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A RESEARCH STAND FOR MEASURING FRICTION PARAMETERS IN A BELT TRANSMISSION

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Summary

In this paper it has been presented a research stand that allows to measure static and dynamic friction parameters between the belt and the pulley in a belt transmission. It has been shown the structure of the stand with all sensors included. It also has been presented the computer program made, which was developed to analyse results of measurements. It has been shown main capabilities of the stand, especially that it can be rebuilt to three configurations to measure: static friction, the so-called kinetic and dynamic friction characteristics as well as complete belt transmission. It can measure friction parameters of any belts transmissions occurring in cars: flat belts, V-belts or poly-V belts, except toothed belts. In the stand there are build-in torque and force sensors – to measure engine torque and tension of the belt, and rotation and displacement sensors measuring angular velocities of the pulleys and displacement of the slack part of the belt. Finally, some sample results of poly-V belt 5pk, achieved from the research stand are presented.

Key words: friction, research stand, belt transmission

1. Introduction

Currently, belt transmissions are being used more frequently. The theoretical transmission efficiency should be more than 90%. Unfortunately, a large number of transmissions operates at a much lower efficiency. Among the most common mistakes made by people operating transmissions is insufficiently frequent monitoring of the running belt. This control refers not only to checking the belt tension and damage but also, which is particularly important for the topic of this project, the impurities that occur there.

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It should be remembered that the transmission may be contaminated by both solids (such as stones, sand, dust) and liquids (oil, water). As a result of the presence of contaminants in the transmission, both solid and liquid, different types of damage to the belt may occur, among which the following can be mentioned: excessive wear, chipping (breakage in the lower part), the formation of a spongy or sticky structure on its surface, twisting the belt in the groove, excessive wear of the ribs (in the case of ribbed belts), or even breaking [17]. In such cases it is recommended that the pulley be cleaned or changed, to change the belt and, if possible, to use appropriate covers.

A contaminated belt transmission does not only mean faster wear of its components, often leading to damage of the belt, but also decreases the transmission efficiency and increases energy losses. The consequences of poorly designed and supported belt transmissions are discussed in papers [16, 17].

The belt is an element transporting the load in belt transmissions. It is usually a loop made of leather, fabric, rubber, plastic, composite material or steel. Generally, the advantages of these materials are combined by applying the respective layers composed of them. A classic belt consists of a load-carrying and a flexible layer. The load-carrying layer mostly consists of steel or polyamide cords, and the flexible layer is made of rubber or rubber-and-fabric materials. The entire belt is wrapped by canvas or cord vulcanised tape. Such a structured belt obtains high strength, low elongation and good adhesion. The materials used, especially on the contact layer, have a significant impact on the values of the friction parameters.

V-belts and poly-V belts are the most often used in the industry, especially in industrial drives, agricultural machines and in the automotive industry. Poly-V belts are usually used in situations where there is a potential risk that the belt will work with extreme shock or pulsing loads. This type of load is most common in combustion engines (which is the reason for its wide application in the automotive industry), compressors, vibrators, crushers, road machines, etc. Moreover, these types of belts are used when the distance between the wheels in relation to their diameter is relatively large, with vertical shafts, reversing work, with clutches or transport technology.

It is also worth mentioning that poly-V belts are particularly sensitive to impurities. An example of such a transmission is that driving the alternator and the air conditioning in cars. This widespread application results in that it is a common problem. A more thorough examination of this group of belts has been planned. In the first phase of the research it is planned to test clean belts and, in the next phase, to test the contaminated belts.

Research studies on friction in the belt transmission started in the 18th century and were initiated by Leonard Euler [7]. More important tests performed over the centuries, with a specification of the more important works, are presented in Fawcett's widely cited work [8].

Research studies on clean belt transmissions are presented, among others, in works [1, 4, 5, 6], which present several empirical models, e.g. of friction, belt slip, contact between the poly-V belt and the pulley, axial and bending stiffness and damping of the belt. The most popular structure of the stand consists of DC engine connected to the drive pulley and hydraulic pump connected to the driven pulley.

