Journal of the Balkan Tribological Association *Vol. 26, No 1, 1–10 (2020)*

Fundamentals of frictions

DEVICE AND METHOD FOR SIMULTANEOUS DETERMINATION OF ROLLING AND SPINNING FRICTION IN A CONCENTRATED CONTACT

S. ALACI[a], L. IRIMESCU[a], F.C. CIORNEI[a], M. KANDEVA[b,c]

[a] *Mechanics and Technologies Department, Stefan cel Mare University of Suceava, Str. Universităţii 13, Corp B, 720229 Suceava, jud. Suceava, România*
**E-mail: stalaci@yah oo.com*
**E-mail: luminita.irimescu@usm.ro*
**E-mail: florina.ciornei@usm.ro*

[b] *Faculty of Industrial Engineering, Tribology Center, Technical University – Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria,*
** E-mail: kandevam@gmail.com*

[c] *South Ural State University, 76 Prospekt Lenina, Chelyabinsk, Russia*

ABSTRACT

This paper represents the methodology and its related device for the simultaneous determination of the spinning friction moment and the rolling friction moment in a concentrated contact. The method is exemplified for a concrete example, the values obtained for the two coefficients being of the order of the microns in accordance with other papers and with the roughness characteristics of the ball and rod surfaces.

Keywords: tribology, spinning friction, rolling friction, experimental.

AIMS AND BACKGROUND

In applied engineering, the cases when in a concentrated contact the angular velocity has a direction parallel or perpendicular to the normal in contact are rare. When the angular velocity is parallel to the normal, only spinning friction occurs in contact and when it is perpendicular to it, only rolling friction is present in the

* For correspondence.

contact[1]. In a general case, the angular velocity has a random position with respect to the normal and both parallel and normal components can be observed. From here, the conclusion is drawn that in a concentrated contact both spinning friction and rolling friction are simultaneously present. Moreover, under the assumption of dry friction contact, while the velocity components are interdependent, the two friction torques are independent.

The two moments can be estimated separately[2÷8] or at the same time. The first manner is widely met in literature but for the second methodology there are no references available. This remark is the basis of the present paper. In a first stage, the proportionality between the friction torque (rolling/spinning) and the normal reaction is accepted[9] and the two spinning and rolling friction coefficients in a concentrated contact are found out. As experimental method, the oscillatory motions were involved since they permit the characterization of the properties strictly from the contact region[10,11].

THEORETICAL ASPECTS

A theoretical model for simultaneous finding of rolling friction moment and spinning friction moment in a concentrated contact was developed in a recent work[12]. The principle of the methodology, in succinct presentation, consists in establishing the law of variation of the angular amplitude of a pendulum. The pendulum is constructed using a bearing ball of R radius and a cylindrical rod attached to it. The ball is in contact with two parallel cylindrical beams (with r the radius of the cross-section), placed at a distance $2d$ between the longitudinal axes, situated in a horizontal plane, as it is shown in Fig. 1.

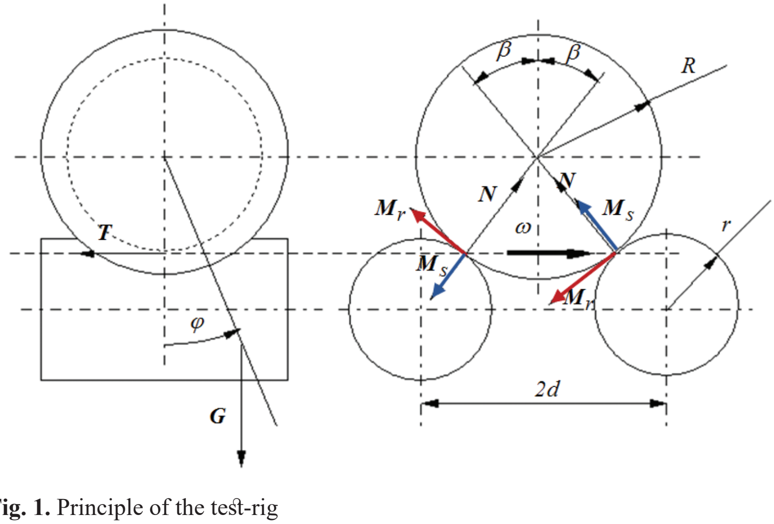


Fig. 1. Principle of the test-rig

In each of the two concentrated contacts a normal force N, a friction force T together with the friction moments will act. The spinning friction moment M_s is orientated along the normal in the contact point and the rolling friction moment M_r is contained in the tangent plane to the contact point. In a general case, the pendulum behaves as two degrees of freedom system, that is: the rotation about the horizontal axis passing through the center of the ball and the horizontal motion of the center of the ball.

