*National Conference in Mechanical Engineering Research and Postgraduate Studies (2nd NCMER 2010)*
*3-4 December 2010, Faculty of Mechanical Engineering, UMP Pekan, Kuantan, Pahang, Malaysia; pp. 804-813*
*ISBN: 978-967-0120-04-1; Editors: M.M. Rahman, M.Y. Taib, A.R. Ismail, A.R. Yusoff, and M.A.M. Romlay*

# A REVIEW ON CONTROL STRATEGY FOR ELECTRO-MECHANICAL RUBBER BELT CONTINUOUSLY VARIABLE TRANSMISSIONS (CVT)

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## ABSTRACT

Because of its significant advantages over other transmissions, including its simple construction, smooth operation, easy drivability, low cost, easy maintenance, the rubber V-belt continuously variable transmission (CVT) has been widely used in low-power vehicles such as snowmobiles and motorcycles. The works on control strategy for electro-mechanical have been published including in journal, conference as well workshop proceedings, standard, books and others. The current paper reviews the basic concepts of operating system CVTs, system of electro-mechanical rubber belt CVT, and related works. Challenges for future research on modeling and control strategy for electro-mechanical CVT are also discussed.

*Keywords:* Continuously variable transmission, rubber V-belt, control, electro-mechanical.

## INTRODUCTION

Today, The rubber V-belt continuously variable transmission (CVT) has been widely used in low-power vehicles such as snowmobiles and motorcycles because of its significant advantages over other transmissions, including its simple construction, smooth operation, easy drivability, low cost, easy maintenance, etc. A continuously variable transmission (CVT) offers a continuum of gear ratios between desired limits, which consequently enhances the fuel economy and dynamic performance of a vehicle by better matching the engine operating conditions to the variable driving scenarios (Srivastava and Haque, 2009). The characteristic of low transmission efficiency of the rubber V-belt CVT tends to be a major problem as it is used in electric motorcycles. The electric-powered motorcycles may mostly run in densely populated cities with frequent stops-and-goes. The essence of limited energy supply from batteries and especially low transmission efficiency has interested researchers in either improving the existing products or developing a class of new-type CVTs (Chen et al., 1998). CVTs allow the engine to operate near maximum power point by automatically varying speed, so theoretically, rubber V-belt CVTs have an economic efficiency advantage over other transmissions. However, rubber V-belt CVT are not perfect. CVTs makes the engine work at its minimum fuel consumption point at and maximum operation time, the fuel economy of the whole vehicle will not be good enough if the efficiency of the whole power train is low. So how to improve the efficiency of CVTs is one of the hottest topics in CVT research (Zhu et al., 2010). Therefore, improving the efficiency of CVTs has been of interest to researchers and engineers. T.F. Chen conducted an experiment to study the transmission efficiency of a rubber V-belt CVT (Chen et al., 1998; Chen and Sung, 2000; Chen et al., 2000). A power split high-efficiency CVT was developed by Mantriota (Mantriota, 2001a, 2001b, 2001c). A novel hybrid electric motorcycle transmission with low power loss was further implemented by K.B. Sheu (Sheu and Hsu, 2006). Karstens calculated maximum reachable efficiency of the CVT variator and the clamping that will occur (Karstens et al., 2006). Therefore, in this paper is organized as follows:

1. Operating principle of CVTs describes transmission mechanism of the V-belt CVT.
2. Electro-mechanical rubber belt of CVTs section describes CVT system that combining between mechanical, hydraulic, and electrical element.
3. CVT control strategy section describes the development of control strategies and its improvement.
4. Finally, the conclusion of our work is described in conclusion section.