The study of belt transmissions under conditions conducive to the presence of water or an ice layer between the belt and the pulley and the effect on the value of the coefficient of friction were presented by the authors of papers [2, 9, 15]. More general friction research on belt-steel contact with some impurities can be found in paper [3]. In this paper it is also presented how the amount of impurities has an influence on the friction parameters. The influence of a change in the rubber structure in long-term contact with oils on the friction parameters was presented in [14]. The conclusion, after looking through the literature, is that there are few works presenting studies on contaminated belts.

Because of the complexity of phenomena occurring in belt transmissions, it seems particularly difficult to describe friction and contact via an appropriate mathematical apparatus. The most common are piecewise linear friction models, such as Coulomb-like tri-linear creep-rate-dependent friction law [12, 13] or elastic / perfectly plastic friction law (EPP) [10].

2. Stand structure

Figure 1 presents the research stand designed and made by the TOP company which is located in Bielsko-Biała in Poland. The stand was created upon the request of the Department of Mechanics at the Faculty of Mechanical Engineering and Computer Science of the University of Bielsko-Biała.

Fig. 1. Research stand for measuring friction in a belt transmission

During the tests for which the stand is used it is possible to designate friction coefficients in the belt transmission. These tests can be implemented in three configurations: to determine the static friction coefficient, to determine the dynamic friction coefficient and to measure the vibrations of a completed transmission.

The results of the research will be used as input data to the model of a belt transmission that is currently being developed and which has already been presented, among others, in [11].

The first configuration, which is shown in Fig. 2, allows to determine the static friction coefficient by measuring the torque required to achieve the belt slip on the pulley.

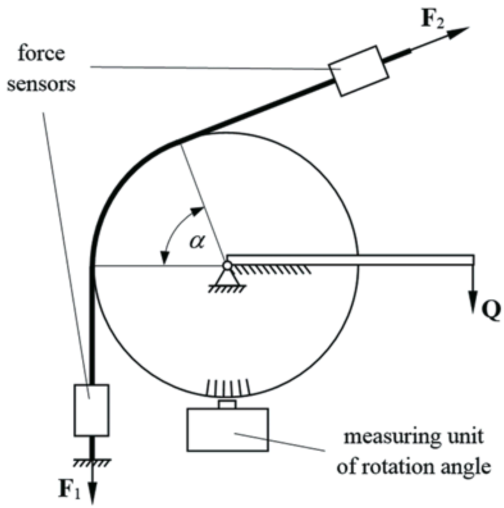

Fig. 2. First configuration of the research stand which allows to measure the static friction coefficient

A stand configured in this manner allows for tension of the belt segment by axial forces $\mathbf{F}_1$ and $\mathbf{F}_2$. The belt is pressed to the pulley with an assumed wrap angle of α under the influence of these forces. In addition, the stand allows to set the appropriate load torque of the pulley (via force $\mathbf{Q}$) which rises to a certain arbitrary value causing belt slip. Moreover, precise measurement of the pulley angle is necessary, not only to establish the precise moment of when the belt slip starts but also to measure the deformation of its elastic section. For this purpose we used a reflective sensor operating in the infra-red range connected to the Arduino platform.

Our own software captures moments of detection of arm motion. The software allows to separate the courses of forces F_1 and F_2 at this time without the need to interrupt the registration for subsequent measurements. Figure 3 shows this software, which was created in the Lazarus development environment.

