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A REVIEW ON CONTINUOUSLY VARIABLE TRANSMISSIONS CONTROL

Da Wen Ge, Sugeng Ariyono and Daw Thet Thet Mon

Faculty of Mechanical Engineering, Universiti Malaysia Pahang,
26300 UMP, Kuantan, Pahang, Malaysia;
Phone: +6012-3456789, Fax: +609-87654321
E-mail: dqpidwg@gmail.com

ABSTRACT

Over the last two decades, significant research effort has been directed towards developing vehicle transmissions that reduce the energy consumption of an automobile. Good ride performance is one of the most important key attribute of a passenger vehicle. One of the methods to achieve this is by using continuously variable transmission. 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. The current paper reviews the state-of-the-art research on control of friction-limited continuously variable transmissions. As CVT development continues, costs will be reduced further and the performance will continue to improve, which in turn make further development and application of the CVT technology desirable. Challenges and critical issues for future research for control of such CVTs are also discussed.

Keywords: CVT, control , belt , chian , continuously variable transmission

INTRODUCTION

With growing socioeconomic and environmental concern, automobile energy consumption has become a key element in the current debate on global warming. Over the past few decades, vehicle fuel economy plays a crucial role in determining the emission of greenhouse gases from an automobile. There are three fundamental ways to reduce greenhouse gas emissions from the transportation sector [1]: (a) increase the energy efficiency of transportation vehicles, (b) substitute energy sources that are low in carbon for carbon-intensive sources (i.e. the use of alternative fuel technologies), and (c) reduce transportation activity. With tremendous growth in consumerism and urbanization, there is little scope for emissions reduction to occur through a decrease in the amount of vehicle use.

In order to achieve lower emissions and better performance, it is necessary to capture and understand the detailed dynamic interactions in a CVT system so that efficient controllers could be designed to overcome the existing losses and enhance the fuel economy of a vehicle. There are many kinds of CVTs, each having their own characteristics, e.g. Spherical CVT [2], Hydrostatic CVT [3,4], E-CVT [5,6], Toroidal CVT [7–9], Power-split CVT [10–12], Belt CVT, Chain CVT, Ball-type toroidal CVT [13], Milner CVT [14], etc. However, belt and chain types are the most commonly used CVTs, among all, in automotive applications. Thus, this paper reviews the state-of-the-art research, in the context of controls, of belt and chain CVTs for achieving the targets of increased fuel economy and enhanced vehicle performance.

The basic configuration of a CVT comprises two variable diameter pulleys kept at a fixed distance apart and connected by a power-transmitting device like belt or chain. The pulley on the engine side is called the driver pulley and the one on the final drive side is called the driven pulley. Figure 1 and Figure 2 depict the basic layout of a metal V-belt CVT and a chain CVT[15,16]. In a metal V-belt CVT, torque is transmitted from the driver to the driven pulley by the pushing action of belt elements. Since there is friction between bands and belt elements, the bands, like flat rubber belts, also participate in torque transmission. Hence, there is a combined push–pull action in the belt that enables torque transmission in a metal V-belt CVT system.

