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A Study of Electronically Controlled Actuation Mechanism for Belt-Driven CVTs in Gearless Two Wheelers

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ABSTRACT

A continuously variable transmission (CVT) is an automatic transmission that can change seamlessly through an indefinite number of effective gear ratios between maximum and minimum values. Most gearless scooters available in the market today, employ a variator based CVT mechanism to effect the changing of gears in them.

The main objective of this paper is to convert the actuating mechanism of this variator based design into a better electro-mechanical system. The aim is to address the obvious shortcomings of the design and provide suitable solutions in the new system. The idea is to make the control more electronic. In doing so, certain components such as the roller weights and the centrifugal clutch, which are perceived to reduce the power of the engine, are removed and replaced with a suitable motor controlled mechanism. Sensors are then used to continuously monitor various parameters like engine speed, wheel speed etc. while the actuating mechanism changes the gear ratio to keep these parameters within the optimum values. This mechanism consists of a linear actuator made up of a DC motor-powered rack and pinion which is linked to a first class lever system for force multiplication. This mechanism is used to force the cone halves of the driving shaft towards each other. The contra spring or torque spring would balance this force at the other end. The two opposing forces, i.e the spring force at the driven shaft and the actuating force at the driver, along with the fixed center distance between them, would allow for achieving an infinite number of accurately controllable gear ratios.

Keywords

Rack and pinion, D.C. motor, permanent magnets, belt clutching, clutch assembly, variator assembly.

1. INTRODUCTION

A continuously variable transmission (CVT) is an automatic transmission that can change seamlessly through an indefinite number of effective gear ratios between maximum and minimum values.

In the most common CVT system, two V-belt pulleys are split perpendicular to their axes of rotation, with a V-belt running between them. The gear ratio is changed by moving the two sheaves of one pulley closer together and, at the same time, the two sheaves of the other pulley farther apart. Due to the V-shaped cross section of the belt, it is pushed higher on one pulley and lower on the other. This changes the effective diameters of the pulleys, which in turn changes the overall gear ratio. The distance between the pulleys and the length of the belt remain constant. Hence, both sets of pulley halves must be moved, one towards each other and the other away, by the same amount simultaneously in order to maintain the proper amount of tension on the belt. The V-belt needs to be very stiff in the pulley's axial direction in order to make only short radial movements while sliding in and out of the pulleys. An example of Belt-driven CVT drive is shown in figure 1.

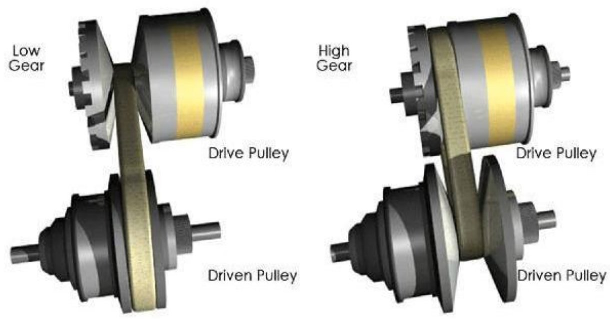

Figure 1- Variation of effective diameters and gear ration in a belt driven CVT drive.

A belt-driven design offers approximately 88% efficiency [10], which, while lower than that of a manual transmission, can be

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offset by lower production cost and by enabling the engineto run at its most efficient revolutions per minute(RPM) for a range of vehicle speeds. Thus a small car can strike a balance between fuel efficiency and cost of manufacture.

