Some control problems of continuously variable belt transmission

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Abstract. Control problems of continuously variable belt transmission used in passenger cars have been discussed. Pulley adjustment solutions and choice of control and feedback signals are the main topics. Intention to use such a transmission as part of a complex system containing mechanical energy storage caused that the adjustment transition time becomes crucial problem.

1. Introduction
Continuously variable belt transmission are increasingly used in conventional drivetrains of passenger cars. They allow to adjust the ratio of drivetrain to the currently prevailing traffic conditions kipping the operating point of the internal combustion engine in the area of greatest efficiency. In currently used solutions of gearboxes equipped with continuously variable transmissions produced by one of the leading manufacturers - JATCO company, high-pressure hydraulic system provides the necessary clamping force and adjusts the ratio of variator. Control of all functions of the system performs control valve assembly [6]. In this system, input pulley is responsible for establishing ratio and output pulley is responsible for generating clamping force causing belt tension caused in minimum level avoiding belt slipping during torque transmitting. This division is due to the fact of placing axial movement limiters of the movable conic wheel on the input pulley. To obtain maximum efficiency of continuously variable belt transmission and minimum power consumption by the hydraulic system, belt should be all the time tension to an extent no greater than is required for the safe transfer of the instantaneous torque without slipping. In the hybrid drivetrain, the secondary power source must be connected to the drive wheels by variable speed system for providing energy transfer to and from the drive wheels.

2. Discussed gearbox
Figure 1 shows a schematic of JATCO CVT7 gearbox used in Nissan Micra K12 - the gearbox was used as a basis for consideration of the application in a hybrid drive system. More details on the study of such a transmission and analysis of control valve assembly can be found in [1] and [2].
Figure 1. Mechanical scheme of JATCO CVT7 gearbox; 1 – oil pump; 2 – torque converter; 3 – pushbelt; 4 – Ravigneaux planetary transmission; 5 – final drive; 6 – control valve assembly; P1 – pressure in primary (input) pulley actuator; P2 - pressure in secondary (output) pulley actuator.

The diagram portion of control valve assembly in part responsible for the development of the pressure in the pulleys actuators and the preparation of lubricating oil is shown in Figure 2.

Figure 2. Portion of hydraulic scheme of TOSOK control valve assembly in part responsible for generating control pressures for the CVT and controlling lube oil pressure (part no 6 in figure 1); 1, 4, 7 – spool valves; EV – electrovalves; A – receivers responsible for pushbelt lubrication and oil cooling.
3. Disturbance signals
Control systems with open loop-scan make the control process faster than control systems with closed loops. Moreover open loop systems can be cheaper because of the absence of some sensors.

3.1. Oil temperature influence on the process of generating oil pressure[3] and [4]
Based on the study it was found that in the control system used by TOSOK, temperature have big impact on the process of pressure generating in pulleys actuators. This impact is visible on electro valves characteristics.

\begin{align*}
P_2 &= f(PWM_1, t) \\
P_1 &= f(PWM_2, t)
\end{align*}

Figure 3. Influence of oil temperature on pressure in pulley actuator with PWM as a input signal.

The graphs placed in Figure 3, shows that with increasing temperature of the oil in order to achieve the same pressure, PWM signal should increase.

However, the studies and observations found that phenomenon presented in Figure 3 is not related with an increase of the oil temperature but it is related with the rises of temperature of the coil of solenoid resulting from the operation of the flowing current. In fact, coil changes resistance with temperature. Solenoid coil actuated with maximum PWM heat up the coil to a temperature of 115°C, so it can be stated that the oil flow causes cooling of solenoid coil. Another important aspect is oscillating within some limits voltage in vehicle electrical system. In order to disambiguate the input signal responsible for generating the force in the coil, and therefore the pressure, it is necessary to introduce the concept of average current supply solenoid valve.
Figure 4. Influence of oil temperature on pressure in pulley actuator with average current as an input signal.

The graphs placed in Figure 4 show that by controlling the average current of solenoid valve, it is possible to be completely independent in the algorithm responsible for the development of the pressure in the pulleys actuators of temperature. Then electro valves characteristic presented in equation 3 is not required.

\[ P = f (PWM, t) \]  \hspace{1cm} (3)

3.2. Torque influence on the P1 pressure selection

In this study, the continuously variable transmission ratio was calculated on the basis of information provided by pulleys speed sensors. Continuously variable transmission ratio is defined as:

\[ l_{CVT} = \frac{\omega_i}{\omega_h} \] \hspace{1cm} (4)

List of pressures required to obtain requested ratio of continuously variable transmission without torque load with constant pressure in secondary pulley are shown in Figure 5. Those graphs are open loop control maps.
Figure 5. Listing of P1 and P2 pressures for CVT ratio for different input rotational speed and oil temperature.

The use of open-loop in the given form does not give grounds to change the belt tension depending on the value of the input torque, which, as it turns out the study, at steady pressures in both actuators definitely affects the value of continuously variable transmission ratio.

It is important to keep in mind that three of the four signals \( P1, P2, l_{CVT}, T_{in} \) determine fourth of them:

\[
P1 = f(l_{CVT}, P2, T_{in})
\]  

Figure 6. Input torque influence to continuously variable transmission ratio for \( P2=40 \) bar.
This should be understood in such a way that with increasing of input torque, in order to prevent the occurrence of belt slippage, the pressure in the output pulley actuator should be increased. Then, in order to maintain the same ratio, the pressure in the input pulley actuator should increase.

4. The combination of a continuously variable belt transmission with flywheel
Using the continuously variable belt transmission in a conventional drivetrain is to consider the transferred torque in control algorithm in order to maximize system efficiency. Information on the value of the transferred torque can be derived from the characteristics of the engine in the form of:

\[ \text{Torque} = f(\text{throttle position, engine speed}) \]  

When joining in hybrid drivetrain the secondary energy source in the form of mechanical energy accumulator (flywheel), both of these sources are connected to the drive wheels through the continuously variable transmission. Realising the potential of the hybrid drive is expressed when:

- The driver demands braking torque (resulting charging of the flywheel)
- The driver request drive torque (resulting discharging of the flywheel)

Scheme of such a hybrid drive system shown in Figure 7[5].

![Diagram of a prototype hybrid powertrain.](image)

In this system, during deceleration of the vehicle, its kinetic energy is converted into kinetic energy of the rotating flywheel. In this situation, during reduction of the vehicle speed the rotational speed of the flywheel should increase. To do this the ratio of continuously variable transmission should continuously increase - simplified example is shown in the graphs in Figure 8, where driver request is to achieve braking torque (vehicle deceleration). Similarly, while putting the kinetic energy of the flywheel to increase the kinetic energy of the vehicle, continuously variable transmission ratio should be reduced continuously. In both cases it is necessary to ensure the occurrence of angular acceleration or deceleration of the flywheel to form a braking or driving torque.
**Figure 8.** Sample curves of vehicle and flywheel speed and the course of ratio of CVT.
5. Conclusions

- To become independent from the influence of temperature in pressure generation process, average current as a input signal should be used
- For continuously variable belt transmission transmitted torque is important disturbing signal
- It is necessary to design an algorithm that allows, for a requested deceleration process of the vehicle, calculate required ratio of continuously variable transmission
- The instantaneous values of the continuously variable transmission ratio (so the rate of continuously variable transmission ratio change) depend on the driver’s desired braking and driving torque
- Rate of ratio change of continuously variable belt transmission is critical from flywheel point of view
- To check the dynamic properties of the continuously variable belt transmission currently used in conventional drivetrains is crucial

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