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Series Hybrid Drive-System: Advantages for Velomobiles

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Abstract

It is briefly explained what a human powered series hybrid (SH) drive is. Basically only a few, encapsulated modules are needed to build a complete human-electric hybrid drive system which has no mechanical transmission elements, and thus also no bicycle chain.
The base functionality of a human powered series hybrid drive is the same as that of today's electric bicycle drives (parallel hybrids, PH). A SH drive however can do much more than a PH drive at about the same cost. And a SH drive does not weight more than a PH drive.
Key advantages of the SH drive for velomobiles are mentioned in the article.
Since the series hybrid drive has no exposed mechanical transmission elements it is easy to automate. Very good ergonomics and therefore ease of use are possible. Maintenance is simplified.
The history of the "base" research of the series hybrid drive and of the developments with the aim to industrialize such drives is reported up to the year 2005.
In the appendix an extensive list of the technical publications about SH drives is given (pdf's of some papers available on request).

Introduction

Slightly more than a decade after the start of research for advanced human power drive systems and of the development of chainless series hybrid (SH) drive systems, it is time to report the findings also with respect to velomobiles. The last talk about this topic for velomobilists took place in the frame of the 4th Velomobile Seminar "Assisted Human Powered Vehicles" during the World Championships for Human Powered Vehicles at Interlaken, Switzerland, in August 1999.
A parallel hybrid (PH) human electric drive combines a mechanical transmission such as a chain or a shaft by mechanical means with an electric motor.
In a series hybrid (SH) human electric drive the contributions of human and machine (electric motor) to propulsion are added electrically. Mechanical human power is converted into electricity using a pedalled generator.
First publications and talks by the author and his collegues ran under the labels "chainless" and "transmission". In recent years the author started to use the naming

by Frank Jamerson as used in the "Electric Bikes Worldwide" Reports: parallel hybrid (PH) and series hybrid (SH).
A list of all major papers by Fuchs and collegues about the SH drive is given at the end of the paper.

How a Series Hybrid (SH) Human Power Drive works

Mechanical human power output of a pedalling human is converted into electric power by a generator driven by pedals and speed increasing gears. The generator is electrically loaded by power electronics.
The SH drive is a transmission in the sense that the electrical energy from the generator is not charged into a battery, but is fed directly into (a) motor control(s) of (an) electric motor(s) that propel(s) one (or two) wheel(s) of a vehicle.

If the vehicle at some moment needs less energy to drive the wheel(s) than is being produced by the generator, the energy can be stored in a battery (or an other electrical storage such as super capacitors). In velomobiles such a situation would happen while coasting down a slope or when being pushed by a wind from the side or from the rear and, of course(!), when standing while the velomobilist still pedals.

If the energy storage (battery) is depleted it is being charged from the electrical net (or from an other power source such as a renewable electricity source). So a SH drive is basically a drive like that of an ordinary electric bicycle.
Of course a bicyclist could use the SH vehicle like a home trainer and charge the battery by pedalling. But to fully charge a typical e-bike battery would take quite some time!

Components

Basically four modules and wiring are sufficient to build a complete SH drive system. Traditional bicycle drive components like chain-wheel, chain, cogs, derailleur, rear-wheel gear hub, etc. are no longer needed.

No.	Module	Remark
1	Generator-Module	Replaces the complete, traditional mechanical bicycle drive system that is found in todays parallel hybrid e-bikes
2	Motor-Module, e.g. hub motor or trailing arm including motor and transmission to the drive wheel	A parallel hybrid e-bike has a motor, too
3	Battery-Module (or other energy source or storage)	A parallel hybrid e-bike has a battery, too
4	Human Machine Interface (Display- & Control-Module)	A parallel hybrid e-bike has such a module, too, sometimes in the form of a few LEDs, sometimes as a LC display
5	Wiring	Electrical wiring is needed in a parallel hybrid e-bike, too

Table 1. Modules of a series hybrid (SH) drive system

Some believe that a redundant mechanical transmission is still needed to achieve reliability. Our experience is that SH drives are reliable: The Leitra prototype works perfectly even if its drive is only a working model made just for demonstration!