Assuming pure rolling between the ball and the beams, a relationship between the two parameters of position can be written and therefore finally, only one of the parameters is sufficient for describing the position of the pendulum. The parameter chosen in[10] for describing the position of the pendulum was φ, the angle made by the rod with the vertical direction.

The center of mass theorem and the angular momentum theorem were applied and the following differential equation of the law of motion was found out:

$$\ddot{\varphi} = -\frac{\left(\frac{s_{sp}}{\xi}\sin\beta + \frac{s_r}{\xi}\cos\beta\right)sgn(\dot{\varphi})\cos\varphi + \frac{R}{\xi}\sin\varphi\cos^2\beta}{\left[\begin{array}{l}\left(\frac{s_{sp}}{\xi}\sin\beta + \frac{s_r}{\xi}\cos\beta\right)sgn(\dot{\varphi})\sin\varphi + \left(\frac{r_c}{\xi} - \cos\varphi\right)\frac{R}{\xi}\cos^2\beta + \\ \left(1 + \frac{J_z}{M\xi^2} - \frac{r_c}{\xi}\cos\varphi\right)\cos\beta\end{array}\right]}\left(\frac{g}{\xi} + \dot{\varphi}^2\right) \tag{1}$$

together with the expressions of the magnitude of the tangential reaction T:

$$T = \frac{M}{2}\left[(r_c - \xi\cos\varphi)\ddot{\varphi} + \xi\sin\varphi\dot{\varphi}^2 + g\sin\varphi\right] \tag{2}$$

and the magnitude of the normal reaction N from the two contacts:

$$N = \frac{M}{2}\,\frac{\xi\ddot{\varphi}\sin\varphi + \xi\dot{\theta}^2\cos\varphi + g\cos\varphi}{\cos\beta} \tag{3}$$

It has to be mentioned that the above relations were found out accepting linear dependence between the friction torques and the normal reaction. The spinning friction torque was assumed to be expressed as follows:

$$M_s = s_{sp}N \tag{4}$$

and the spinning friction torque has the following form:

$$M_r = s_r N \tag{5}$$

The conditions are not restrictive since if power law relationship is accepted for the general situation, applying for the case of small oscillations, by linearization of the relations, the dependencies of the form (4) and (5) are retrieved.

In the relations (1), (2) and (3), r_c is the distance from the center of the bearing ball to the rolling axis and β is a characteristic constructive parameter of the test-rig, as it is seen in Fig. 1, given by the relation:

$$\beta = asin[\, d/(R+r)\,] \tag{6}$$

It has to be remarked that for the particular case when $2d \to 0$ the relation (1) takes the form corresponding to the oscillations of a cycloidal pendulum[2].

EXPERIMENTAL SET-UP

The principle used in the estimation of the two parameters characteristic to rolling and spinning friction consists in equalizing the velocity of theoretical angular amplitude decrease, described by the relation (1) to the experimental velocity of diminishment of angular amplitude of the pendulum. Two parameters, s_{sp} and s_r are required and therefore it is necessary to carry out two experiments, differing by the values of a constructive parameter of the test rig. The device was designed in a manner that allows modifying the distance *d* between the two beams. From relation (1) it results that an experimental test provides the value of the combination:

$$s_g = s_{sp}\, sin\,\beta + s_r\, cos\,\beta \tag{7}$$

denoting global coefficient of friction torques. Two experimental tests performed for the distances d_1 and d_2 give the corresponding s_{g1} and s_{g2} values, and the following system can be written:

$$\begin{cases} s_{sp}\, sin\,\beta_1 + s_r\, cos\,\beta_1 = s_{g1} \\ s_{sp}\, sin\,\beta_2 + s_r\, cos\,\beta_2 = s_{g1} \end{cases} \tag{8}$$

which has the solutions:

$$\begin{aligned} s_{sp} &= \frac{s_{g2}\, cos\,\beta_1 - s_{g1}\, cos\,\beta 2}{sin(\,\beta_2 - \beta_1\,)} \\ s_r &= \frac{s_{g1}\, sin\,\beta_2 - s_{g2}\, sin\,\beta 1}{sin(\,\beta_2 - \beta_1\,)} \end{aligned} \tag{9}$$

The pendulum used is made by a bearing ball of radius R = 20 mm, to which an aluminium rod of L = 400 mm length and ϕ = 4 mm diameter is attached, Fig. 2.

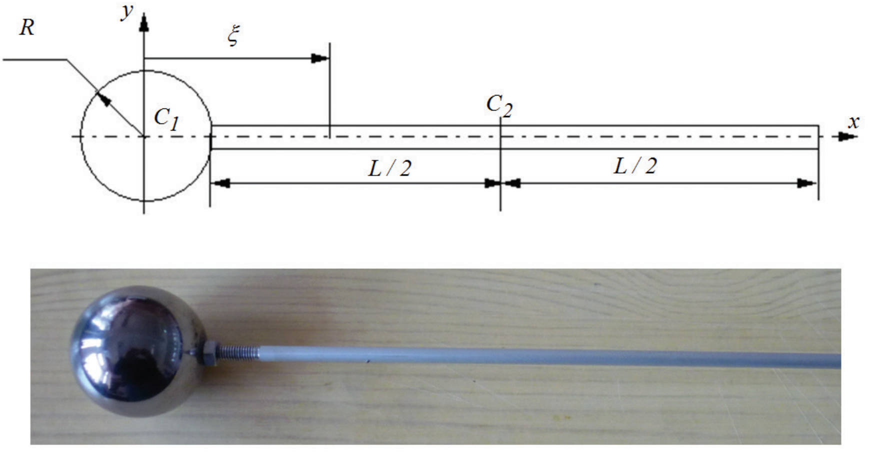


Fig. 2. The pendulum: geometry and experimental assembly

In order to apply the relation (1), the mass of the pendulum M, the position of the center of mass with respect to the center of the ball and the moment of inertia with respect to the center of mass must be known. The mass is found out by weighting the ball of mass M_b and the cylinder of mass M_c:

$$M = M_b + M_c \tag{10}$$

The position of the center of mass is given by:

$$\xi = \frac{M_c(R + L/2)}{M_s + M_2} \tag{11}$$

and the Steiner's theorem is applied for finding the moment of inertia:

$$J_z = J_s + M_s \xi^2 + J_c + M_c (R + L/2 - \xi)^2 \tag{12}$$

where the moments of inertia about central axes are the following:

$$J_s = \frac{2}{5} M_s R^2 \; ; \; J_c = \frac{1}{12} M_c L^2 \tag{13}$$

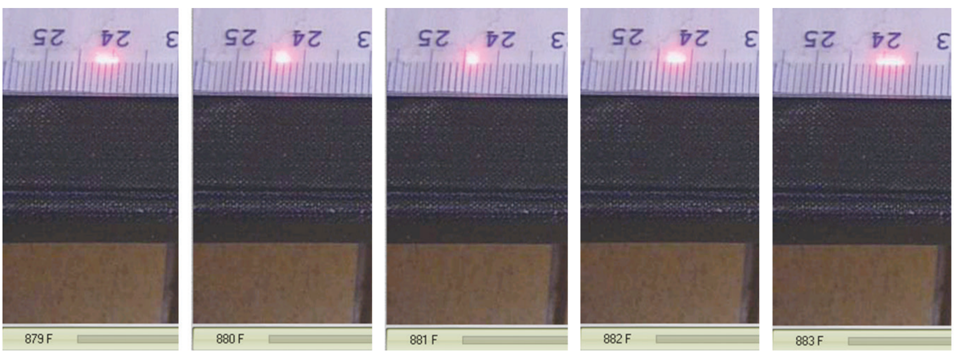
A small laser generator is attached to the rod at the opposite end with respect to the ball, Fig. 3.c. This generates a laser beam, projected as a spot moving along a ruler and allowing for finding the tilting angle of the pendulum. In Fig. 3.b it is shown that the two beams are kept at constant distance by means of two plastic discs. Holes were made into the discs by simultaneous boring at different distances.

