing stiffness, this program is also useful for gaining insight into how loads are distributed throughout the frame. With some additional calculations, we can even obtain values of stresses at the ends of the elements. This information can help detect possible failure of joints at the loading conditions we are dealing with.

AN EXAMPLE OF ACTUAL USAGE

To illustrate the complete procedure of using this method, I cite my attempt to design a stiffer tandem-bicycle frame. The intention of this project is to increase the overall stiffness through the use of a different frame configuration and different tube dimensions while keeping the material and the weight the same as a "reference frame". The reference frame is a commercial aluminum tandem frame on which I have acquired information about its geometry and its tube dimensions.

I start by establishing the loading conditions I wish to test the frame in. In my case, I determine the typical maximum values of forces and moments applied to every node of the tandem-frame model in three situations: an out-of-saddle-sprinting situation, a steady-pedaling situation and a frontal-impact situation.

I obtained the values for the forces and moments through a variety of ways: *general industrial standards*, as in "a strong healthy individual can exert a force of up to two-and-a-half times his own body weight on the pedal"; *calculations*, as in "the force on the chain is equal to the force on the pedal multiplied by the length of the crank and divided by the radius of the chainring"; and *estimations*, like "the instantaneous maximum pull on the handlebar from a very strong rider would be slightly over 100 lbf".

The next step is to model a tandem bicycle frame as a space frame consisting entirely of nodes and elements (Figure 1).

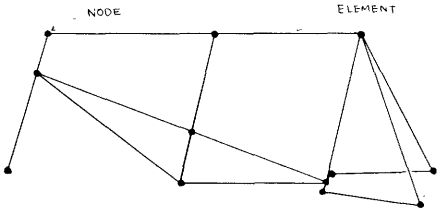


Figure 1. A matchbox model of a tandem frame: 12 nodes, 17 elements

Loads will have to be assigned to the respective nodes and the rest of the computer input, like the coordinates and the degrees of freedom of the nodes, EA,

EI, GI_p of the elements etc., will have to be determined. Here is where the designing comes in. Besides the several nodes that are common and essential in all my tandem designs, the placement of the rest of the nodes and elements as well as the element dimensions are entirely up to my whim. The whole process is basically one of trial, error and luck. For those interested, the common nodes in my tandem-frame models are the front-axle and rear-axle nodes, the stem node, the two saddle nodes and the two bottom-bracket nodes.

I run the program and first obtain the output for the reference frame. I then rerun the program and obtain an output of my design frame. I compare the displacements in the 6 DOF of all the common nodes and note the displacements on my frame that are an arbitrary 10% more and 10% less than those on the reference one. I repeat the procedure for a second design and a third design . . . and so on. I continue until the number of DOF that are stiffer is more than the number of DOF that are less so by a happy amount.

For that stiffest frame, I will proceed to test for fatigue failure using the forces and moments at the ends of the elements as calculated by the computer program. If the stresses are too high, I will have to modify the design and rerun the program.

Note that this program does not take into account fillet radius and stress concentration and therefore a safe matchbox model does not guarantee a safe real-life frame. However, a safe matchbox frame is a better start than an unsafe matchbox frame to base a prototype design upon.

FINITE-ELEMENT METHOD, THE APPROACH

The mechanics of the FEM program relies basically on the equation:

stiffness x displacement = force applied.

Let me explain this using a two-dimensional truss element as an example (Figure 2).

Every node of this truss element has two degrees of freedom, one in the x-direction and one in the y-direction. The element in our example has one node at each of its ends and therefore a total of four degrees of freedom possible. A force applied in the direction of any one of these DOF will have an effect on all DOF throughout the element.

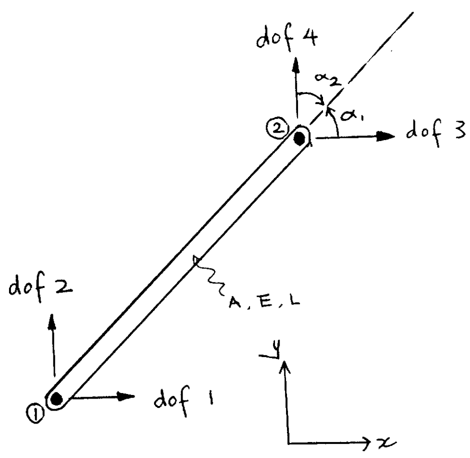


Figure 2. A 2-D truss element

Now let us assume only DOF4 in our truss element is active and we apply a force F that has a horizontal component $F_x = F\cos\alpha_1$ in the direction of DOF3. We can write a stiffness coefficient k_{34} where

$$k_{34} = \frac{\text{force along DOF3}}{\text{unit displacement of DOF4}}$$

To find the value of k_{34}, we give DOF4 a unit displacement. In order for DOF4 to have a unit displacement, the truss element needs to extend a length of

$d = 1\cos\alpha_2$ (Figure 3). For the truss element to extend that much, we need a force $F = AEd/L = AE\cos\alpha_2/L$ where L=length of the element, A=cross-sectional area and E=modulus of elasticity.

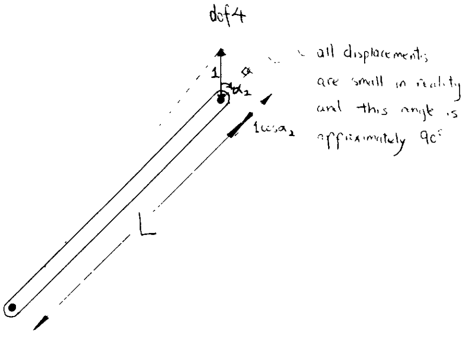


Figure 3. Truss element has to extend $1 \cdot \cos\alpha_2$ for a unit displacement in the direction of DOF 4

The component of this F in the direction of DOF3 is $F\cos\alpha_1$ and therefore,

$$k_{34} = F\cos\alpha_1/1$$
$$= AE\cos\alpha_1\cos\alpha_2/L$$

Having found k_{34}, we know that if there is a force in DOF3 that measures R_3, there will be a displacement of $d_3 = R_3/k_{34}$.

Since forces and displacements are additive, if DOF2 is also active, this force R_3 will have to be shared by both DOF2 and DOF4. We will get an equation:

$$R_3 = k_{34}d_4 + k_{32}d_2$$

If all DOF are active, we will get the equation:

$$R_3 = k_{31}d_1 + k_{32}d_2 + k_{33}d_3 + k_{34}d_4$$

Actually even when some DOF are inactive, we can still write the equation this way. The reason is inactive DOF have $d_i=0$ and their terms will drop out of the equation naturally.

It is now obvious that by calling a force component in the direction of DOF n, R_n, and repeating the above argument for forces in all DOFs, we can obtain a set of linear equations in R_i, k_{ij} and d_i. Sets of linear equations lend themselves easily to matrix representation and in our case, we have

$$[R] = [k][d]$$

k_{34} is $AE\cos\alpha_1\cos\alpha_2/L$. Doing the analysis that we did for k_{34} for all other k_{ij}'s will get us the contents of the matrix [k]:

$$[k] = AE/L \times \begin{bmatrix} C_1C_1 & C_1C_2 & -C_1C_1 & -C_1C_2 \\ C_2C_1 & C_2C_2 & -C_2C_1 & -C_2C_2 \\ -C_1C_1 & -C_1C_2 & C_1C_1 & C_1C_2 \\ -C_2C_1 & -C_2C_2 & C_2C_1 & C_2C_2 \end{bmatrix}$$

where $C_1 = \cos\alpha_1$, and $C_2 = \cos\alpha_2$

This matrix is what we call the "local stiffness matrix". It is a matrix that belongs to one truss element. The next step is to assemble local matrices for all the elements we are dealing with and combine them to form a single "global stiffness matrix".

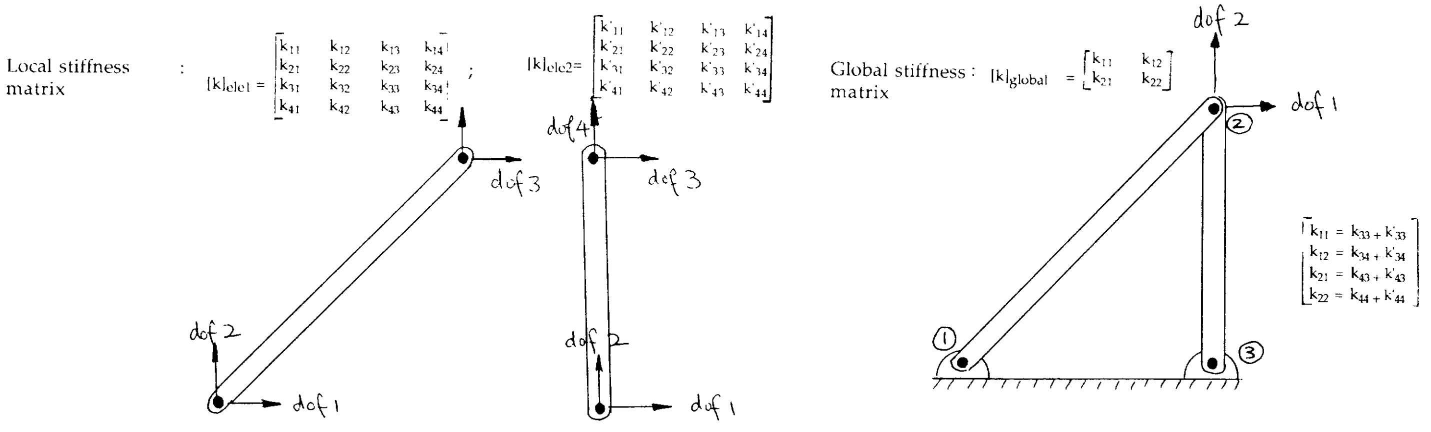


Figure 4. How local matrices combine to form the global matrix in a truss

Assume we have a truss with two elements as shown in Figure 4. Node 1 and node 3 are pinned to the ground and are completely fixed in position. Node 2 is active in two degrees of freedom. In assembling a global stiffness matrix, we ignore DOF that are completely inactive. Hence we have a 2x2 global stiffness matrix in this example. The entries for this matrix are simply the sum of the entries of the corresponding local stiffness matrices (Figure 4).

With this global matrix known and the external forces given, we can calculate the displacements of all active DOF. The computer program uses gaussian elimination to find the solution of the displacement matrix. Knowing all displacements, we go back to the local stiffness matrix and calculate the forces at each DOF using simple matrix multiplication.

In three-dimensional truss and beam problems, the only major differences are larger local stiffness matrices (12x12) because of a greater number of DOF and the use of several different equations for stiffness—e.g. in torsion we use

$$\text{stiffness} = M_t/\phi = GI_p/L$$

where M_t is the torsional moment and ϕ is the angle of twist.

The basic procedure, however, of first finding the local and global stiffness matrices and then the global displacement matrix and finally the local forces remains unchanged.

FURTHER INFORMATION

This finite-element method is very well documented in the book written by Nathan H. Cook called *Mechanics and Materials for Design*, 1984, McGraw-Hill Inc. This book not only contains a detailed description of FEM in chapters 4, 9 and 11, but also has a complete listing of the computer program in BASIC from p. 359 to p. 368.

If you are interested in obtaining a copy of the program for your IBM PC or compatible machine on a 5" diskette, please send $10.00 payable to the IHPVA to David Gordon Wilson, 21 Winthrop St., Winchester, MA 01890, USA.

This program is for private use only and should not be copied for commercial distribution.

Don Chan
63 Bowdoin St.
Newton Highlands, MA 02161
USA

(Don Chan did this summer project as an MIT junior in mechanical engineering. He is currently (1989) working on his senior thesis at Cannondale. Don is from Hong Kong—ed.)