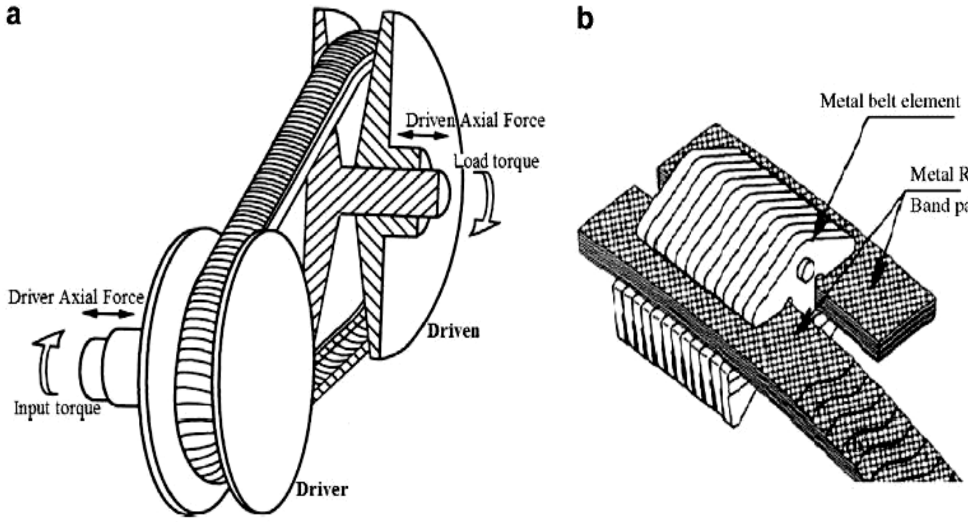

Figure1: Metal V-belt CVT drive (a) basic configuration (b) belt structure

In a chain CVT system, the plates and rocker pins, as depicted in Fig. 2b, transmit tractive power from the driver pulley to the driven pulley. Unlike a belt CVT, the contact forces between the chain and the pulleys are discretely distributed in a chain CVT drive. This leads to impacts as the chain links enter and leave the pulley groove. Hence, excitation mechanisms exist, which are strongly connected to the polygonal action of chain links. This causes vibrations in the entire chain CVT system, which further affects its dynamic performance. Both belt and chain CVT systems fall into the category of friction-limited drives as their dynamic performance and torque capacity rely significantly on the friction characteristic of the contact patch between the belt/chain and the pulley.

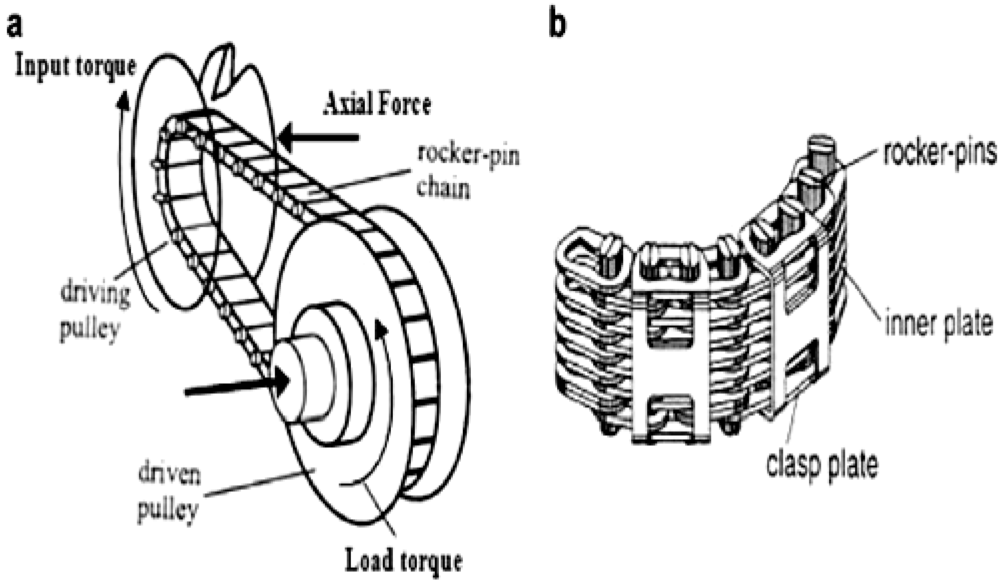

Figure 2: (a) Chain CVT drive; (b) Chain Structures

BACKGROUND AND BRIEF HISTORY

Leonardo de vinci sketched his idea of CVT in the year 1490.In automotive applications , the history of CVTs has begun in the early era of car development, and certainly in the same period of conventional automatics. In early 1930s, General Motors had developed a fully toroidal CVT and conducted extensive testing before eventually deciding to impement a conventional stepped-gear automatic due to cost concerns. General motor Research reworkd on CVTs in the 1960s, but none ever saw their production. British manufacturer Austin used a CVT for several years in one of its smaller cars, but it was dropped due to its high cost, poor reliability, and inadequate torque transmission [17]. Many CVTs in the early stage used a simple rubber band and come system,like the one developed by a Dutch firm, Daf, in 1958. However , the Daf's CVT could only handle a 0.6L engine, and severe problem with noise and rough stars eventually to hurt its reputation [18]. The electronmechanical CVT based on metal belt is not yet available in the market, but in early 90's electromechanical CVT based on dry hybird rubber belt has been applied for motor cycle [19]. Now ,almost all CVTs in the market use the van Doorne company's steel push belt as the transmission element. This steel pushing belt was first introduced in 1987.