(a) (b) (c)

Fig. 3. Experimental device (a); beam positioning (b); laser spot on the ruler (c)

The pendulum is set into motion and the displacement of the spot is video-captured with a camera. Using software dedicated to image editing, the film is split into frames and the instants, when the pendulum reaches extreme positions, are established, Fig. 4.

The coordinates of the spot on the ruler take the extreme values denoted by x_{left}, x_{right}. These values are accurately found, as it is seen in Fig. 4, where a succession of five consecutive frames is presented; it can be noticed that



(a) (b) (c) (d) (e)

Fig. 4. Finding the extreme position of the spot

the extreme position is found out for the frame, where the spot takes minimal dimension on the direction of motion, respectively Fig. 4.c. The conclusion from here is that the precision of time measurements, related to the position of the spot, equals the period of image acquisition during filming, 1/30 sec for the present experiment.

A next necessary step is to establish the equilibrium position of the pendulum, given by the x_0 coordinate of the laser spot. To this end, the imposed condition is to find out the line positioned at minimum of distance from all the points corresponding to the extreme positions of the spot; mathematically formulating, the minimum of the function is required:

$$F(x_0) = \sum_{k=1}^{n}(x_{left} - x_0)^2 + \sum_{k=1}^{n}(x_{right} - x_0)^2 \tag{14}$$

Taking into account that the motion of the pendulum is an oscillatory motion and accepting that the linear displacements of the contact points are insignificant, the angular amplitudes of the pendulum are found out using the relationship:

$$\Psi_{left,right} = atan\frac{x_{left,rigt} - x_0}{D} \tag{15}$$

where D is the distance from the contact point to the surface of the ruler.

On the same graph the experimental data are represented and the solution of the differential equation (1). The initial condition is that the pendulum starts from rest and the initial solution is the same with the launching amplitude $atan[(x_{left} - x_0)/D]$; after few trials for the values of s_g, the periodical function with linearly decreasing amplitude and maximal values approximating the experimental points are found.

RESULTS AND DISCUSSIONS

The pendulum described in Fig. 2 has the inertial characteristics M = 0.29 kg, ξ = 0.03 m, J_z = 0.00171 kg.m^2 and the tests were carried out for two distanced between the beams, $2d$ = 23 mm and $2d$ = 33 mm respectively. The experimental results were obtained finding the amplitudes after sets of five complete oscillations. The experimental data and the theoretical solutions of equation (1) are represented for the two distances in Fig. 5 and Fig. 6.