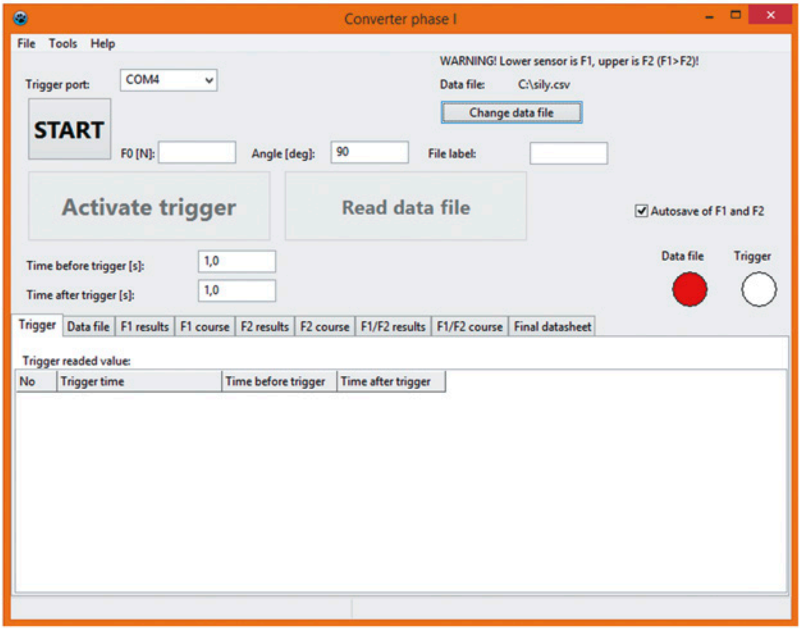

Fig. 3. Computer program for identification of forces F_1 and F_2 at moments of relative movement noticed between the belt and the pulley in the 1st configuration

The second study of the stand is presented in Figure 4.

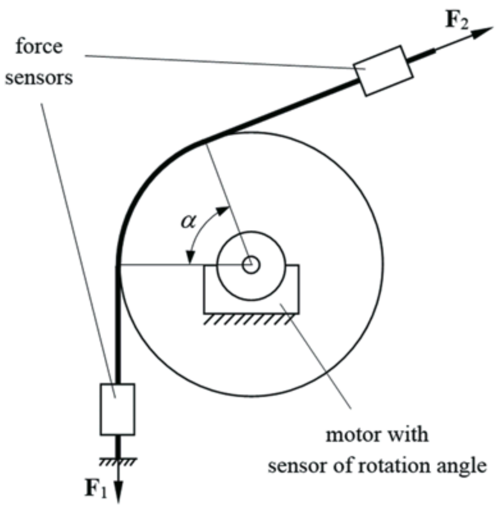

Fig. 4. Second configuration of the research stand which allows to measure the dynamic friction coefficient

This configuration of the stand consists of a pulley and a belt with an appropriate wrap angle of α and tension forces $\mathbf{F}_1$ and $\mathbf{F}_2$. The angular velocity of the pulley is measured during the test. Knowing this course and the courses of the forces on both ends of the belt makes it possible to determine the course friction force, which then allows to determine the coefficient of dynamic friction. A test stand built in this manner also allows to specify the form of the kinetic and dynamic characteristics, which are the courses presented as a function of the relative velocity of the belt and pulley, respectively, designated under steady and transient conditions.

Because the data recorded by the software as provided by the sensors' manufacturers is located in separate files, a second own program was made in order to simplify the tests (Fig. 5). Use of this program allows for all the results of certain measurements to be combined in one sheet. The results are interpolated as the recorded samples are registered at different moments.

