A New Method of Semi-automated Measurement of Shear Friction Coefficient

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Abstract – **The paper is intended for engineer laboratory teaching and measurements in production engineering. The aim is a new method of measuring using the semi-automated measuring set and presenting the results of static shear friction coefficients and kinetic shear friction coefficients, depending on the relatively low speeds of the uniform translational movement of the body. In the framework of a specific engineering task, the methodological questions concerning the interpretation of measurement results in the context of engineering physics and its teaching are solved.**

Keywords **– *S*hear friction coefficient, intelligent drive.**

1. Introduction

The theory of shear friction in tribology is rigorously elaborated [1, 2], but practical tribometry is neglected mainly due to the fact that it requires precise measurements. The shear friction coefficients of a given combination of materials are most often tabulated for a static and dynamic dry surface and for a static and dynamic greasy surface [3]. Tabulated values are, however, only "estimates", sometimes estimated numbers and sometimes estimated numerical ranges. However, the numbers or the mean values of the numerical ranges can only approximately represent the properties of the given combination of contact surfaces, their actual roughness, the influence of various admixtures and impurities, the duration of the frictional forces, the temperature of the contact materials, etc. From a terminological point of view, the shear friction coefficient should be more precisely called the shear friction parameter because its value is never constant, but it changes over time due to many different physical and chemical influences.

In university teaching of general physics, the validity of the "laws" of friction is often presented. Although physical rule and physical law have their irreplaceable positions in science, they have incomparable informative values. The physical rule is valid except for exceptions ("exceptio regulum probat" - the exception checks the rule), while the Physical Law applies generally, i.e. it applies without any exceptions. The basic physical quantity describing the phenomenon of friction is the frictional force as the tangential force in the contact surface between two bodies, which acts against the change in the resting state in the case of static friction or against the direction of mutual movement of the bodies in the case of kinetic friction. The origin and effect of frictional force can be understood only empirically and experimentally, its magnitude can be measured on the basis of knowledge of three rules. According to the first Amontons rule, the magnitude of the frictional force in the case of static and kinetic friction is proportional to the perpendicular compressive force, and the dimensionless shear coefficient can be defined from the ratio of these forces. In the case of shear friction between the body and the underlay, the shear friction coefficient applies to a wide range of perpendicular compressive force. An exception is the case of relatively small perpendicular compressive force acting on the surface of the material with a layer structure.

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According to the second Amontons rule, the magnitude of the frictional force is independent of the size of the contact surface of the bodies. This rule is considered by students to be particularly "paradoxical", but in principle, it is the consequence of the first rule: if the two bodies are equal in weight, they must have the same normal compressive force acting on the same underlay, even in the case of different sizes of contact surfaces. Although the pressure as an action of a perpendicular compressive force on the contact surface is not solved in principle, the exception to the rule is the case of application of a pressure greater than the strength limit. The third Coulomb rule determines that the frictional force in the case of kinetic friction is not dependent on the speed of movement, or that its change in relation to the speed of the movement is not "assumed" [4]. During the dry friction, however, the load is transmitted only by contact between the inequalities of the friction surfaces. Inequalities in contact surfaces are most often measurable in micro-meters, so they may not be distinguishable by the naked eye, but their interactions are demonstrated to be importantly measurable. The elevations of one surface gradually fit into the recesses of the adjacent surface and vice versa, which gradually results in mutual elastic deformations of these surface inequalities, possibly leading even to intermolecular interactions. An exception to this rule is the relatively high velocity of motion, at which the frictional force / kinetic shear coefficient decreases more significantly. Apart from the issue of dry friction, the cases of friction of imperfectly rigid surfaces or surfaces coated with liquid grease (see Stribeck curve) are studied in detail.

Methodologically, physics is a science of nature and also a foundation of technology, therefore both qualitative experiments and exact measurements are of undisputed significance in both secondary school and university teaching of science and technology, and they have also very important verification significance for technical practice [5, 6]. The theoretical and experimental components of the cognitive process should be kept constantly in equilibrium, however, the experimental component is often neglected or at least replaced by (theoretical interpretation, simulated experiments, etc.) for various reasons. The development of the cognitive component should be adequately associated with the students' personal empirics and thus organically linked to the development of their logical and analytical thinking so that students can not only correctly interpret their acquired knowledge but above all apply it flexibly and creatively in their future graduate practice [7].

