

Influence of In-Plane and Out-of-Plane Ultrasonic Oscillations on Sliding Friction

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ABSTRACT

Vibrations of varying frequency and amplitude are used in many technological areas to control friction. In this study we report the most comprehensive results of high precision measurements of the sliding friction as a function of ultrasonic oscillations. The friction force between a steel plate and a steel sample oscillating in sliding direction, perpendicular to the sliding direction, and perpendicular to the sliding plane at a frequency of 30-50 kHz has been studied.

We have found that for dry friction in the absence of vibrations, it is characteristic that the frictional force slightly decreases as the velocity increases. The friction coefficient is a monotonically decreasing function of the sliding velocity. However, it will be shown, that if we excite the system using ultrasonic oscillations with an amplitude of about 0.1 μm , the frictional force becomes a monotonically increasing function of the sliding velocity. This effect can be used to suppress frictionally induced instabilities and thus might be used as a mechanism to suppress braking noises. Additionally it is shown that the friction coefficient is significantly decreased in value. The largest reduction of the friction coefficient is reached for small velocities at high amplitudes.

INTRODUCTION

Vibrations of varying frequency and amplitude are used in many technological areas to control friction forces. The most prominent low frequency applications are vibration compactors and plates. High frequency oscillations are used to control friction in metal working, wire drawing and cutting, and also in nanotribological devices such as atomic force microscopes [1]. For all these applications as well as for further investigations of the possibilities of active control of

friction it is important to know how the static and sliding friction forces depend on the oscillation amplitude.

There have been several experimental and theoretical examinations of the influence of oscillations on friction. Pohlman and Lehfelddt [2] studied the influence of oscillations on wire drawing and found an estimated threefold decrease in the friction force. Godfrey [3] studied the influence of oscillations normal to the contact surface. In this case, the friction gets smaller (or even disappears) if the sample begins to “jump”. The same result was drawn by Tolsotoi [4], who studied the influence of normal vibrations on contact friction, by applying piezo ceramic elements. Weishaupt [5] investigated the control of friction in connection with the design of micro positioning devices - again by vibrations normal to the contact surface - to avoid wear. The influence of harmonic vibrations perpendicular to the contact plane for a Hertzian contact was theoretically investigated by Hess and Soom in [6], who found an 10% decrease of the friction coefficient due to vibrations at resonance frequencies. Siegert [7] studied the influence of ultrasonic oscillations on micro machining and the quality of surfaces produced. Wallaschek and co-workers developed the first theoretical model on the influence of ultrasonic vibrations on friction forces [8,9]. They found that, both in the sliding direction and normal to the sliding direction, at relatively large sliding velocities, the experimental results were in good agreement with the theoretical model. However, contrary to theoretical predictions, there was a non-vanishing static friction force even if an oscillation was applied.

In the present paper we report the most comprehensive results of high precision measurements of sliding friction as a function of ultrasonic oscillations along with theoretical investigations of all measurements. For the in-plane oscillations as well as the out-of-plane oscillations, we

especially investigate the tribological pairing steel-steel in the whole relevant range of oscillation amplitudes and sliding velocities. For further material pairings and further investigations we refer to [10,11,12].

We will first give an overview on the experimental set-up. Then the theoretical investigations and the measurement results of three different oscillation directions are presented: an oscillation in sliding direction, an oscillation perpendicular to the sliding direction, and an oscillation perpendicular to the sliding plane. The paper will conclude with a summary of the most important results along with the comparison of all directions.

EXPERIMENTAL SET-UP

The measurements have been performed on a pin-on-disc tribometer as shown in Figure 1 and Figure 2. This tribometer consists of a rotating friction disc of varying materials, which is operated by a step motor. The fixed friction probe is pressed on the rotating disc. The oscillations are induced by build-in piezo-electric elements which are controlled by the ultrasound generator.



Figure 2. Experimental setup of the pin-on-disc tribometer.