## OPERATING PRINCIPLE OF CVTS

Transmission mechanism of the V-belt CVT is shown on Figure 1 Each of driver and driven pulley consists of a fixed and a movable pulley. The fixed pulleys are fixed on the shafts and the movable pulleys are able to move in the axial direction on the shafts. Continuously variable transmission can be achieved by control of the pulley axial distance between the fixed and the movable pulleys. If the movable pulley of the driver shaft is moved towards the fixed pulley, the V-belt is forced to be pushed in the radial outward direction, which causes the belt pitch diameter to increase. Since the belt length and the center distance between the shafts are fixed, the belt pitch diameter of the driven pulley decreases. Therefore, the speed ratio decreases in a continuous manner. Any desired speed ratio can be obtained by control of the pulley axial displacement. Since the pulley axial displacement is controlled by axial force on the driver and the driven pulleys, an accurate relationship between the speed ratio and the axial force is required to maintain an optimum driving condition. Also, the axial forces are directly related with the belt tension. If the belt tension and associated axial forces are kept only as high as necessary to prevent slip at all load levels, then an enormous improvement in belt life will result compared to tension set for maximum design power. Therefore, we can say that it is an integral part of the V-belt CVT design to obtain an accurate relationship between the axial force and torque load for given speed ratios.

The rubber V-belt CVT investigated at this point featuring a mechanical-type feedback control system is mainly used in motorcycles. The CVT shown in Figure 2 consists of a driving and a driven pulley joined by a rubber V-belt. Each pulley consists of a fixed flange and a movable flange that moves axially to result in speed-ratio change. The movable flange of the driving pulley is forced toward the fixed flange axially under the actuation of the centrifugal roller as the input speed increases.

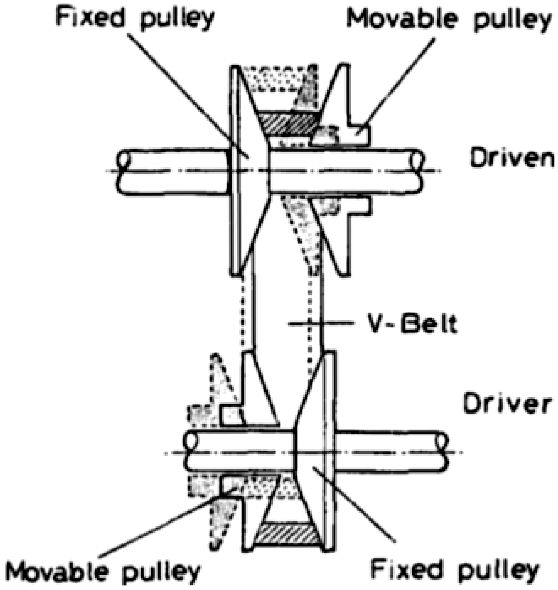


Figure 1: Principle of a V-belt CVT.

The movable flange of the driven pulley is equipped with a torque-controlled tensioning mechanism. This mechanism consists of a simple helical cam being attached to the fixed flange, a cam follower that is incorporated into the movable flange, and a compression coil spring which keeps the belt tension induced axial force and the force exerted by the helical cam in equilibrium. As the torque load increases, the belt tends to rotate the movable flange and force it to slide toward the fixed flange. This decreases the width of the pulley's groove and causes a slightly larger belt diameter, and then results in the rise of the belt tension which can force the movable flange of the driving pulley to slide away from the fixed flange and therefore create a smaller belt diameter. As the torque load increases, it will cause the elongation of the belt. Such elongation increases the belt tension which, in turn, enables the drive to transmit higher load without slippage. Section headings should be typed centered on the page and in capital letters only. The type, fonts and style above.

The CVT consists mainly of a primary pulley, driven pulley, and the rubber V-belt. The main components of the primary pulley are fixed and movable sheaves, a set of flyweights, and a compression spring. The driven pulley includes fixed and movable sheaves, spring-loaded in compression, as well as a torque sensing cam Figure 3 (Zhu et al., 2010). The input shaft of CVT is directly connected to the output axis of the engine. As the engine speed increases, flyweights installed on the primary pulley tend to swing open and push the movable flange inward toward the fixed flange. However, this movement is not possible until the axial force caused by flyweights is able to overcome the force resulted from the primary spring embedded in primary pulley. Once this occurs, these flyweights must also overcome the resisting force caused by side pressure between the belt and the sheaves as well as the spring forces in both the primary and the driven pulleys. As the primary pulley begins to move, the driven movable flange moves against fixed one due to the constant belt length. This is the process that shifts the system to a higher gear ratio (Zhu et al., 2010).

