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CONTINUOUSLY VARIABLE TRANSMISSION LEAKAGE TEST RESULTS

Abstract
After a short introduction characterizing the general outline of the issue, this paper describes the test results of oil leakage measurements through CVT actuator seals. The research was done using Jatco company's CVT 7 model, the popular gearbox for small passenger cars. Several curves of leakage values are given for both actuators, concerning different conditions such as rotational speed, oil temperature or pressure.
In the summary several conclusions are formulated, based on presented test results. The determined maximal value of leakage is about 1 l/min. It emerged that the influence of centrifugal force is negligible. What is more, the observed phenomena are shortly described and projected for more detailed investigation.

Key words
passenger car‘s driveline, power loss, efficiency improvement, continuously variable transmission, hydraulic control system, leakage values

Introduction

The stepless transmissions in passenger cars called CVT (Continuously Variable Transmission) are becoming increasingly more popular [1]. This is because of their advantages and progress made during the last two or three decades concerning their design and control [2, 3]. They make it possible to accelerate a car at a constant value of an engine's rotational speed, which may be set to maximal efficiency, torque, power or minimal fuel consumption [4].

Unique feature of CVT is that it permits the KERS [5] system (Kinetic Energy Recovery System) to work in a car. With this system, it is possible to recover a car's energy during braking and use it later for accelerating. The idea of a hybrid system with CVT and mechanical energy accumulator is described in [6]. They are different methods of braking energy recuperation (e.g. popular electric storage [7], [8] or pneumatic storage [9], [10]) but the kinetic energy accumulator (which is actually a rotating mass) is much more ecofriendly than a set of batteries and their long-term effect on CO_2 balance, considering the manufacturing process, utilization, recycling, etc.

Minimization of energy consumption is one of a vehicles' essential requirements from the viewpoint of sustainable transport. The features of this type transmission lead to savings in fuel consumption [2, 11]. Nevertheless, the method of ratio control system remains problematic because of its high energy-consuming character [12, 13]. The Department of Vehicles and Fundamentals of Machine Design of Lodz University of Technology (TUL), has devised a new solution which has a good chance of solving this difficulty [14].

Currently, the most common CVT solution employs a pair of conical sheaves which are moved axially for changing the ratio. The axial movement is executed by hydraulic actuators. The characteristic feature of the actuators is they are located inside the conical pulleys (sheaves) and rotate. The phenomenon of leakage through their sealings can be noticed and of course contributes to the deterioration of the system's efficiency [15], [16]. Study on CVT's sealings is presented in [17]. Research is incessantly carried out around the world both to improve the efficiency of pump of hydraulic control system [18] and to elaborate more efficient way of controlling CVT ratio [19].

Maintaining value of leakage is vital for CVT control's operation, particularly when considering the new, TUL solution. In this design, there are two pumps driven electrically. The first pump, described as P1 is responsible for ratio changing and placed between the pulleys' actuators [14]. It can rotate in both directions and transmit oil between the actuators. A second pump called P2 is accountable for the belt's tension and compensating leakages in the circuit.

If the value of leakage is negligible, there is a possibility to change the positions of actuators (and ratio) by controlling the volume of oil which is pumped between them. In this case, the P2 pump's delivery will be very small as well as its power consumption. In case of serious leakages (about 6[l/min]) it can turn out that pump P1 (responsible for ratio changing) might have only one direction of rotation. This is because when this pump is being stopped, the decrease of pressure due to the leakages will be so fast that the ratio's change speed will be sufficient.

Significant values of leakage deteriorate the mentioned conception of ratio control because this phenomenon changes the volumes of oil inside the actuators. This issue must take in account the algorithm of the control system. Designers of transmissions have to make a compromise between the leak tightness and the resistance caused by the sealings.