❑

Daedalus—the aircraft

(continued from page 5)

Mark Drela stressed the importance of the seats for so long a flight. The pilots did some of their training on a Ryan Vanguard recumbent, and on a recumbent ergometer, but used their regular bikes for much of their conditioning.

Their long-distance stamina was improved through the development of a glucose-polymer salt-water mixture by Ethan Nadel of Yale, who worked with Steve Bussolari on the human factors of the flight. The drink inevitably became known as "Ethan-ol". One of the tangible results of this remarkable flight may be the commercial development of this drink.

In the question period, Mark was asked about the final crash of Daedalus. He said that the plane could not have landed in any case: a crash was inevitable. The black pebble beach was almost too hot for bare feet. The ocean was very cold. A roller convection cell developed that imposed "g" forces much higher than those for which the plane was designed. The same type of crash had happened to the other Daedalus aircraft when it crashed over the Mojave desert last year.

—Reported by Dave Wilson

❑

Stability? or control?

by Doug Milliken

After the IHPSC in Visalia, I stayed on a week in the Bay Area with my good friend Max Behensky. The conversation often turned to practical HPVs and at one point I brought up the old question, "Where should the center of pressure be on a streamlined bicycle to deal with cross winds?"

We both knew that on three and four wheelers a center of pressure (CP) near the center of gravity (CG) is desirable in cross winds. This has been established for years in the automotive business, perhaps by Dr. Kamm and associates in Germany, pre-WWII. The basic effect of a cross wind on an "aerodynamically neutral" car is to move the car sideways with little change in heading direction. If the CP is aft of the CG (big tail fins?) the cross wind will produce a yawing moment (about a vertical axis through the CG) that rotates the car slightly up-wind. This in turn produces a tire side force that counteracts the side force due to the side wind. If the CP is ahead of the CG (most common) the yawing moment rotates the car down-wind and the tire forces add to the aero side force. With some knowledge of the aerodynamic and tire/suspension properties, it should be possible to produce cars (and non-banking HPVs!) that "go straight", hands-off the wheel, in cross winds. References 1 and 2 are suggested.

The situation is not so simple for a two-wheeler because the roll (lean) degree of freedom counts as much or more than the yaw degree of freedom.

Max is a "quick-and-dirty" experimentalist of the first rank and he quickly suggested that I roll slowly along on the Moulton while he jogged alongside and applied simulated side force to the frame at different points. A suitable string was found and it was attached to the frame at various points to simulate different CP locations for frame-mounted fairing/rider combinations. We located the string about .8 meter (32 inches) above the ground to get the CP height about right for an upright bike like the Moulton.

This experiment is so easy to do that I hope you repeat it. I am tempted to leave out the results but, for the curious, here is what we found.

A. With the string tied at the head tube, Max pulled sideways (gently at first!) and I found that it was very easy to make a slight steering correction to return the bike to roll-and-yaw equilibrium and to keep the path essentially straight. With a little practice, I was steering and rolling the bike slightly and could resist as much side force as he could pull. Sharply varying side forces (gusty winds) were tried next with the same ease of control.

B. Next, we moved the string back to the seat post simulating a CP aft of the CG. We kept the height above ground the same. Here the control required was much more difficult. With practice, I could steer and roll the bike to counter this side force but there always were several big swerves and the heading always changed. A varying "gusty" side force was very difficult to control—most of the effort went into roll stability (keeping balanced) and the heading went all over the road!

C. Finally, we moved the string back to the head tube and reversed the front forks to increase the trail. Now the side force also produced a large steering torque. This torque steered the bike "down-wind" which resulted very quickly in a roll angle "up-wind", just what is required to "lean into the wind". With a loose grip on the handlebars, the bars wiggled around as the string was jerked but the bike kept going nearly straight.

The interesting conclusion is that the "aerodynamically unstable" location of the CP forward of the CG is the easiest to control and appears preferable over an "aerodynamically stable" configuration! Control appears more important than stability for this situation. The experiment we tried did not go to very high speeds so I am not suggesting that this result is valid at higher speeds. My experience with large, frame-mounted front fairings has generally been good at speed (on long hills) in moderately gusty winds.

One variant of this experiment would be to attach the string to the handlebars to simulate a bar-mounted fairing (ZZipper™ or Breeze Cheater™); because the Alex Moulton AM-7 lends itself so nicely to frame-mounted fairings, this was not of direct interest to us. If a large paved area was available, you could ride at higher speeds in a big circle while the assistant stayed near the center and provided the simulated side-wind force.

I am sure that some of you more theoretical people will be able to work out a mathematical model for this situation. It must be dynamic and has to include some type of rider control, perhaps "force control", where the steering angle is a function of both the rider control torque and the steer torque arising from the trail. The motorcycle dynamics and aerodynamic data and models in References 3-4 may be a good starting point but bicycles differ in several respects, especially speed range, tire performance and weight of rider relative to machine. Reference 5 comes close but the effects of moving the CP are not treated.

With a suitable dynamic model, it may be possible to predict a "best" location for the CP relative to the wheelbase and/or the CG. Likewise, it may be possible to recommend a desirable CG location for best disturbance response (this may conflict heavily with other design considerations!!) It may also be possible to choose a steering geometry that minimizes the control workload for the rider, given known CP and GC locations.

References:

1. I don't read German but the figures are pretty obvious. Cn is the standard nomenclature for yaw moment coefficient and plots are shown of Cn against alpha, (angle of attack due to a side wind) for cars of different shapes and with big rear vertical tails:
Koenig-Fachsenfeld, F. R., *Aerodynamik Des Kraftfahrzeugs.* Frankfurt: Umschau Verlag Frankfurt, 1951.

2. In English (but again from Germany):
Hucho, W-H, ed., *Aerodynamics of Road Vehicles.* Cambridge, England: University Press, 1986. See pages 214 and following. Available in the USA through the Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096.

3. Here is some motorcycle wind-tunnel data and some analysis:
Cooper, K. R. "The Effect of Aerodynamics on the Performance and Stability of High Speed Motorcycles" in *Proceedings of the Second AIAA Symposium on Aerodynamics of Sports and Competition Cars.* Ed. Bernard Pershing. Los Angeles, 1974.

(continued on page 14)

A human-powered helicopter

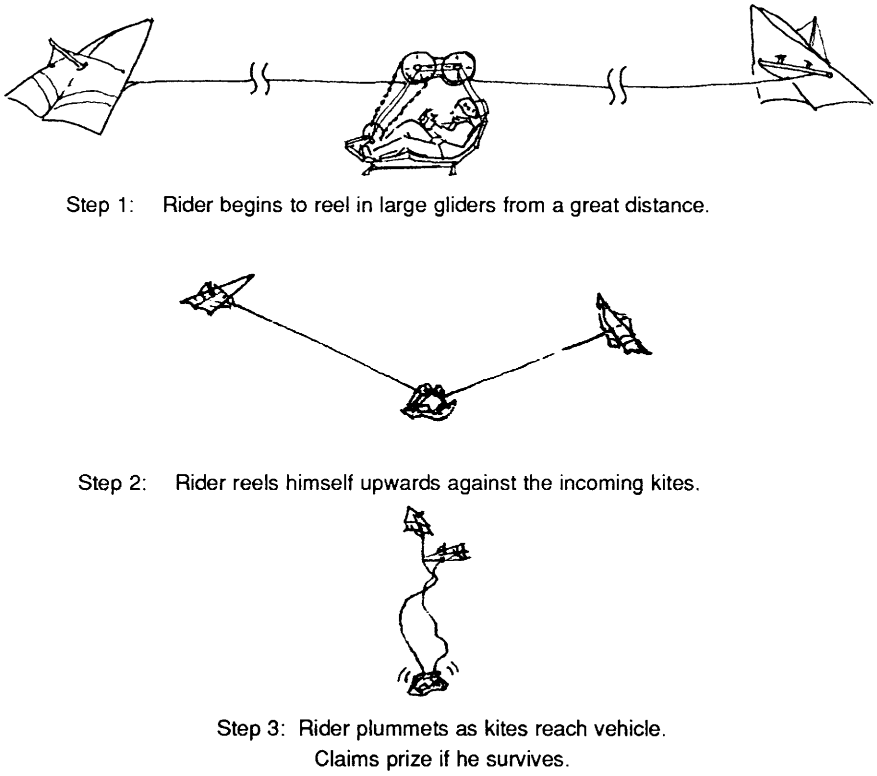
(continued from page 1)

pressure under the cylinder due to its rotation coupled with its forward motion.

This could conceivably be used in place of airfoils. There are structural advantages in using cylindrical tubing, although the great length required would probably make the rotation unstable due to flexing of the rotors.

A NON-ROTARY HELICOPTER?

Consider the vertical-ascent vehicle shown in Figure 5. This scheme is completely within the restrictions of the Sikorsky competition, although it would certainly be deemed 'not in the spirit of the prize'! (A clause in the fine print.)



Step 1: Rider begins to reel in large gliders from a great distance.

Step 2: Rider reels himself upwards against the incoming kites.

Step 3: Rider plummets as kites reach vehicle.
Claims prize if he survives.

Figure 5. A sure-fire prizewinner!

MINIMUM ROTOR DIAMETER

For a given mass and power input, a minimum rotor length required for flight may be calculated for any helicopter. This restriction can be summarized in a single equation which is used by engineers to evaluate a helicopter's performance or to determine whether a design is feasible. Although this is an important aspect of human-powered-helicopter design, it is not immediately obvious, and often neglected.

Let's assume we have an ideal rotor consisting of an infinite number of blades (actuator disk) with no loss of thrust at the tips, uniform acceleration of air through the disk, no profile-drag losses, and no rotational energy imparted to the airstream. Furthermore, the vehicle is stationary and hovering in free air.

In Figure 6, A is the area of a cross section of the air column at the rotor, V_a is the induced velocity of the air entering the blades, and V_b is the velocity of the air at a large distance away.

The total mass of air passing through the disk in a time interval dt is given by

$$dm = \rho A V_a dt \qquad (1)$$

where ρ is the ambient air density.

The kinetic energy imparted to the air mass is

$$dT = 1/2\, V^2_b\, dM = 1/2\, \rho A V_a V2_b dt \qquad (2)$$

The thrust developed by the disk can be expressed as the rate of change in the axial momentum of the air.

$$F = \frac{d}{dt} V_b dm = V_b \rho A V_a \qquad (3)$$

The work done on the air mass during a time interval dt is given by

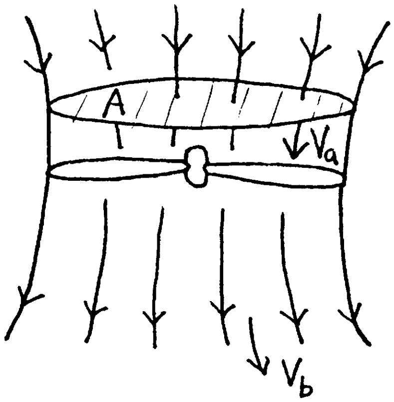


Figure 6.

$$dW = FdZ = FV_a dt = V_b \rho A V^2_a dt \qquad (4)$$

where dz is the distance through which the thrust is applied relative to the moving airstream. Equating (2) and (4) by the conservation of energy yields

$$V_b = 2V_a$$

Applying this to (3) results in

$$F = 2A\rho V^2 a$$

Therefore, the power required to hover is simply

$$P = \frac{dw}{dt} = FV_a = F\sqrt{\frac{F}{2\rho\pi R^2}}$$

where R is the radius of the rotor(s). Using F = mg where m is the mass of the vehicle plus rider and g is the gravitational acceleration, we have

$$R = \sqrt{\frac{(mg)^3}{2\pi\rho P^2}}$$

which yields the minimum blade radius for a given total mass, power input and air density for any helicopter, regardless of the shape or number of the rotors or airfoils. R is the minimum radius allowable since any deviation from ideal conditions will lower the value of P, the power directly available to develop thrust.

