Geometry and kinematics of the plate on disk contact type influencing friction measurements on UMT tribometer

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Abstract. The paper presents theoretical bases and experimental test on the pin on disk module of the UMT tribometer. In order to determine the friction coefficient between a chain and a guide, the rotational pin on disk module of the UMT tribometer has been adapted using a plate of the chain (instead of the pin) pushed against a rotating disk made from the guide material. In this case the contact surface between plate and disk is a rectangle. In comparison with the pin on disk case, the differences between sliding velocities on the rectangular contact surface of the plate on disk case may be considerably bigger. Study of kinematics shows the maximum and minimum sliding velocities and friction forces. The relative extreme sliding velocities and friction forces are expressed depending on geometrical inputs. The study continues with the measurements of friction coefficients maintaining the same couple of materials, surface dimension, normal force and sliding velocity at the centre of the rectangle with variation of the radius. Conclusion is drawn on the influence of the geometry and kinematics of the plate on disk measured friction.

1. Introduction
Improvement of friction performance in automobile engine systems generates benefits like increased engine power, reduced fuel and oil consumption; improved durability, reduced maintenance requirements and longer service intervals [1]. The analysis from [2] shows the friction loss contribution into fuel consumption and potential savings. The part of the fuel energy needed to overcome friction can be divided, based on data from [1, 2, 3, 4] as: 35% (12–45%) to overcome the rolling friction in the tire–road contact, 35% (30–35%) to overcome friction in the engine system, 15% (7–18%) to overcome friction in the transmission system and 15% (10–18%) to overcome friction in the brakes.

Considering the benefits of reducing, even with a small amount, of the friction losses in the engine system and transmissions of automobiles is setting the evaluation of friction and reduction of power loss by friction as a main direction of research. Friction measurements have an important role in correct evaluation of the tribological behaviour of different couples of materials and choosing the right couple must be based on measurements. The models for simulation of friction losses are a very important instrument in optimizing frictional behaviour of mechanical systems. All these models must be based on correct evaluation of friction coefficients, resulted from measurements and considering all the influences. This is why, measurements of friction coefficients, for different conditions (rolling or
sliding, dry or wet environment, static or dynamic) must be performed in absolute control considering
accuracy, applied load, speed etc.

Universal friction testing machines, generally called tribometers, have been developed. One of
these is the UMT tribometer [5]. One of the modules for friction measurements is the rotational
module, so called pin-on-disk module, which is common for many other tribometers. This module is
mostly dedicated to measurements of friction coefficients in linear sliding movement between a couple
of materials, for different normal forces and relatively high speed. The principle of measurements is
based on controlled pushing (normal force) of one part of the friction joint (the pin) on a disk made of
the other material of the joint, the disk having a controlled rotational speed. The path of contact on the
disk is a circle described by the radius of positioning the pin relative to the center of the disk. The
friction coefficient results as the ratio between the measured friction force (tangential) and normal
force.

An issue on the correct measurements of friction coefficients with this module is coming from the
different sliding velocities and frictional forces, other than the ones on the direction of measured
friction force. The researches based on this kind of measurements do not give importance to this issue
considering that the difference to the linear sliding is not so big. Anyway, it is clear that the decrease
of the radius of the circular path of movement will induce bigger differences. The usual parts used for
pushing on the disk are pins or balls. In both cases there is a circular area of contact with the disk.
Another case is the one studied in this paper. In order to determine the friction coefficient between
the links of a chain and the guide [6], the rotational module of the UMT tribometer is pushing a chain
plate on a disk made from the material of the guide [7, 8]. In this case the friction surface is
rectangular. For the precision of these measurements, we consider that it is very important to evaluate
the accuracy of measurements considering the specific components of sliding velocities and frictional
forces, depending on the dimensions of the rectangular surface and the radius of the circular path of
movement.

This paper starts with the study of the kinematics of the plate on disk case and compares it with the
pin on disk case. The conclusions are then used to explain the results of experimental measurements
developed in order to highlight the influence of plate position on measured friction coefficient.

