The influence of the pressure force control signal on selected parameters of the vehicle continuously variable transmission

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Abstract. The paper presents results of research on the effect of frequency control signal on the course selected operating parameters of the continuously variable transmission CVT. The study used a gear Fuji Hyper M6 with electro-hydraulic control system and proprietary software for control and data acquisition developed in LabView environment.

1. Introduction
Modern cars are often equipped with gears, in which the shifting is carried out automatically. From year to year notes increased interest in new vehicles equipped with automatic transmission. Among the various solutions used in automotive vehicles, we can distinguish transmissions with continuously variable shifting.

Figure.1. The share of different types of gear in the global market for automotive powertrain (AMT – Automatized Manual Transmission, DCT- Double clutch transmission, CVT- Continuously Variable Transmission, AT – Automatic Transmission, MT- manual transmission) [16].

The share of continuously variable transmission in the global market is significant amounting to approx. 11%, and among transmissions with automatic gear larger share have only traditional solutions based on the torque converter (figure 1). Also, the forecast for 2017 years provide a significant increase in the production of propulsion systems equipped with continuously variable transmission (figure. 2). These types of transmissions are used mainly in vehicles, municipal compact and equipped with combustion engines with little power class, although they are used also in the vehicle middle and upper classes and SUVs equipped with diesel engines that achieve significant power and generate high torque values.
Figure 2. Number produced different transmission types in 2010 and 2017 (AMT - automatized Manual Transmission, DCT- Double clutch transmission, Continuously Variable CVT- Transmission, AT - Automatic Transmission, manual transmission MT-) [15].

In the first case, the most commonly used transmission with a metal belt segment, which segments combined package of steel belts cooperate with treadmills bevel gears and the continuously variable transmission combines with torque converter forming a major part of the drive train to the wheels. In the latter case the construction of the transmission linkage is based on a metal chain, which bolts compressed between the raceways gears move by the effect of friction torque (Audi - Multitronic). Continuously variable transmission chains combined with a friction clutch usually carriage wet controlled automatically. The use of variable speed drive systems belt segment cooperating with the torque converter cause a considerable comfort of use, on the other hand contributes to the occurrence of significant slippage between the pump and the turbine, and thereby decrease efficiency of the entire drive system.

2. Tension control of the continuously variable transmission

Continuously shifting CVT equipped with a metal strand takes place under the control of oil pressure in the hydraulic system. The conical gear pulleys are mounted on shafts the gear unit in such a way that one of the conical discs of each pulley is mounted on a fixed, while the other is axially movable. Chambers sliding discs from each of the transmission pulleys is supplied oil under pressure, giving rise to an axial thrust force, which compresses the tension member cooperating with transmission pulley. The pressure in each thrust cylinder moving targets is the result of the valves installed in the hydraulic circuits of each of the chambers. The most commonly used are the valves, which are controlled by PWM, the different parameters such as the filling degree of the PWM signals directly affect the pressure in the hydraulic circuit. Control of the oil pressure value in the individual circuits, ie. A circle around the primary and secondary pulley will work continuously variable transmission with specific indicators. The pressure in the cylinders of thrust sliding transmission pulleys affects the ability of the torque transmission, hence the thrust force required for primary transmission pulley.

$$A_{t,\text{min}} = \frac{T_0\pi(i_p + 1)}{2\mu_T(l - 2a)\cos \beta}$$

where:
- \(T_0\) - load (torque) input, Nm
- \(i_p\) - transmission ratio
- \(\mu_T\) - friction coefficient between the transmission pulley and the belt
- \(l\) - length of the belt, m
- \(a\) - transmission pulley base, m
- \(\beta\) - angle of inclination of the conical surface of the transmission pulley.
The thrust force depends on the pressure and thrust surface \( (A_{dyn}) \) associated with the centrifugal forces on the fluid in the cylinder pressure of [6].

\[
A_i = S_1 \cdot p_{stat1} + A_{dyn1}
\]

where:
- \( S_1 \) - the surface pressure of the primary transmission pulley cylinder \([m^2]\),
- \( p_{stat1} \) - oil pressure (static) in a primary cylinder, \([kPa]\),
- \( A_{dyn1} \) - component of the thrust of which is the result of the dynamic oil pressure on the pressure cylinder.

This component can be determined from the relationship:

\[
A_{dyni} = \frac{\pi \alpha_i^2 \rho_{oil}}{4} \left( R_{oci}^4 - R_{sci}^4 \right)
\]

where:
- \( \alpha_i \) - angular velocity at the \( i \) transmission pulley \([rad / s]\),
- \( \rho_{oil} \) - density of hydraulic oil, \([kg / m^3]\),
- \( R_{oci} \) - outer radius of the cylinder pressure of the transmission pulley "i", \([m]\),
- \( R_{sci} \) - the inner radius of the cylinder pressure the transmission pulley "i", \([m]\),
- \( i \) - marking transmission pulleys \( i = 1 \) – primary pulley, and \( i = 2 \) – secondary pulley.