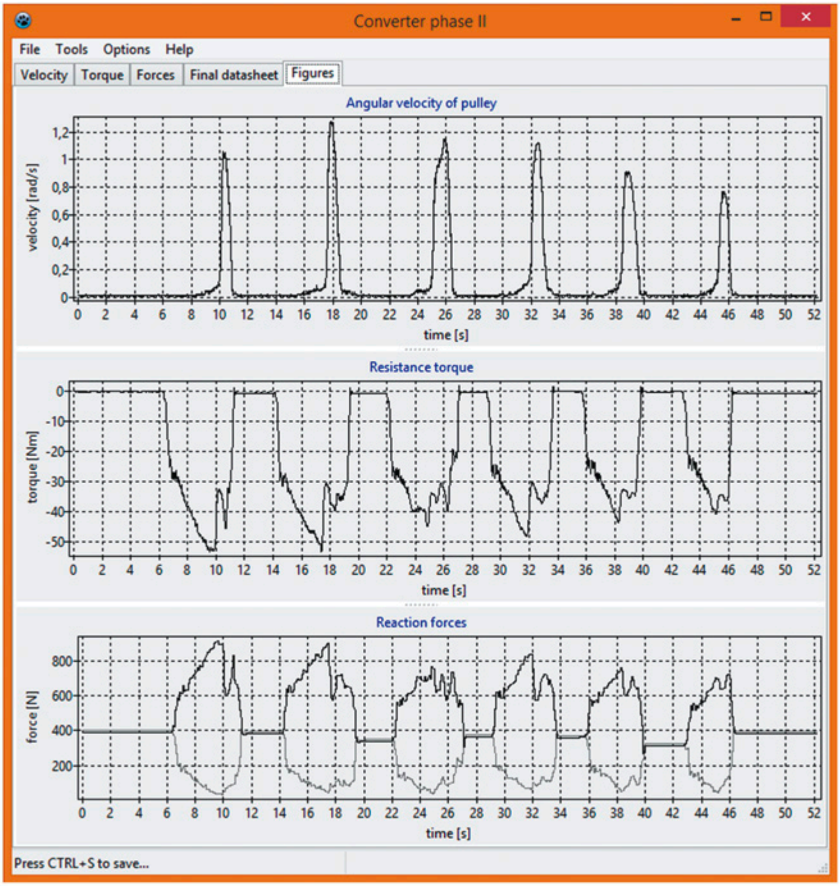

Fig. 5. Computer program which allows to register the measuring results done with the second configuration of the stand

In both configurations the choice of the value of the wrap angle has an effect on the belt-pulley normal forces but also helps to avoid zones of adhesion and slip around the pulley.

The last configuration can be used to determine the shape, amplitude and frequency of the vibration and belt slip values as a result of applied resistance torque. A schematic diagram of the configured stand is shown in Figure 6.

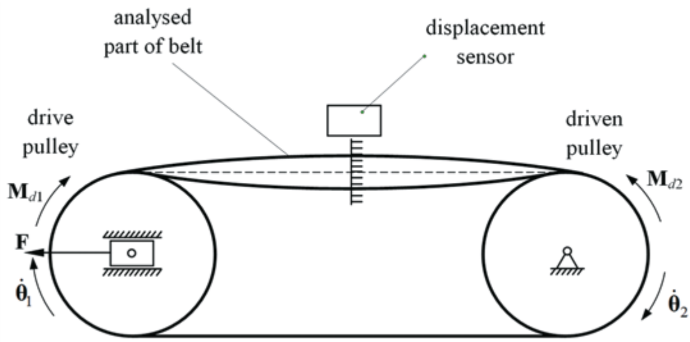

Fig. 6. Third configuration of the stand which allows to measure a complete belt transmission

Because the passive part of the belt is tensioned the least during transmission operation under steady conditions, it was decided that this part of the belt would be observed. The measurement can be done through a non-contact displacement sensor. A stand constructed in such a manner allows to estimate the frequency of these vibrations. The results will be used to verify the computer models of the developed belt transmissions.

It is worth noting that (perhaps by a slight reconstruction of the stand) by comparing the results of tests carried out on the stand and calculations made using some dynamic model, it would also be possible to designate the values of stiffness and damping of the modelled belt. An appropriate method for non-linear optimisation could be applied for this purpose. The decision variables for the optimisation problem would be the determined coefficients and the objective function minimised, i.e. some measure of the difference of the belt vibrations obtained from the tests and calculations.

Figure 7 schematically presents the structure of the research stand, in which the main parts have been marked as follows:

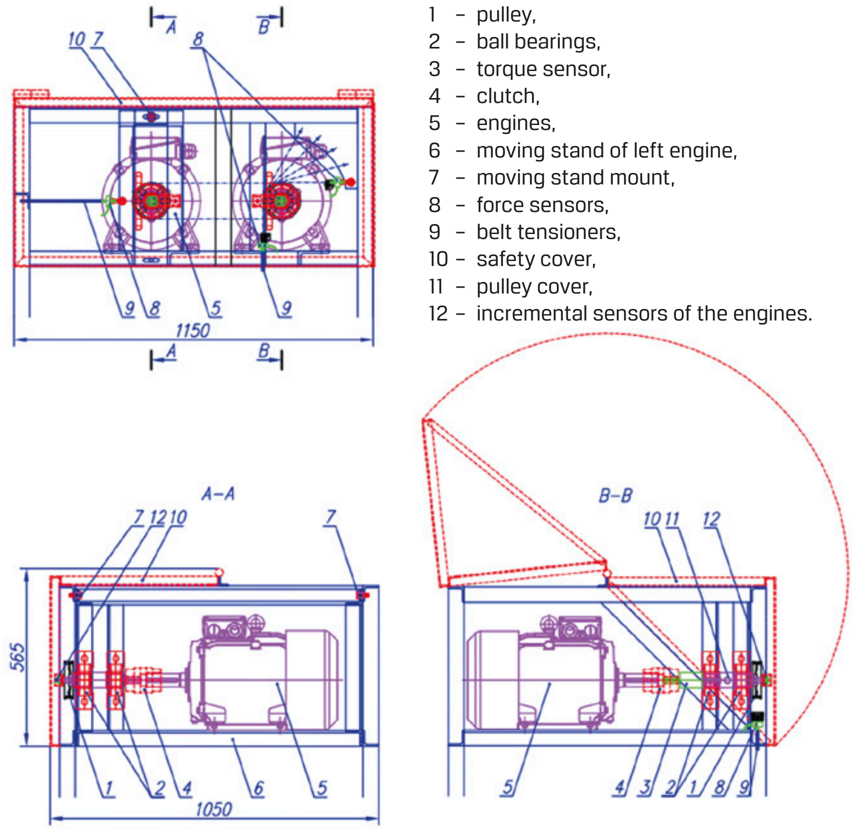

Fig. 7. Structure of the research stand [18]

Table 1 shows the specifications of the sensors used in the research stand.

Table 1. Measuring sensors used in the research stand

Application	Specification of the sensor and registering system	Measurement range	Measurement accuracy
Tensioning forces measurement	Strain gauge KMM20 with converter ADT42	5 kN	Linearity tolerance 0.2%
Resistance torque measurement on pulley shaft	Torque sensor DFM22 with display MD150M	250 Nm	Linearity tolerance 1%
Shaft angular velocities measurement	Incremental encoder DBS36E with reading panel K3HB-R	8000 rot/s	500 imp/rot
Belt deflection measurement	Displacement sensor ZX1-LD100	100±35 mm	resolution 7µm

Poly-V pulleys are mounted on the stand, although it is worth mentioning that changing these pulleys to other pulleys, e.g. V-belt or flat belt pulleys, allows to measure most types of available belts; the limitation may be only the length that needs to be adapted to the distance of the shafts and the diameter of the pulleys.

After mounting additional covers it will be possible to measure the friction parameters in the contaminated belt (i.e. water or oil), which is planned in the next part of the research.

The rotation of the pulleys was done by using two electric engines SG 160M-8A. The rotation can be applied either manually or automatically. In the 1st and 2nd configuration of the stand the belt is cut and coupled on the ends to the stand by force sensors KMM20. In the 3rd configuration the belt is tensioned by the screw moving the base of the left engine. The resistance torque is measured by sensor DFM22. In the 2nd and 3rd configuration the angular velocities of the pulleys are measured by the incremental encoders DBS36E.

The measurements are recorded in a computer using an analogue-digital card USB-1208FS and converters. As was mentioned before, the software used here comes from the sensors' manufacturers and own software that was written in Lazarus software development. The final analysis of the achieved results was made in MATLAB software.

Doubts may appear about the SG 160M-8A engines used here. These are asynchronous engines, so it is possible to apply the appropriate angular velocities through the accompanying inverters. This is especially important in the 3rd configuration, when the complete transmission with an uncut belt is tested. It was decided to choose these engines because the angular velocities in each of the engines have to be stabilised in this configuration. Stabilisation of these velocities can be easier than, for example, when using DC engines. Thus it is possible to measure the resistance torque in the transmission during a stabilised value of slip.

The author of this paper realised that this type of solution would be debatable. One would also have to be aware of the fact that these engines have higher vibrations in some angular velocities. The applied kind of inverters have an impact on the intensity of these vibrations, and these velocities should be avoided when measuring the transmission.

Figure 8 presents the course of vibrations of the stand (acceleration of the stand body) caused by the work of one of the engines (left engine). The results correspond to the unloaded engine. Significant acceleration values are visible for certain values of angular velocities, with a perceptible vibration amplitude.