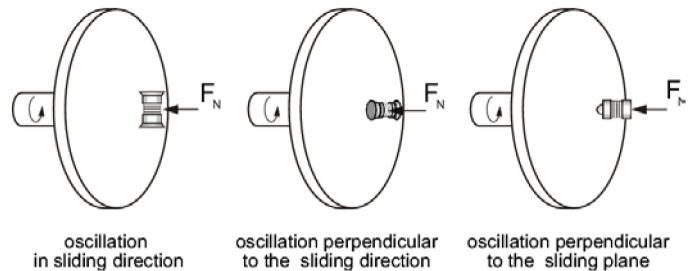


Figure 3. Three kinds of probes with different oscillation directions.

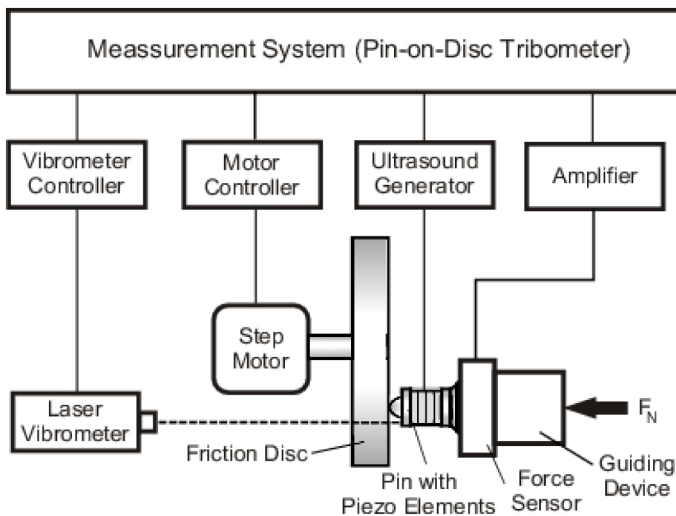


Figure 1. Schematic view of the pin-on-disc tribometer.

The three possible oscillation directions for different kind of probes as they have been investigated are illustrated in Figure 3. Two kinds of in-plane oscillations, one in sliding direction and one perpendicular to the sliding direction but both in the sliding plane are illustrated. The third configuration illustrated is an out-of-plane oscillation perpendicular to both, the sliding plane and the sliding direction.

IN-PLANE OSCILLATION OSCILLATION IN SLIDING DIRECTION

We first consider the influence of in-plane ultrasonic oscillation in sliding direction on friction from the macroscopic point of view. The geometric values are defined in Figure 4.

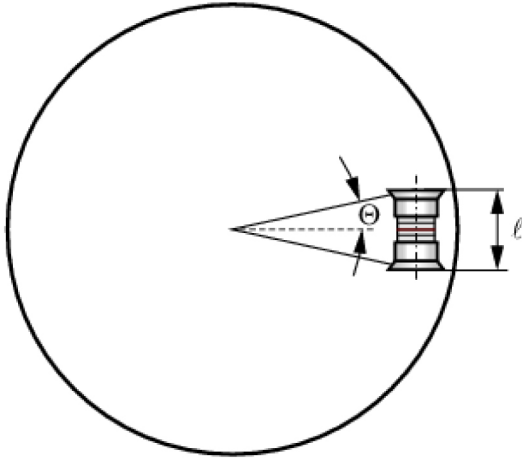


Figure 4. Geometry of the probe oscillating in sliding direction

If we introduce l_0 as the initial length of the probe shown in [Figure 4](#) while Δl and ω are the amplitude and frequency of the oscillating probe, respectively, the length of the sample oscillates according to [Equation \(1\)](#).