History of the Series Hybrid (SH) Drive System

SH Drives for Bicycles and other Vehicles

The history of some developments of SH Drives for various kinds of vehicles can be found under http://homepage.bluewin.ch/andreasfuchs/ and http://en.wikipedia.org/wiki/Hybrid_vehicle

Feasibility of the SH drive for single-track vehicles e.g. electric bicycles

The rotor of a generator accelerates much faster than a bicycle that is hooked up to a pedal by a chain.
In vehicle configurations with upright seating and/or in single track vehicles the pedal generator module has to be operated in a way that no accelerations of the pedal occur that are too fast for the human.
Applying findings reported in the patent EP 1165188 by www.swissmove.ch, ergonomic behaviour of the pedal can be achieved. Basically the generator needs to be heavily electrically loaded.
Or, by feeding current into one or more generator phases (e.g. by using 4-quadrant motor control) the pedal can even be hold before the human starts to pedal.
So two-wheelers with SH drive are possible and therefore such drives could also be installed in single–track velomobiles like for example the Desira's by S. Gloger or the Aeolos by J. Fuchs.

SH Drives for Velomobiles

Main motivation to first research and then develop new kind of human power drive systems was the will to realize "Ultraleicht-Mobile" (ultra lightweight mobiles), a sort of velomobiles, but feasible for mass-production. Research about such vehicles was conducted at the University of Applied Sciences in Berne during the time period 1994 to 1999, after 1996 under the lead of the author. Results are reported in the paper "Urban Quadracycle" presented by Bergeron and collegues at the 4th Velomobile Seminar 1999.

It was assumed that a velomobile for the masses would be a power assisted one since on slopes the additional weight of a fairing could be compensated by the help of a motor. Electro-mechanical drives based on planetary gears to mix human and electric power proved to be too expensive to be developed further, were not reliable, and inefficient as soon as two chains were hooked in series between pedal and wheel. In production, these electro-mechanical drives would have been too expensive, too.

To radically simplify the vehicle and the drive system the series hybrid drive was studied since 1995 and realized in the years 1996 and 1997 in a working model drive which ran in an ordinary upright bicycle (see papers by Fuchs and collegues about this new kind of drive system, listed at the end of this article).

The tests of the working models conducted in 1997 and 1998 yielded positive results: Test riders especially liked (and still like) the Leitra with the chainless transmission working model.
Therefore, in 1998/99, the author started to search for ways to develop a commercial version of the SH drive system; he developed stragegies and searched funds.

Figure 1. The author on a Leitra tricycle equipped with the 1998 working model of the SH drive system
(photo from ducret.ch)

In 1997/98 very little was known about pedalling a commuting- or utility-human powered vehicle because sport medicine focusses more on cadence and power of athletes rather than e.g. torque and pedalling acceleration by non-athletes, youngsters or elderly people. Therefore quite some literature search and some measurements had to be done to find e.g. the torque-cadence-relationship of human beings (which is, in shape, very similar to that of a DC motor). This relationship is essential to understand pedalling of a generator.

Electric machines feasible for commercial versions of pedal generators were searched. But since in 1997/98 not too many high torque, low speed, brushless electric machines of high efficiency were available for a reasonable price, together with M. Lindegger and J. Gilgen electric machines were developed. Today this type of electric machine is being produced by www.circlemotor.ch.
The first electric machines developed run below 1000 rpm and could brake a human. Since these slowly turning machines were still too heavy the speed of the generator was increased to between 1000 and 2000 rpm, and the generator became smaller.

Then, in the period 2000 to 2002, under the name of autork ltd., a decentralized control system for the series hybrid drive was developed to the stage where a prototype of the "Urban Quadracycle" run (early version being shown in Fig. 2), using electric machines by Circlemotor AG.
Within this control system, the information is distributed using a serial CAN bus. Electric power is switched using components by Infineon developed for the 42V "PowerNet" e.g. for mild hybrid cars (See the paper by Blatter and Fuchs, 2003, in the book by Expert Verlag).
However, development stopped, since a major shareholder of autork went into bankruptcy. After 9/11 private investors were hesitating to invest into start-up companies and therefore autork never got all the funds budgeted to perfectly finalize the SH drive into a product.