As an example in SI units, let's set the total vehicle plus rider mass at an extremely optimistic 100 kg. Assuming a rider can briefly sustain 1 hp, let P = 746 watts. A good air density is sea level at 0°C which is P = 1.29 kg/m³. (g = 9.8 m/s²) This yields a minimum diameter of

$D = 2R = 28.8$ meters, which is a very large rotor indeed. If one takes into account the profile-drag losses, this value would be much larger, perhaps upwards of 40 m.

Often helicopters will appear to be on the verge of success by briefly hopping to a height of a few centimeters. This is chiefly due to a phenomenon known as 'ground effect' whereby a backwash of air off the ground increases the pressure under the rotors and provides a much greater lift. A vehicle may require several times as much power to hover in free air as it does under the influence of ground effect.

However, as a rule of thumb for conventional helicopters, this extra boost can still be perceived up to a height equal to the diameter of the rotors. Therefore, a blade diameter in the range of 30 m should allow a craft to take advantage of ground effect to claim the Sikorsky H.P.H. Prize, which requires that the helicopter momentarily rise to a height of 3 m during a one-minute flight. The main drawback of this strategy is that in order to reduce drag losses, the rotors of a human-powered helicopter should revolve relatively slowly, which will reduce the ground- effect contribution.

This should not ground any aspiring helinauts, as it is meant only to point out a particular design parameter. The Wright brothers were successful because they paid close attention to the physical principles of flight. A human-powered helicopter is certainly possible. It simply reduces to an engineering problem of building a very large, incredibly light rotor attached to an equally ethereal vehicle.

Reference:
Alfred Gessow & Garry Meyers Jr., 1952. *Aerodynamics of the Helicopter.* Ungar Publishing, New York.

Author's Note: A very informative article about human-powered helicopters is in the May '88 edition of *Popular Science.*

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Greg Trayling has published a bibliography of HPV publications, and many articles about practical and theoretical aspects of HPVs—ed.

❑

The 1988 Delft Waterbike Regatta

Philip Thiel, professor of naval architecture and indefatigable proponent of HPBs, now our associate editor for watercraft, sent the final report of this regatta, the ninth in a series starting in Germany and the first to be held outside that country. Ten university teams from Germany, Holland, Poland and Sweden took part. The rules are as follows.

1. Each HPB must be propelled by no more than the feet of two people.
2. The length must be between 2 and 6 meters.
3. The maximum draft is 2 meters.
4. The breadth may not exceed the length.
5. Any part of the HPB may be replaced during the race, but only on open water, using parts and tools on board throughout.
6. HPBs may be individually sponsored unless the organizing committee finds overall sponsors.

The trials are of speed over a course between 1000 and 1500 meters; a maximum bollard pull during a 30-second effort; a double forward-and-astern sprint over a 40-meter course; a slalom run; a special relay race involving a swimmer; a "secret mission" involving eating a "cake on a rope" from the HPB; and two judging categories for originality and innovation, and safety and construction.

Here are some comments on the designs and performance from the report of the chair, Andre Vaders.

THE HULLS

All the HPBs were displacement ships. Waterbikes which can be lifted out of the water just like hydrofoils, hovercrafts and surface-effect ships, are very hard to realize due to the limited power of the human body.

For displacement ships there are three different hull forms: the monohull, the catamaran and the trimaran. The monohulls have a good maneuverability, better than the other two. The catamarans are fast and light in weight, but their maneuverability is poor. The trimaran can be as light as the catamaran, but is better to maneuver. The stability of the multihulls is better than the stability of the monohulls.

Three waterbikes are special because of their hulls. First the "Korab" from Gdansk. This is a short catamaran with a float at the fore-end in between the two hulls. This float has two functions. First it improves the longitudinal stability of the short hulls and prevents diving of the

The "Korab"

The "af Chapman"

bows. Secondly there is a rudder under the float, which can be used to steer. By this "floating rudder" and the two independent paddles, the maneuverability of this catamaran is good. Another feature of the hull is that it has been designed in the "hollow" of the resistance curve.

The second waterbike is the "af Chapman" from Goteborg. This is a trimaran. The two stabilizers have hydrofoils beneath. As soon as the water bike makes some speed, the two hydrofoils lift up the stabilizers and lower their water resistance.

The last waterbike is the "Pride of Delft" from Delft. This water bike is a catamaran with hulls which can plane above a certain speed. Therefore the hulls have a flat bottom. There is no lower resistance when they plane, but it is easier to reach a higher speed. When the water bike sails, the planing is clearly visible, because the sterns don't "sink" in the water, but "glide" instead.

THE TRANSMISSIONS

Also the transmissions were an object of study. The most simple transmission is the one that couples directly the feet with paddles. It is a strong and simple concept, but the transmission ratio is 1:1. An improvement is to use a chain and gearwheels. The transmission can be varied, but the construction has to be stiff to prevent run-out of the chain.

When you use a propeller instead of paddles, the transmission becomes more complex. You have to change a transverse rotation into a longitudinal rotation. One possibility is to use a chain and two gearwheels which have a right angle with each other ("Pride of Delft"). Another possibility is to use driving belts ("Lattenjammer", Berlin, "Arriel", Aachen). The change of rotation is easy to achieve, but the efficiency is not that high.

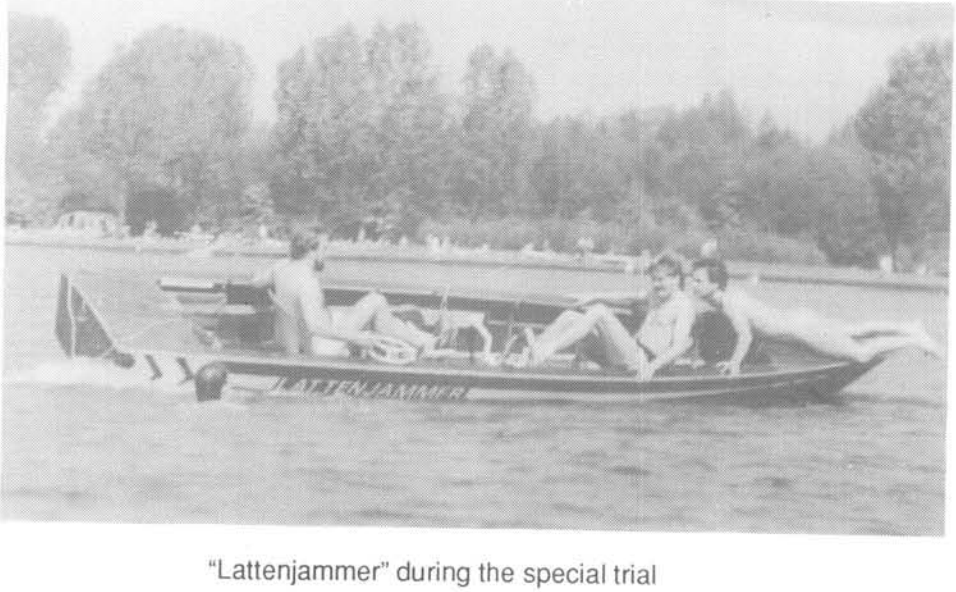
A special transmission is the one from the "Viking Peddler" from Stockholm. They use chains and gearwheels and a hydraulic system. The hydraulic system is reliable and converts the rotation easily. A very complex transmission was used in the "af Chapman" from Goteborg, which will be explained together with its propulsion.

THE PROPULSION

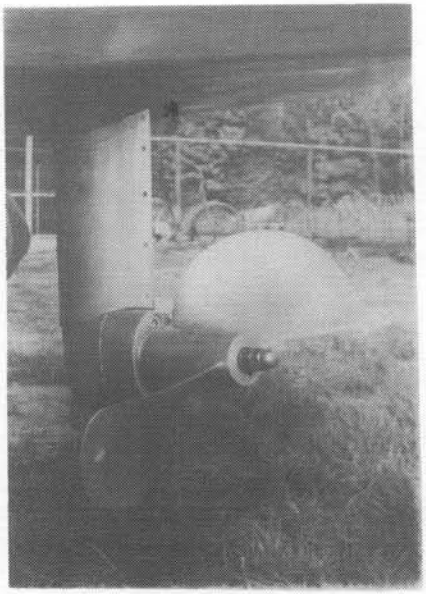
The most important feature of a ship is below water level: the propulsion. A traditional form of propulsion is paddles. The angle between the paddle and the water, as it enters, is very important. A wrong angle will damage your efficiency. The breadth of the paddles, the number of paddles and the diameter of the wheel are parameters which must be optimized. The problem of designing good paddles is to find literature, because the research stopped many years ago.

Not only the form but also the place of the paddle can be varied. "Affenschleuder" from Hamburg has one paddle in between the two hulls. "Anni" from Hannover, a monohull, and "Korab" from Gdansk, a catamaran, have two independent paddles at the outside of the hulls.

The usual ship propeller is the most popular propulsion for the naval-architect students. There is a lot of recent literature available and the design methods are known and taught at the university. Most of the waterbikes were equipped with the usual ship propeller. The "Arriel" from Aachen and the "Lattenjammer" from Berlin had Schottelpropellers. This sort of propeller, which can turn around its vertical axis, gives excellent maneuverability. In combination with a specially designed hull form, the "Arriel" sails as hard aft as forwards. Because of this propeller combination the "Arriel" has



"Lattenjammer" during the special trial



The Schottelpropellor of Spectakel

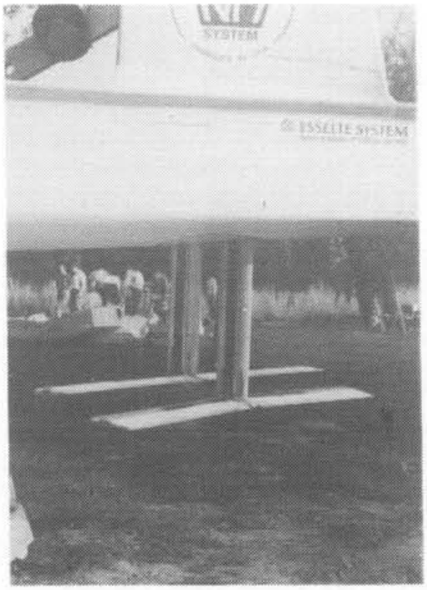
won the "overall" prize several times, including this year.

However, the maximum theoretical efficiency which can be reached with the usual ship propeller is about seventy percent. This challenged the students from Delft to develop a different propeller with a better efficiency, the "high-efficiency-propeller". This propeller has a large diameter, a low blade-area ratio and just a few revolutions per minute. Following computations of the NSMB (the Netherlands Ship Model Basin) at Wageningern, a theoretical efficiency of eighty percent can be reached. At the speed trial this waterbike proved to be the fastest boat and won the speed prize.

A surprising concept came from Goteborg, the "foil-propeller". It has a horizontally symmetric profile, which moves through the water like a whale tail. After computations at the University of Goteborg, a similar high efficiency of eighty percent was predicted. The transmission from the feet movement to the whale-tail movement is rather complex and demands a lot of bearings. But in Delft the transmission and the whale-tail concept worked surprisingly well. For this new type of propulsion the "af Chapman" received the prize of originality and innovation for 1988.

A floating object which hardly can be qualified as a water bike is the "Roll West" from Hamburg. It is formed by two round floats, in which the students walk around as in a joy-wheel. With this design they won the prize of originality in 1987.