The Energy Conservation Law is, of course, the pillar of natural science, but its unequivocally precise definition is conventionally quite demanding. One of the classic definitions is this: "The total mechanical energy of an isolated system of bodies remains constant during the mechanical process." In other words, the general law of energy conservation does not take into account in the conservative system the conversion of mechanical energy into thermal energy produced by friction. The primary problem of "theoretical" exclusion of friction, which is virtually inseparable from reality, lies in the fact that there is no perfectly "isolated" body or a perfectly isolated system; the conservative and dissipative system must, therefore, be always systematically differentiated [8, 9]. The secondary problem is the fact that the measurement of the dissipative energy generated by the friction effect is experimentally very difficult and it can only be realized with sufficiently precise indirect measurements. Similarly, the influence of friction is not presupposed by the first Newton's law, the law of inertia. One of its classic definitions is: "The body stays at rest or in uniform linear motion if it is not forced by external forces to change this state." In reality, however, no perfect uniform linear motion exists because there is no perfectly "isolated" body that would not be affected by friction.

The moving body has the ability to maintain its motion state "by inertia" from the moment when last force ceased to act on it, but sooner or later, as a result of frictional forces, it stops. Therefore, especially in engineering education, the interdisciplinary link between the general physics, applied physics, and technology must be continually created so that the student of technology does not consider for example absurdly the general physics as a "fictitious" science that has little in common with the reality of phenomena and actions around us. Exactly the understanding the "measure" of friction influence is one of the suitable examples of how to build and strengthen the interaction between the physics and technology. The importance of friction forces in the automotive industry as braking forces for clutches or for the wheel to ground contact is absolutely crucial, while friction between piston and cylinder is undesirable; civil engineering deals with anti-slip floors or friction losses in contact with pre stressed reinforcements and surface, etc. All classical and advanced applications of friction actions require an increased attention both in technical practice and in teaching.

For the measurement of shear friction coefficients, multifunctional, sophisticated, computer-controlled tribometers produced by various global hi-tech companies (such as Anton Paar, Bruker, TRIBOtechnic, Rtec instruments) are very costly, either by their purchase price or by their price for one-off tailor made measurements. The material

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technical equipment used in the design of the presented measurement set is easily accessible because it is based on an innovative connection of the self-manufactured components with relatively simple and inexpensive commercial devices, i.e. in particular on the connection of a computer with intelligent drive and a digital dynamometer.

2. Measuring set

The configuration of the measuring set is based in particular on the connection of the laptop with the intelligent drive and digital dynamometer. These devices are fixed at the opposite ends of the self-manufactured horizontal friction bench (Figure 1.) made of spruce wood.

The digital dynamometer Dual-Range Force Sensor made by the company Vernier Software & Technology (Figure 2.) serves for measurements of the tensile force. The sensor is based on a resistance strain gauge. In principle, the measured force bends the internal beam, the deformation of the beam causes a slight change in its electrical resistance and simultaneously a corresponding change in the voltage inside the sensor circuit. The connected interface evaluates the change in voltage and recalculates it to the force in newtons. The digital dynamometer is connected to another external equipment LabQuest (Vernier) designed to analyze, display and process the converted data. This data logger (Figure 2.) is set in a time base mode, with optional frequency, a period of recording and total duration of the experiment. The sensor has a sensitivity of 0.01 N for the used range from -10 N to 10 N, i.e. the relative maximum uncertainty of the force measurement (at a maximum value of 3.25 N) is 0.3%.

Figure 1. Friction bench for measuring the length of the contact surface (69.5 cm) its horizontal plane is established with the use of the libel

a) b)

Figure 2. Connection of a digital dynamometer with a data logger, when setting relatively small a) and relatively larger constant angular speed of the intelligent drive shaft revolutions b)

The tensile force is provided by an intelligent drive Dynamixel MX-64 T made by the company Robotis (Figs. 3. and 4.). The intelligent drive is designed not only for changing the power or movement parameters of the transmitted energy through the transmission between the driving and the driven component, between the motor and the shaft. This device contains a DC motor, which reduces the shaft speed at an increased load and vice versa; i.e., it also compensates for the gradually increasing Euler friction of the cable threads on the external shaft. The intelligent drive shaft, therefore, rotates at the desired constant angular velocity even at different loads. This is facilitated particularly by the fact that, in addition to the motor, the intelligent drive comprises also its own control unit and a set of sensors, so it manages "auto-control". The intelligent drive is "self-controlled", but at the same time, it is connected to the "superior" external control unit CM-700 (Robotis), which is used in parallel to monitor the intelligent drive data. This data is displayed in the connected laptop so that the user can effectively evaluate and interpret it after conversion in a spreadsheet (Excel). Servo-motors Dynamixel have a non-contact magnetic position sensor and a PID controller (i.e., a continuous-action controller composed of proportional, integration and derivation parts) for ensuring high accuracy and reliability with 12bit resolution (4096 steps) and they can operate in the range of 360° at a resolution of 0.008°; the relative uncertainty of setting the desired angular speed of revolutions is 0.002%.

