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THE ABILITY OF THE CONTINUOUSLY VARIABLE TRANSMISSION TO CONTROL THE ENGINE AT MAXIMUM POWER: LITERATURE REVIEW

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Abstract
Good ride performance is one of the most important key attributes of a passenger vehicle. One of the methods to achieve this is by using Continuously Variable Transmission (CVT). This is because a CVT can provide an almost infinite ratio within its limits smoothly and continuously. The flexibility of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities. New developments in gear reduction and manufacturing have led to ever more robust CVTs, allowing them to be applied in more diverse automotive applications. As CVT development continues, costs will be reduced further, and the performance will continue to improve, making further development and application of the CVT technology desirable. This cycle of improvement will offer CVT a solid foundation in the world's automotive infrastructure. This paper aims to provide some background and relevant information that is necessary for this study. Specifically, a brief description of CVT, advantages and their brief history is presented. This paper also evaluates the current state of CVT, investigate the technology frontline of drivetrain control and the development of CVT. The stepless transmission is able to maintain the engine running at its maximum power.

Keywords:
CVT Control;
Engine Power;
Mechatronic CVT;
Rubber Belt CVT;
Transmission Control Unit;

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INTRODUCTION

A Continuously Variable Transmission (CVT) is a transmission system that can change the transmission ratio stepless, resulting in an infinite number of effective transmission ratios between maximum to minimum values. The condition contrasts with other mechanical transmissions that only allow a few different discrete gear ratios to be selected. The flexibility of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities. With the advent of durable materials, advanced manufacturing systems, sophisticated electronic controls, and improved lubricants, CVT power train systems with innovative ratio shift control strategies have become more feasible. In addition, new developments in gear reduction and manufacturing have led to ever more robust CVTs, allowing them to be applied in more diverse automotive applications. As CVT development continues, costs be reduced further, and the performance will continue to improve, making further development and application of the CVT technology desirable. This cycle of improvement will offer CVT a solid foundation in the world's automotive infrastructure.

This chapter aims to provide some background and relevant information that is necessary for this study. Specifically, a brief description of CVT, advantages and their short history is presented. In addition, this chapter also evaluates the current state of CVT, investigate the technology frontline of drivetrain control and the development of CVT.

BRIEF HISTORY

Background

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 the early 1930s, General Motors had developed a fully toroidal CVT and conducted extensive testing before eventually deciding to implement a conventional stepped-gear automatic due to cost concerns. General Motor Research reworked 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 [1].

Many CVTs in the early stage used a simple rubber band and cone system, like the one developed by a Dutch firm, Daf, in 1958. However, the Daf's CVT could only handle a 0.6 L engine, and severe noise and rough problems eventually hurt its reputation [2]. In 1962, the Honda company introduced the first mass-production hydraulically operated CVT into the market with the Juno, a scooter with a 0.175 litre engine generating 8.8 kW. Honda continued manufacturing small motorcycles with the V-Matic in 1977. Until the end of 1996, this company has successfully developed a new generation CVT for the Civic series, the 1.6 litre economy car [3]. The electromechanical CVT based on metal belts that not yet available in the market. But the early 90's electromechanical CVT based on dry hybrid rubber belts were applied for motorcycles [4]. Almost all CVTs in the market use the van Doorne company's steel push belt as the transmission element.

Advantages and Benefits

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. Thus, theoretically, a CVT would cause less engine fatigue and produce a more reliable transmission, as the harshness of shifts and discrete gears force the engine to run at a less than optimal speed [5].

CVTs offer improved efficiency and performance. For example, Table 1 shows the power efficiency of a typical five-speed automatic, the percentage of engine power transmitted through the transmission. This yields an average efficiency of 86%, compared with a standard manual transmission with 97% efficiency [6]. By comparison, Table 2 shows the efficiency range for several CVT designs.

These CVTs offer improved efficiency over conventional automatic transmission, and their efficiency depends less on driving habits than the manual transmission. Since CVT allows an engine to run at its most efficient point virtually independent of the vehicle's speed, a CVT equipped vehicle yields fuel economy benefits compared with a conventional transmission [7]. Several years ago, testing by ZF Getriebe GmbH found that the CVT uses at least 10% less fuel than a 4-speed automatic transmission. In addition, the CVT was more than one second faster in 0-100 km/h acceleration tests than that of manual transmission [8].

Table 1. The efficiency versus gear ratio for automatic transmission [6]

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

Table 2. The efficiency of various CVT designs [7, 9, 10]

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

Challenges and Limitations

The progress in CVT development has been slow for various reasons, with much of the delay in its development being attributed to the lack of demand. In contrast, 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 [11].