The race day started early, the weather prospect was brilliant and everybody was willing to win the first part of the regatta, the speed trial. As is well known, boats with a long waterline run faster; this was clearly shown by the fact that the first waterbikes were the longest. Also striking was that the first four boats were propeller powered. There was no clear difference between mono- and multihulls.



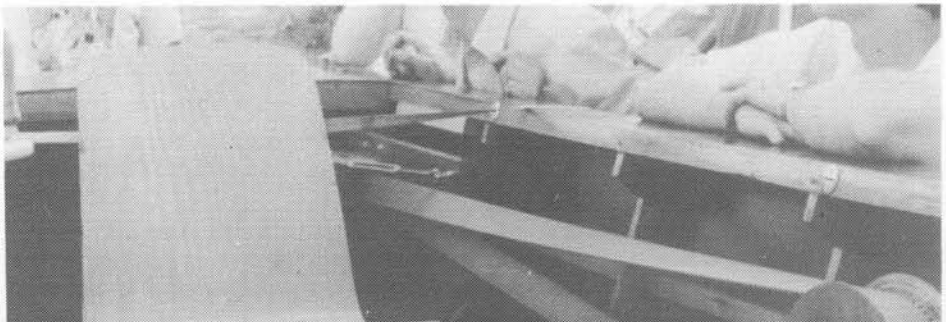
The foilpropellor

The third part was a test for teamwork, rescue skills, stability and ease of use, the special trial. Some boats were not able to carry an extra person and towed the swimmer. This changed the original intention of the discipline.

With the bollard pull the high-speed waterbikes gave moderate results. The best results were given by the waterbikes with a normal ship propeller. The paddleboats performed very well compared with other disciplines.

The turning circle was tested with a slalom and the rounding of a buoy. Here the fast waterbikes with the schottelpropellers were the best. The paddleboats with two independent paddles performed better than the single-paddle boats. The multihull waterbikes without schottelpropellers or independent paddles did not perform very well.

The results of the last test, "Koekhappen" (in which a cake on a rope had to be eaten) were almost independent of the sort of water bike. The multihulls had a slight advantage because of their better stability.



Drivingbelt of the "Lattenjammer"

RECOMMENDATIONS

To keep the special atmosphere of the event we wish to make some recommendations to the next organizers. The accent of the event should be to stimulate new ideas in designing a waterbike rather than to win a game. The prize of originality and innovation should be more important than the "overall" prize. Therefore all the waterbikes older than two years should be excluded. In this way you have one year to construct a new waterbike and one year to make it perfect. This rule means the replacement of the "old" waterbikes by new ones.

Another recommendation is to limit the registration to the students of maritime studies (both ship-building and ship-operation studies). One avoids the forming of professional teams with large financial budgets and the participation of graduated students who haven't the time to develop new ideas.

The organizing committee of the "International Waterbike Regatta" in 1989 is:

Schiffbauvereinigung "H.F. Latte"
Universitat Hamburg
Institut fur Schiffbau
Lammersieth 90
D2000 Hamburg 60
West-Germany ❑

Stability? or control?

(continued from page 9)

4. A collection of papers with an excellent bibliography:
Motorcycle Dynamics and Rider Control, 10 SAE papers published as SP-428, 1978. Available from the SAE.

5. As a teenager I rode a mini-bike with a small rocket engine attached to the frame at the CG to simulate a side wind for the following authors; someone else rode the instrumented bicycle described in this paper. Very complete and complex model with correlation experiments:
Roland, R. D., and R. S. Rice, "Bicycle Dynamics, Rider Guidance Modeling and Disturbance Response". Calspan Corp. Report ZS-5157-K-1, April 1973.

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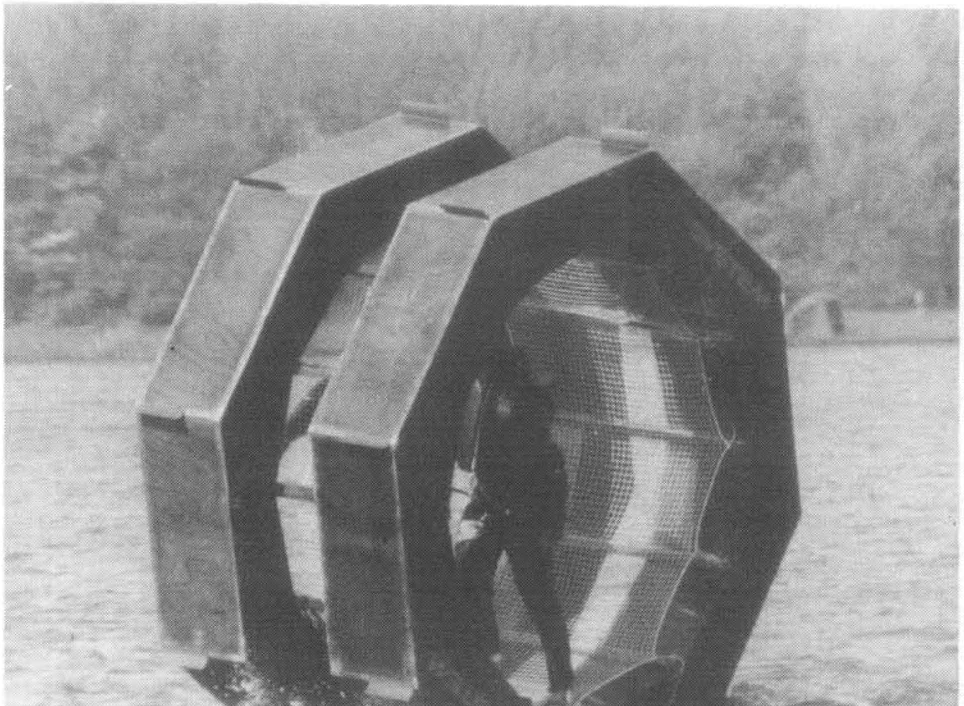
Doug Milliken is perhaps best known for his superb aerodynamic work with and for Alex Moulton for his bicycles. He is also an enthusiastic and vital worker for the IHPVA behind the scenes—ed. ❑



The "Roll West"

Reviews

Alternate Energy Transportation

This typewritten newsletter that should, presumably, be called "alternative-energy transportation", unless it is designed to complement one of those schemes in which motorists are allowed to use their cars every other day, is published monthly by Campbell Publishing in NY, NY. It is subtitled "The newsletter of technology in motion. Incorporating chopper noise." I cannot help you decipher this. But once beyond the title and sub-title you can find interesting pieces about HPVs, inter alia. It's true that Daedalus, for instance, is referred to as a "flying moped", which seems to indicate further confusion by the headline writer. The Sunraycer and the Tour de Sol are covered extensively and an HPV NEWS comment on the inclusion of hybrid vehicles in our fold is quoted well.

Alternative Vehicle Forum

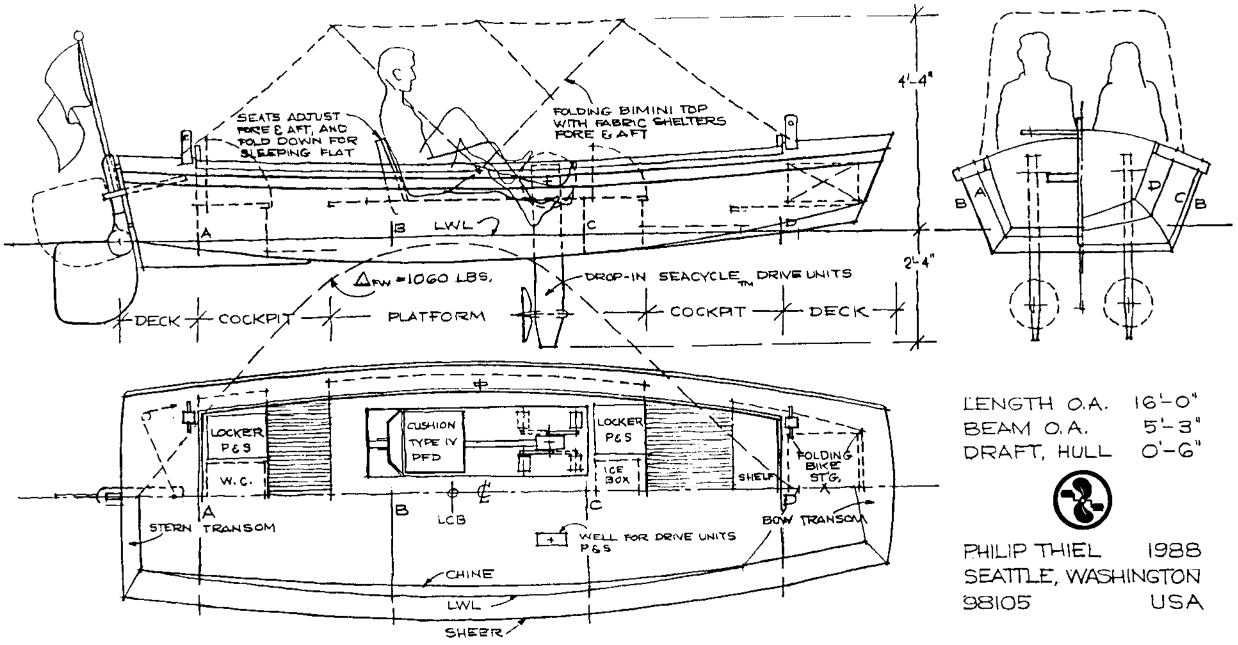
This newsletter is put out by "a growing organization whose purpose is to further the state of the art in innovative forms of lightweight personal land vehicles. . . . AVF is patterned somewhat after the IHPVA, to which several AVF members also belong. . ." Their interests are principally in lightweight vehicles powered by small engines. You may find more by writing to the AVF at 4534 La Cuenta Drive, San Diego, CA 92124, USA, with a SASE.

—Dave Wilson

Medical and Scientific Aspects of Cycling

This is a hardbound book edited by Edmund R. Burke and Mary M. Newson from the papers presented at the 1986 World Congress on the Medical and Scientific Aspects of Cycling, Colorado Springs, and published (1988) by Human Kinetics Books, Champaign, IL. The first 98 pages contain nine papers on biomechanics and physiology (eg "noninvasive determination of the anaerobic threshold in cyclists" by Francesco Conconi et al). The second group is of eleven papers, 85 pages, on research techniques and results, mostly again to do with biomechanics (eg "physiological changes riding a bicycle ergometer with

(Continued on page 22)



PEDAL-POWERED SCREW-PROPELLED CANAL-CRUISING CAMPER

Canal cruising by Philip Thiel

As a professional my "ideal boat" is always the next one I design. At this point in my life-cycle I am looking toward retirement and an adventure in exploring the back-country canals of Europe (where the ruling draft is less than two meters and the speed limit six kilometers an hour) camping aboard a pedal-powered, screw-propelled two-person canal cruiser. Having designed and built two similar boats (the *Dorycycle* and the *Sharpycycle*) I am enchanted by the pleasure of cycling on water, with its independent, sure control and freedom from noise, vibration, and odor. Thus my ideal boat is intended for easy construction at low cost by reasonably competent lay-persons, perhaps at some canal-side site on the Continent, maybe by a group of like-minded people who would enjoy sharing a spring of boat construction and a summer of cruising the European canals as part of a small flotilla. Here are my preliminary specifications: a shapely but essentially flat-bottomed square-ended hull, with dimensions about sixteen feet by five feet, to be built of exterior-grade plywood and soft-wood framing. A six-foot-six navigating platform amidships, sheltered by a Bimini top, would serve as a place for spreading sleeping bags at night. Aft would be a cockpit and storage for a W. C. and dressing, and forward a similar space for cooking, with icebox and spirit stove; both enclosable with removable fabric shelters. Also forward would be space for a folding bicycle, essential for procuring fresh bread, wine, fruit and cheese from the nearest villages. An outboard swing-up rudder would be controlled by a tiller and lines to the amidships operating position, and propulsion provided by two side-by-side retractable drop-in Seacycle drive units in wells built into the hull.