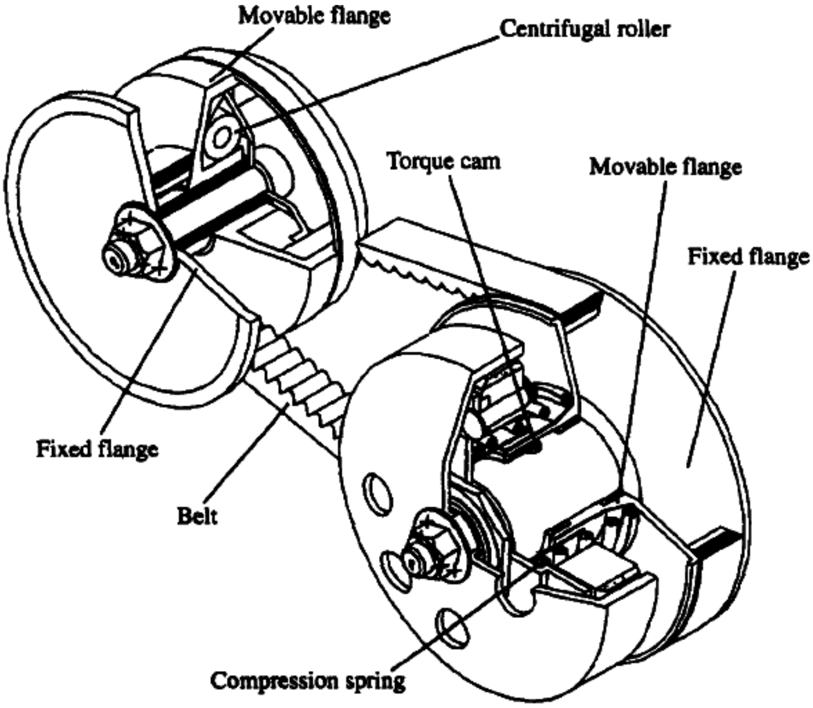
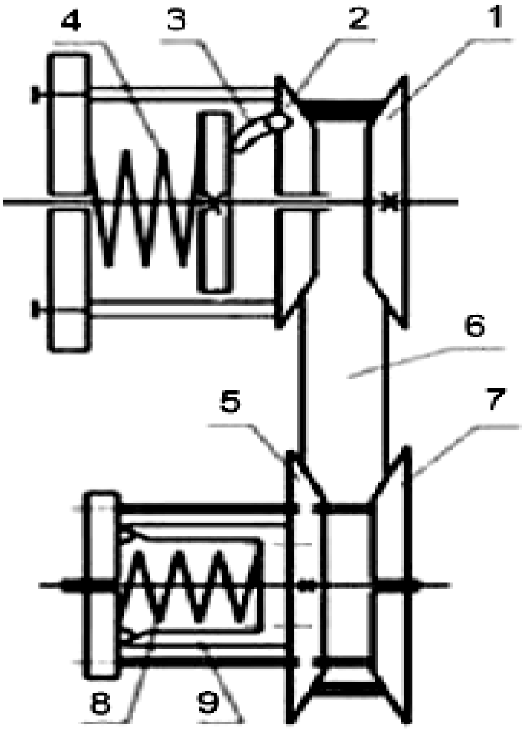


Figure 2: The main components of CVT.



1. fixed sheave of primary pulley; 2. movable sheave of primary pulley; 3. flyweight; 4. primary spring; 5. Fixed sheave of driven pulley; 6. V-belt; 7. movable sheave of driven pulley; 8. secondary spring; 9. torque cam

Figure 3: The main components of CVT.

## ELECTRO-MECHANICAL RUBBER BELT OF CVTS

Electro-mechanical CVT consists of two systems, there are mechanical linkage and electrical device as power source to operate mechanical linkage usually DC motor. Single input changing ratio means that there is a single power source to activate mechanical linkage. This power source should be able to activate both pulleys (primary and secondary pulley) to move axially.

Currently, CVT system is combining between mechanical, hydraulic, and electrical element to control the appropriate ratio. The macroscopic CVT behavior, relative to the engine and drive train, is governed by highly non-linear dynamics. Figure 4 Shows, the basic elements of a vehicle power train and clearly, the CVT is central in transmitting torque and power from the engine to the wheels. The classical controller such as Proportional, PD, PI, PID is not satisfied to overcome non-linear system (Guzzela, 1995).