Figure 3. Self-manufactured external part of the composite shaft screwed onto the internal shaft of the intelligent drive

Figure 4. Dismantled external part of the composite shaft of the intelligent drive

An increased attention was paid to the preparation of the sample. The plate of the test material was fixed to the self-manufactured travel (Figures 5. and 6.). This travel was additionally loaded with the measuring apparatus, i.e. a dynamometer coupled with a data logger and with additional weights, the total weight of the load being $m = 0.504$ kg. The travel was manufactured on an assembled 3D-printer kit (Figure 7.).

3. Measurement of shear friction coefficient

The transformation of dry static shear friction into dry kinetic shear friction at start-up (or vice versa during braking) is practically immediate, taking place at very low initial velocities and very small times in relation to the overall system dynamics. The transition between both types of friction is characterized by two basic values: the minimum speed threshold and the limit value of the static friction force.

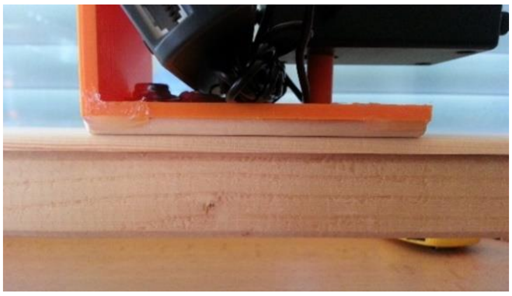

Figure 5. A spruce wood sample on a horizontal tribometer made of spruce wood, detail of the load by the measuring device

Figure 6. A spruce wood sample on an inclined tribometer made of spruce wood, detail of the load by the measuring device

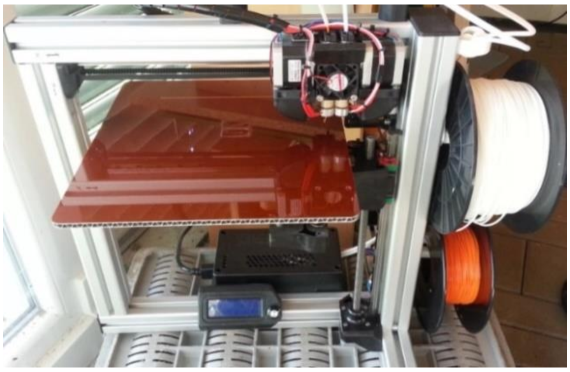

Figure 7. Assembled 3D-printer kit used for the manufacture of the travel

Robotis is an open system that uses intelligent drive and allows modelling of the change in the shear friction coefficient according to speed in principle in two ways: it is possible to set the constant speed of the shaft revolutions of the intelligent drive or to program it as a variable; in this case most appropriately as a linearly increasing speed. The method of linearly increasing speed has an advantage in comparison to the method of constant speed since there is no need to eliminate the travel delay in the "jump setting" of the selected constant speed. However, the principal complication lies in finding the "onset" of a steady average value of the kinetic friction force and in determining the response to small changes. This search must be in practice realized in two stages. During the first stage the measurements are made discreetly (using the constant speed method), afterward the results are analyzed so that in the second stage a "continuous" speed change can be solved. This change is naturally quasi-continuous because it is based on the final, large number of partial iterations and the "step-like" evolution of the resulting curve $f = f(v)$ must be approximated. In the paper, therefore, for the methodological reasons, the primary and simplest method of constant angular velocity was chosen. Altogether 7 values of shear friction coefficients were discreetly measured in dependence on the relatively small velocity of the translational movement of the body, and all other function values of the speed interval $f = f(v)$ were interpolated (Figure 15.). The transition of the static friction force into the kinetic friction force has a physically different character than that of the "travel delay" at the start-up of the intelligent drive, i.e. during the transition from a state of the body at rest to a state of translational uniform motion. The transition of the value of the static shear coefficient to the kinetic shear friction coefficient in relation to the translational velocity was interpolated (Figure 15.), however, the coefficient of static and kinetic shear friction must be measured by different methods (see 3.1, 3.2, 3.3).