Advantages and Benfits

The clunking sound of a shifting transmission is familiar to all drivers. By contrast, a CVT is perfectly smooth and naturally changes its ratio discretely such that the driver or passenger feels only steady acceleration. Theoretically, a CVT would cause less engine fatigue and would produce a more reliable transmission, as the harshness of shifts and discrete gears force the engine to run at a less than optimal speed [20]. CVTs offer improved efficiency and performance. Table I shows the power efficiency of a typical five speeds automatic, which is the percentage of engine power transmitted through the transmission. This yields an average efficiency of 86%, compared with typical manual transmission with 97% efficiency [21]. By comparison, Table II shows the efficiency range for several CVT designs.

Table 1: Efficiency versus gear ratio for automatic transmission [21].

Gear	**Efficiency Range**
1	60~85%
2	60~90%
3	85~95%
4	90~95%
5	85~94%

Table 2 : Efficiency of various CVT designs [21,22,23]

CVT Mechanism	**Efficiency Range**
Rubber belts	90~95%
Steel belts	90~97%
Toroidal traction	70~94%
Nutating traction	75~96%
Variable geometry	85~93%

These CVTs offer improved efficiency over conventional automatic transmission, and their efficiency depends less on driving habit than manual transmission. Since CVT allows an engine to run at its most efficient point virtually independent of the vehicle speed, a CVT equipped vehicle yields fuel economy benefits when compared with a conventional transmission. Testing by ZF Getrie be GmbH for U.S. Environmental Protection Agency City and Highway Cycles several years ago found that the CVT uses at least 10% less fuel than a 4 speed automatic transmission. The CVT was more than one second faster in 0~100Km/h acceleration tests than that of manual transmission [24].

Challenges and Limitations

The progress in CVT development has been slowly for a variety of reasons , with much of the delay in its development can be attributed to the lack of demand, while the conventional manual and automatic transmission have long offered sufficient performance and fuel economy . In addition, this problem is also possibly influenced by unsuccessful efforts to develop a CVT that can match the torque capacity, efficiency, size, weight, and manufacturing cost of step-ratio transmission [25]. One of the major complaints with previous CVTs is the slippage in drive belt or rollers. This is caused by the lack of discrete gear teeth, which form a rigid mechanical connection between two gears; friction drivers are inherently prone toslip, especially at high torque. For many years , the simple solution to this problem has been by limiting the usage of CVTs only in cars with relatively low torque engine . Another solution is by employing a torque converter , but this reduces the CVT's efficiency[17].

With the improvements in manufacturing technique, technology material processing , metallurgy , advance electronic control and advance engineering , CVTs can be applied in cars with high torque engine. In the need of a CVT to operate at the optimal transmission ratio at any speed, the selection of the ratio has to be addressed. Manual transmissions have manual controls, where the desired gear ratio totally depends on the driver to shift it and automatic transmissions have relatively simple shifting algorithms between three to five gears. However , CVTs require a more complex algorithm to accommodate an infinite division of speed and transmission ratios.

New CVT Research

Until 1997,CVT research has been focused on the basic issues of drive belt design and power transmission. Now , as belts developed and produced by Van Doome's Transmissie (VDT) and other companies are better and reliable , the CVT becomes sufficiently efficient. The research is now focused primarily on control and implementation of CVT. CVT control has recently come to the forefront of research. Although mechanically efficient CVT can be designed , control algorithm is needed for optional performance. Optimal CVT performance demands integrated control , such as the system developed by Nissan to obtain the demand drive torque with optimum fuel economy [26]. The control system determines the desired CVT ratio based on a target torque, vehicle speed, and desired fuel economy. Honda has also developed an integrated control algorithm for its CVTs, considering not only the engine's thermal efficiency but also work loss from drive train accessories and the transmission itself. Testing of Honda's algorithm with a prototype vehicle resulted in one percent fuel economy increase compared with a conventional algorithm. Although it is not a significant increase, Honda claimed that its algorithm is fundamental, and thus will becomes "one of the basic technologies for the next generation's power plant control"[27].

TYPE OF CVT CONTROL

CVT Ratio Control

CVT control has recently come to the forefront of research and there has been a substantial amount of research publications related to CVT ratio control [28,29,30]. In almost every publications ,the authors present well developed control algorithms to achieve the desired ratio, where the desired ratio is usually chosen to improve fuel efficiency and performance .The fuel efficiency target ratio is fairly straightforward and well-defined , while the 'performance' mode is usually some arbitrary function commanding a relatively higher engine speed for all throttle inputs [30] reported a study of drivetrain parameters for an automatic transmission-equipped vehicle. They developed the relationship between engine powers with the throttle pedal. They found that the throttle position is directly proportional to the desired engine power. This result may or may not appear obvious , given that other drivetrain paramenters considered include vehicle speed , vehicle acceleration and drive and engine torques have not shown good correlation with the throttle input.

