Sustainable Materials and Technologies 1–2 (2014) 36–41

Contents lists available at ScienceDirect

Sustainable Materials and Technologies

A continuously variable transmission for efficient urban transportation

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ARTICLE INFO

Article history:
Received 22 April 2014
Received in revised form 13 October 2014
Accepted 23 October 2014
Available online 15 November 2014

Keywords:
Continuously variable transmission
Locomotion efficiency
Bicycle

ABSTRACT

This paper describes a new continuously variable transmission (CVT) that may be used in a variety of machines and transport devices. Unlike many CVTs that are relatively heavy and bulky, the present CVT, named “eDrive”, is fairly small and lightweight. These attributes allow eDrive to be used in human-powered transport devices such as bicycles. The eDrive incorporates a sprocket able to vary its effective diameter via computer controlled actuation. The sprocket accommodates a rotational input and provides an output using a loop belt rotationally engaged with sprocket. The eDrive promises to increase a bicyclist's user experience, provide more efficient conversion of human energy to locomotion, and overall promote sustainable urban transportation. In addition, eDrive can be configured and scaled to provide CVT functionality for a variety of other vehicles and machines, such as wind or water turbines and electric vehicles.

1. Introduction

Finding solutions for efficient modes of urban transportation is becoming more pressing given concerns over fossil fuel depletion and climate change [1]. Human powered vehicles can play a role in overall urban transport solutions. Of such vehicles, the bicycle has met with the most overall popularity given that it is fairly lightweight, maneuverable, inexpensive, and efficient to operate. Cities such as Amsterdam have had a long history of using bicycles as a primary urban transportation solution. City bike programs have become increasingly popular. In such programs, bikes can be picked up in one location and dropped off in another, and the use is often free [2].

The invention of the bicycle has allowed the relatively efficient human locomotion to be amplified. A 73 kg bicyclist expends approximately 292 calories traveling 1 h at 16 km h^{-1}. Therefore, a walker expends 56 calories per kilometer, while the bicyclist expends 18 calories per kilometer [3], equating to around a threefold increase in efficiency. Moreover, nutrients used to power locomotion of biological forms can be produced using low energy and renewable forms of energy. Human power is also advantageous in that it has low impact on noise and air quality levels. Exercise is also beneficial to human health and wellbeing, and has shown to reduce costs in the health care industry [4].

2. Background

Herlihy [5] details the invention and evolution of the bicycle. The first bicycles had no transmission, and were operated by a single ratio determined by the fulcrum of a pedal arm relative to the powered wheel diameter. In order to better negotiate varied terrain, various types of variable ratio transmissions were developed.

One early bicycle transmission was a hub type that uses multiple gears enclosed in the rear wheel hub housing. A first patent for a two-speed hub-transmission type was invented in 1895. Initial rear hub transmissions were limited to two or three gear ratios, and the number has increased to the present day fourteen in the Rohloff Speedhub 500/14[1]. Hub transmissions are most commonly used in flat terrain urban conditions due to their limited number of ratios, and fairly high weight. For example, according to the manufacturers published information[2], the Rohloff Speedhub 500/14 weighs 1.82 kg.

The first derailleur type transmission was invented in 1905. In a derailleur transmission a loop drive chain connects the front and rear sprockets, and provides means to move the chain between two or more adjacent sprockets located on either the front or the back of the bicycle. Derailleur transmissions include up to three adjacent front sprockets (or chainrings) rotationally engaged to the bicycle pedals, and up to eleven adjacent rear sprockets (or cassette) rotationally engaged to the rear wheel. In such a configuration the transmission will offer 33 different rider selectable sprocket combinations or ratios. To aid the rider in shifting gears, an index shifter was introduced in 1985. This system moves the drive chain the precise distance between adjacent sprockets. In 2009 an electronic actuator was incorporated in the first commercially available index shift derailleur transmission[3].

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1 http://www.rohloff.de/en/technology/speedhub/technics/index.html.
2 http://www.rohloff.de/en/products/speedhub/.
3 http://www.gizmag.com/shimano-dura-ace-di2-electronic-shift/11407/.

http://dx.doi.org/10.1016/j.susmat.2014.10.002
2214-9937/

The derailleur type is perhaps the most common bicycle drive in contemporary use. Unfortunately, such drives have disadvantages, including a relatively high mechanical complexity, weight, and unreliability. A derailleur is a fairly sensitive mechanism, requiring precise adjustment, and damage or misalignment may occur as the derailleurs are exposed to the weather and vulnerable should the bicycle fall over. Misalignment may cause the chain to become misplaced from the drive system and jam other moving parts of the bicycle, therefore causing the speed or direction of the bicycle to be abruptly altered. The steps between the user-selected ratios in derailleur drives are often ill suited for the given circumstances of terrain and available input power. Additionally, the variety of ratios offered by a combination of multiple front and rear sprockets may be confusing to all but the most experienced riders, requiring much trial and error to select the most suitable ratio. While a given drive using both front and rear derailleurs may provide up to 33 user-selectable combinations, all such combinations will not produce a substantially different ratio than the others. Therefore, the number of distinct gear ratios is typically around 70% of possible gear ratios, and the number of easily usable distinct gear ratios is typically around 50% of possible gear ratios [6]. Therefore all but the most experienced bicyclists will find the selection of the proper ratio from the multiple front and rear sprockets to be confusing, and result in poor ratio selections and waste of human energy. It will be finally noted that no known existing bicycle drives are capable of collecting data as regards their use and function, e.g., as collecting data points in real time, such as to shift points, torque, and speed (RPM).