The static shear coefficient can be determined by the friction angle φ (Figure 8.) on the horizontal plane or by the elevation angle α (Figure 11.) on the inclined plane where it is necessary to overcome still existing strong bonds in the interacting contact surfaces. According to Figure 13., it can be seen that the tensile force generated by the intelligent drive never reaches value of the static friction force (2.97 N), whereas in Figure 14. it can be seen that the tensile force generated by the intelligent drive exceeds the same static friction force by the value of 3.25 N, and only at the first flash during the travel delay. The intelligent drive with a constant angular velocity of the shaft can be therefore used for highly reliable measurements of the kinetic shear friction coefficient only, where the solid bonds in the interacting surfaces do not exist anymore.

3.1 Measurement of the static shear coefficient by a horizontal tribometer

If no external force acts on the body, only the gravity $G = m \cdot g$, acts on it where m is the mass of the body and g is the gravitational acceleration (at the latitude of 45° the value of g is approximately $9.81\ m \cdot s^{-2}$) acts on it due to the gravitational field. The body acts by its gravity (with the point of application T in the centre of gravity of the body) perpendicularly to the underlay. The underlay "responds", that is, it acts on the body by the normal force N, from the point of application P on the underlay. These are, therefore, two different forces simultaneously emerging and disappearing, of the same magnitude, oppositely orientated and with different points of application in the same vector line. The effects of action-reaction forces do not interfere mutually with each other, so they cannot be added together because each of these forces acts on the different body.

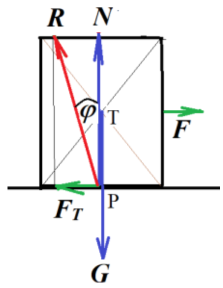

Figure 8. The friction angle tangent φ determines the value of the static shear coefficient

The resultant of reactive force components N, F_T is the force R, which is deviated from the normal force N exactly by the friction angle φ, the tangent of which (Fig. 8.) can be according to (1) expressed as the static shear friction coefficient f_0

$$F = F_T \wedge G = N \wedge G = m \cdot g\ ;$$
$$F_T = f_0 \cdot N \Rightarrow f_0 = \frac{F_T}{G} \Rightarrow f_0 = tg\varphi \qquad (1)$$

The classic laboratory method for determining shear friction coefficient is manual. The body is put into motion along the friction surface of the tribometer by pulling the fibre through a pulley that is embedded in a horizontal tribometer frame. A bowl of weights is suspended at the other end of the fibre. The bowl is gradually loaded in small increments with elemental weights (or grains of sand) until the body starts to move. The tensile force caused by the weight of the total load and the bowl is transmitted to the body. The mass of the suspension bowl and load is weighed. The ratio of the tensile force to gravity indicates the value of the static shear coefficient f_0. Manual measurement is very demanding since it requires particularly the experimenter’s precise execution and experience, but it is not as accurate as a semi-automated measurement. Out of 10 repeated measurements, the mean value for static frictional force $F_T = 2.97$ N, was determined at a total mass m = 0.504 kg. The value of the coefficient f_0 was determined to be 0.6, i.e. it corresponded to a friction angle of 31°. This value also corresponds to the mean value of the tabulated interval for the combination of materials of spruce wood-spruce wood, however, due to the manual handling it was verified with the use of an inclinable tribometer (see 3.2).

3.2 Measurement of static shear coefficient by inclinable tribometer

The horizontal friction surface was modified as a semi-automated inclinable tribometer (Figure 9.).

Figure 9. Friction bench arranged as a semi-automated inclinable tribometer

For the purpose of achieving possibly the most accurate measurement result, a stepping of an elevation angle of the inclined plane was originally developed; the setting used specifically the stepping increments of 0.1°. If the friction plane is inclined by an elevation angle approximately equal to the friction angle, it is sufficient just to manipulate sensitively with the inclination of the inclined plane (Figure 10.).