Other researchers involved in ratio control are [31]. They proposed a CVT controller involving four different types of control operations including static shift control , lock up control , shift ratio control , and line pressure control. Static shift control is a forward and reverse direction control according to the shift lever position change. Lock-up control determines the connection or release state of the torque converter on the basis of engine speed and throttle opening angle. In order to optimally maintain maximum fuel consuption and maximum power performance , shift ratio control determines the map data on the basis of throttle opening and vehicle speed. Line pressure control determines the effective line pressure between the primary pulley and the secondary pulley without belt slip for a given shift ratio.

CVT CONTROL STRATEGY

Although CVTs are currently in production, many control issues still need to be addressed. Generally CVT control strategy can be classified into two major topics-classical control and adnvance control.

Classical Control

PID (Proportional, Intergral and Derivative) controller has been the basis in 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. In the early development of metal pushing V-belt some researchers use PID to control CVT [32]. by using some information on the gear ratio or on the transmitted torque which is then fed back by the PID-type controller. According to [33] this approach is not encouraging, because the drivetrain is nonlinear system. They claimed that this approach would work by using a gain-scheduled controller with typically more than 80 different gain points. Later , they introduced linearization control approach to improve the drivetrain control simulation. The results showed that the proposed control scheme is robust and that the closed-loop performance remained acceptable despite the presence of disturbance, but their simulation was based on a wide open throttle opening (WTO) and there were some questions to be solved whwen the control schem was simulated at different throttle opening and in the presence of disturbances.

[34] had considered a powertrain incorporating a CVT and flywheel to be divided into a number of system layers with descending response time. Among these layers were the electronic circuits supplying control currents, solenoids controlling CVT

pulley pressures, the engine throttle valve, the CVT, the engine , and finally the vehicle. Hierarchical control was applied to each layer and the two PI controllers were used to regulate the pulley pressures by manipulating the currents to the solenoids [34]. In their experiments, a kick down acceleration that change the speed from 60 to 80km/h was performed, with and without flywheel.It was shown that the controller system performed satisfactorily in a test vehicle.

According to [35,36], decreasing the clamping forces in the variator greatly improves the efficiency of the CVT . However , lower clamping force increases the risk of excessive belt slip, which can damage the system. They introduced a method to measure and control slip in a CVT in order to minimize the clamping forces while preventing destructive slip of the belt . To ensure robustness of the system against torque peaks, a controller was designed with optimal load disturbance response. A synthesis method for robust PID controller design was applied to maximize the integral gain while making sure that the closed loop system remained stable. The implementation of this algorithm in a test vehicle has been studied. The method was based on a constrained optimization problem that maximized the integral gain of the PID controller while making sure that the maximum sensitivity was less than a specified value. Using the maximum sensitivity as the main design parameter , a trade-off can be made between load disturbance response and robustness with respect to model uncertainites. The resulting controller parameters of this optimization process can be obtained graphically for a PI controller [36].

The latest system using self adjusting PD was proposed by [37]. The self adjusting PD is not a pure PD but in combination with fuzzy controller . The simulation result indicated that the speed ratio controller has good control effect and produce reasonable match between engine torque and CVT ratio . It demonstrates that the simulation model established is acceptable and reasonable. This can offer a theoretical guide line to devise and develop a CVT system.

Adavance Control

An advance control strategy using LQI control theory in CVT was introduced by [38] They modified LQR control strategy by adding an integrator to each input. In their study the engine-CVT-load model was developed based on fuel optimization and vehicle dynamic was assumed linear. Relatively good result was obtained ; however , it was shown that the engine power should be included in the cost function.

Iintroduced fuzzy controller to keep engine speed at its target by regulating the ratio and changing the throttle opening [39] .The engine speed is improtant to be maintained at an optimal working condition according to the car's moving resistance. This can be achieved by using synthesized control. Since the characteristics of the engine and transmission vary with different conditions , it is very difficult to control the ratio and throttle opening to meet such demands. Fuzzy control strategy has been investigated to soleve this problem . The simulation results showed that the synthesized controller realized by fuzzy strategy can maintain the engine speed operating at the maximum efficiency point for any power demand level.