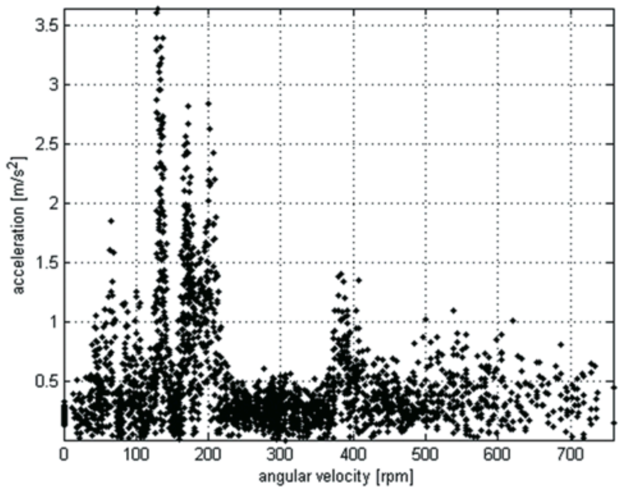

Fig. 8. Dependence of vibrations of the stand of the angular velocity of the left engine

In addition, under a significant load these engines do not maintain the angular velocity resulting from the settings of the inverters. This is due to slippage occurring in the magnetic fields of the engines. This problem was solved by using encoders on the pulleys.

More powerful engines as well as force and torque sensors with a much larger measurement range were assumed than should be expected during monitoring of the transmission. The stand can be used for other purposes, e.g. to measure the friction parameters of ropes.

Fig. 9. Top view of the control unit

Figure 9 shows the stand's control unit. The panel is connected to the stand with cables and it can easily be positioned by using castor wheels. Thus it is possible to move it to a convenient place. The panel allows to add a load individually for each engine by applying an angular velocity and the direction of rotation. It is also possible to directly monitor the angular velocity of the engine and the resistance torque.

3. Sample results

Figure 10 shows a sample fragment of the course of reaction forces F_1 and F_2 in the poly-V belt 5pk for the 1st configuration. The forces have been measured with a wrap angle of α=135°. The recorded course shows that force F_1 in the lower end of the belt increased to a value of ca. 800 N, while force F_2 in the upper end of the belt decreased to values of ca. 100 N. In a time of ca. 0.8 s relative movement of the wheel and belt is noticed which is recorded on a sensor. At the same time, the values of both of these forces stabilise, as can be observed in the figure.

The average coefficient of static friction can be calculated from the classic Euler formula:

$$\mu = \frac{\ln F_1/F_2}{\alpha} \cong 0.9. \quad (1)$$

The examples of the experimental results as shown below can be obtained in the 2nd configuration of the stand. These results were obtained for wrapping angle α=90°. The belt was pre-tensioned with a force of ca. 400 N. During the measurement the engine power was manually increased by regulating the inverter. The engine was stopped after obtaining a significant value of the angular velocity, which did not allow to heat the belt. These steps were repeated several times.

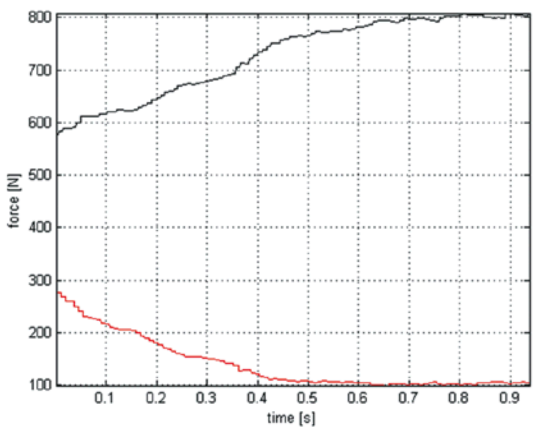

Fig. 10. Calculated courses of reaction forces for wrap angle α=135°: —— lower force F_1, —— upper force F_2

Figure 11 shows the measured courses of force values F_1 and F_2.