One of the major complaints with previous CVTs is the slippage in drive belts or rollers. This is caused by the lack of discrete gear teeth, which form a rigid mechanical connection between two gears; friction drives are inherently prone to slip, especially at high torque. For many years, the simple solution to this problem has been limiting the usage of CVTs only in cars with relatively low torque engines. Another solution is by employing a torque converter, but this reduces the CVT's efficiency [1].

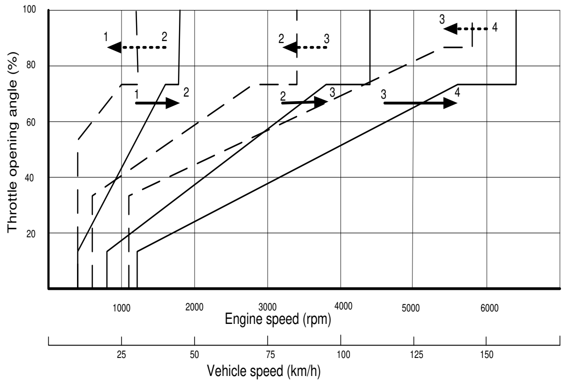

Figure 1. A typical automatic transmission shift pattern

With the improvements in manufacturing technique, technology material processing, metallurgy, advanced electronic control, and advanced engineering, CVTs can be applied in cars with high torque engines. In the need for 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 depends on the driver to shift it, and automatic transmissions have relatively simple-shifting algorithms, as shown in Figure 1, to accommodate 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 Doorne's Transmissie (VDT) and other companies are better and reliable, the CVT becomes sufficiently efficient. The research is now focused primarily on the control and implementation of CVT. CVT control has recently come to the forefront of research. Although mechanically efficient CVT can be designed, a 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 [12]. The control system determines the desired CVT ratio based on target torque, vehicle speed, and desired fuel economy. Honda has also developed an integrated control algorithm for its CVTs, considering the engine's thermal efficiency and work loss from drivetrain accessories and the transmission itself [13]. Testing Honda's algorithm with a prototype vehicle resulted in a 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 become one of the basic technologies for the next generation's power plant 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 [3, 14, 15, 16, 17]. In almost every publication, the author's present well-developed control algorithms to achieve the desired ratio, where the desired ratio is usually chosen to improve fuel efficiency and performance [18]. 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 [16]. Vahabzadeh and Linzell (1991) reported a study of drivetrain parameters for an automatic transmission-equipped vehicle [19]. 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. Other drivetrain parameters considered include vehicle speed, vehicle acceleration, and drive and engine torques, have not shown a good correlation with the throttle input.

Other researchers involved in ratio control are Hyun et al. (2005). 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 [20]. Static shift control is a forward and reverses direction control according to the shift lever position change. Lock-up control determines the connection or release state of the torque converter based on engine speed and throttle opening angle.

In order to optimally maintain maximum fuel consumption and maximum power performance, a shift ratio control determines the map data based on throttle opening and vehicle speed. Finally, 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 [21]. Generally, CVT control strategy can be classified into two major topics - classical control and advanced control.

Classical Control

PID (Proportional, Integral 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, specific parameters' tuning, and robust performance. In the early development of metal pushing V-belt, some researchers used PID to control CVT [9] by using the information on the gear-ratio or on the transmitted torque, which is then fed back by the PID–type controller. According to Guzzella and Schimd (1995), this approach is not encouraging because the drivetrain is a nonlinear system [22]. They claimed that this approach would work by using a gain-scheduled controller with typically more than 80 different gain points. Later, they introduced a 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 disturbance. Still, their simulation was based on a wide-open throttle opening (WTO), and there were some questions to be solved when the control scheme was simulated at different throttle openings and in the presence of disturbances.

The control strategy that ensures the engine speed is at the maximum engine power can only be achieved using CVT. This is because the power line saturates at the maximum engine power once the low gear reaches the maximum power. The intelligent controller designed and developed in this study is to implement this strategy.

With this control rule, two controller algorithms are proposed as an outer loop controller, namely PID and a neural network controller. The classical PID controller is used as a benchmark to study the performance of the proposed outer loop controller. Figure 2 shows the control scheme of PID classical control as the outer loop controller.

