Friction in the Continuously Variable Transmission. Test bench and initial test results

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ABSTRACT
The article concerns friction problems in the Continuously Variable Transmission (CVT) with a pushbelt or a chain. A small test bench is prepared with the aim to expand knowledge about friction phenomena which occur in the CVT between steel belt elements and pulleys. The literature explains this problem not sufficiently. After short theoretical introduction, the paper contains a description of the test bench and its correlation to the real CVT gearbox as it is in a car. Afterwards the initial test results are presented and completed with some remarks. At the end, summary and conclusion are defined.

Keywords: CVT, model, friction, forces, belt tension, power loss

1. INTRODUCTION
Due to the technological progress which has been done over last decade, continuously variable transmission are getting more and more popular. One of its advantages is the ability to change the ratio in a smooth and stepless way, which makes it possible to use fully the performance characteristic of the internal combustion engine. CVT have aroused a great deal of interest in the automotive sector due to the potential of lower emissions and better performance[1]. Nevertheless, the general efficiency of the transmission can still be improved by the reduction of the power consumption of hydraulic system or improving the control system. To achieve the aim by the second possibility, the better mathematical model of
phenomena which occurs in this transmission (i.a. friction) is needed. Because of the variety of phenomena which occur in the CVT, the modeling of such a transmission is complicated. Different models take (or not) into account such phenomena as the micro-slip of the belt, different friction characteristics, centrifugal force, pulley deformation, inertia and other in dependence of the model [1-5]. The direction of friction force used to transmit the torque by CVT is tangential to the circumference of the pulley. Whereas the radial friction forces significantly influence the ratio changing mechanism and the value of forces acting on the conical pulleys to achieve requested ratio. In the Fig. 1 is presented drawing, how does the CVT actually work.

Figure 1. CVT’s work principle[6]

Between two conical pulleys works a chain or a belt. On each side (driven/drive side) there is one fixed and one movable pulley (see Fig. 2b). Due to the axial movement of the movable pulley, the radius of the belt/chain contact changes. The transmission ratio is defined by the relation of both radii. Fig. 2 shows the scheme of pushbelt design and the simplified drawing which makes it easier to understand how does the ratio changes. During the change of ratio (and radii), but also in steady state operation, it is clear that the radial friction has to occur.

Figure 2. a) The design of pushbelt [2], b) How does the CVT changes ratio.
Simultaneous appearance of friction forces in both directions makes the issue much more complex. The lack of knowledge about the dependence of friction force components in both direction made the designers apply a considerable simplification during elaboration of CVT’s mathematical model. They ignore often the radial friction component of the friction force (like in [7]). In the Fig. 3, the layout of forces acting at the element of the pushbelt is shown[8]. The resultant force “T” is searched as a vector sum of circumferential component of friction (“T₁”) and the radial friction component (“T₂”). The angle “β” between one of the friction components and the resultant force is also unknown. The shape of the belt element in the Fig. 3 is a model of the real belt segment. It is designed and made for using at the test bench.

Figure 3. The layout of forces acting on the belt element

Such an inaccurate model caused the need to use a big excess of the belt tension in order to avoid its sleep. This extra tension obviously leads to unnecessary losses in power and an increase in fuel consumption. The proposed test bench aims to widen the knowledge about the friction phenomena in the CVT and improve the mathematical model of the transmission.

2. TEST BENCH

In the Fig. 4 the 3D model of the test bench is shown. The assembled test rig is very close to the model and it differs only with details, unimportant for the operating principles.

The steel element (5) is moved on the rails (12) from the left side of the test bench to the right one. It is pulled by the electric motor (8) with built-in reducer. The pulling force is measured by the force sensor (4). The radial load is made by adding weight on the weight pan (7). The load force is measured by the force sensor (3). The reaction forces on the rails (lateral forces) are measured by force sensors (1) and (2). The element (10) is added to keep the weight balance of the element (5). The frame of the test bench (6) is assembled to the table (11). Green box (9) contains power supplier and amplifier of the measured signals. All measured data are sent by amplifier to the data acquisition card and later on to the PC computer with corresponding software. In the Fig. 5 is shown the completed test bench. Visible sensors are described in the photo. The movement of the element is performed from
the right side of the test bench (from sensor 1 position) to the left side (to the sensor 2 position).

Figure 4. The model of the test bench

Figure 5. The photo of the assembled test bench
3. TEST RESULTS

Hereafter a few graphs with test results will be shown. The first one, presented in the Fig. 6 shows the layout of the forces just before and during the movement of the element.