Attempts have been made to adapt CVT technology to lighter weight drives that would be appropriate for use in bicycles. The most common and perhaps simplest CVT transmission operates by engaging a first rotating cone-shaped element with a second rotating element, whereby the second element may be moved to engage with progressively larger or smaller diameters of the cone found in the infinitesimal cross sections along its length [7]. In order to provide engagement of the two respective elements at any selected position, sufficient friction is needed to overcome the torque between them. In order to provide such high levels of friction, considerable force must be applied normal to the curved contact points of the two elements. Typically such transmissions use elastohydrodynamic lubrication (EHL) to transfer power between the contacting elements. Under high force, the fluid undergoes a phase change from liquid to solid and thereby provides a traction patch [8]. To provide such force, a fairly heavy and robust structure is required to hold the two elements. A variant of this common CVT type has been under development by Fallbrook Technologies marketed under the name of NuVinci Continuously Variable Transmission[4]. This technology uses a series of radially disposed spheres that may be tilted on their axis, and takes advantage of EHL for power transfer. The EHL contact patch allows a small percentage of slippage that lowers the transmissions input–output efficiency. The manufacturer has not published results of efficiency testing. According to the manufacturer's published information the NuVinci model N360 weighs 2.45 kg. By contrast, according to the manufacturer, the weight of the Shimano SLX derailleur system (front and rear derailleurs, shifters, freehub, and cassette) is 1.3 kg.[5] Weight is an important factor in a human powered vehicle such as a bicycle, as any advantage gained in the drive system efficiency is overcome by the mass needing to be carried. A typical racing bicycle in total weighs 7 kg.[6] It became apparent to the authors that this common CVT transmission type would not readily scale to work in applications requiring small size and low weight.

Another solution for CVT transmissions has been the subject of some investigation by prior inventors. This solution involves providing a sprocket having the ability to change its effective diameter. Several difficulties arise with this approach. First, if a loop chain is engaged with the variable diameter sprocket, the increment of the engagement of chain and sprocket limits the steps between ratios, and the seamless transition from one ratio to the next is unattainable. A similar condition is present when using a notched belt engaged with a mating sprocket. Second, the means to coordinate the radial displacement of the sprocket segments has led to development of overly complex, heavy, and high-maintenance mechanisms.

In summary, existing bicycle transmissions fail to provide the full benefits of CVT technology. Derailleur or hub gear transmissions do not provide continuous drive train ratios, and the one bicycle CVT currently marketed loses efficiency due to slippage and increased weight.

3. eDrive design and development

3.1. Design fabrication

The design, research, and development of eDrive sprung out of the understanding of the limitations of existing bicycle transmissions. The design objectives were determined to provide a continuously variable transmission that has a relatively low initial cost and ease of maintenance, a simple, intuitive, and highly controllable drive mechanism, seamless steps between drive ratios, that provides intuitive ease of use, is relatively lightweight, and can be fitted or retrofitted into common bicycle frames and formats. In addition, many bicyclists seek to obtain information about a ride, such as altitude, inclination, temperature, distance, speed, torque, gear ratio, heart rate, cadence, and other inputs. Therefore, eDrive was designed to cooperate with an onboard computer, wirelessly communicate with external devices, and extend the range of data collection. By combining these features, eDrive promises to provide the efficiency, ease of use, and extended functionality to significantly augment the use of bicycles, enabling them to play a more significant role in sustainable urban transportation. If bicycle use were to increase, a number of benefits would be obtained, such as reduced traffic congestion, quieter streets, less energy use and pollution, and improved human health.

Fig. 1 illustrates one embodiment of eDrive fitted on the back wheel of a bicycle. It will be seen that the primary components of eDrive consist of a computer, shifter, and drive assembly. Each of these components is depicted as a separate element. However, a number of other variations could exist. For example the computer and shifter could be combined into a single device, or the shifter could be incorporated in a brake handle or handlebar grip, or the computer could be worn by the bicyclist. The functionality provided by the computer could be accomplished by a specialized device, or it could be accomplished by a specialized software application running on a portable device such as a small tablet computer or a smartphone. Fig. 1 shows the eDrive drive assembly. A transparent plastic housing is used to seal the drive assembly and protect it from the intrusion of dirt and water.

A number of drawbacks were found in the prior attempts in using a variable diameter sprocket; however, it also seemed possible to the authors that these limitations could be overcome with other design approaches. First, it became apparent that a belt might be superior to a chain as the means to engage with the variable diameter sprocket [9]. Belts can be made with carbon or aramid fiber reinforcement, and therefore have a higher strength-to-weight ratio than the typical steel chain. A belt can also be configured to have less friction than a chain, and to thereby increase drive train efficiency [10]. Further, a belt can be made with generally smooth surfaces, and therefore does not present an increment, such as is presented in the spacing of openings in a roller chain which are required to mate the teeth on a sprocket.

Therefore, design proceeded using a belt as the means to engage with the pulley segments contained in the variable diameter pulley. However, the challenge in this approach was in how to provide sufficient sliding resistance between the belt and pulley segments that would result from the transfer of torque between the two elements. Inspiration came from a spring-loaded camming device (SLCD) — a quite

[4] http://www.fallbrooktech.com/cycling/faq.
[5] http://www.gramslightbikes.com/2013/07/shimano-slx-review.html.
[6] http://www.uci.ch.