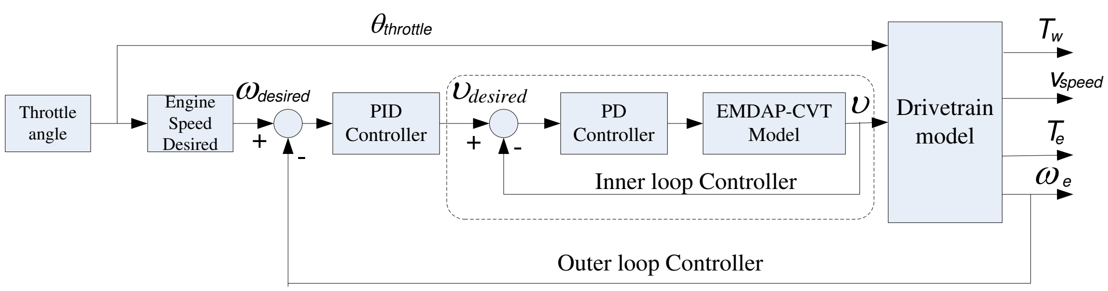

Figure 2. PID controller used for outer loop drivetrain control

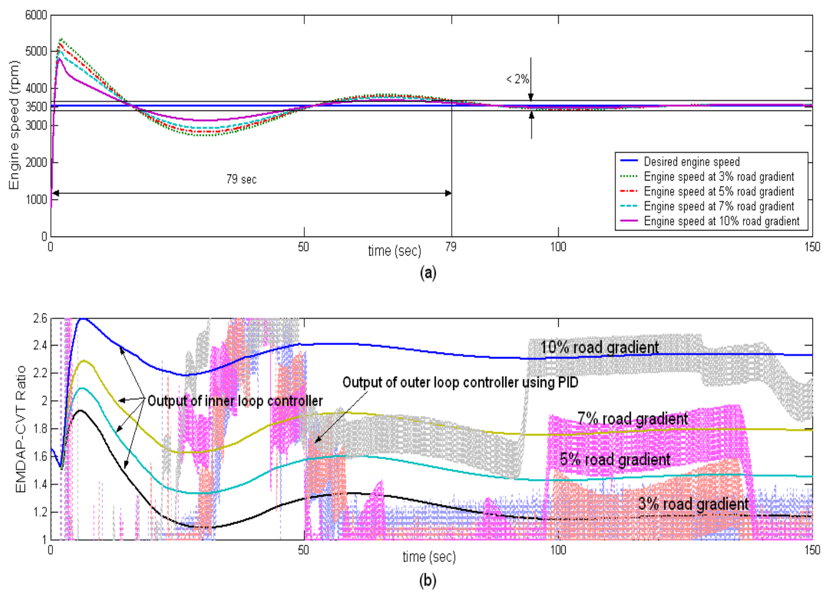

Figure 3. Performance of PID controller as outer loop controller at 80% throttle opening with road gradient variation

Figure 3 shows the simulation result of the outer loop controller using the PID control system. The throttle is set at 80%, and the road gradient is assumed to be 3, 5, 7, and 10% inclination. The time response is almost similar for the different road gradients, but the overshoot for every road gradient is slightly different, as shown in Figure 3(a). The CVT ratio response to keep the engine speed constant at its desired speed is presented in Figure 3(b), where the outputs of the outer controller are chattering.

Figure 3(b) shows that a high inclination road gradient will increase the CVT ratio. As the road gradient increases, the vehicle load will increase. Hence to overcome the increased load, the CVT ratio has to be increased. The vehicle load of 10% load gradient is higher than the vehicle load at 7% road gradient so that the transmission ratio at 10% road gradient is higher than the ratio at 7% road gradient.

Advanced Control

An advanced control strategy using an LQI control theory in CVT was introduced by [23]. They modified the 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 assumed linear vehicle dynamics. A relatively good result was obtained; however, it was shown that the engine power should be included in the cost function.

Hongyan et al. (1999) introduced a fuzzy controller to keep the engine speed at its target by regulating the ratio and changing the throttle opening [24]. The engine speed is important to maintain optimal working conditions according to the car's moving resistance. This can be achieved by using synthesized control. Since the engine and transmission characteristics vary with different conditions, it is very difficult to control the ratio and throttle opening to meet such demands. A fuzzy control strategy has been investigated to solve this problem. The simulation results showed that the synthesized controller realized by fuzzy strategy could maintain the engine speed operating at the maximum efficiency point for any power demand level.

Xudong et al. (2006) and Meilan et al. (2006) introduced a fuzzy-PID controller for engines equipped with CVT [25][26]. The whole vehicle model, including the engine, clutch, CVT and load, and the CVT system dynamics model, was developed based on different stages of engaging clutch and studied through simulation. A similar study has been carried out by other researchers [27]. They found that a conventional proportional control strategy could not satisfy the control demand for an 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 a good control effect and implements a reasonable match between engine and CVT. Moreover, it demonstrates that the simulation model established is acceptable and reasonable, which can offer theoretical help to devise and develop a CVT system.