Fig. 2a. Urban Quadracycle, prototype chassis
Ultraleicht-Mobiles are related to velomobiles in many ways but are somewhat heavier because fibre plastics are avoided. The vehicle shown was built by Jakob Gilgen from www.gilgen.com
(Reference: Bergeron 1999)

In Fig. 2a the housing for the pedalled generator, the voluminous chassis which holds the batteries, as well as the two rear wheel hub motors (electronic differential foreseen) can be recognized.

Fig. 2b. Urban Quadracycle prototype, with fairing put onto chassis.
Doors foreseen, but not in picture.

In 2003 the decentralized control system was put onto a two-wheeled EZ1 recumbent cycle equipped with electric machines from www.perm-motor.de to test if a SH drive is feasible not only for "Ultraleicht-Mobiles", but even for e-bikes!
It was found that range using a typical e-bike battery was competitive compared to the ranges of commercial parallel hybrid e-bicycles as tested by extraenergy in 2001 and 2002.

Andreas Fuchs continued to search for partners willing to implement an improved version of the SH drive system. During 2004 and 2005, in collaboration with a swiss company, a recumbent tricycle was equipped with such a drive. In this last version of the SH drive all modules, generator, motor and battery as well as the display- & control-module, are fully mechanically encapsulated.
Gear ratio of the pedalled generator is no longer about 1:50 as in the first working models from 1997/98, but is now smaller than 1:30 (or even 1:20) !
The speed reduction ratio of the gear between motor and wheel is, dependent on maximum slope and maximum acceleration, somewhere between 8 and 16 on 20" wheels. With this gear ratio the motor can climb most slopes common in mid-Europe and the Alps.

Qualities of a SH Drive System

Ergonomics

A commercial drive system of a velomobile, especially if it should be an assisted velomobile, needs to be very ergonomical in order to be a success for non-expert users (Eslava, 1999).

Type of Drive System	**Operational Task for User**	**Easy of operation**
E-Bike, PH	User has to operate two drive systems in parallel	Dynamic riding requires learning
Pedelec, PH	User has to operate only the mechanical gears since the electric system is automatically operated	The different machines have different behavior and require some "optimal" way of operation
Kutter-Drive, PH (Kutter, 1993)	Mechanical gears have to be changed only when the slope changes much	Starting on slopes requires some training. Else operation is easy
Series Hybrid Drive, SH	Components are fully electronically controlled: Any level of automation is easily realized and optimal task allocation to user and to machine is possible e.g. any degree between full manual control and full automatical control can be realized at nearly no additional "automation cost"	Easy to operate

Table 2. Difficulty of operation of various types of drive systems existing today
(Drives with mechanical elements could be automated in a manner Shimano is doing e.g. within the Smover concept)

The Leitra working model from 1998 is fully automated. Choosing the "operational mode" is the only thing a rider has to do besides pedalling, steering and braking.
In later prototypes the motor was controlled using a throttle. Pedalling is either automated or also controlled using e.g. a throttle or an other kind of control device.

Drive Dynamics

In a SH vehicle human and machine (electric motor) are only coupled by electrical means rather than by mechanical means as in a PH vehicle. Since they do not interfere, both human and electric motor can work in an optimal manner. This allows dynamic riding/driving - and much fun!
The motor of a SH vehicle needs to set free 100% of the power, that is, the sum of human and electric power, because while accelerating or climbing there is no help by a chain drive as in a PH. The motor of a SH vehicle is therefore about twice as strong as a PH motor.
Therefore, too, in a SH vehicle any combination of human and electric power is possible, whereas in a PH vehicle, under electric power alone, acceleration and climbing rate is strongly limited. The fact that pure electric driving is possible is very much appreciated in case where elderly or people in rehabilitation want to use a SH vehicle.