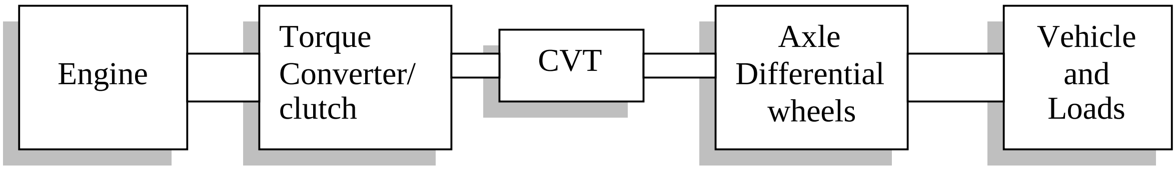


Figure 4: Basic element of vehicle power train

Generally, PID (Proportional, Integral and Derivative) controller has been the basis in the simple linear control systems. The PID controller is a well-known and well–established technique for various industrial control applications. This is mainly due to its simple design, straightforward parameters tuning, and robust performance. As actuators, DC servomotors are extensively used in many automatic controls, including drive for robotic manipulators, machine tools, rolling machines, photocopy machines, etc (Supriyo et al., 2006). The classical way to control CVT based cars is to use the information on gear-ratio or on the transmitted torque, which is then fed back to a PID-type controller. To design an effective PID controller, three gain parameters, namely, proportional gain, integral gain and derivative gain need to be specified properly. The conventional approach to determine the PID parameters is to study the mathematical model of the process and try to come up with a simple tuning law that provides a fixed set of gain parameters. One famous example of such approach is the Ziegler-Nichols method (Hwang, 1999). (Guzzela, 1995) reported that according to his experience, PID Type Controller is not very encouraging. Only using a gain-scheduled controller with typical 100 different gain points the required controller-performance could be achieve. This observation was the motivation for this work that has the goal to analyze the possible benefits of using a non-linear controller.

## CVT CONTROL STRATEGY

The control aspect of achieving a desired gear ratio profile by pulley actuation forces has also been an inevitable part of CVT research over the last two decades. The development of an optimum CVT control strategy is not an easy task owing to two partially opposite features that have to be satisfied: the reduction of fuel consumption and the requirement of appropriate drivability/acceleration performance (which is dependent on the torque capacity of the CVT system). An accurate and fast control of the rate of change of speed ratio is a prerequisite for meeting these goals. The advanced control strategy must implement an accurate model of transmission shifting dynamics in order to foresee the actual clamping forces needed to change the CVT speed ratio and the axial position of pulley sheaves. So, the challenges for an efficient CVT controller primarily are to increase the torque capacity of a CVT system, minimize belt slip losses, and maximize vehicle fuel economy and acceleration performance (Srivastava and Haque, 2009). Figure 5 shows, Optimal operating line (OOL) for minimum fuel consumption is shown on the engine characteristic map. The OOL for minimum fuel consumption can be obtained from the specific fuel consumption contours and iso-power curves. The optimal engine operation point is defined as the point where the optimal engine power curve intersects with the OOL. Minimum fuel consumption can be achieved by operating the engine at the optimal operation point by simultaneous TVO (throttle valve opening) and CVT ratio control, i.e. an integrated control (Kim and Kim, 2002). (Yasuoka et al., 1999) developed an integrated engine-CVT control algorithm to obtain the demanded drive torque for optimum fuel economy. The authors used the engine torque to compensate for the drive torque response delay caused by the CVT response lag. The authors calculated the target torque by assuming that the accelerator pedal travel represents the demanded drive torque and used the target gear ratio as the CVT ratio.