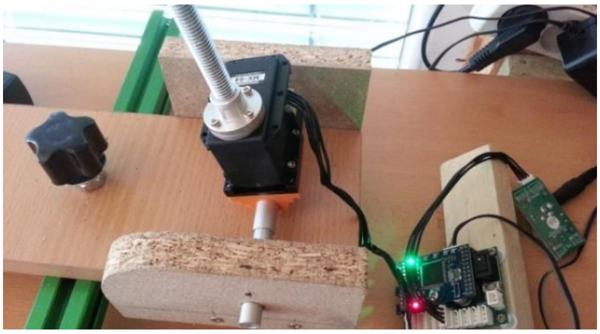

Figure 10. Detail of the setup of the measuring set for the precise detection of the moment, when during increasing/decreasing the elevation angle the body starts/stops moving over the friction surface

If the body on the friction plane set at the desired angle still moves, the elevation angle should be slightly reduced to stop this movement. Conversely, if the body does not move on the inclined plane, the elevation angle should be slightly increased to make it move. At the moment of change of state of motion of the body, it is possible to stop stepping of the inclination of the inclined plane with the use of the user-friendly software LoggerLite program in the data logger.

The inclined plane of the inclinable tribometer has a length l, height h, length of the base z, and elevation angle α. If the body moves on the inclined friction surface, the motion tangential component F_P and the pressure normal component F_N of the force G (Figure 11.) act on it, while the effects of both components are mutually independent.

The reaction to the pressure component is the normal force N, the reaction to the motion component is the frictional force F_T. The smaller the inclination of the inclined plane, the smaller is the moving component of the gravity at the expense of the normal force and vice versa. According to the goniometric relations of the rectangular triangle, the following is valid for the force F_P/friction force F_T and the compressive force F_N/normal force N (2)

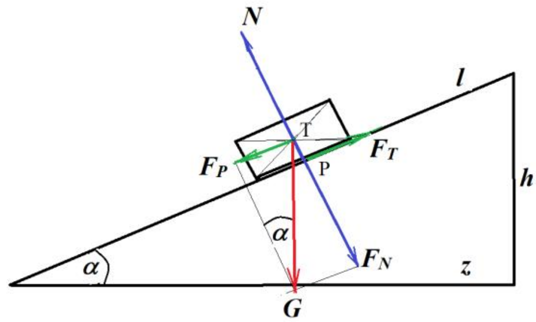

Figure 11. The tangent of the elevation angle α determines the static shear friction coefficient

$$F_P = F_T \wedge F_N = N; F_P = G \cdot \sin\alpha \wedge F_N = G \cdot \cos\alpha \qquad (2)$$

The force F describing the resulting motion of the body can be expressed according to the Second Newton Law by equation (3) and at the same time with the use of (4) as a motion component F_P of the gravity G decreased by the friction force F_T acting in an opposite direction.

$$F = m \cdot a \qquad (3)$$

$$F = F_P - F_T \wedge F_T = f \cdot F_N \Rightarrow$$
$$a = g \cdot (\sin\alpha - f \cdot \cos\alpha) \qquad (4)$$

The acceleration a is zero at the moment of rest, it is, therefore, valid that $f = f_0$ (5)

$$f_0 = tg\alpha \qquad (5)$$

The elevation angle of 31° was verified by a protractor and the value of the static shear coefficient $f_0 = 0.6$ (see 3.1) was confirmed. The magnitude of the elevation angle α was also checked by measuring the dimensions h, z of the inclined plane (6)

$$tg\alpha = \frac{h}{z} \Rightarrow \alpha = arctg\frac{h}{z} \qquad (6)$$

3.3 *Measurement of the kinetic shear friction coefficient by a horizontal semi-automated tribometer*

Measurement of the kinetic shear friction coefficient is offered on the website of the company Vernier as an advanced and demonstrative measurement using the Vernier digital dynamometer. The body is manually pulled on the underlay by a fixture attached to the digital dynamometer. The exertion of the tensile force manually is incomparably inaccurate because it cannot be predicted. Incorporating an intelligent drive into a measuring set ensures an exertion of a constant angular speed of shaft revolutions or of a variable angular speed of revolutions according to the desired function. The total duration of each of 6 dynamic experiments was 10 seconds, whereas a uniform step of measurement of 0.005 was set. This means that during one experiment 2,000 data were recorded in total. Since each experiment was repeated 10 times, a total of 120,000 data was recorded. The travel delay was variable at a setting of different shaft revolutions (maximum 1.8 s). Due to the requirements for accuracy of calculations, the travel delay was not included in the evaluation of indirect measurement results of the mean values of kinetic shear coefficients at different velocities for the first 2 s. Figure 12. shows the evolution in time of the mean values of the tensile forces developed by the intelligent drive. During the travel delay phase, a total of 24,000 data were averaged (i.e., 400 data for 10 repetitions of each of 6 dynamic experiments).