Because of the above mentioned triggers, the need of research of currently available CVT sealing systems becomes evident. For typical solutions with one pump, results of this investigation will contribute to improve the control algorithm and a slight improvement of fuel consumption. The results are much more significant for TUL's solution where not only algorithm tuning will be possible. Outcomes of the research enable the design of a proper hydraulic circuit with a new solution, e.g. fit all size pumps. It is crucial to equally optimize software as well as system hardware because it results in the best reduction of energy consumption. According to Bradley [20, 21], the results of vehicle testing show that a similar control system reduces the required control power by more than 83% and TUL's solution, after mentioned optimization, could be even more efficient.

Test stand description

The object chosen to be tested was the popular Jatco model CVT 7 [22] gearbox. It has a built-in pump which had to be disconnected from the actuators in order to measure the leakage values by using (external) flow-meters. After the analysis of the design, special plugs were made and put inside the gearbox's channels to block the oil flow from the internal pump.

The external oil flow was delivered to both actuators by technological holes which were unplugged, as presented in Fig. 1 on the gearbox's side view.

Fig. 1. Picture of the tested gearbox
Source: Author's

The next task was to devise a way to supply the actuators with the proper pressure values. First, it was pointed out that to determine the dependence of leakage from pressure value, both actuators can operate at equal pressures – therefore there is no need to control them independently.

The first idea was the use of a simple hydraulic pump and a PWM-controlled solenoid valve [23] to change the pressure. Unfortunately, severe disturbances in oil flow measurement were observed. It could be caused by the solenoid valve, which connects 200÷300 times per second the oil supply with the output line. When using a precise flow-meter with high resolution (circa 2200 samples per liter) the oscillations from the solenoid valve could have been transferred to its output.

After this misfortune, another solution to supply the actuators was selected and is presented in the scheme of the test bench in Fig. 2. The CVT transmission (No. 6) is driven by an electric motor (No. 5) characterized by its maximum rotational speed of 3000[rpm]. The needed pressure value is supplied from the hydraulic group (No. 3) (H-G). Hydraulic group contains an oil filter with 3 micron solid particulate filtration, a flow-meter and regulation of temperature of output oil. An oil filter in original gearbox's hydraulic circuit is employed as well to keep oil uncontaminated.

The oil is delivered to both pulley's actuators. The oil which enters each chamber is measured by flow-meters No. 1 and No. 2. One of them, has a small range of 1,6[l/min] with measurement tolerance 1[%] and values from this flow-meter were taken for all further analyzes because the expected maximal value of leakage was about 1[l/min]. After tests of the P1 pulley, the position of this flow-meter was changed from "1" to "2" in order to precisely measure the value of leakages on the second actuator. Oil which passed through the sealings dripped to the oil sump and when the amount exceeded a specified level was directed to the hydraulic group - Fig. 2.

Two oil temperature sensors were applied. The T_1 sensor (Fig. 2) measures the CVT's input oil temperature which delivers the H-G. This temperature is controlled by the cooling system of H-G and was always kept constant during particular test series. Because this is supply line for CVT, this value of temperature was selected as a reference during research. The T_2 sensor was employed to check the temperature of oil which quit the CVT gearbox. To achieve the best uniformity of temperature in the gearbox and most accurate results, both temperatures had to be similar at the beginning of the test. The fan (No. 4) was used to intensify the dissipation of heat from the gearbox during tests at high rotational speed. Temperature phenomena will be described further.

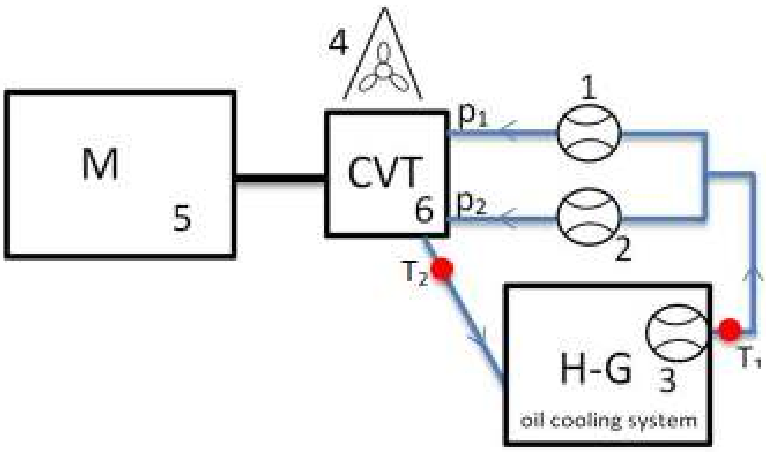

Fig. 2. Scheme of the test bench
Source: Author's

The test stand correspond to real conditions in a car because electric motor (No. 5) substitutes the engine. Additional fan (No. 4) simulates the air flow which occurs during driving and cools the gearbox. H-G (No. 3) replaces the original oil sump with integrated radiator.