Camping in a pedal-powered screw-propelled canal cruiser, anyone?

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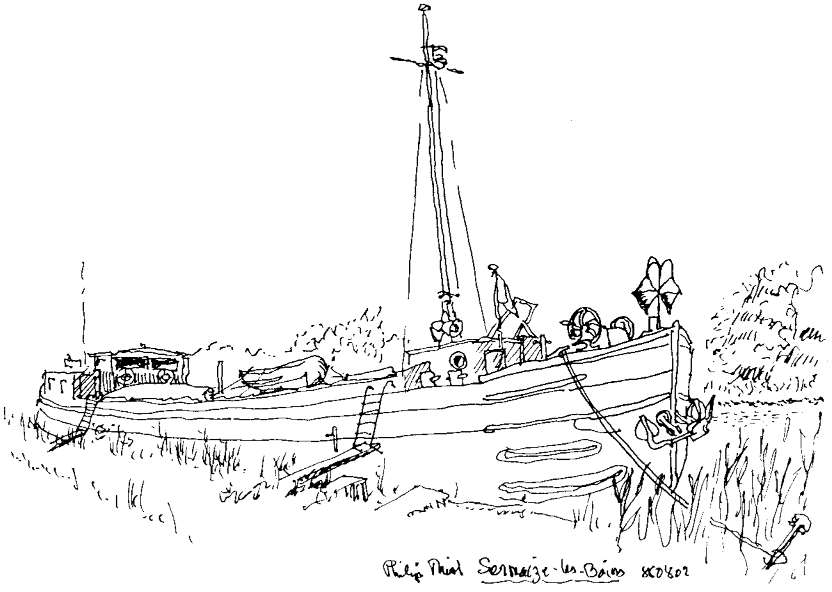


Recent progress in blending HPV efficiency with practicality

by Gerald E. Pease

SUMMARY

At least one practical streamlined bicycle, the Lightning F-40, is now commercially available. The author has purchased one and found it to be far more efficient than other bicycles, or HPVs in general, that meet usual standards of practicality.

It is now common knowledge that IHPVA members have achieved remarkable success in the area of land speed records for human-powered vehicles. It is no secret that these accomplishments, in the tradition of UCI records, have been attained using vehicles totally unsuited for any other purpose. Indeed, a UCI sprint bike would be considered a model of practicality compared with the typical streamliner, which usually requires a pit crew to assist the rider in entering, starting, stopping, and exiting. The fastest vehicles have a reputation for being easily blown over by light cross winds. The lack of adequate ventilation means they are unfit to ride even moderate distances. Thus has efficiency come to be equated with uselessness in the real world, where cost effectiveness and convenience rule above all else.

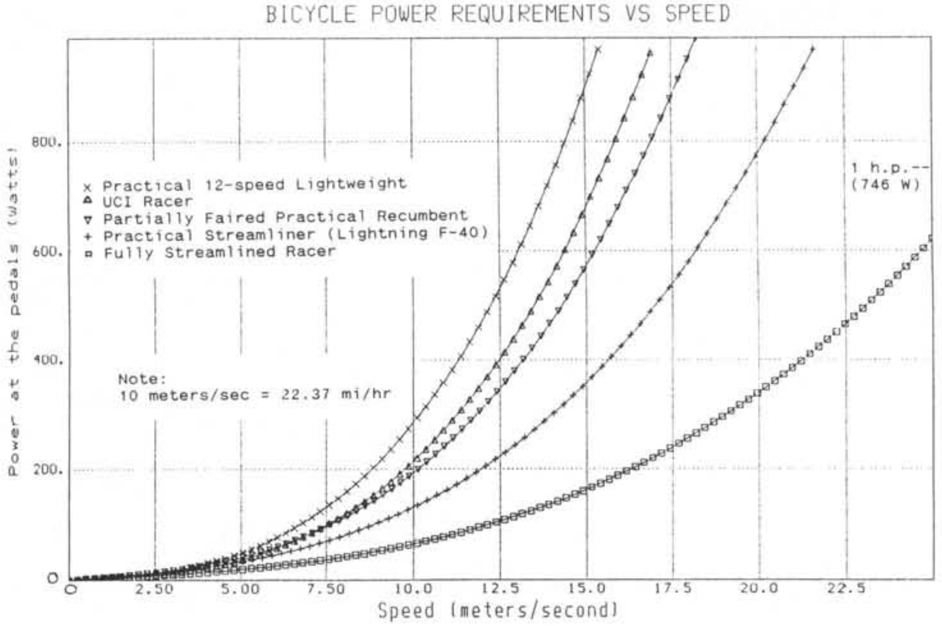
The most popular bicycle combining practicality with some measure of efficiency is still the lightweight multi-gear diamond-frame Safety concept, available with a wide choice of tires, handlebars, and saddle designs. A current trend appears to be away from efficiency in order to achieve modest improvements in comfort, safety, and durability. This tradeoff is exemplified by the ubiquitous Mountain Bike and its City Bike cousin. The popularity of these machines seems to hinge on their jack-of-all-trades nature, particularly the ability to perform competently on rarely encountered bad road or even off-road conditions. This is somewhat analogous to the current popularity in metropolitan areas of four-wheel-drive trucks, which also are significantly compromised in street efficiency by their rarely used off-road capabilities. But in the case of motorized vehicles, high performance and efficiency are also popular. Where are the Porsches and Ferrari F-40s of the bicycle world?

Enter the darling of the HPV enthusiast, the recumbent bicycle. In unfaired and partially faired forms, recumbents offer a big improvement in comfort and a worthwhile improvement in efficiency. They are not popular. Not a single recumbent design has ever been mass produced. We know that people say they don't buy them because they are confused by the lack of standardization and because the racers claim they are no good on hills. They are also usually more difficult to transport, and the ratio of price to perceived quality is not favorable. As marketed, there is no competition class for them (they are not competitive with fully faired racing recumbents), so the flat-road performance edge doesn't count for much. None of them is a match for the UCI road racer in an out-and-out hill-climbing contest which is, naturally enough, considered by traditionalists to be one of the most important tests of real-world performance.

With the sudden appearance of the Lightning F-40 on the scene and its startling victory in the 1988 Argus Tour, a new standard of efficiency for practical vehicles now exists. This commercially available 15-kilogram streamlined recumbent bicycle is easy to enter, start, stop, and exit without assistance. Ventilation is outstanding for a streamlined vehicle and is adjustable. Best of all, the bike is not blown around by normal crosswinds. In extreme conditions of temperature or wind (over 32 degrees Celsius or 9 meters/sec windspeed) the major part of the fairing, made of nylon Spandex, can be removed and stowed in less than a minute. A worthwhile bonus for touring in cold or wet weather is the protection offered by the fairing, which can be ordered in waterproof stretch Gortex. Other touring options that are available include extra-wide-range gearing, a front drum brake, mudguards, and aerodynamic pannier carriers integrated with the fairing.

The efficiency of the Lightning splits the huge gulf between the partially faired practical recumbent and the impractical full streamliner required to be competitive in short-distance HPV races. The F-40 requires only half the power at the pedals needed by a UCI racer on a flat surface at 18 meters/sec. In other words, we are

Gerry Pease is ready for some fast touring in his Lightning F-40. (Photo by Matt Decell)



looking at a new generation of bicycle for touring and long-distance road-racing. These tasks are performed inefficiently by standard bikes and not at all by most fully streamlined recumbents. A legitimate question is whether or not the improvement in efficiency justifies the cost (about double that of a good partially faired recumbent) and the additional inconvenience in transporting by automobile. It was affordable enough for my budget but I'm still working on the transportation problem. A good roof rack should do the job if the Spandex part of the fairing is removed from the bike prior to transporting. This is a relatively minor inconvenience.

The accompanying figure illustrates the efficiency spectrum of existing types of bicycles for which speed is an important design consideration. The Lightning F-40 curve more or less defines the present limit of efficiency for a practical vehicle. There may be some "practical" tricycle designs with comparable level-road power requirements, but I feel their additional width and lower profile causes them to be too dangerous in traffic, while the extra weight, complexity, and cost may not be justified by the stability advantage. At this point I also think it makes more sense to attempt incremental improvements to the workable streamlined recumbent bicycle design rather than to try to make the fully streamlined racer either more practical or faster. I would like to see a shock-absorbing front suspension added to decrease rolling resistance and to improve the ride quality and handling on rough surfaces. The ride quality is presently good, provided that the tires are inflated to touring pressures rather than racing pressures.

The well-known equation for power requirement, P, as a function of level-road speed, v, in windless conditions was used to generate the curves, expressed as

$P = av^3 + Bv$, where

$A = (Cd \times Af \times Da)/(2 \times Em)$, and

$B = (Cr \times Wt)/Em$.

Cd and Cr are the respective aerodynamic drag and rolling coefficients. Af is the frontal area. In each case 1.226 kilograms per cubic meter was assumed for air density, Da, at sea level. Total weight, Wt, was obtained by multiplying the total mass of bike and clothed rider in kilograms by the acceleration of gravity, 9.806 meters/sec^2 at sea level. Mechanical efficiency, Em, was assumed to be 0.95 except for the Lightning, which has a drive-side idler with precision bearings. For the Lightning, 0.94 was assumed for overall mechanical efficiency. The other constants peculiar to the type of bicycle and rider are tabulated on the following page. The estimates of drag coefficient and frontal area were based on coast-down tests and accelerometer measurements of effective frontal area performed by experimenters other than myself. Because of the population sample variation in most of the constants in the table, they should be considered "ball park" representative estimates, but numerous speed comparisons performed by me indicate that they are reasonably accurate for the class of practical vehicles (I don't have access to a fully streamlined record HPV).

For more information on the Lightning F-40, contact

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Tradition meets Innovation on the bike path. (Photo by Matt Decell)

Constants affecting bicycle power requirements

	Practical 12-speed Lightweight	UCI Racer	Partially Faired Recumbent	Practical Streamliner (F-40)	Full Race HPV
Drag Coefficient	0.95	0.89	0.6	0.3	0.12
Frontal Area (m^2)	0.40	0.33	0.39	0.44	0.45
Rolling Coefficient	0.004	0.003	0.0045	0.0045	0.0031
Total Mass (kg)	85	81	94	95	95
A (kg/m)	0.25	0.19	0.15	0.086	0.035
B (kg-m/sec^2)	3.5	2.5	4.4	4.5	3.0

$P_{Watts} = Av^3 + Bv$ for Vm/sec

To calculate v directly as a function of P, A, and B:

$$v = (X + Y)^{1/3} + (X - Y)^{1/3},$$

where $X = P/2A$

$Y = [X^2 + (B/3A)^3]^{1/2}$.

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Gerald Pease is a 51-year-old satellite-orbit-determination analyst at the Aerospace Corporation in El Segundo, California, who is finally fulfilling his 25-year quest for a practical bicycle fast enough to allow him to stay in front of any pack of racers he is likely to encounter.—ed. ☐

Human-powered vehicle steering and suspension design

by Robert L. (Rob) Price

INTRODUCTION

The first part of this article discusses human-powered-vehicle steering. After briefly reviewing bicycle steering geometry, automotive steering is used to illustrate steering with two wheels. The second part discusses suspensions, using motorcycles and cars as models. The lean-steer mechanism and linkage I will use in my next HPV are shown as a summary.

STEERING

Many articles have appeared on the theory of bicycle steering. The intent here is to illustrate only some basic principles and compare them to steering geometries developed for automobiles.