Efficiency

Here we do not compare the series hybrid drive system with a chain drive of a purely mechanical bicycle because it was not made to replace such drives e.g. in off-road bikes or in racing bikes. The series hybrid drive was made to replace mechanically complex (hybrid) drive systems in any kind of pedal powered machine for urban-, fitness- or rehabilitation-cycling.

The first working models of the series hybrid drive were equipped with brushed generators with peak efficiencies of between 55 and 70% and with brushed motors with about 80% peak efficiency. Before we tried those first series hybrid drives we believed that such drives would only be feasible for very aerodynamical Ultraleicht-Mobile's and other new forms of pedalled machines such as velomobiles. However, in 1997/87, we were astonished to learn from tests, with battery capacities typical for the e-bikes of this time, that we rode about as long and as far as the commercial PH e-bikes and pedelecs! At VUB, Capelle (Capelle 2002) confirmed later with measurements what we concluded: That the efficiencies of PH e-bikes are sometimes much lower than one would expect based on the efficiencies of purely mechanical bikes! Chapelle and collegues, in PH's, found efficiencies of between more than 55% and less than 95%.
Mechanical additon of two sources of torque/power is not loss-free. Especially not when two very different "motors" like a human – torque is highly variable – and an electric machine – torque is smooth – are mechanically coupled! Therefore it happens that some pedelecs with tight coupling of human and electric machine in or near the bottom bracket perform well in the flats or on hills but not on both.
If mechanical coupling of two sources of torque/power is never loss free, why not couple in a purely electrical way by adding currents from various sources like

generator and battery (or supercapacitors or fuel cell) in a DC-link (with variable or nearly constant voltage)? At least the advantages linked to electrical coupling like ease of assembly – just plugging together some electrical cables! – and many other advantages, could be won!
Therefore in 1998 the author intensified the studies about the feasibility to equip upright bikes with series hybrid drives. He found that it is easy to build SH's that are more efficient than the PH's with the poorest efficiencies.

Energy Budget

So far we have discussed efficiency in the form of "peak efficiency". If the "energy budget" is considered which is somewhat similar in meaning to "average efficiency over some time", e.g. the time needed to accelerate a vehicle from standstill to travel-speed, or the time needed for a ride from home to work, then the story "efficiency of SHs compared to that of PHs" starts to look interesting.
In urban traffic a vehicle is on constant speed only for a minor part of the travel time. Therefore the advantage of high peak efficiency in one load-point (torque and speed) of a parallel hybrid (PH) remains only advantageous if efficiency in other load-points is good, too, and if very fast changes between gears is possible.
People that are not trained in optimal manual operation of traditional bicycle gears are often pedalling off their own maximum efficiency because humans have a quite narrow peak of efficiency versus cadence at a certain power level. The associated losses of pedalling off-maximum efficiency may be considerably big and then the absolute value of efficiency of the mechanical gears becomes relatively less important (see Table 5 in the article by: Rohloff GmbH, "Wirkungsgradmessungen von Fahrradantrieben – eine unendliche Geschichte?!").

One major advantage of the SH is that fast change of "gears" is possible since in an arrangement with fixed mechanical gears and power electronics changes between different states of operation happen almost instantaneously. At every moment the efficiency of the system can be maximized by electronical means.

And, somewhat similar to a battery (an electrochemical one) the human as a "biochemical battery" is "discharged" more efficiently if load is nearly constant than highly variable. So on a SH the human is not forced to perform an intervall training such as on a PH vehicle! The "load-leveling" capability of SH's is very advantageous from the point of view of a physiologist.
The first experiences with respect to the physiological advantages by Fuchs and collegues and by Daniel Couque (who constantly pedals a generator while manually operating the throttle of the electric motor of his velomobile) are too few to draw final conclusions now. However, at the moment, it can not be excluded that the phyiological advantages of a SH could over-compensate the few percent reduction in peak efficiency of a SH compared to a PH!

Weight

The generator module shown in Figure 3 weighs only 4.3 kg including pedals and pedal arms. This is about the same as the weight of a chain drive with derailleur or less than the weight of a drive with 3 x 7 gear hub!