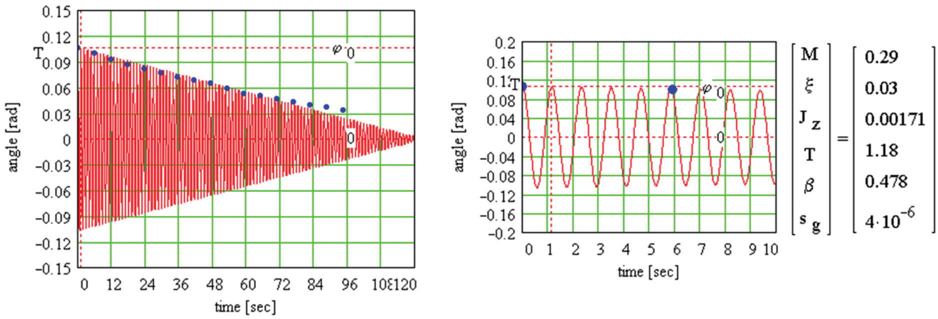


Fig. 5. Experimental data and interpolation curve for $2d$ = 23 mm

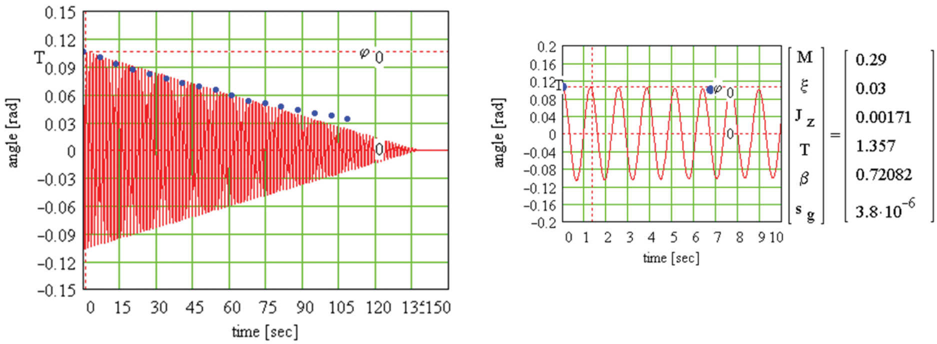


Fig. 6. Experimental data and interpolation curve for $2d$ = 33 mm

It has to be noticed that the values of the global coefficient s_g are very close, though the experimental conditions differ, $2d$ = 33 mm, $2d$ = 23 mm. Using the values found out for global friction torque coefficient s_g, the values of the rolling and spinning friction coefficients were also found, s_r = 3.2 μm and s_{sp} = 2.4 μm respectively.

The small values found out for these coefficients are due to the fact that: both the ball and the beams are hardened, with high hardness of the surface and with surfaces highly finished. In Fig. 7 it is presented the scanned profile off the beam and in Fig. 8 it is shown the scanned profile of the ball; both figures represent the roughness parameters and it can be remarked that the R_z parameter is comparable to the values of the friction coefficients, for both surfaces.

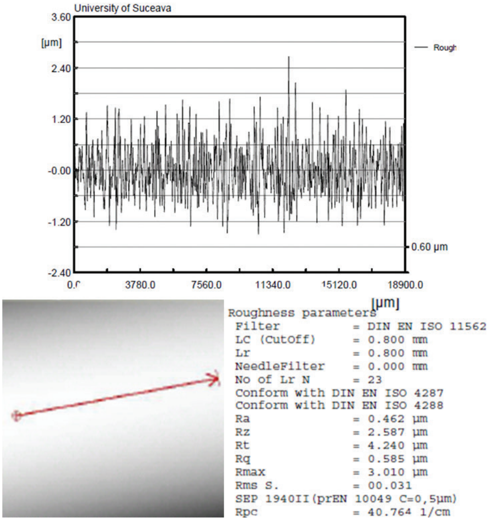


Fig. 7. Laser scan profile and roughness parameters for the beam

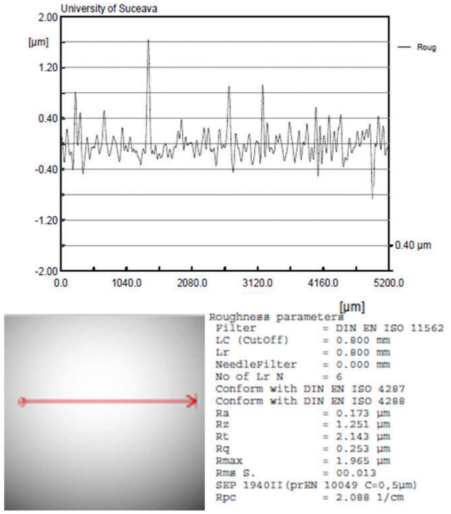


Fig. 8. Laser scan profile and roughness parameters for the ball

CONCLUSIONS

The paper continues the research work, where theoretical aspects of the oscillation motion of a ball-rod pendulum were analyzed. The ball is supported by two point contacts and the assumption of linear dependence between the friction torques and the normal reaction in contact is made. The nonlinear differential equation of damped oscillations of the pendulum is used. The coefficients of rolling friction and spinning friction can be obtained using two different values for the distance between contact points applied into the law of angular amplitude decrease.