2. RELATED WORK

1. Shahnawaz Ahmed Khan, et al., created a mathematical model for controlling variation in transmission ratio of CVT. The objective was to implement the mathematical model with an electronic controlled CVT in a two wheeler engine for improved performance [1].
2. Jing Yuan developed belt clutching CVT drive instead of traditional centrifugal clutch. By using this clutch system, forty eight percentage mass reduction of driven clutch was achieved. In addition to cost saving, fast throttle response and better acceleration / deceleration was achieved. [2]
3. Sameh Badran, et al., made a study on push-belt CVT with concepts of ratio, slip and the rate of ratio change control. Accurate control of the CVT transmission is essential to achieve the intended fuel economy, ensure a good drivability and moreover maximize the efficiency of CVT. [3]
4. Yusuke Okimura et al., made a study which gives an insight into the acceleration characteristics if the clutch is removed and belt tension alone is used for clutch action. Certain experimentally-proven, simulation techniques are available for predicting the accelerating feel by adopting belt tension clutching, which can be fine-tuned to achieve the same acceleration characteristics as the conventional, centrifugal clutch based system. [4]
5. Kei-Lin Kuo conducted a study which focused on the maneuverability and safety of CVT equipped motor scooters by actively adjusting the gear ratio which could prevent accidents caused by wheel locking with engine braking getting engaged during an emergency stop. The study aimed to achieve these goals using a system which can be easily applied to a production vehicle, reducing development costs. [5]
6. Akama S., et al, conducted a study that dealt with torque control of a rear wheel of a motorcycle equipped with a rubber/aramid belt electronically-controlled continuous variable transmission where the primary sheave position was controlled by an electric motor. A method to calculate the required engine torque and required primary sheave position was thought of using the rear-wheel torque and engine rotational velocity which helped devise an effective algorithm for optimum traction control. [6]
7. MichinoriTakeuchi, et al, studied thecharacteristics of a mechanical CVT used in scooters at part-load conditions in order to develop a motorcycle with low fuel consumption. The research proposed equations representing the speed characteristics of the Mechanical CVT at with simulations of CVT driving cycles to estimate fuel consumption and dynamic behavior at par-load conditions. [7]
8. Abhijeet Sanchawat, et al, simulated and modelled the drivetrain of an ATV which used a CVT. A detailed mathematical model was reverse engineered from existing components and simulated to study the characteristic behavior of the transmission under various speeds and loads. A complete simulation was developed and the effect of flyweights and torsion springs on the performance of the CVT was quantified. [8]
9. Toshihiro Saito, et al, studied the effects of CVT pulleys on strength and transmission efficiency of metal Pushing V-belts taking into account effect of the fit clearance of the pulleys and their stiffness on friction force, effective diameter of the belt etc. It was found that when fit clearance is reduced, the transmission efficiency of the belt is increased and if it was found that if pulley stiffness was reduced transmission efficiency was also reduced. [9]
10. Michael A. Kluger et al, provide a detailed overview into the efficiencies of various types of CVT drives and materials as well as an analysis on the forces and mechanisms. The working principles of the same are glanced upon and the knowledge is instrumental in deciding upon the drivetrain type different operating conditions. [10]
11. Nilabh Srivastava et al, reviewed the state-of-the-art research on dynamic modeling and control of friction-limited continuously variable transmissions. Basic concepts, mathematical models and computational schemes as well as challenges and critical issues for future research on modeling and control of such CVTs were discussed in a detailed overview. [11]

3. VARIATOR BASED CVT MECHANISM

Most gearless scooters available in the market today, employ a variator based mechanism to effect the changing of gears in them. In this system, both front and rear pulleys are an assembly of moving plates. At low engine speeds, the plates of the front pulley are pushed apart by the tension of the belt as it forces itself between the plates. At the same time, the plates in the rear pulley are pushed together by the spring beneath the automatic clutch. Behind the moving plate of the front pulley, there exist weighted rollers. These rollers are thrown towards the outer edge of the variator by centrifugal force, as the speed of the engine/variator increases.

When the rollers move towards the outer edge of the variator, the inside plate is forced together towards the outer plate and this moves the drive belt towards the outside of the pulley. This effectively makes the diameter of the front pulley larger. As the belt moves out on the front pulley, the tension in the belt is increased, which overcomes the spring pressure holding the two plates together in the rear pulley. The belt moves towards the center of the rear pulley, which effectively makes the diameter of the rear pulley smaller. In this way, the ratio between the two pulleys, and consequently the gear ratio of the drive is changed. Figure 1 represents how the gearing ratios change as the road speed/engine rpm changes.

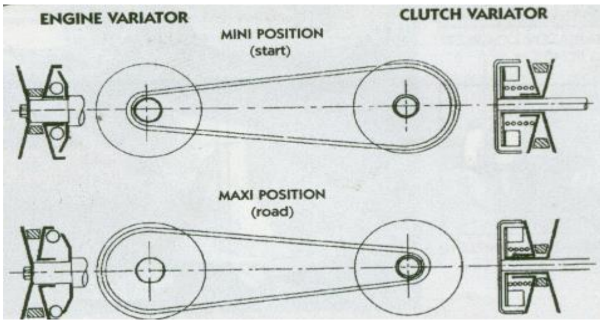

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Figure 2- Schematic of the variator behavior at different conditions.

Front Pulley: The front pulley, or variator, is where the rollers and ramp plate are located. As the engine speed increases, centrifugal force pushes the roller weights outward onto the ramp-plates surface. This causes the sliding variator to move toward the outer fixed pulley half. As the variator slides closer to the front pulley, it applies pressure to the belt forcing it up to a higher effective diameter.