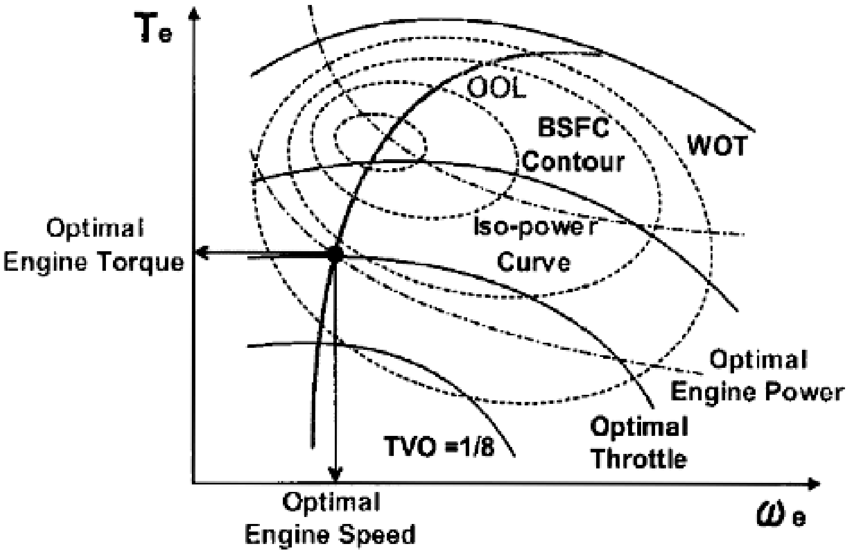


Figure 5: Typical operating characteristics of a CVT system.

Kim and Kim (2002) conducted experiments to conclude that the optimal engine speed compensation algorithm gives better engine operation around the OOL, compared to the optimal torque compensation algorithm, while showing nearly the same acceleration response and developed an integrated engine-CVT control algorithm by considering the powertrain loss and inertia torque due to CVT ratio change during transient states. In order to surveyed the basic shift control strategies of a CVT system for a vehicle which is already launched and operating in forward driving conditions (Liu and Paden, 1997) and (Pfiffner and Guzzella, 2001) categorized shift control strategies into three broad philosophies: ‘‘Speed envelope” strategy where the desired operating area of the CVT system is formed by two curves in the engine speed versus vehicle speed plane, as shown in Figure 6(a). The improvements in the fuel economy of a vehicle are realized by simply choosing a relatively low desired engine speed at cruising conditions; as shown in Figure 6(b) ‘‘Single track” strategy where the engine torque is brought as quickly as possible to the ‘quasi-static’ peak efficiency curve X. Concurrently, the gear ratio is adjusted to correspond to the proposed final steady state operating point; as shown in Figure 6(c) ‘‘Off-the-beaten track” strategy where two or more trajectories that represent different driving modes (the economy and the performance mode) are used to continuously adjust the gear ratio to reach the final steady-state operating point based on varying throttle input conditions (Pfiffner and Guzzella, 2001).