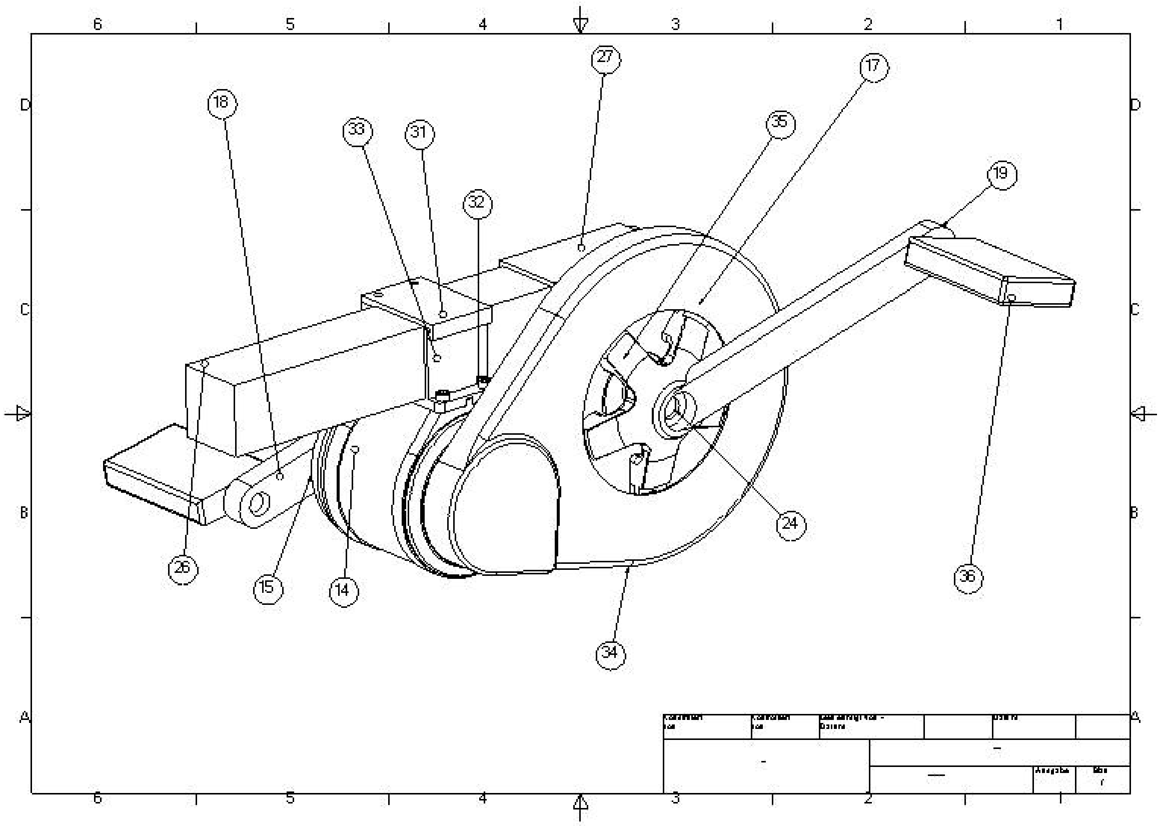

Figure 3. Pedal generator type 2004/05. Two-stage gear with 1:28.5 ratio.
First stage of the gear is by an industrial chain because this allows to precisely couple the generator to a standard bottom bracket. Second stage is a planetary gear.
Indication of Size: Pedal arms (19) are standard bicycle pedal arms.
(27) standard bottom bracket on rectangular boom (26) of recumbent trike, (34) chain cover, (14) housing of planetary gear and electric generator
2003/04 concept: by A. Fuchs. Prototyping 2004/05.

Please note that the size of the generator module in Fig. 3 is much smaller than the size of the one on the Leitra in Fig. 1. Size could be reduced because stronger and smaller generators could be built or sourced. If the gear ratio is just below 20 then the electric generator needs to brake a non-athletic but trained cyclist with between 1 and 2 Nm nominal torque.

The motor of a SH drive is somewhat heavier than the motor of a PH drive because it needs to be about twice as strong.