[40] introduced fuzzy-PID controller for engine equipped with CVT .The whole vehicle model including the engine, clutch,CVT and load , and dynamics model of CVT system was developed based on different stages of engaging clutch and studied through simulation, similar study has been carried out by other researchers. They found that a conventional proportional control strategy could not satifsfy the control demand for engaging clutch; hence they designed a fuzzy controller for the clutch control and applied self-adjusting PD for the ratio control . The simulation results indicated that the speed ratio controller has good control effect and implements reasonable match between engine and CVT. It demonstrates that the simulation model established is acceptable and reasonable, which can offer theoretical help to devise and develop CVT system.

[41] proposed a fuzzy controller to control a tractor equipped with CVT . In a traditional control system the optimum fuel economy or dynamic performance control rules only relect the tractor working state. On the other hand , the driver's demand is partially ignored in the control system; therefore the applications are limited. To solve this problem a rule based fuzzy inference of dirver's demand was proposed, with the aim of improving the tractor's dynamic performance under tarnsient operating conditions and fuel economy during steady state operating conditions. Using a fuzzy inference engine which is introduced to indicate the driver's demand for tractor dynamic performance based on the rate of change of the accelerator pedal, the tractor dynamic factor was obtained. According worked out by compromising between fuel economy and dynamic performance control rules. After the acceleration process finishes, the transition control rule is adopted to achieve a smooth transition from intelligent transient dynamic rule to the steady fuel economy rule. The simulation results showed that the intelligent control rule enables tractors to reach the optimum conprehensive pergformance . The works provided a new design method for developing an intelligent tractor equipped with CVT.

[42] studied an integrated powertrain and CVT controller to improve fuel consumption and emission . They used two different network controllers to control torque demand and engine speed demand. Measured engine speed is passed to the engine operating point optimiser, which is used to set the corresponding ideal engine torque which is the first torque demand. The second torque demand is the output of network controller 1.These two torque demand are used to drive the vehicle through CVT. The network controller 2 is used to control engine speed demand. By these two novelty network controllers, the vehicle exhaust emission and economic fuel consumption are improved compared with the existing diesel engine controller although these must be achieved without adversely affecting vehicle driveability.

Artificial neural networks (ANN), with their self-organising and learning ability, are now used as promising tools for such purpose. A neural network consists of neuron-like computing elements which are basically nonlinear. These nonlinear properties of neural networks allow the possibility of nonlinear mapping, and thus , ANN control can realise new nonlinear control scheme such an online ANN technique. A control system consisted of an outer loop using neural network and inner loop using PD controller will be implemented to the drivetrain system equipped with electromechanical CVT. Since the drivetrain and vehicle dynamic are highly non linear, ANN is a suitable control system due to its non-linear characteristic. To meet the research objective which is to design and develop an electromechanical dual acting CVT pulley controller for small size automotive application , intelligent and robust controllers are considered necessary .With this controller the engine RPM can kept at its desired speed by adjusting the CVT ratio. Adaptive ANN will act as expert driver to control and select proper CVT ratio.

Although a continuously variable transmission plays a crucial role in the plan to improve the fuel economy and dynamic performance of a vehicle, its complete potential has not been realized so far in a mass-production vehicle. The expected increase in fuel economy and acceleration performance has not been achieved in many cases. The control logic has not been accurate enough to deliver a desired shifting behavior. Since belt and chain type CVTs are the most commonly used drive transmissions, this paper reviews the state-of-the-art research that has been accomplished to understand the dynamics and control of such CVT systems. Further, the literature reviewed reveals significant opportunities of research that could be necessary to gain better insight into the dynamics of such CVT systems to maximize the dynamic performance and fuel economy of a CVT-equipped vehicle, design better/efficient controllers, identify loss mechanisms, and characterize operating regimes for maximum torque transmissibility or efficiency.

CONCLUSION

Further, new research frontiers should be investigated in the context of CVT design and configuration. Certain new configurations of CVT designs have been reported to achieve continuous variations in transmission ratio with lower losses, however, the range of applicability of such CVTs for high torque applications is yet to be analyzed/ verified. A continuously variable transmission is a promising automotive transmission technology that can provide higher fuel economy, reduced emissions, and better vehicle performance. The current paper not only addresses the state-of-the-art research accomplished towards understanding CVT dynamics and control, but also hopefully highlights the challenges/directions for future research, which could foster better understanding and designing of such systems and their controllers.

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