Test results

Tests were conducted at three constant values of oil temperature: 30[°C], 60[°C] and 80[°C]. Temperature 80[°C] is the typical operational temperature of oil in vehicle's gearbox and that is why selected test results are presented only for this temperature. Research of lower values was conducted in order to check the influence of temperature and phenomena which occurs when gearbox gets warm.

Leakages were tested at the following pressures: 0,5[MPa], 1,5[MPa], 2,5[MPa], 3,5[MPa] and 4,5[MPa] in order to verify the suspected pressure influence.

Each pulley's leakages were tested at rotational speed of the pulley set to: 0[rpm], 500[rpm], 1000[rpm] and 3000[rpm].

In most cases, the leakages were checked twice in order to examine the reliability and repeatability of measurements. If both series gave similar results, averaged values are presented. After finishing all the measurements for the P1 pulley, a precise flow-meter was installed on the P2 pulley and all points were repeated - in this test series, the rotational speed was set on the P2 pulley.

It should be underlined, that the P1 pulley has a doubled actuator chamber (with a total area of 175[cm^2]) while the P2 actuator chamber is single and has 82[cm^2] area, as shown in Fig. 3. P_2 pressure is highest in the Jatco CVT 7 and it was necessary to double the P1 actuator to achieve greater axial force to the P1 actuator to enable the ratio change.

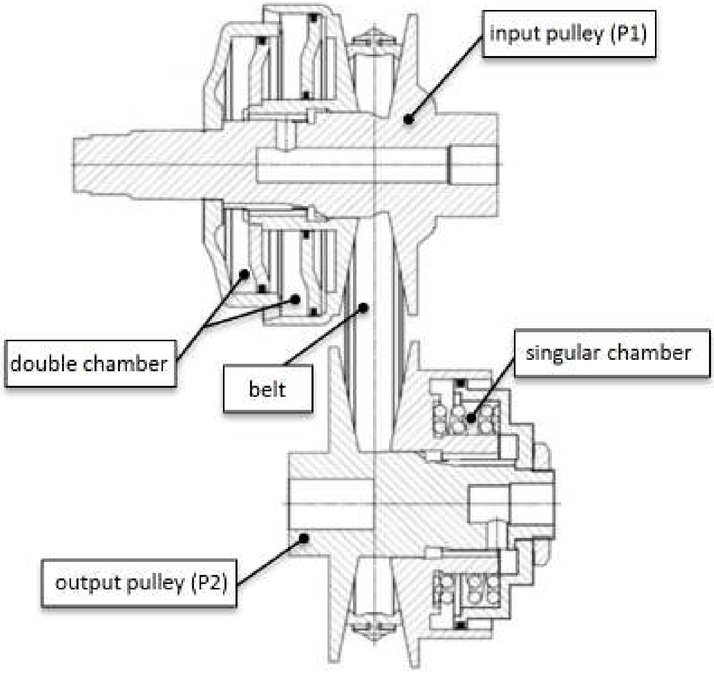

Fig. 3. Cross section of CVT
Source: Author's

First, test results for 0[rpm] are presented. These are the simplest among all scheduled tests because there is no heating disturbance phenomenon (caused by friction when turning the gearbox's shafts) and no oil flow perturbation caused by (small) axial oscillations of the pistons which occur when the transmission is turning - this phenomenon is described further.