The experimental set-up designed for the test, simple as principle, is represented. Under the hypothesis of pure rolling in the contact points, the pendulum becomes a system with one degree of freedom. The motion of the pendulum is related to the displacement of a laser spot along a ruler.

The extreme positions of the pendulum are found out by filming the spot motion and splitting the film into frames. The condition that the analytical solution has the same attenuation velocity of angular amplitude as the results given by experimental pendulum, allows for finding a linear equation between the two friction coefficients envisaged. The test is carried out for different values of constructive parameters and the values of the friction coefficient can thus be obtained.

The obtained experimental values are of order of micrometers, in full agreement to the results from other papers. Additionally, the scanned profiles of the contacting parts prove the roughness R_z with values close to the experimentally found out coefficients of friction.

The method may be improved by using a high speed camera for image acquisition, but this also increases the time necessary for experimental data analysis in order to establish the law of angular amplitude variation. The last aspect can be surmounted by employing a image analysis software, aimed for further research.

ACKNOWLEDGEMENT

This study and the results are related to the implementation on tasks of project: CEEPUS III Network: CIII-BG-0703-07-1819 "Modern Trends in Education and Research on Mechanical Systems – Bridging Reliability, Quality and Tribology".

REFERENCES

1. K. L. JONSON: Contact Mechanics ,Cambridge University Press, 1985.
2. M. C. CIORNEI, S. ALACI, F. C. CIORNEI AND I. C. ROMANU: A Method for the Determination of the Coefficient of Rolling Friction using Cycloidal Pendulum. IOP Conf. Series: Materials Science and Engineering, 227, 012027 (2017).
3. S.ALACI, F. C. CIORNEI, A. CIOGOLE, M. C. CIORNEI: Estimation of Coefficient of Rolling Friction by the Evolvent Pendulum Method. IOP Conf. Series: Materials Science and Engineering, 200 – 012005 (2017).
4. F. C. CIORNEI, S. ALACI, V. I. CIOGOLE, M. C. CIORNEI: Valuation of Coefficient of Rolling Friction by the Inclined Plane Method. IOP Conf. Series: Materials Science and Engineering, 200 – 012006 (2017).
5. I. Z. DZHILAVDARI, N. N. RIZNOOKAYA: Studies of the Dynamics of Free Microoscillations of a Pendulum Supported by Two Balls. J Frict Wear, **29** (1), 1 (2008).
6. I. Z. DZHILAVDARI, N. N. RIZNOOKAYA: An Experimental Assessment of the Components of Rolling Friction of Balls at Small Cyclic Displacements. J Frict Wear **29** (5), 330 (2008).
7. I. Z. DZHILAVDARI, N. N. RIZNOOKAYA: Features of Small Oscillations of Pendulum on Elastic Surface with Hysteresis Friction. Journal of Friction and Wear, **28** (2), 145 (2007).
8. D. P. TOWNSEND, M. V. DIETRICH, E. V. ZARETSKY: Speed Effects on Ball Spinning Torque (Lewis Research Center Cleveland Ohio NASA Washington D. C.), 1969.
9. D. MANGERON, N. C. IRIMICIUC: Mecanica Rigidelor cu Aplicatii in Inginerie. Volumul I. Mecanica Rigidului. Ed. Tehnica Bucuresti, 1978.
10. V. JIVKOV, PH. PHILIPOFF, N. NIKOLOV: Velocities in Contact Area of Turning Elastic Tires. J Balk Tribol Assoc, **22** (3-I), 2210 (2016).
11. V. JIVKOV, N. NIKOLOV, PH. PHILIPOFF: Wheels Slip Angles in a Hybrid Vehicle with KERS during Movement in a Turn. J Balk Tribol Assoc, **23** (1), 23 (2017).
12. S. ALACI, R. D. PENTIUC, F. C. CIORNEI, I. C. ROMANU, S. T. SIRETEAN, M. C. CIORNEI: Method for Simultaneous Estimation of Rolling and Spinning Friction in a Higher Pair. Prasic 2018, Brasov, to be published.

Received 5 February 2019
Revised 2 April 2019