Figure 1 shows head-tube angle, which is measured from horizontal; fork rake, measured from the center of pivot of the fork-tube bearings to the center of the axle; and trail, being the distance from the intersection of the fork-tube centerline and the ground at the point where the center of the tire patch meets the road. Common value ranges are shown in the figure.

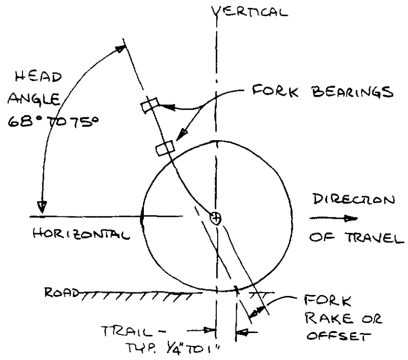

Figure 1. Bicycle fork geometry

There are several tracking stabilities inherent in well-designed bicycles. Trail is the first stability. The tire patch tends to follow the point where the steering axis intersects the road. This is known as 'caster' in the automotive world and can be easily observed on grocery-store carts. These have vertical steering axes on their castering wheels. Bicycles have angled steering or fork axes, which complicates matters.

Figure 2 illustrates the second stability, which is the 'well' the head tube sinks into when the bicycle is going straight ahead. When the handlebars are turned, the effective fork rake along the centerline of the bicycle is reduced and the head tube rises slightly. The steering tube wants to centralize in the well, making the bike track straight under the weight of bike and rider.

Bicycles have fork rake to reduce the amount of trail. This increases the sensitivity of the steering. When the fork has too much rake for the head-tube angle, trail approaches zero and the machine becomes unstable. When the fork has too little rake or is installed backward (as was popular a few decades ago) there is plenty of trail, but the 'well' becomes a 'hump.' The effective shortening of the fork rake when the wheel is turned occurs behind the fork-tube-bearing centerline, making the head tube fall slightly in a turn.

A bicycle leans in a turn, which increases the effective depth of the well.

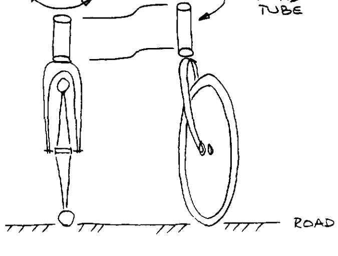

Figure 2. Bicycle steering stability

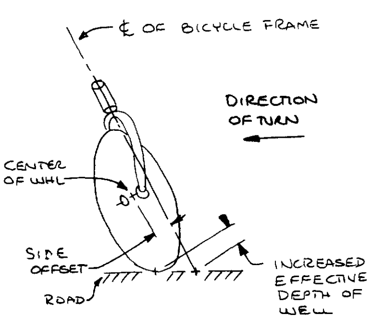

Figure 3. Bicycle leaning in corners

This is partly offset when cornering by side offset. Both are shown in figure 3. Because the drive effort, which runs along the bicycle centerline, is offset from the tire patch of the front wheel in a turn, the vehicle wants to steer further, called oversteer. While shallower (lower numerical) head- tube angles generally give more directional stability, coupling very shallow angles with large fork offsets to reduce trail, as is done on some recumbent machines, also increases side offset to the point of instability.

Automobile designers have solved most of the problems of two-wheel steering geometry, so a look at how cars do it is in order.

Figure 4 illustrates camber, which is the angular offset of the wheel disk from vertical. Positive camber splays the wheels out at the top. Wheels on horse drawn wagons had positive camber because of the built-up construction of their conical wooden wheels. Cars continued using positive camber long past the wood-spoke days until increased tire widths forced the wheels to be more nearly perpendicular to the road. HPVs that are cornered hard can benefit from negative camber, tires farther apart at the bottom, for better wheel loading, as will be discussed later, but a vertical orientation minimizes tire wear and maximizes coasting efficiency.

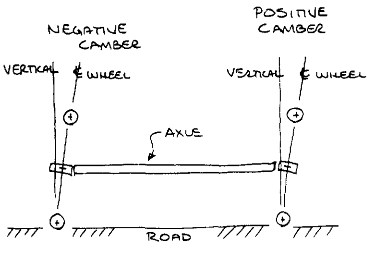

Figure 4. Wheel camber

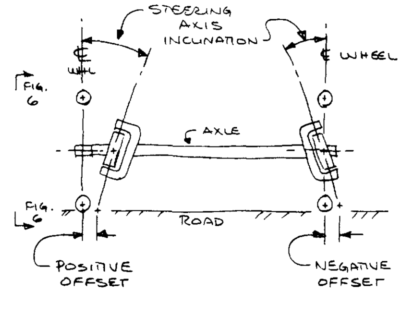

Figure 5. Steering axis inclination

Steering-axis inclination is illustrated in figure 5, which also shows how the intersection of the kingpin, or steering axis, and the ground relative to the center of the tire patch can result in positive or negative offset. Positive offset is most common on cars.

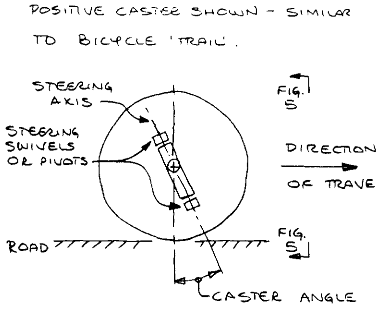

Figure 6. Caster angle

If the offset used with the narrow tires typical of HPVs is large, it can lead to 'bump steer,' where the steering handle is constantly kicked about when riding on rough roads. Both positive and negative offset will result in bump steer, but the direction of the turn induced by the bump hitting one wheel can be partly offset by the tendency of negative offset to steer the wheel in the opposite direction.

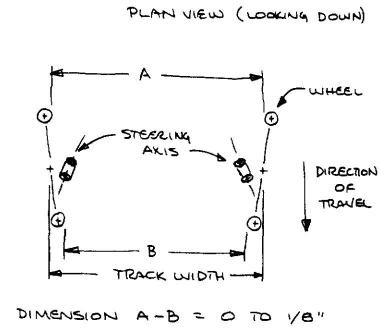

Figure 7. Toe in

HPV steering offset should be close to zero, with the axis intersection inside the tire-patch area, which is within 6mm (1/4 inch) of the wheel centerline on narrow-tired machines.

Caster angle is pictured in figure 6. Positive caster causes the centerline of the steering axis to intersect the road ahead of the center of the wheel, analagous to trail on a bicycle.

Figure 7 shows toe-in, where the front of the tires are slightly closer together than the rear of the tires. This is from 0 to 3mm (1/8 inch) on cars, less than 1°. A slight amount of toe-in helps a machine track straight but too much causes tires to scrub sideways, increasing tire wear and reducing coasting distances. A car with toe-out tends to swoop into a turn, which can be unnerving. Also illustrated in figure 7 is track width, the distance between the centers of the tire patches.

Figure 8 shows the two most common linkages used to steer automo-

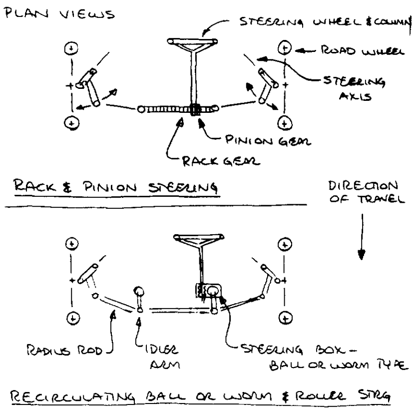

Figure 8. Steering linkages

biles, rack-and-pinion steering and recirculating-ball or worm-type steering. The fine points of the design of these linkages are complex, but one major feature common to both is important.

This is Ackerman angle, which causes the wheel on the inside of the turn to steer through a greater angle than the wheel on the outside of the turn, resulting in a toe-out condition. This causes the wheel axles to point to a common pivot point as shown in figure 9 and is accomplished by angling the steering arms inward from the fore-aft plane of the steering axis.

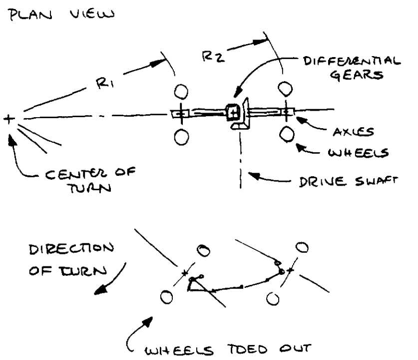

Figure 9. Ackerman angle

Figure 9 also illustrates why two driven wheels on a common axle need a differential unit to compensate for the different radii along which the wheels travel.

In the real world of freeway travel at 30m/s (100 feet per second), cars round turns pivoting about a point extended inward from between the center of gravity and the rear axle. The tires all slip at different angles with the pivot point, as in figure 10, reducing the importance of Ackerman compensation. And so it is not important on many HPVs with small-tire contact patches and high cornering loads

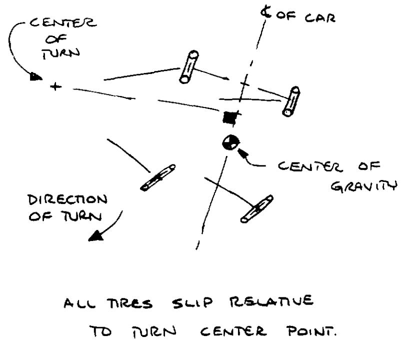

Figure 10. Tire slippage in turns

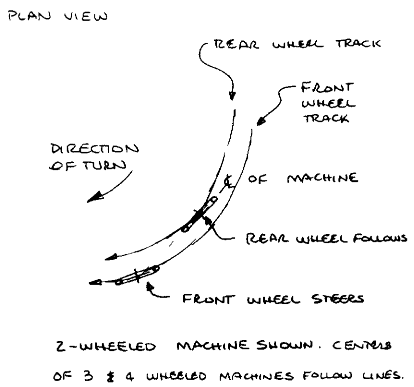

Figure 11. Front steering

The last topic to be discussed in this part has to do with which end of the machine to steer. HPVs have been built with front or rear steering. As shown in figure 11 for the conventional case, the front wheel is steered in the desired direction and the rear wheel tracks slightly inside the front. Figure 12 illustrates the rear-steer case where the rear wheel is initially steered to aim the front, then partially unsteered to maintain the turn. Successful rear steerers have very conventional fork angle, rake and caster dimensions, but navigating them precisely is an acquired knack.

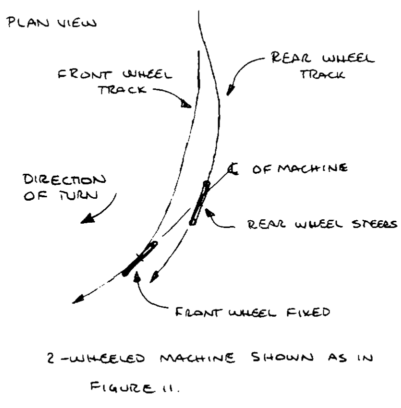

Figure 12. Rear steering

SUSPENSIONS

Some bicycles have featured suspensions over the years but cushioning over the worst bumps can be obtained by raising one's bottom off the saddle and using the legs to absorb shocks. Bicycle suspensions also add weight and absorb that precious commodity, power. HPV designs often do not allow the rider to use the bicycle technique and can benefit from the addition of suspensions. Automotive and motorcycle designs are used here as examples.

Vehicle suspensions are designed to keep all the wheels in contact with uneven road surfaces and to smooth out irregularities in the road, reducing fatigue in the riders and in the vehicle structure. Springs support the weight of a vehicle but once set in motion, springs can oscillate for many cycles before arresting. Springs are constantly excited when the vehicle is moving, so shock absorbers or dampers are associated with each suspension member to eliminate the oscillations within a few cycles. Springs come in many varieties, but today shock absorbers are closed-loop hydraulic cylinders, although friction dampers have been used in the past.