$$l = l_0 + \Delta l \sin \omega t \quad (1)$$

We assume that the motion of the contact point is just a superposition of the average sliding velocity v_0 (namely the velocity of the rotating disc) and a harmonic oscillation with velocity amplitude $\hat{v} = \frac{\Delta l}{2} \omega$ for each endpoint of the probe, if considering the oscillation velocity $\dot{l}(t) = \Delta l \omega \cos \omega t$. We further assume that the Coulomb friction law in its simplest form

$$F = -\mu_0 F_N \text{sign}(v_{rel}) \quad (2)$$

is valid for two contact points, where μ_0 is the sliding friction coefficient and F_N is the normal force. If we further assume the probe to be a system of two masses connected by a rod of varying length as described in [Equation \(1\)](#) and loaded each

with a normal force $\frac{F_N}{2}$ each mass has a relative velocity in direction of the oscillation combined by the mean sliding velocity v_0 and half the oscillation velocity $\dot{l}(t)$. Under these assumptions, the velocities of the two masses become

$$v_{1,rel} = v_0 \cos \theta - \hat{v} \cos \omega t \quad \text{and} \quad v_{2,rel} = v_0 \cos \theta + \hat{v} \cos \omega t \quad (3)$$

respectively. The macroscopically measured friction coefficient $\mu = \frac{F}{F_N}$ (averaged over the oscillation period) is a function of the ratio $v_0 / \hat{v}$ only and can be computed as

$$\begin{aligned} \frac{\mu}{\mu_0} &= \frac{1}{F_N} \left(\frac{F_N}{2} \frac{v_{rel,1}}{|v_{rel,1}|} + \frac{F_N}{2} \frac{v_{rel,2}}{|v_{rel,2}|} \right) \\ &= \frac{1}{2\pi} \int_0^{2\pi} \frac{v_0 \cos \theta - \hat{v} \cos \xi}{\sqrt{v_0^2 + \hat{v}^2 \cos^2 \xi - 2v_0 \hat{v} \cos \theta \cos \xi}} d\xi \end{aligned} \quad (4)$$

where $\xi = \omega t$

According to the theoretical prediction, the friction coefficient tends to a constant value at large sliding velocities ($v_0 / \hat{v} > 1$). In the limit $v_0 \rightarrow 0$, the predicted friction force approaches zero. This is illustrated in [Figure 5](#).

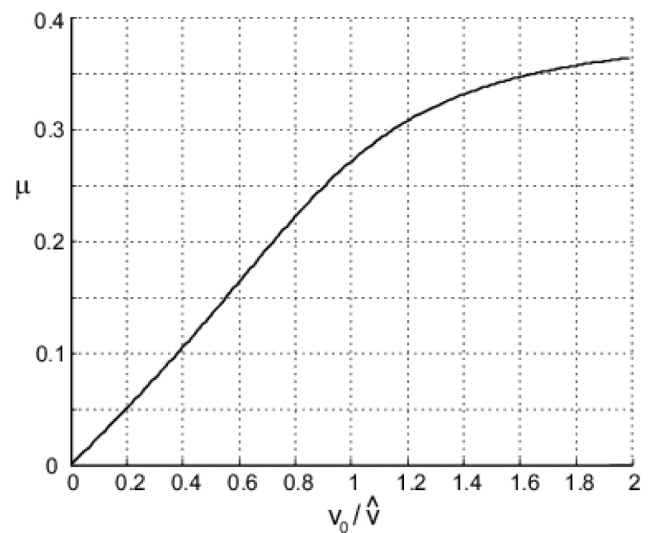


Figure -5. Dependence of the friction coefficient on the oscillation amplitude ($\Delta l = 0.03 \mu\text{m}$) and sliding velocity for an angle of $\theta = 31.5^\circ$.

The experimental data indicates that the friction force always tends to a finite value at vanishing velocity as shown in [Figure 6](#). The largest discrepancy between experiment and theory concerns velocities close to zero and hence the static friction has been further investigated in [9].

Let us point out the main results of these graphs. For small amplitudes the friction coefficient is, except for very small sliding velocities, a monotonically decreasing function with respect to v_0 . As the amplitude increases, the friction coefficient becomes a monotonically increasing function of the sliding velocity and tends to a finite value. The friction coefficient has a finite value for the static friction, which cannot be predicted by the considered mechanical model. However, it is evident that along with a change in the monotonic properties of the friction coefficient one also gains a drastic reduction of the friction coefficient especially for small sliding velocities and large amplitudes.