2. Plate on disk contact geometry
The general case of describing the geometry of plate on disk contact is presented in figure 1. It
considers: the $B$ and $L$ dimensions (half width and half length) of the rectangular surface of contact;
radius $R$ at the centre of the rectangle; deviation angle $\delta$ of the rectangle from the tangential direction.

The needed outputs of the geometrical calculus of the plate on disk contact are: the extreme radii of
contact, minimum radius $R_m$ and maximum radius $R_M$; the angles describing the extreme points of the
rectangle, $\beta_m$ and $\beta_M$.

The calculus relations established for output parameters depending on input parameters (see
figure 1) are:

\begin{align}
\beta_m &= \arctg \frac{L \cos \delta - B \sin \delta}{R - L \sin \delta - B \cos \delta}; \\
R_m &= \arctg \frac{R - L \sin \delta - B \cos \delta}{\cos \beta_m}; \\
\beta_M &= \arctg \frac{L \cos \delta - B \sin \delta}{R + L \sin \delta + B \cos \delta}; \\
R_M &= \arctg \frac{R + L \sin \delta + B \cos \delta}{\cos \beta_M}.
\end{align}
Figure 1. General geometry of plate on disk contact.

A deviation angle $\delta$ may be possible in general case but for this study, a controlled accurate tangential position of the plate is looking for an angle $\delta = 0$. For this particular case, relations (1) – (4) become:

$$\beta_m = \arctg \frac{L}{R - B};$$  

$$R_m = \arctg \frac{R - B}{\cos \beta_m};$$  

$$\beta_M = \arctg \frac{L}{R + B};$$  

$$R_M = \arctg \frac{R + B}{\cos \beta_M}.$$

3. Analyses of sliding velocities

Figure 2 presents, side by side the diagrams of extreme sliding velocities in the case of rectangular surface of contact and in the case of circular area of contact with the disk. The sliding velocity at the centre of the surface is $v$ and all the points under the medium circle, with radius $R$, have a sliding velocity smaller than $v$, while the points above the medium circle, with radius $R$, have a sliding velocity bigger than $v$. The minimum and maximum sliding velocities are:

- in the case of rectangular surface (see figure 2, a)
  $$v_{\min} = v_m = \frac{R - B}{R}; \quad v_{\max} = v_M = \frac{R_M}{R}.$$

- in the case of the circular surface (see figure 2, b)
We propose to analyse of differences between the two cases based on the calculated maximal increase ($v_{\%+}$, positive value) and decrease ($v_{\%-}$, negative values) of sliding velocity, relative to velocity $v$, in percent:

$$v_{\text{min}} = v \frac{R - r}{R}, \quad v_{\text{max}} = v \frac{R + r}{R}. \quad (10)$$
\[ v_{\%+} = \frac{v_{\max} - v}{v} \times 100 \]; \[ v_{\%-} = \frac{v_{\min} - v}{v} \times 100 \]. \tag{11}

In order to compare the differences between the two cases (rectangular surface and circular surface) the same area of the two surfaces must be considered \( (r = \sqrt{\frac{BL}{\pi}}) \). The influences of the parameters \( R/r \) and \( B/L \) must be considered on the calculated maximal increase \( (v_{\%+}) \) and decrease \( (v_{\%-}) \) of sliding velocity. Relations (1) to (6) can be expressed depending on \( R/r \), \( B/L \), \( B/R \) and \( L/R \), with the assumption of equal area of the two type of surfaces

\[ L = \frac{R}{r} \left( \frac{\pi}{4} \right)^{1/2} \left( \frac{B}{L} \right)^{1/2}; \]

\[ B = \frac{R}{r} \left( \frac{\pi B}{4 L} \right)^{1/2}. \tag{12} \]

Figure 3 presents the maximal increase \( (v_{\%+}) \) and decrease \( (v_{\%-}) \) of sliding velocity, with a comparison between the cases of rectangular and circular contact surfaces, with the influence of \( R/r \) and \( B/L \).