Fig. 4 shows the test results for the P1 actuator and different values of oil temperature. The maximal value of leakage (0,65[l/min]) can be observed for the highest oil temperature (80[°C]) and pressure 3,5 [MPa]. The shape of the achieved curves is thought provoking. The higher the pressure, the lower the increase of leakage can be observed. This was particularly for the highest temperature range when leakages dropped a little at top pressure.

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There could be two explanations of this phenomenon. First concerns the oil temperature - before the test the gearbox was warmed to the required temperature by turning the gearbox shafts. When the test started (for 0[rpm]) the oil inside CVT started to cool which caused a drop of leakage, regardless of the pressure increase. Nevertheless, the impact of this process should be slight because the whole test lasts only a few minutes. The second explanation relates to the sealings and their features. It is possible that due to higher pressure the sealing tightens which contributes to lower leakages. Most likely the answer is a combination of both mentioned theories.

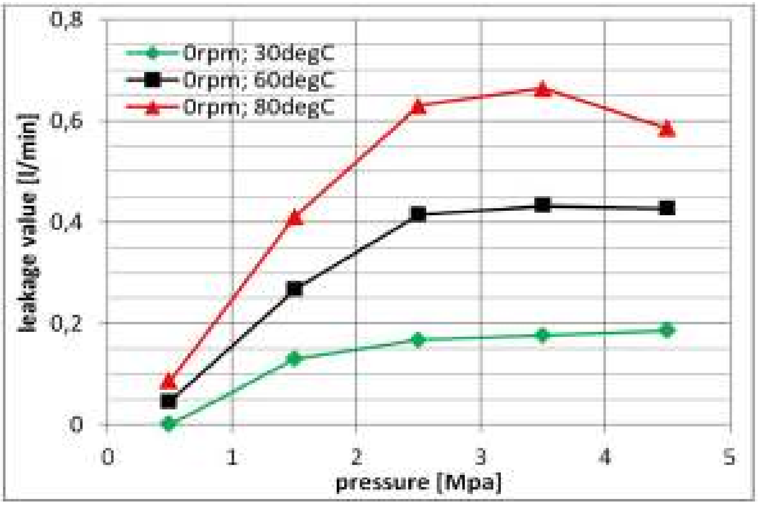

Fig. 4. Test results for P1 actuator, 0[rpm] and different values of oil temperature
Source: Author's

Fig. 5 shows test results for the P2 actuator, 0[rpm] and various values of oil temperature. The maximal value for 80[°C] is close to 1,2[l/min] which is noticeably more than for the P1 actuator. When compared to P1 results it can be observed different shape and there is no leakage fall when pressure is increased. Different properties can be explained by the distinct design of actuators presented in Fig. 3.

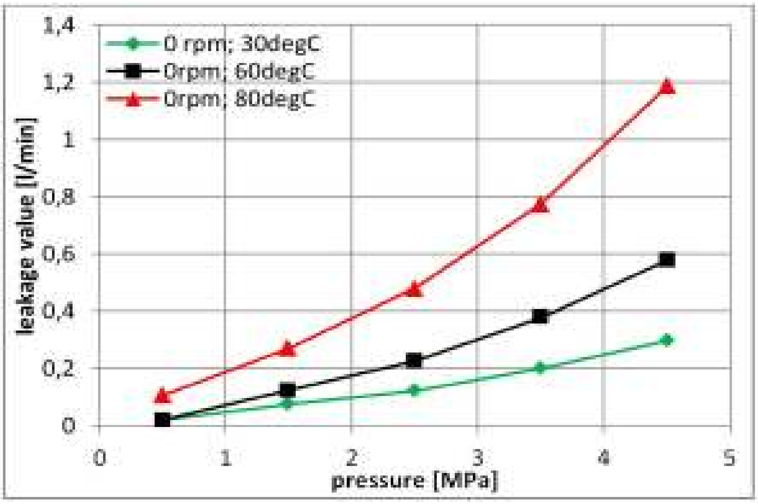

Fig. 5. Test results for P2 actuator, 0[rpm] and different values of oil temperature
Source: Author's