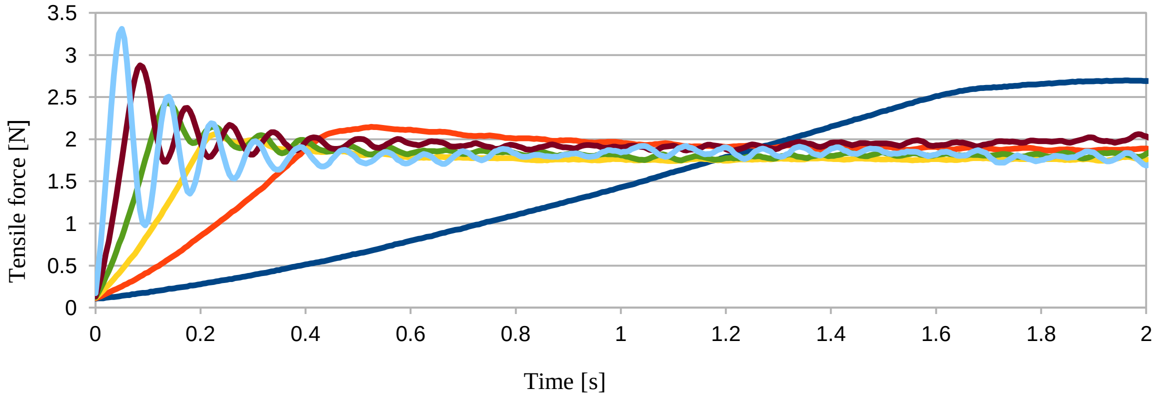

Figure 12. Comparison of evolution in time of tensile force developed by the intelligent drive during the travel delay, with the following setup of the angular speed of the intelligent drive shaft revolutions: 1.25rpm dark blue, 3.75rpm orange, 7.5rpm yellow, 15rpm green, 30rpm brown, 60rpm light blue)

It can be seen that the lower set angular speed of the intelligent drive shaft (1.25rpm, 3.75rpm, 7.5 rpm), the longer is the onset of the mean value of the tensile force, but this onset at the same time shows a relatively smooth trend. When relatively higher angular speeds are set (15 rpm, 30 rpm, 60 rpm), the onset of tensile force begins on average more quickly, but at the cost of higher oscillations with higher double amplitudes. The setting of the mean tensile force is limited by the power of the used intelligent drive, by the radius size of the part of the composite shaft, on which the pulling cable is wound in the context of the selected load of total mass *m*.

The values of the kinetic shear friction coefficients fi (i = 1..., 6) were measured indirectly according to the definition relation (7).

$$f_i = \frac{F_i}{G} \quad (7)$$

Figures 13. and 14. illustrate the evolution in time of the tensile force developed by the intelligent drive when the smallest and biggest angular speed of the shaft revolutions is set.

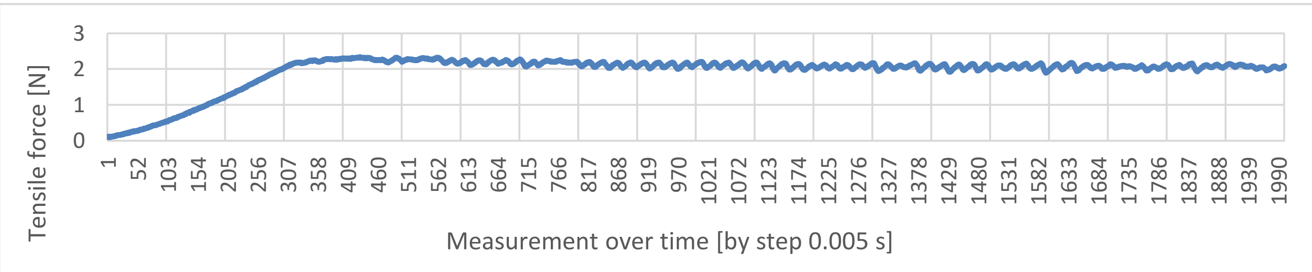

Figure 13. Example of evolution in time of tensile force when an angular velocity of the intelligent drive shaft is set to 1.25rpm (Table 1.)