![Figure 3](image)

**Figure 3.** Maximal increase \( (v_{\%+}) \) and decrease \( (v_{\%-}) \) of sliding velocity.

By analysing the results presented in figure 3, the following conclusion could be drawn:

- in case of circular surface, the maximal increase \( (v_{\%+}) \) and decrease \( (v_{\%-}) \) of sliding velocity have a symmetrical distribution, which should lead to an average closer to the \( v \) value;

- in case of rectangular surface, the maximal increase is bigger than the absolute value of the maximal decrease of sliding velocity; values are smaller than in the case of circular surface, with the exception of \( \frac{B}{L} = -1 \), for smaller values of \( R/r \);
the trend is asymptotic to 0, with increase of \( \frac{R}{r} \), with values \( v_{%+} \approx 6.5\% \) in case of rectangular surface and \( v_{%+} \approx 10\% \) for circular surface, for \( \frac{R}{r} = 10 \); closer values result also for \( \frac{R}{r} \geq 8 \).

4. Analyses of measured friction forces

Figure 4 presents the diagrams of friction forces on plate/pin in the case of rectangular surface of contact and in the case of circular area of contact.

![Figure 4](image)

**Figure 4.** Extreme friction forces: a – rectangular contact surface, b – circular contact surface.

The friction force is measured on the tangential direction at the circle of rotation in the centre of the surface, according to the force \( F_c \). With the assumption of uniform pressure distribution and friction force independent of sliding velocity, the same elementary friction force results in any point.
\[ F_{fm} = F_{fM} = F_f. \] For any point of the contact surface (extreme positions with index \( m \) and \( M \)) the friction force is tangent to the direction of rotation, having two components: the one with index \( t \) will be measured and the one with index \( n \) will not be measured. The minimum measured friction force is, for both cases:

\[ F_{f_{\text{min}}} = F_{f_{\text{mt}}} = F_{f_{\text{mn}}} \cos \beta_m = F_f \cos \beta_m. \] (13)

We propose to analyse of differences between the two cases based on the calculated maximal decrease \( (F_{f_{\text{n}}} \text{ negative values}) \) of theoretically measured friction force, relative to real friction force, in percent

\[ F_{f_{\text{n}}} = \frac{F_{f_{\text{min}}} - F_f}{F_f} \times 100. \] (14)

In order to compare the differences between the two cases (rectangular surface and circular surface) the same area of the two surfaces must be considered. The influences of the parameters \( R/r \) and \( B/L \) must be considered on the calculated maximal decrease \( (F_{f_{\text{n}}} \) of friction force.

Figure 5 presents calculated maximal decrease \( (F_{f_{\text{n}}} \) of theoretically measured friction force, with a comparison between the cases of rectangular and circular surfaces, with the influence of \( R/r \) and \( B/L \).

![Figure 5. Maximal decrease \( (F_{f_{\text{n}}} \) of measured friction force.](image)

By analysing the results presented in figure 5, the following conclusion could be drawn:

- The absolute values of maximal decrease \( (F_{f_{\text{n}}} \) of measured friction force are smaller in the case of circular surface; for the rectangular surface, the absolute values are increasing with decrease of \( B/L \); the influences of shape and \( B/L \) are totally opposite to the one for sliding velocities (see figure 3);
- the general trend is asymptotic to 0, with increase of \( R/r \), with absolute values of \( F_{f_{\text{n}}} \) smaller than 5%, for \( \frac{R}{r} = 10 \);
- by imposing a maximum value of 2.5% for the absolute value of \( F_{f_{\text{n}}} \) it results a minimum \( \frac{R}{r} = 4.2 \) in the case of circular surface and a minimum \( \frac{R}{r} = 8 \) in the case of rectangular surface with \( \frac{B}{L} = 0.25 \).
5. Experimental testing
Figure 6 presents the parts [9] and the plate-on-disk module of the UMT tribometer, used for experimental testing.