On the other hand, introducing a safety factor gear \( kp \) obtain the expression for the required thrust, for the primary pulley:

\[
A_{dem} = \frac{k_p M_o \pi (k_p + 1)}{2 \mu_s (l - 2a) \cos \beta}
\]

The thrust force depends on the pressure and the pressure of the surface and the effect of centrifugal force, [6], and the quotient of the cylinder pressures \( \zeta \), could be described with

\[
\zeta_p = \frac{P_p}{P_s}
\]

where:
- \( P_p \) - pressure in the primary pulley \([Pa]\),
- \( P_s \) - pressure at the secondary pulley \([Pa]\).

and in fact the thrust forces ratio:

\[
\zeta_F = \frac{F_p}{F_s}
\]

where:
- \( F_p \) - thrust force at primary pulley \([N]\),
- \( F_s \) - thrust force at secondary pulley \([N]\)

is associated with obtaining a particular transmission speed ratio [3, 4]. The curve quotient of the pressure ratio depends on the given transmission safety factor \( kp \).

Such knowledge on the impact of signal parameters of control valves and the inclusion of specific CVT transmission design features such as thrust areas for each pulley is important for the design of the transmission control algorithm.

Transmission control must primarily take into account the safety of its operation, ie. such a choice of pressure in the thrust cylinder of each pulley and taking into account that there is no slip linkage between belt and pulleys surface [2, 5, 7, 11, 12, 14]. On the other hand, it is very important to ensure adequate
dynamics of changes in operating parameters of the transmission [8, 11, 12, 13] and to enable optimum operation of the power unit [10, 13] resulting in the improvement of properties of dynamic, economic and environmental reasons [1, 7, 9].

3. Experimental research

The research was carried out on the automotive continuously variable transmission mounted on the bench. During the test transmission worked without a load in the stationary states. There was transmission pulleys rotational speeds, and the pressure in the individual hydraulic circuits recorded. Used for this purpose factory rotational pulley speed sensors and pressure sensor in the secondary pulley, and additionally installed a pressure sensor in the primary pulley. Tests were conducted at a constant rotational speed of the electric motor, respectively 800, 1000, 1200, 1400 rev / min.

As a research facility used automotive continuously variable transmission Fuji Hyper M6 fitted with a metal belt pushed. Continuously variable transmission consists of two components: a continuously variable transmission with a metal belt tensioning and cooperating with its hydrokinetic torque converter. Table 1 shows the basic properties characterizing the test transmission.

Table 1. The Fuji Hyper M6 main properties.

| No | Properties                                      | Value                  |
|----|------------------------------------------------|------------------------|
| 1  | Transmission ratio range D, DE                  | 0.442 – 2.432          |
| 2  | Transmission ratio range S1                     | 2.432 - 1.890          |
| 3  | Transmission ratio range S2                     | 1.473 - 1.300          |
| 4  | Transmission ratio value S3                     | 0.980                  |
| 5  | Transmission ratio value S4                     | 0.742                  |
| 6  | Transmission ratio value S5                     | 0.602                  |
| 7  | Transmission ratio value S6                     | 0.520                  |
| 8  | Transmission ratio value R                      | 1.931                  |
| 9  | Control system type                             | el.-hydraulic          |
| 10 | Hydrokinetic torque converter                   | 3 part + lock          |
| 11 | Hydrokinetic conv. torque ratio                 | 1.71                   |
| 12 | Hydrokinetic conv. diameter                     | 200 mm                 |
| 13 | Belt type                                       | metal belt             |
| 14 | Hydraulic pressure range                        | 1.80 – 5.35 MPa        |
| 15 | Primary wheel thrust area, S1                   | 0.0207 m²              |
| 16 | Primary wheel thrust area, S2                   | 0.0097 m²              |
| 17 | Wheel notch angle, β                            | 11°                    |
| 18 | Wheel center distance, a                        | 0.155 m                |
| 19 | Belt length, l                                  | 0.648 m                |
| 20 | Construction index, κ                            | 0.3871                 |

The test transmission was mounted on a test bench equipped with an electric motor is used to drive the test facility coupled with Optidrive inverter, which enables realization of the selected scenarios of the transmission pulleys rotational speed changes (Fig. 3).
Transmission control was carried out using valves installed in a hydraulic unit of primary and secondary pulleys. There was controlled using the author's application control and the measurement made in the package Lab-View via PWM control signals of different frequencies and different degrees of filling. The block diagram of the control the measurement is shown in figure 4.

Control and measurement hardware was NI interface which allows simultaneous recording of selected operating parameters of the transmission and control of solenoid valves placed in the hydraulic system. The frequency control signal varied in the range of 10 to 400 Hz and the degree of filling of the PWM signal was in the range of 0-100%.