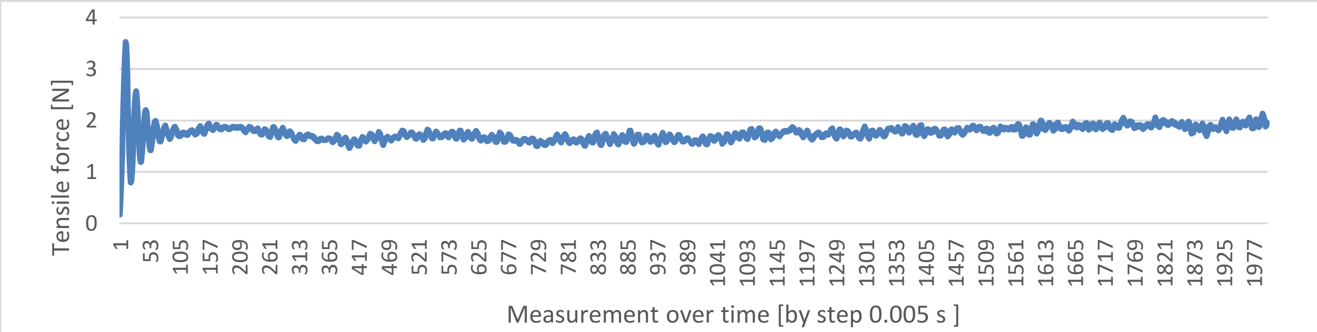

Figure 14. Example of evolution in time of tensile force when an angular velocity of the intelligent drive shaft is set to 60 rpm (Table 1.)

Table 1. Conversion of a number of revolutions of the intelligent drive shaft per minute (rpm) to the translational velocity of the pulled body ($m \cdot s^{-1}$), for adequate shear friction coefficients f_0, f_1… f_6

Frequency [rpm]	Translation velocity [$m \cdot s^{-1}$]	Symbol	Shear friction coefficient [-]
-	0	f_0	0.61
1.25	0.00092284	f_1	0.47
3.75	0.00276852	f_2	0.38
7.5	0.00553706	f_3	0.37
15	0.01107411	f_4	0.37
30	0.02214823	f_5	0.37
60	0.04429646	f_6	0.36

Physical and technical measurement units must be compatible (Table 1.). If relatively very small angular velocities are used, multiple units of measurement are commonly and advantageously used in technical practice. The rpm measurement unit is used in technical practice as a secondary unit of the SI system for the frequency, it expresses the number of revolutions per minute (1 Hz = 60 revolutions/minute = 60 rpm). For conversion of n [rpm] to angular velocity ω [rad/s] the following is valid $\omega = 2 \cdot \pi \cdot n / 60$. The relation between the angular velocity ω and the radius r ($v = \omega \cdot r$) is then used for conversion of the translation velocity measured in the physical units $m \cdot s^{-1}$. The radius of the used shaft was 0.00705 m.

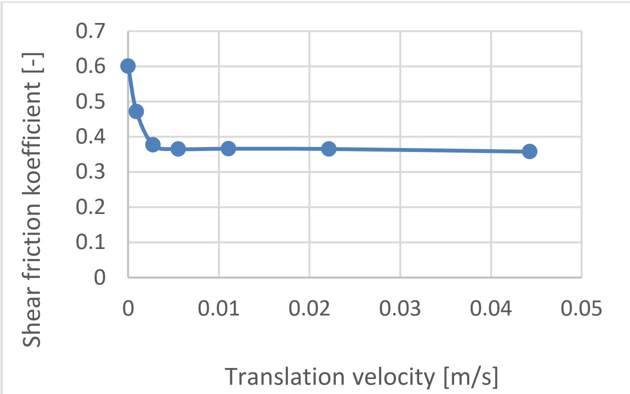

Figure 15. Change of the shear friction coefficient in dependence on the translation velocity of the body

Figure 15. shows the dependence of the shear coefficient on the translation velocity. The decrease of the values f_1, f_2 relative to the value f_0 is relatively steep, it corresponds to the phase of the transition between static and kinetic friction. These are the onsets of the average values of tensile force at relatively slower shaft revolutions (1.25 rpm to 7.5 rpm). With accuracy to 2 decimal places, the change of the values f_3, f_4, f_5 appears to be approximately constant, the value f_6 again represents a slight decrease. These are onsets of the average values of tensile force at relatively faster shaft revolutions (15 rpm to 60 rpm).