Cost

The main difference between a parallel hybrid drive and a series hybrid drive is the generator module (list of all modules, see table 1). To compare the cost of these drive systems it is sufficient to compare the cost of the generator with the cost of a mechanical bicycle drive system.

A pedalled generator can be made for approximately the cost of a hub wheel motor and motor controller. Compared to the continuously variable mechanical or to the hydraulical transmissions for bicycles <u>that do not exist on the market</u> it can be stated: There is no cheaper and simpler CVT (continuously variable transmission) than a drive with pedalled generator!

To those that still do not believe that a series hybrid drive can be realized at low cost: A pedalled generator contains about the same sub-modules as a modern electric drill. And these are available at very reasonable prices!

The main initial cost is the cost to develop the system (software and power electronics) and the components that are not available on the market (pedalled generator).

Compared to drive systems which include mechanical transmission elements further cost reductions are achieved because:

- The vehicle frame or chassis becomes much simpler if a pedalled generator replaces a mechanical transmission
- Sourcing of drive components reduces to only four rather than many
- Assembly of vehicles with SH drives including pedalled generators is much faster than that of corresponding PH (parallel hybrid) versions
- After-sales costs are much cheaper because chain wear and costly replacements of chain and cogs no longer have to happen
- Etc.

Drive Systems for Velomobiles

Recent Velomobile Hybrid Drive Systems

Electric assist power for velomobiles can make sense because it eases accelerating and climbing for the velomobilist (Rasmussen 1999). And it makes more sense to recuperate energy and to brake electrically while descending a slope with a velomobile than with a standard bicycle because the velomobile weighs more and aerodynamical drag is less.

So far the velomobiles equipped with electric assist power as well as the electric bicycles and the pedelecs are all parallel hybrids.

For now more than a decade very common are the drives by Heinzmann (www.estelle.de). Michael Kutters system (Kutter, 1993) using the planetary gear to mix human and electric power was tried in velomobiles, too. In the last year the Bionx (www.bionx.ca) came into use in some velomobiles.

SH Drives in Velomobiles

The author sees the main advantages of SH drives for velomobiles in the simplification of the mechanical design of velomobiles (Fuchs, 1998). The channels for chains can be eliminated completely. Also, if the mechanical transmission, which may include an intermediate axle, exists no longer a major source of noise has disappeared!

The gear ratio between pedal and wheel of a SH drive is infinity. This fits velomobiles which are slow on slopes and fast in the flats perfectly.

Velomobiles are among the most aerodynamical, but also among the heaviest human powered vehicles. Therefore it makes sense to equip them with a strong and very efficient drive on the wheel-side. Like hub motors in the front wheel or in the rear wheel of a PH e-bike the SH drive motor works without any interference by the human (e.g. no clocking of the electric motor like in a pedelec with bottom-bracket motor). Therefore the motor can be controlled in an optimal and energy-saving way.

The energy harvested by the vehicle from the biochemical storage “human” is maximized because the pedals of a generator accelerate fast and therefore the time spent by the human pedalling at an optimal load-point is maximal. Conversely, in a velomobile with mechanical drive the pedal accelerates slower because the full load of the vehicle is hooked up to it.

Conclusions

During the last decade Andreas Fuchs and collegues worked intensively on the series hybrid (SH) drive system in order to make it ready for industrialisation. It was recognized that:

- A SH drive can be operated very dynamically since there is no interference of man and machine by mechanical means
- If a SH drive weighs more than a PH drive the difference is small (compared to the weight of the rider)
- A SH drive does not have to cost more than a PH drive. Simplification on the vehicle equipped with a SH drive may result in dramatic cost reductions
- Energy efficiency of SH is sufficiently high for practical use and can be considered excellent if physiological effects on the human are taken into account

The author continues to work towards the implementation of the SH drive system in commercial vehicles because for some applications and uses there exists no better human-electric hybrid drive system!

Acknowledgements

To all those that have contributed to the research and development of the SH drive for pedal powered machines in whatever way I say: "Thank you, in the name of the future users !"

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