4. Analysis of the results

4.1. The influence of the frequency of the PWM control signal to transmission operation

The results of stand tests found that the stabilization of the operating parameters of the transmission after crossing the frequency of approx. 50 Hz. Further increasing the frequency does not significantly affect the achieved operating parameters such as rotational speed. This applies to the control valves of both transmission pulleys. Noticeable is the only occurrence of unevenness larger secondary pulley
rotational speed. The smallest value is obtained from the control signal frequency of approx. 250, 350 Hz, nevertheless considered in the entire frequency range for both the standard deviation of the transmission pulley rotational speed is small. In the case of a secondary pulley, but the situation is reversed, than the primary pulley. A statement of the value of the average velocity and the standard deviation for the selected frequency ranges are shown in figure 5.

![Figure 5](image)

**Figure 5.** The impact of frequency on the average wheel speed and the standard deviation of the speed.

Simultaneously with increasing frequency control signal, an increase in pressure in the both primary and secondary cylinder pulley, and for the control signal frequency of 15 Hz the value of the average pressure in the primary pulley ($P_{cz}$) is 13.6 bar ($\sigma = 0.12$), whereas for a secondary pulley $P_b = 22.58$ bar ($\sigma = 9.1$). Increase the frequency to 35 Hz increased the pressure at primary pulley $P_{cz} = 19.22$ bar ($\sigma = 0.11$) and secondary pulley $P_b = 34.28$ bar ($\sigma = 1.35$). A further change in frequency control signal caused an increase in pressure and a decrease in the value of the standard deviation.

4.2. The impact of filling the PWM control signal on the transmission operation

The analysis of experimental results allowed us to assess the impact of filling the PWM signal on the selected parameters of the transmission. There was analyzed the following parameters of the transmission operating indexes: the rotational speed of the primary and secondary pulley, primary and secondary pulley cylinder pressure and transmission ratio $i_T$, and the pressure thrust ratio $\zeta_P$. The evaluation was conducted in transmission for given constant values of electrical motor rotational speed, driving torque converter coupled with the primary pulley. The results showed that with increasing duty cycle slightly increases the rotational speed of the secondary pulley. Exceeding characterizing the PWM filling degree of 60% followed by a sudden change in speed and then after crossing the 70% duty cycle control to re-stabilize the speed (Fig. 6).

![Figure 6](image)

**Figure 6.** The influence of the fulfilment degree of the PWM signal for the secondary pulley rotational speed
The course of the continuously variable transmission ratio understood as the quotient of the rotational speeds of the transmission pulleys, depending on the degree of filling of the PWM signal shown in figure 7. The duty cycle of the PWM range from 0-60% transmission ratio is kept constant values. In terms of a preset duty cycle of 60-70% suffer from rapid change and stabilize the PWM value above 70%. In turn, the results of primary pressure indicate that the pressure in the cylinder pulleys decreases with a PWM wheel active in the range of 0-60% PWM, and then stabilized. The highest pressure values are for the engine speed of 800 rev / min, while the lowest for a speed of 1200 rev / min. The differences in pressure in the primary pulley for different engine speeds are particularly evident for low PWM (0-30%). All observed changes in pressure are uninterrupted, and there were no sudden abrupt pressure changes (Figure 8, 9).

The course of the pressure in both cylinder pulleys are similar (Figure 8, 9). With the increase of the PWM pressure it decreased to the PWM value of about 60% and then plateaued. Pressure values for the individual engine speeds were very close to each other in practically the whole range of changes in the degree of fulfilment of the PWM signal. Only for low PWM (0-10%) you will notice small differences.
The influence of the fulfillment degree of the PWM signal for the secondary pulley pressure

The quotient of the pressure thrust \( \zeta_P \), Figure 10 shows an example of waveforms for control valves of both wheels with the same parameters of the control signal \( f = 100 \text{ Hz} \) and the degree of PWM varying between 0 and 100%.

Theoretically, it is possible to obtain the quotient of the pressure of a very wide range, however, transmission operating under load by a defined, in practice, considerably narrows the range of variation of up to approx. 0.8 – 2.6. Such a range of changes quotient of the pressure, however, is sufficient to produce a full range of gear changes.

5. Conclusion
The use of solenoid-controlled PWM signal allows for a smooth change of pressure in the cylinder pressure of the transmission pulleys. Research has shown that in the low speed range used real degree of fulfillment of the PWM signal is about 60%. However, the use of higher speed, and thus a proportional increase in the efficiency of the hydraulic pump supply hydraulic transmission may require the use of the entire range of the degree of fulfillment of the PWM signal. Controlled by a signal from a different degree of filling enables smooth change of the pressure in each cylinder pulley which translates into a wide range of transmission ratio change and affect its ability to carry the load and the properties such as the safety and overall efficiency. The studies also indicate that in the case of stationary conditions sufficient stabilization of the operating parameters of the transmission is obtained at a frequency greater than approx. 50 - 100 Hz.
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