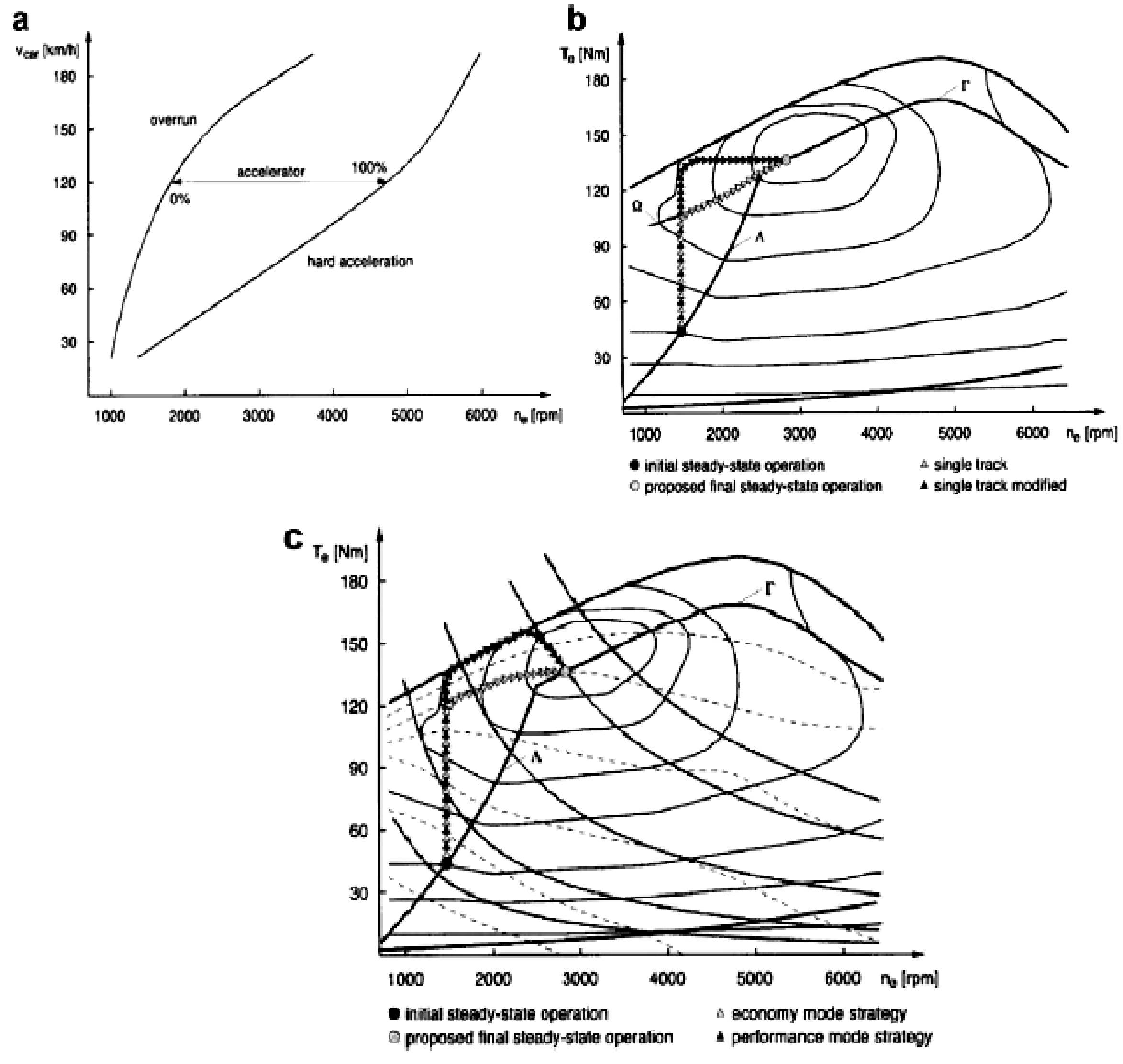


Figure 6: CVT control strategies: (a) speed envelope strategy; (b) single track strategy; (c) off the beaten track strategy.

Kim et al. (2000) suggested a fuzzy logic based ratio control algorithm for the metal belt CVT system considering the on–off characteristics of the ratio control valve and the nonlinear characteristics of CVT dynamics. Experimental results showed that a desired speed ratio could be achieved at steady state by fuzzy logic in spite of the fluctuating primary pressure. In addition, it was found that faster response and better robustness characteristics could be obtained by fuzzy logic control than with a standard PID control. (Ryu et al., 2005) developed a model based control algorithm for the pressure-control type CVT using the steady state characteristics of the ratio control valve. In a pressure-control CVT system, the desired speed ratio is obtained by controlling the primary actuator pressure. The authors proposed that linear control algorithms such as PID type control could be used for the pressure-control type CVT whereas nonlinear or adaptive control logic should be implemented for the flow-control type CVT. Further, other interesting CVT modeling and control strategies proposed in the literature include (Pfiffner et al., 2002), (Frank et al., 2002), (Laan et al., 2004), (Sorge, 2007), (Tani et al., 2007), (Kong and Parker, 2008), etc.

## CONCLUSION

Review on control strategy for electro-mechanical rubber belt continuously variable transmissions (CVT) has been discussed; the literature reviewed suggested that there is considerable disparity in the type of CVT models that have been used for control development. A continuously variable transmission is a promising automotive transmission technology that can provide higher fuel economy, reduced emissions, and better vehicle performance. Further, new research should be investigated in the context of CVT design and configuration.

## ACKNOWLEDGEMENT

The authors would like to thank University Malaysia Pahang (UMP) for providing the International Postgraduate Student and the financial support.

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