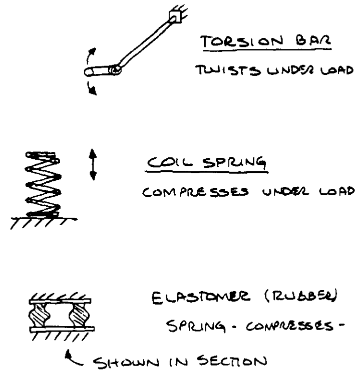

Figure 13. Some types of spring units

Figure 13 shows several varieties of spring, including torsion bars, which twist to provide spring force, and coil springs, which can be considered cylindrically wound torsion bars. Elastomer or rubber springs have the advantage of being small and light weight, so are well suited for use on HPVs, and are used on some Moulton bicycles.

Leaf springs, figure 14, may be laminated of several leaves or be made of a single leaf. Multiple leaves provide some internal friction damping. A disadvantage of elliptical springs is that they require additional struts to locate the wheels relative to the chassis. Semi-

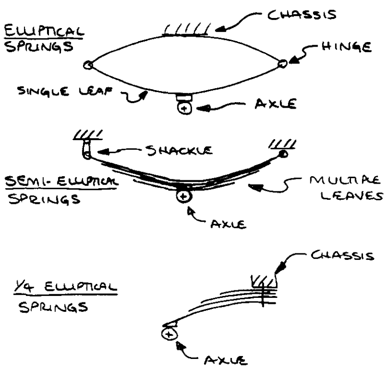

Figure 14. Leaf type springs

elliptical springs were universal on cars for decades but require a shackle to compensate for the variable length under deflection. Quarter-ellipticals have the advantage of requiring neither a chassis mount aft of the axle or a shackle. Semis and quarters mounted to a 'live axle' or beam axle are excellent at locating the vehicle wheels, as shown in figure 15.

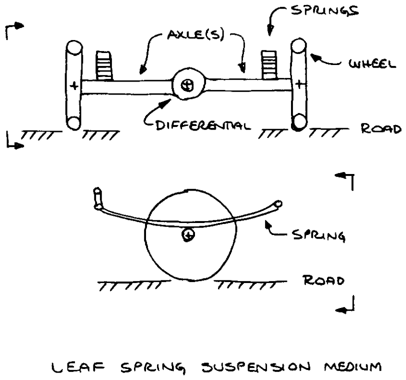

Figure 15. 'Live axle' suspension, 1

Coil springs in connection with a live axle, shown in figure 16, use locating arms for fore-and-aft location and a Panhard rod for lateral location.

Motorcycles universally use coil springs as a suspension medium. A front suspension is set up much like a bicycle's but the fork compresses coil springs with internal telescopic shock absorbers. Figure 17 shows that trail increases slightly under bump. A short swing arm, figure 18, known as a leading link, can also be used on front suspensions and in this case trail will vary under bump as the fork rake varies.

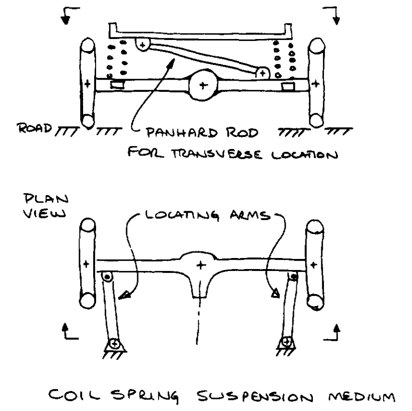

Figure 16. 'Live axle' suspension, 2

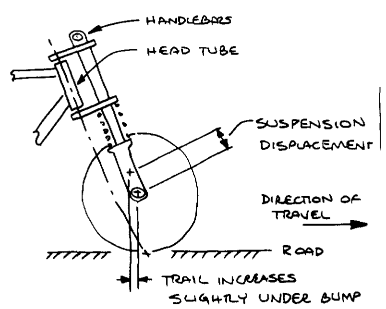

Figure 17. Piston type front suspension

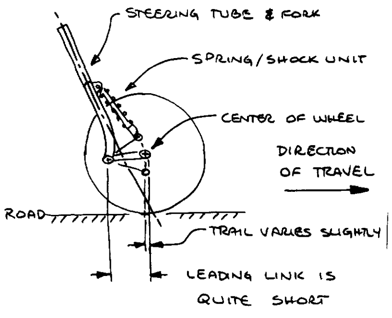

Figure 18. Leading link front suspension

Figure 19 shows a rear swing-arm suspension. Location of the arm pivot point below the drive-side chainline will result in suspension compression under power. A pivot above the chainline results in some unloading of the suspension, which, though slight, can partially compensate for the compressive effects of

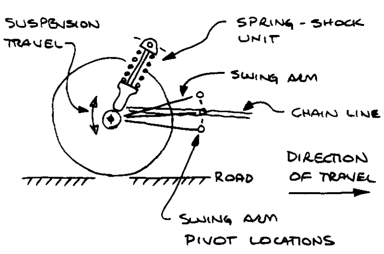

Figure 19. Swing arm rear suspension

a strong pedalling downstroke. It is difficult to achieve the neutral condition, where the chainline passes through the suspension pivot, on a derailleur-gear bike because the chain location varies with sprocket combinations.

Many cars have independent suspensions, where, unlike beam axles, each wheel can move independently of the others. A common front suspension of this type uses two 'A' shaped arms at each wheel to locate the upper and lower pivots on the steering axis as in figure 20.

Cars tend to roll axially about the center of gravity in a turn, making them lean outward at the top. This is often compensated for by linking the two sides of the vehicle with an anti-roll or sway bar, also in figure 20. The bar is fastened to the sides of the chassis and at the outboard ends to the suspensions, so that when the suspension compresses on the side of the car in the outside of a turn, it lifts the inside wheel, causing the car to corner with less axial roll. Of course an

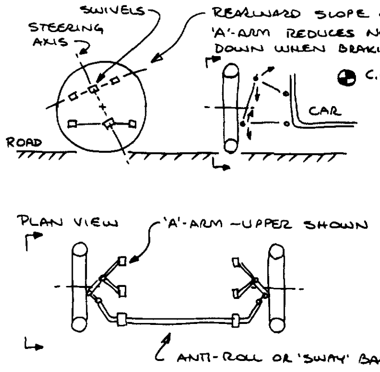

Figure 20. 'A' arms and 'sway' bars

independent suspension so equipped is no longer completely independent.

A popular and inexpensive variant of the A-arm suspension is the MacPherson strut, figure 21, which utilizes the lower A-arm but substitutes the telescoping strut of the shock absorber for the upper arm. This strut is surrounded by a coil spring which twists to allow for steering. Also shown in figure 21 is the swing-arm suspension, primarily used on rear suspensions of older Volkswagens and Corvairs. A universal joint on the drive shaft near the differential is the pivot point for the axle and attached rear wheel. As the suspension travels through its full stroke the wheel camber changes considerably.

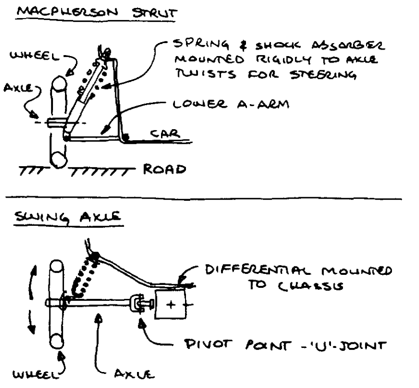

Figure 21. McPherson strut and swing axles

Part of the trick of bicycle balance is leaning into a turn, which balances the inward radial-force vector and the vertical weight vector into a resultant vector which acts straight down through the inclined bicycle. In this way the bicycle's wheels do not receive any sideward loading. Many HPVs have three or more wheels, so do not lean in a turn, and the wheels receive side loads for which they are usually not designed. Figure 22 shows that a bicycle wheel is only about 15% as strong in side loading as in downward loading. A bicycle wheel overloaded sideways will often 'potato chip'. Many HPVs also have narrow tracks which makes them easy to roll onto their sides. For these reasons it is desirable to make HPVs lean in a corner if that can be arranged in the suspension design.

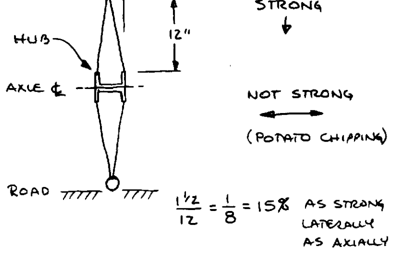

Figure 22. Bicycle wheel side loading

SUMMARY

By way of summary, I utilized the concepts explained in this article to develop a suspended lean-and-steer mechanism for an HPV (known as P-14) I recently designed. The lean-steer mechanism is illustrated in figure 23 and utilizes a fixed tubular steering axis inclined at the proper caster and offset angles. The wheel hub moves up the tube on the inside of the turn and down the tube on the outside. A roller, which is connected to the wheel hub, rides in a vertical track behind the steering tube, forcing the hub to rotate as it moves along the tube, making the machine steer.

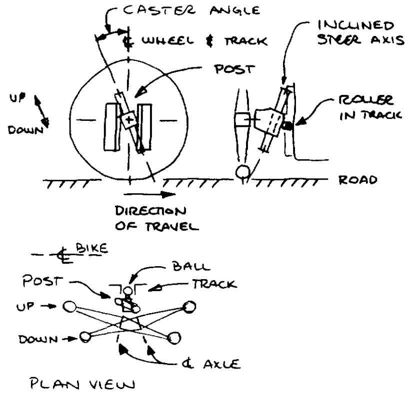

Figure 23. P-14 lean steer mechanism, 1

The steering linkage is shown in figure 24. It uses dampers to reduce bump-steer forces transmitted to the control stick, the twisting shafts act as torsion springs, and the linkage is set up to raise the outer wheel more than the inner wheel falls, to provide a tracking well.

Designing and building human-powered vehicles can be a lot of fun, and a little attention to the basics of steering and suspension design as shown here can make them easy and fun to ride as well.

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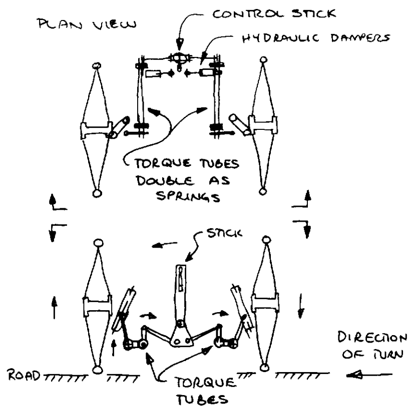


Figure 24. P-14 lean steer mechanism, 2

Rob Price is an Airborne Structures Staff Engineer in the NASA Space Systems Group at Martin Marietta Astronautics Corporation in Denver. He designs installations of equipment in the Shuttle cargo bay. He has a B.S. in mechanical engineering and is a member of the American Institute of Aeronautics and Astronautics and, of course, the IHPVA. He has been designing and building HPVs that utilize aluminum monocoque construction for 12 years.

Rob conveys his thanks to the members of the Colorado Human Powered Vehicle Club for their suggestions in preparation of this article. He intends to combine this and several other articles planned for Human Power *into a how-to book on HPV design and construction.—ed.* ❑

Reviews

(Continued from page 14)

and without toe stirrups", by Paul S. Visich). Part III has three papers on injuries and psychology, eg "acute mountain sickness in competitive cyclists" by Jon G. McLennan et al. The last part has three papers on vehicle design by Chet Kyle, Paul MacCready and your editor. These three have been reprinted in substantially the same form in the IHPVA Third Symposium or in HP. ("Substantially" because in my piece at least, a meddling editor made extensive and wholly unnecessary—in my opinion—changes in my carefully constructed sentences. HP authors who bristle at my red pen can thus rejoice at the turning of the tables).