Zhang et al. (2006) proposed a fuzzy controller to control a tractor equipped with CVT [28]. The optimum fuel economy or dynamic performance control rules only reflect the tractor's working state in a traditional control system. 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 driver's demand was proposed to improve the tractor's dynamic performance under transient 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 dynamic tractor performance based on the rate of change of the accelerator pedal, the tractor dynamic factor was obtained. The intelligent transient dynamic control rule can be worked out by compromising 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 comprehensive performance. Furthermore, the works provided a new design method for developing an intelligent tractor equipped with a continuously variable transmission.

Deacon et al. (1999) and Brace et al. (1999) studied an integrated powertrain and CVT controller to improve fuel consumption and emission [29, 30, 31]. They used two different network controllers to control torque demand and engine speed demand. Measured engine speed is passed to the engine operating point optimizer, which is used to set the corresponding ideal engine torque, the first torque demand. The second torque demand is the output of network controller 1. These two torque demands are used to drive the vehicle through CVT. Finally, network controller 2 is used to controlling engine speed demand. By these two novelty network controllers, the vehicle exhaust emission and economical fuel consumption are improved compared with the existing diesel engine controller, although these must be achieved without adversely affecting vehicle driveability.

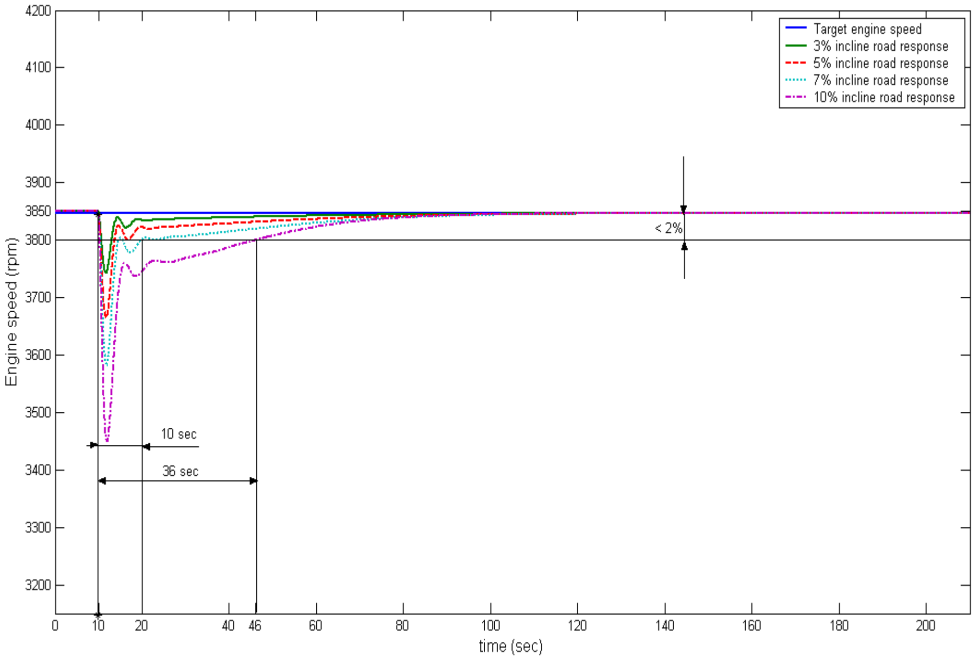

Figure 4. Performance of adaptive ANN controller for constant throttle and various road gradients

Figure 4 shows the simulation results of the effect of constant throttle opening with various road gradients. The road gradients are set to 3, 5, 7, and 10% and the throttle opening is set at 80%, where the target engine speed is 3526 rpm. Dorf and Bishop (2008) state that the settling time is defined as the time required for the system to settle within a 2% percent error of output steady-state amplitude [. The graph shows that the outer loop controller can reach the target engine speed of about 10 seconds except for the 10% road gradient. This may be due to the small engine's performance, which has the maximum torque of 43 Nm to overcome the external load caused by the 10% road gradient. Comparing with the PID controller for the outer loop control, as shown in Figure 3, the actual engine speed oscillates for all road gradients. Thus, the adaptive ANN is more suitable for this type of nonlinear system.

CONCLUSION

The development of CVT grows tremendously during recent years due to the advent of durable materials, advanced manufacturing systems, and sophisticated electronic controls. Publications concerning the development, history, advantages, benefits, limitations and current CVT research have been presented. Since the early development of the metal belt, a CVT controller has been based on classical control such as PID or some electronic control system. In line with the new development of control technology, some researchers develop the CVT control strategy to optimize the benefit of CVT. Intelligent control schemes such as fuzzy or neural networks combining with classical control such as PID have been studied.

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

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