Rear Pulley: The rear pulley has a large and powerful spring, known as the contra spring holding the halves together. The halves of the rear pulley get placed under pressure by the rising tension in the belt due to change in diameter at the front pulley. This pushes them apart till the tension is balanced by the spring force. There are angled grooves that the pulley travels on. As torque is applied, this limits the belt from travelling in too quickly and adversely affecting the gearing ratio.

Clutch Assembly:In order to achieve idling of the engine, a centrifugal clutch assembly is used. This is achieved by the clutch plates moving radially outward due to centrifugal force if the engine goes beyond idling speed. The friction surfaces of the clutch plates then come in contact with the clutch bell, causing it to rotate along with it, which in turn spin the wheel.

4. LIMITATIONS OF THE VARIATOR BASED DESIGN

In the variator based design, movement of the cone halves is based on the principle of centrifugal force. To achieve a suitable gear ratio as well as transfer sufficient torque, centrifugal force, belt tension and spring force should be finely balanced. This is hard to achieve. Also, the mechanism works on centrifugal action provided by the rotating crankshaft. Thus, a part of the engine's power is continuously being used to power the CVT reducing the efficiency of the drive.

Modification and customization of the existing system is not convenient. Customization of the system for higher acceleration or a greater top speed requires the system to be dismantled, modified and reassembled back again. Greater acceleration at the expense of top speed may be achieved by incorporating heavier roller weights in the system and greater top speed can be achieved by use of lighter roller weights.

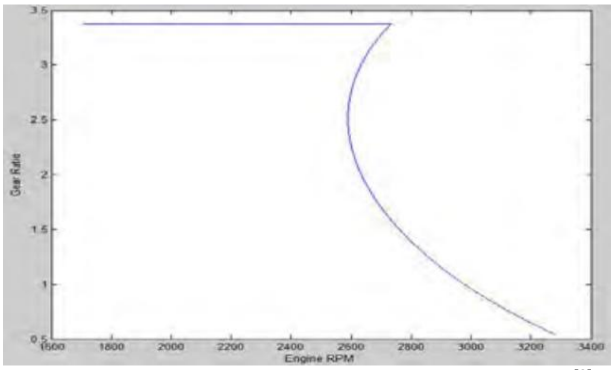

Figure 3- Variation of gear ratio with engine speed. [8]

In the current system the CVT operates over a very limited range of engine speeds which is evident from the example curve in figure 3 where the CVT operates between 2500-3500 rpm. This is done to provide the necessary starting torque. At higher engine speeds the CVT remains ineffective. This doesn't ensure maximum utilization of the CVT principle.

The variator based design is incapable of responding to varying load conditions since the only control variable is engine speed. As a result, the CVT characteristic curve is a constant in cases where higher torque is required, or at higher road humps, or when getting out of a pit / ditch, the torque available at the wheel is found to be insufficient.

5. PROPOSED DESIGN

The main objective of this paper was to convert the existing design of a gearless two wheeler's CVT into an electro-mechanical design. The aim was to address the obvious shortcomings of the earlier design and provide suitable solutions for these in the new system.

The core idea of the design is to make the control more electronic. This is achieved by elimination of the dead weights and springs, which reduce the engine efficiency, and replace them with a suitable, motor controlled mechanism. Sensors are used to continuously monitor various parameters like engine speed, wheel speed, etc. while a motor changes the gear ratio to keep these parameters within the optimum values.

Instead of the variator mechanism on the driver shaft, a new mechanism was developed. A test rig was developed with an AC electric motor to simulate various engine loading conditions. The actuation mechanism was fixed at the driver end and consisted of a rack and pinon system powered by a DC motor. This motor spins a co-axial pinion with in turn mates with a rack. The linear motion of the rack is transferred to a bush on the driving shaft via a first class lever system with mechanical advantage of four. To make the design more compact the motor can be attached directly to the siding bush. An isometric view of this arrangement is shown in figure 4. However, in this case a more powerful motor will have to be used. The bush is free to move linearly over the driving shaft along its axis. In order to reduce friction due to relative motion of mating surfaces, the repulsive force of two magnets is used for the actuation of the cone halves. One such magnet is placed on the bush and the other is attached to the moveable cone half with the like poles facing each other. A sectional view of the front assembly is show in figure 5. When the motor runs, the rack moves linearly, pushing the bush on the driving shaft in the forward direction, towards the cone half. Due to the repulsive force between the magnets, the cone half also moves forward, hence providing the actuation and thus increasing the gear (or decreasing gear ratio).