![Figure 6. Plate-on-disk module: (a) assemble, (b) plate holder, (c) plate and disk.](image)

The plate is mounted on a holder which is attached to the force sensor. The tooth chain plate is pushed through a fixed pin on the holder and has enough freedom for assuring a perfect planar contact with the disk. The force sensor measures the normal force and the friction force simultaneously.

The dimensions of the elements are: $L = 4.6 \text{ mm}$; $B = 1.15 \text{ mm}$; $\frac{B}{L} = 0.25$ and corresponding to an identical area circular surface with $r = 2.6 \text{ mm}$; contact radius on the disk $R = 25, 17.5, 10 \text{ mm}$ (corresponding to $\frac{R}{r} = 9.6, 7.3, 4.8$, see figure 3 and figure 5).

The parameters for testing are: average pressure $p_m = 0.33 \text{ MPa}$ (normal force $F = 7N$); two steps of speed $v = 2.6 \text{ m/s}$ and $v = 0.26 \text{ m/s}$. Tests are including: running in at $v = 2.6 \text{ m/s}$, for 2 hrs, for each contact radius on the disk $R$. Measurements of friction coefficient repeated 3 times, for each group of constant parameters. Tested are repeated on 3 identical pairs plate-disks. The material of the disks is PA66.

The average friction coefficients measured for the three different positions of plate on disk, for the two steps of sliding velocity are graphically represented in figure 7.

The results from figure 7 are the base for the following conclusions:
- The measured friction coefficient is decreasing with decrease of the $R/r$ ratio (decrease of the radius of rotation circle; this is according with the decrease of measured friction force depending on the same parameter $R/r$ resulted from figure 5);
- By reducing the radius R from 25 to 17.5 mm, the measured friction coefficient reduces by 4.5% in the case of sliding velocity $v = 2.6 \text{ m/s}$ and by 10.4% in the case of sliding velocity $v = 0.26 \text{ m/s};$ these percentages are bigger than the one estimated by maximal decrease $(F_{p_{m}})$ of measured friction force (see figure 5).
6. Conclusion

For the theoretical comparison between circular and rectangular surfaces, the same contact surface is considered and thus the relationship between $r$, $B$ and $L$. The position of the contact surface on the disk is defined by the ratio $R/r$ ($r$ – radius of the equivalent circular surface). The maximal increase ($v^\%+$) and decrease ($v^\%-$) of sliding velocity have a symmetrical distribution in case of circular surface with usually bigger absolute values than in the case of rectangular surface (with the exception of $\frac{B}{L} = -1$ and smaller values of $R/r$). The general trend is an increasing absolute value of the maximal increase ($v^\%+$) and decrease ($v^\%-$) of sliding velocity, with the decrease of ratio $R/r$. The theoretically measured friction force (measured on the tangential direction at the circle of rotation in the centre of the surface) is smaller or equal with the real friction force. The general trend is an increasing absolute value of the maximal decrease ($F_{ff}$ negative values) of theoretically measured friction force, relative to real friction force, with the decrease of ratio $R/r$. The maximal decrease of measured friction force ($F_{ff}$) is smaller in the case of circular surface than in the case of rectangular surface. In the case of rectangular surface, influence of the ratio $B/L$ is very important on the maximal decrease of measured friction force. The experiments show that the measured friction coefficient is decreasing with decrease of ratio $R/r$ according with, but bigger than the decrease of theoretically measured friction force ($F_{ff}$) and increase ($v^\%+$) or decrease ($v^\%-$) of sliding velocity depending on the same parameter. There is clear that the measured friction coefficient is smaller than the real friction coefficient. For increased accuracy in measurements of friction coefficient using the plate-on-disk module, the radius positioning the plate on disk must be as big as possible. Same test should be performed for an equivalent circular surface. In order to evaluate the precision of measurements, tests on different couples of materials, with different dimensions of plate and different types of lubrication should be performed in the future.

7. References

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