In Fig. 6 the leakage values are presented for the P1 actuator at 80[°C], at various rotational speeds. Based on the results from the mentioned graph, a general tendency can be observed for leakages for all values of rotational speed increase together with increased pressure. The next remark concerns the fact that the curves of higher values of rotational speed are steeper. A probable explanation is connected with temperature phenomena. Analogously, like the small drop of leakages from Fig. 4 was explained by the lowering of oil temperature at the contact area of belt and pulleys, this time higher rotational speed causes more severe warming of oil inside the gearbox (mainly because of friction). As shown in Fig. 6, leakages increase more rapidly during the test. The highest value of leakage slightly exceeds 0,8[l/min]. It was possible to control the T_1

temperature (the input one) but not the T_2 temperature (the output one) because it was not feasible to apply cooling inside rotating CVT (and its actuators). The fan (Fig. 2) was used to reduce this phenomenon.

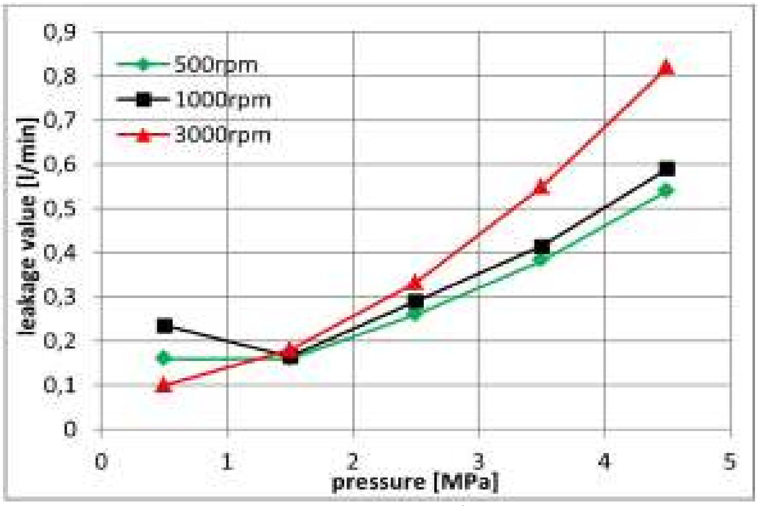

Fig. 6. Test results for P1 actuator, temperature of oil 80[°C] and different rotational speed values
Source: Author's

Fig. 7 depicts test results for P2 actuator at temperature 80[°C] and various values of rotational speed. Results are similar to those from Fig. 6. All previously mentioned relationships are also visible and true. The most significant difference concerns the value of leakages – such as for 0[rpm], leakages for P2 actuators are greater and for results from Fig. 7 achieve nearly 1,2[l/min] for 3000[rpm] and 4,5[MPa].

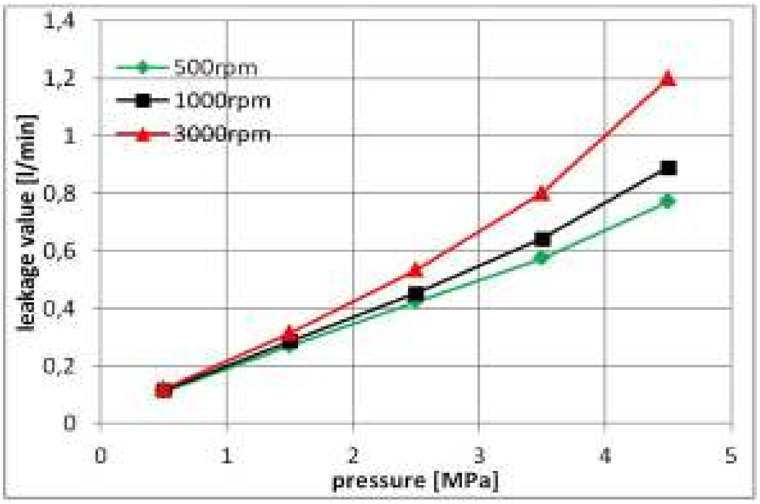

Fig. 7. Test results for P2 actuator, temperature of oil 80[°C] and different rotational speed values
Source: Author's

Noticed phenomena
Several phenomena were noticed while testing the CVT leakages:

- Initially there was an idea to use solenoid-valves to produce p_1/p_2 pressures. High oscillations of oil-flow value were noticed. Solenoid-valves were suspected to be the reason, so a new hydraulic circuit was made (presented earlier within the test bench scheme). Oscillations of oil-flow decreased significantly. What is more, it happened that solenoid valves became excited. This dangerous phenomenon is described in [23].
- Some oscillations still occur and are visible particularly when the pressure is low. The reason could be the axial movement of the pulley (it causes oscillations of oil inside the chamber), and as a result, in oil-flow. Those axial movements are more probable when axial force (pressure) is small.
- Initially, one flow-meter with a small range (1,6[l/min]) was scheduled to be applied. When strong disturbances of oil flow were noticed at the beginning of the test (with solenoid valves) a set of three

flow meters was employed in order to have an additional control of flows and make measurements more reliable. It was interesting how big was the difference between the sum of the value from flow-meter's “1” and “2” in comparison with the value indicated on flow-meter “3”- see Fig. 2. It was noticed that for most measurement points this difference is smaller than 0,05[l/min]. This proved the reliability of the flow-meter's precision.

- For some conditions a very high value of leakages was observed. This happens when the gearbox was not in use for a long time and the pressure inside the chambers decreased to zero. After such a long break, when a small amount of oil pressure was applied, the value of leakage could achieve even a few liter per minute. The reason may be in the type of sealing, which need significant pressure value to be tightened. The last remark is in accordance with the assumption that the shape of curves from Fig. 4 is explained by tightening the seals by increasing pressure.
- Curves presented in this paper are the averaged data from 2÷3 repeated series. Measurement repeatability is generally better for the secondary pulley which could be explained by a simpler structure when compared to the primary one (doubled piston, two sealing sets).

Summary and conclusions

Table below contains a few, the most representative values of elaborated leakages: for significant rotational speed, oil temperature 80[degC] and two values of pressure. Low pressure (0,15[MPa] is typical for low load of engine which occurs during driving with steady speed, high pressure (0,45[MPa]) represents full load of engine, during e.g. acceleration.

Table 1. Selected measurements of leakages

conditions / p [MPa]	80[degC], 3000[rpm]	
	P1 actuator [l/min]	**P2 actuator [l/min]**
0,15[MPa]	0,15	0,3
0,45[MPa]	0,82	1,2

Source: Author’s

Presented research recognized the leakage phenomena in CVT. This outcome makes it possible to improve efficiency of CVT’s hydraulic control system. The results are peculiarly relevant for mentioned TUL’s solution which has a good chance to decline power losses of the transmission and vehicle’s fuel consumption as well. Determined values enable to appropriate design of the proposed solution and optimization of its control algorithm.

According to the test results, there are two main factors which strongly influence leakages: pressure and temperature. It was expected that the higher the pressure, the higher the leakages. Generally, this rule is proved by test results. However, there are a few points of these principles which seem untrue - Fig. 4. This is most likely caused by the second main factor: temperature. Tests from Fig. 4 were performed at high temperature when the motion was stopped. After a few measurement points, the gearbox began to become cold, which probably disturbed the measurement. The opposite situation is visible at high rotational speed. The curve for 3000[rpm] has the highest slope because the transmission becomes hot very fast. This is also probably the reason the values of leakages are more or less the same at the beginning point of the test (0,5[MPa]) for all rotational speeds. The curve at 500[rpm] is sloped weakly, and stronger at 1000[rpm] and 3000[rpm] mostly. If the influence of centrifugal force would be significant, the layout of curves should look different: the difference between all curves (for different rpm) should be noticeable from the beginning and remain more or less the same, to the end of the curves (4,5[MPa]). That’s why the influence of centrifugal force could be omitted here. Summarizing, the layout of temperatures inside the gearbox is hard to be determined precisely. It changes depending on current rotational speed. Changes of temperature inside the pulleys chamber result in changes of leakages.

Research was not directed to investigate the influence of wear on leakages but it is expected that wearing of sealings will result in higher values of leakages.

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