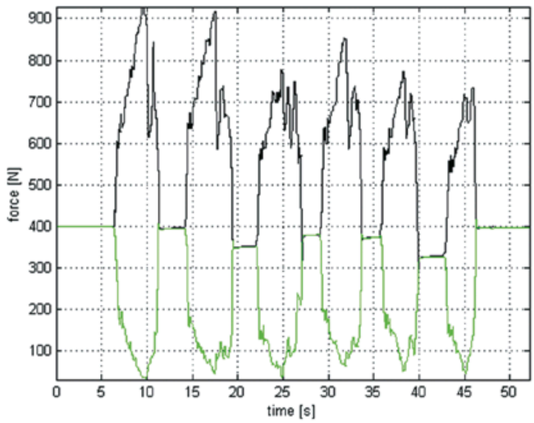

Fig. 11. Sample courses of the values of forces F_1 and F_2, measured using the 2nd configuration of the stand: —— force F_1, —— force F_2

A comparison of this figure with the previous one allows to notice much larger asymmetry in the resulting course. This is due to the presence of slip and adhesion zones, or irregularly occurring phases of friction on the entire surface of the belt and wheel. Furthermore, it can be observed that the values of forces F_1 and F_2 after engine shutdown stabilise in different values than at the beginning of the registration measurement. This is because of the presence of additional friction forces in the bearings of the pulley shaft and the engine shaft.

Figure 12 shows the recorded course of the angular velocity of the pulley. As can be observed, the pulley only rotates (the belt slips) in moments of larger values of the forces' proportion F_1 / F_2.

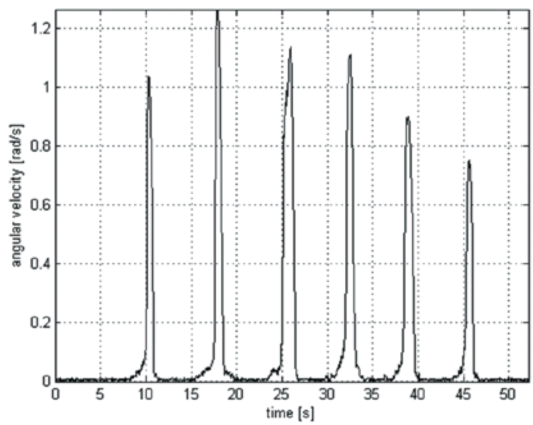

Fig. 12. Sample course of angular velocity measured using the 2nd configuration of the stand

Having the values of velocity and the values of forces F_1 and F_2 makes it possible to calculate the values of the velocity-dependent coefficient of friction. Figure 13 shows the obtained values.

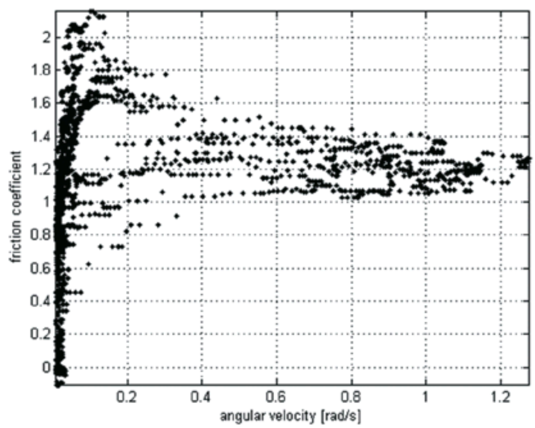

Fig. 13. Sample values of the friction coefficient as a function of the pulley angular velocity measured using the 2nd configuration of the stand

The figure shows that the greatest dispersion of the results is for lower velocities. At speeds in excess of 0.6 rad/s the coefficient of friction has less dispersion. The average remains approximately constant at ca. 1.2.

During the first preliminary measurement it was noted that such a large scatter of results at low sliding speeds occurred regardless of the value of the preload and the wrap angle, although the shapes of the clouds of the obtained results are different. It is possible that the spread was caused by other values of the coefficient during the increase or decrease of the angular velocity. It is important, therefore, to measure the dynamic characteristics of this coefficient.

4. Conclusions

In presented paper shown some results of clean poly-V belt transmission, but the stand can measure friction parameters of any belts transmissions occurring in cars: flat belts, V-belts or poly-V belts. The analysed subject of either a clean or contaminated belt transmission is very important both because of the decrease in power transmitted by the gear as well as because of excessive wear or damage. The results of the stand tests will help develop simplified empirical models of friction between the belt and the pulley in the transmission. The transmission model with a clean belt and the model with a contaminated belt, with such developed models of friction, should have a high computing effectiveness during the dynamic analyses.

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