4. Conclusions

The paper presents a new method of computer-controlled measurement, which is easy to perform in the laboratory, as well as in normal technical practice. The basic components of the measuring set are commercial devices: a computer with a spreadsheet, a digital dynamometer with a data logger and intelligent drive. The layout of the proposed experiment is original. The sample installed by self-help on the travel is connected to the commercial devices of the set. The set comprises also a friction bench, to which the measuring devices are fixed; the outer composite shaft is screwed onto the internal shaft of the intelligent drive.

The results of the illustrated measurement give a satisfactorily accurate actual value of static and kinetic shear friction coefficient for the given combination of spruce wood-spruce wood, in dependence on the relatively small velocities of the translational movement of the body (up to 0.16 $km \cdot h^{-1}$). These results were checked by comparing them with the tabulated values and they were evaluated as appropriate.

Illustratively, a total of 120,000 data were taken by direct measurements. The well-reproducible results are in line with the expected tabulated values and they are also in line with the following conclusions, which the student accepts on the basis of personally acquired experience with a full understanding of the concerned issue:

1. A frictional force always acts against the direction of the kinetic force (in the case of static friction) or against the direction of the tensile force (in the case of kinetic friction), and the effect of its action is heating of the contact surface. The generated heat represents an irreversible conversion of part of the total mechanical energy into the dissipative energy.
2. The static friction force/static shear friction coefficient is always significantly bigger than the kinetic friction force/kinetic shear friction coefficient. The reason for this inequality is the fact that the molecules in the contact surfaces are at rest more strongly attached to each other. Since a great part of the mechanical work needed to overcome these bonds transforms into dissipative energy, this conversion manifests itself most significantly in the phase of the transition between static and kinetic friction.
3. Friction between dry surfaces is of discontinuous character. In reality, the friction-influenced tensile force can never be accurately measured as a constant value but only as a value relatively oscillating value around a certain mean value.
4. With the increasing relatively low speed of the intelligent drive shaft revolutions, the tensile force/kinetic shear friction coefficient decreases non-linearly and more significantly. With the increasing relative speed of the intelligent drive shaft revolutions the tensile force/kinetic shear friction coefficient decrease in a non-linear manner and less significantly.
5. Tabulated values of shear friction coefficients can be used in estimation calculations only as indicative values; the actual values of shear stress coefficients required for accurate calculations, particularly in practice of civil engineering and mechanical engineering can be obtained only by accurate measurements.

The methodological objective of the paper is to use solving of the specific physical-technical task for addressing the most common mistakes made by students of engineering; it concerns specifically strengthening of the link between the teaching of physics, technology, automation and computing and emphasizing the importance of friction for technical practice.

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References

[1]. Gohar, R., & Rahnejat, H. (2012). *Fundamentals of tribology*. World Scientific Publishing Company.

[2]. Krc, K., & Wermager, S., & Sneed, L.H., & Meinhe, D. (2016). Examination of the effective coefficient of friction for shear friction design. *PCI Journal*, 44-67.

[3]. Coefficient of Friction, http://www.engineershandbook.com/Tables/frictioncoefficients.htm

[4]. Halliday, D., Resnick, R., & Walker, J. (1997). Electric Potential. *Fundamentals of Physics*, 342-344.

[5]. Rajamani, R., Piyabongkarn, N., Lew, J., Yi, K., & Phanomchoeng, G. (2010). Tire-road friction-coefficient estimation. *IEEE Control Systems*, *30*(4), 54-69.

[6]. Hennessy, S., Twigger, D., Driver, R., O'Shea, T., O'Malley, C. E., Byard, M., ... & Scanlon>, E. (1995). Design of a computer-augmented curriculum for mechanics. *International Journal of Science Education*, *17*(1), 75-92.

[7]. Peng, Y. X., Zhu, Z. C., Chen, G. A., & Cao, G. H. (2007). Effect of tension on friction coefficient between lining and wire rope with low speed sliding. *Journal of China University of Mining and Technology*, *17*(3), 409-413.

[8]. Rajamani, R., Piyabongkarn, N., Lew, J., Yi, K., & Phanomchoeng, G. (2010). Tire-road friction-coefficient estimation. *IEEE Control Systems*, *30*(4), 54-69.

[9]. Baker, R. S. (2014). Educational data mining: An advance for intelligent systems in education. *IEEE Intelligent systems*, *29*(3), 78-82.