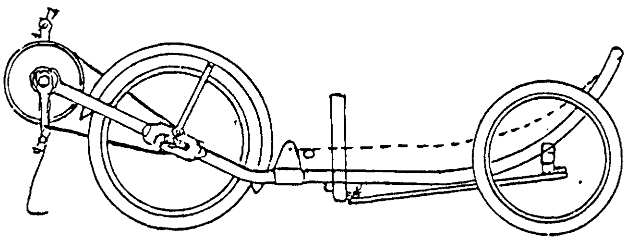
This well-produced book should be valuable particularly to people working in sports biomechanics and physiology.

—Dave Wilson

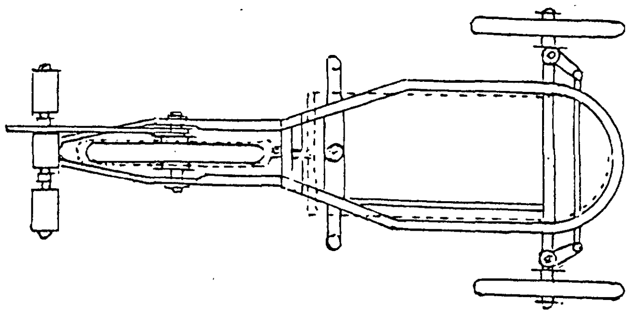
HPV building in the thirties
by Arthur Baxter

It may come as a surprise to know that there were bicycles designed to give a recumbent riding position on sale way back in the thirties. Two on the market were the F.H. Grubb and the Cyclo. The former carried the rider in an almost horizontal position between the wheels. The wheelbase was consequently very long, in spite of the smallness of the wheels (12 or 14 inch, I believe). One of these bikes was seen regularly on club runs in the Leeds area. It was heavy (in an attempt to prevent whip due to long wheelbase) and the rider was much too near the ground, in dirt and danger. The Cyclo machine carried the rider at car-seat height and had a short wheelbase, 36 to 40" as I remember. Rear wheel 26" and front 18 or 20". The rider's feet were ahead of the front wheel. Below are sketches of these two bikes, from memory, so details may be incorrect. They did not 'take off', as the cyclists of those days were mostly hard up and not inclined to risk their cash on what were regarded as costly freaks. Also, the rumor went round the clubs that, although these bikes were wind dodgers, the expected saving was lost somewhere, and they were more tiring than standard bicycles!

A clubmate and I were puzzled by this loss of advantage, and decided to research this loss by making a recumbent for testing. We wanted a low machine with short wheelbase, on the basis that the Cyclo was too high (which it wasn't) and the Grubb too long (which it was). We preferred a bike to a trike, but could not design a low and short two-wheeler except with tiny wheels.

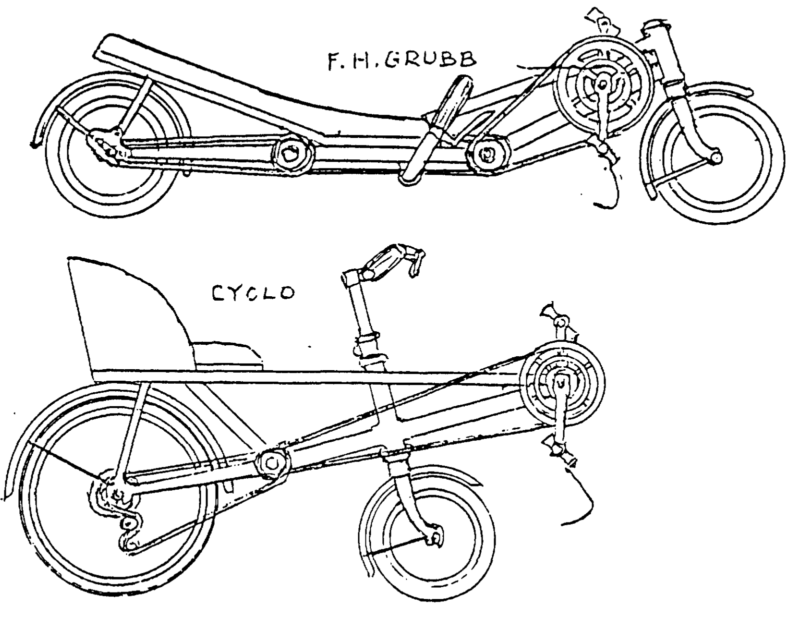


THE '39 TRIKE. FIRST DRIVE



Then we thought of rear-wheel steering, with legs each side of the (fixed) front wheel. A mock-up was made to try out this idea, but after several grazes and bruises, we decided to leave it to the circuses! So it had to be a trike. Preparations for war (1939) meant that engineering materials were almost unobtainable, so we had to use mostly scrap of unsuitable size and quality, made to the required shape by much sawing, filing and turning.

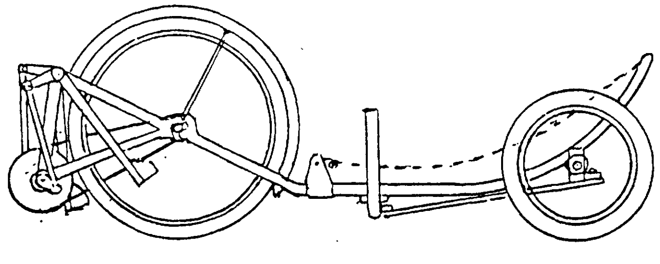
On test, the comfort and safety were very good. Having a 30" track, rear wheels turning into the direction of the side thrust when the rear end would have created mayhem in a club ride, so we had to ride along. We tested to destruction, which was easy as regards rear wheels (spoke breakages, spoke flanges becoming unbrazed from (pedal-centre) hubs, stub axles (pedal spindles) ripping the threads out of the steering pivots, which had been laboriously hand-crafted from 1-1/2" diam. mild-steel bar (too soft).



Recumbents from the thirties—the F.H. Grubb and the Cyclo

However, we found out why the wind-cheating advantage of recumbents was lost (important, I think): —the circular pedal motion wastes power. It is much harder to raise the foot when it is in front of the hip (as on a recumbent-position machine) than when it is below that joint (as on a "normal bike"), so that on the former, much of the power from the 'falling foot' is wasted in helping the other one up to the top of its orbit. Our findings in this respect were so definite that I am surprised that most, if not all, of the bikes and trikes shown in HPV club pictures have circular pedal motion. Some of these pictures also show riders much too near the pedals, their legs still quite bent at the knees while the pedal is at its furthest point of travel. Sitting too near to the pedals has the effect of raising the gear ratio as regards the amount of power required, while not reducing pedalling speed. Loss on the swings but no gain on the roundabouts!

Back to our trike: —Mods for drive system No. 2: we fitted a pair of swinging cranks, as shown in the photo, made from good light tubing which we 'came by'.



THE '39 TRIKE THIRD DRIVE

The pivot bearings were plain (with grease nipples) and we got length, travel and angles all right first time. (A contrast to the everlasting alternations and repairs prior to that!) We then rigged up a 'no-dead-centre' drive. It was a dead loss! The action was much too jerky to be of any use. For the next (No. 3) drive, the seat tube, bottom bracket and chain stays from a spare frame were brazed onto the original frame as shown in drawing 4. Chainwheel and cranks were fitted, after shortening the cranks, and fitting suitable bearings to their ends. These bearings were linked up via rods as shown to projections on our swinging cranks.

Alas, the war caught up with us, and we both had to leave the project. We had both been in lodgings to which we never returned. That, to us, was the end of the trike. No doubt taken away in a dustcart when it had become a nuisance to an ex-landlady! However, we had found out a few things about the design of recumbents:

1. (Important) Pendulum motion of cranks is better than circular motion.
2. Short wheelbase is desirable, but low seating is not, so a tricycle is not a 'must' as it would be for short and low requirements. A two-wheeler is lighter and easier to push and has no side-stresses.
3. Recumbents and partial recumbents should become the standard types of bicycle, providing more safety and ease (or speed), but they will not become popular unless the seat is at least as high from ground level as is the average car seat. This can be provided with short wheelbase and 'streamlining' advantages. Some of these advantages might have to be sacrificed on a general-purpose or touring bike where a torso position of less than 45 degrees to horizontal would not be accepted. Even then, the wind resistance would be less than on a current type of bike.

My sketches show (5) Town model. Shaft drive as shown might appeal on account of its cleaner appearance. (6) Country or touring type. On both of these a light framework is shown to keep a cape clear of the cranks. The cape would have a grommetted hole to fit over the lamp bracket. (Cape in dotted lines). The tyres may seem too fat, but one cannot use the legs (as on a current type bike) to absorb vertical jolts and fat (flexible) tyres may be the best way of providing the softer 'suspension' needed. No. 7 is for racing. Note shoulder 'hooks' to take thrust reaction when sprinting or hill climbing.

Unfortunately I do not have the means (machinery or cash) to make any of these bikes, although it would not take much alteration to convert a BMX bike into the one shown as No. 6. Bicycles after the style suggested should replace the current high, wind-stopping type, but I don't think that they will, as the most advertised sells whether or not it has merit (Remember Chopper bikes?). Sorry to finish on a cynical note.

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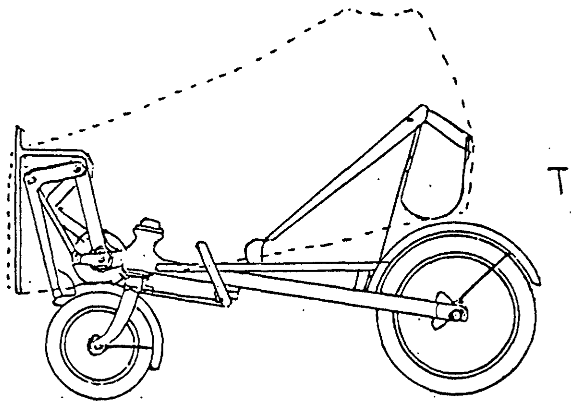
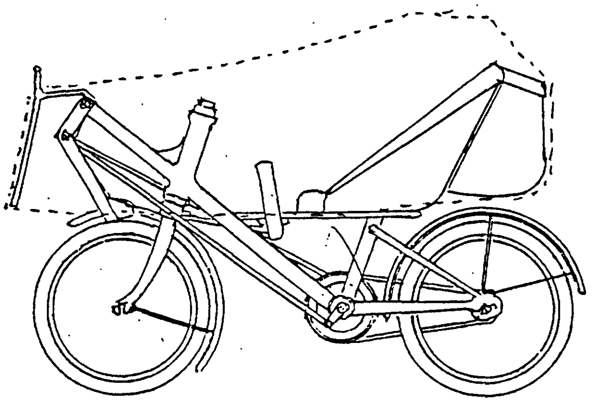
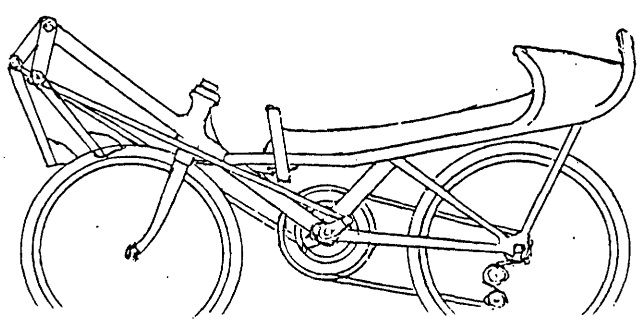
(This is a reprint from the newsletter of the British Human Power Club. Some correspondence with Arthur Baxter will be published in the next issue.—ed.) ❑



TOWN



COUNTRY



RACING