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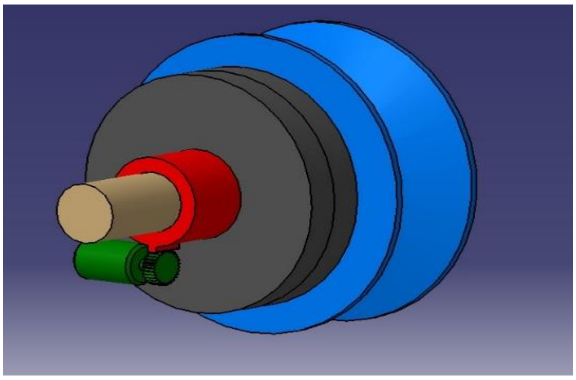

Figure 4- Isometric view of the proposed design

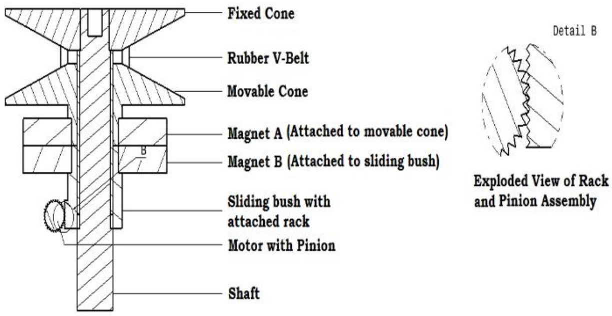

Figure 5-Sectional view of the driver shaft assembly with a magnified view of the rack and pinion

At the rear shaft, a spring with suitable stiffness is placed behind the cone halve. The stiffness of the spring is low enough such that the motor is able to produce enough torque so as to overcome the spring's restoring force. At the same time, the spring stiffness must be sufficient enough to overcome belt tension and raise the belt on the rear cone halves, when the motor is not actuating the front cone halves, thus restoring the highest gear ratio of the system.

The aforementioned motor is a 9 Volt D.C. gear motor with a speed of 40 revolutions per minute. This motor is controlled through an Arduino Mega micro controller. The micro controller can be programmed to read inputs from various sensors such as speed and load at the front and rear shafts in order to calculate the optimum gear ratio that has to be maintained for maximum efficiency via a preset algorithm. Also, different modes can be programmed into the micro controller for different performance characteristics such as higher acceleration, higher top speed or maximum fuel efficiency, thus providing a dynamic behavior of the CVT to respond to different riding styles.

The design eliminates the necessity of the centrifugal clutch and makes use of belt clutching. This is a technique where the belt tension alone is used to provide the functionality of a clutch.

6. RESULTS AND DISCUSSUION

The proposed design overcomes most of the problems that exist in a conventional variator based CVT mechanism as well as attempts to increase the overall powertrain efficiency. A prototype was modelled and from various tests the following conclusions can be made.

The self-locking nature of the rack and pinion means that the reaction force due to belt tension does not move the system back to the least resistance path. Hence the current gear ratio is maintained with minimum effort from the motor. It allows the motor to behave purely as a "positioning device" without having to continuously consume power to maintain a particular gear ratio.

The variator based design achieved actuation of the cone halves due to radially outward movement of the roller weights. This meant that only a component of the centrifugal force, which in effect is consumed from the engine, is used for linear actuation of the cone halves while the rest is lost. Experimentally, it was found that approximately 50N of centrifugal force was required to begin actuation at the lowest radius of the front pulley while the design proposed in this paper requires only around 25N of force for the actuation of the cone halves under the same conditions. This difference can be attributed to the fact that the proposed design achieves actuation of cone halves due to a linear force applied along the axis of the driving shaft rather than centrifugal force which acts radially outward.

Due to elimination of various components such as roller weights and centrifugal clutch from the existing variator based CVT, the proposed design was able to achieve a weight reduction of upto 3 kg or about 20% with respect to the whole assembly. This translates to lower inertia of the entire system which ensures quicker response times.

With the centrifugal clutch removed, the clutching action is handled by the CVT drive itself. The belt is allowed to slip by moving the pulley halves apart at the front end, thereby reducing the tension in the belt. When power is to be transmitted, the cone halves are pushed together which increases the belt tension allowing sufficient torque to be transmitted.

As stated previously, the core idea was to make the actuation system more electronic, thus transforming the existing mechanical system into an electromechanical one. The electromechanical system will be easier to customize towards different riding styles by changing certain parameters in the microcontroller program. Also, an electromechanical CVT would be able to operate at all engine speeds thus optimizing the powertrain performance over a wide range of engine speeds. The mechanical system is static in the sense that it cannot respond to dynamic load conditions. However, an electromechanical system would be able to sense changes in loading conditions and accordingly vary the gear ratio so as to achieve ideal performance.

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