At the beginning of the test, the force at the sensor 2 is almost zero because the element is situated in the vicinity of the sensor 1. The indication of the sensor 1 results from the load of the element (put on the weight pan) which is constant in the whole test (violet line). In the 4th second, the electric motor started to pull the element. The value of the force measured on the sensor 2 started to increase, conversely on the sensor 1. At the end of the test is visible almost full reversal of the level of forces on the sensor 1 and 2 against the beginning of the test. The reversal is not total because the element had to be stopped in some distance before the end of the rail (so also before sensor 2 position). The green line presents the sum of forces from both radial sensors. What is very important, initially the value of this sum equals to about 140N but after the beginning of the movement the value increased to almost 300N. This increase is caused by the change of the friction direction. When the element is motionless, the friction is developed in the radial direction and it “helps” to keep the element. When the electric motor started to pull, the friction had to be developed fully in the circumferential direction and as a result, the radial forces measured by sensors increased.

What is significant, the level of the summary force, represented by the green line is almost constant during the whole movement of the element. It means that the operation of the measuring system is correct because it is clear that sum of the forces from sensor 1 and 2 has to be constant.

![Figure 6. The layout of the forces during the movement of the element](image)

After the test just described, the decision to modify the test bench was taken. Using the electric motor and weights put on the weight pan, it is impossible to increase the load or
pulling force smoothly/slepmlessly. Also, the electric motor disenables to add some pulling force without creating the movement. To achieve this, the electric motor and the weight pan were replaced by containers filled with water.

Fig. 7 shows the graph with next test results: the element was situated at the beginning of the rail (close to the sensor 1). When the time started to run, the water filling started too. The load is represented by the green line. What is the most interesting, it is a part of the graph on the left side from the (added) red vertical line. Despite the load increase, the lateral force is constant. This is because the radial friction force up to 7th second is being developed. Thanks to that the lateral force in this part of the graph is constant. On the graph measurement from the sensor 1 is only presented because sensor 2 indicates none. Right to the red line, the radial friction force is fully developed and smooth increase in load cause the increase in the measured lateral force.

What should be pointed out here, that on the right side of the graph, the stepless addition of load leads to the stepless increase of the radial force. In the Fig. 8 it is presented that such a behavior is not obvious.

![Graph showing smooth increase in load for element situated near sensor 1](image)

Figure 7. Smooth increase in the load- element situated in the vicinity of the sensor 1

The conditions of the next test were almost the same as in the test described above. The only difference is that the element was situated not close to the sensor 1 position but at the middle of the rails. The behavior of the system is in this case different. Despite adding the load smoothly, the increase in radial forces is strongly gradual.

The reason of this phenomenon is deformability of the rails. It is clear, that at the middle of the rails they are the least rigid. As result, they deformed and changed distance between them. The element is wedged which results with presented layout of the forces. In each step the element move vertically to a new position where is so long as the increase of load is not sufficient to made the element do the next step.
Figure 8. Smooth increase in the load- element situated in the middle of the rails

Figure 9. The test results with smooth increase in load in vertical and horizontal direction

Fig. 9 shows a more complex test results. At the beginning of the test all forces were constant. At 5th second the vertical load started to increase. At the 20th second the increase of load was stopped. What is important- the mentioned increase of load does not change the value of the lateral forces- this phenomenon was explained in the test from Fig. 7. Subsequently, in the vicinity of 30th second, the pulling force started to increase and to
develop the friction force in the circumferential direction. Up to 40\textsuperscript{th} second, the increasing pulling force did not caused any reaction in lateral forces. It is due to the reserve in the friction force. From the 40\textsuperscript{th} second, the increase in lateral forces is visible. The radial forces started to increase because the total friction force was exceed and further developing of the friction in the circumferential direction caused the decrease in the radial friction force- it is seen as a rise in radial forces. Just before the movement of the element (about 115\textsuperscript{th} sec.) the friction was fully developed in the circumferential direction (without having any radial component). Further increase in the pulling force caused the overcome of the total friction value and movement of the element.

4. CONCLUSIONS

The designed and assembled test bench seems to be appropriate to conduct further, more sophisticated research. Test results are repeatable and what the Fig. 6 proves- reliable. Based on the presented test result a few conclusions can be formulated:

- The start of the element movement causes the increase in the lateral forces.
- It is possible that increase in load does not result in increase in lateral forces when the total friction force is not exceeded.
- The rails are too elastic and should be made more stiff.

References


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