Technische Universität Berlin
INSTITUTE FOR MECHANICS
Workgroup: System Dynamics
and Friction Physics

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

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Joint ICTP-FANAS Conference on Trends in Nanotribology, Trieste

Outline

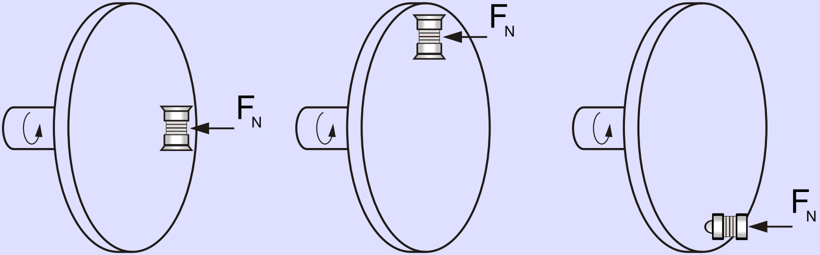
Experimental Set-Up

In-Plane Oscillations
- Oscillations in Sliding Direction
- Oscillations Normal to the Sliding Direction

Out-of-Plane Oscillations

Conclusions

Experimental Set-Up: Oscillation Directions

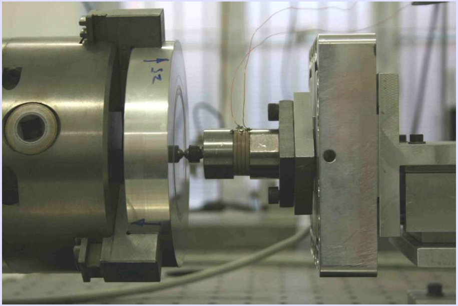


oscillation
in sliding direction

oscillation normal
to the sliding direction

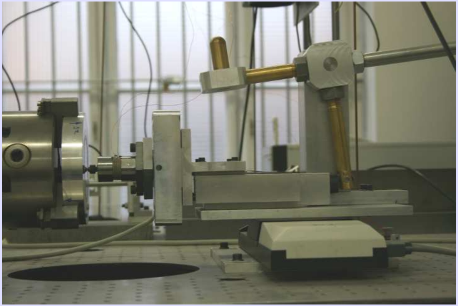
oscillation normal
to the sliding plane

Experimental Set-Up



- Rotary drive (step motor)
- Rotational disc (polished, hardened steel)
- Probe (mostly steel) with build-in piezo ceramic elements
- Oscillations match the eigenfrequency of the sample
- Force application via a lever arm and a guiding device

Experimental Set-Up



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Oscillations in Sliding Direction

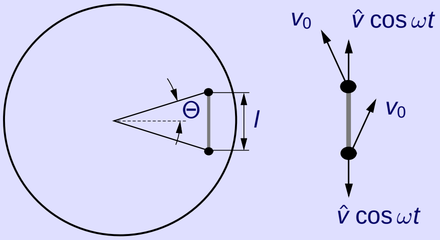


Fig.: Geometrical Set-Up

- $l = l_0 + \Delta l \sin \omega t \Rightarrow$
  $\frac{\mathrm{d}l}{\mathrm{d}t} = \Delta l \omega \cos \omega t$
- Each end of the sample has the oscillation velocity
  $v = \frac{\Delta l}{2} \omega \cos \omega t = \hat{v} \cos \omega t$
- Θ: Opening angle between plate center and sample end
- Coulomb's friction law:
  $F = \mu_0 F_N \operatorname{sgn}(v_{rel})$
- v_0: Sliding velocity of the disc
- $v_{rel,1} = v_0 \cos \Theta - \hat{v} \cos \omega t$
  $v_{rel,2} = v_0 \cos \Theta + \hat{v} \cos \omega t$

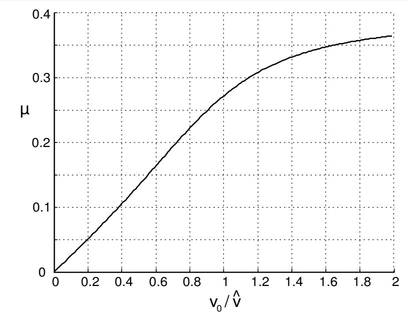
Oscillations in Sliding Direction

μ: Coefficient of friction averaged over one oscillation period

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

Note: μ only dependents on the ratio $\frac{v_0}{\hat{v}}$

Oscillations in Sliding Direction



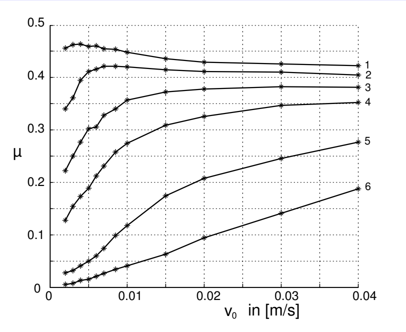
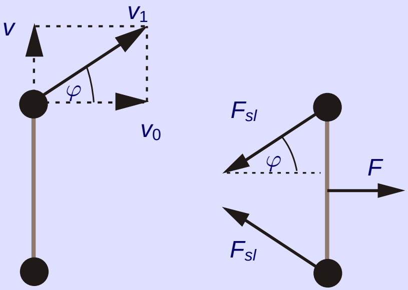


Fig.: Theoretical graph of the coefficient of friction for an amplitude $\Delta l = 0.03\ \mu$m and the angle $\Theta = 31.5^\circ$

Fig.: Experimental data of the coefficient of friction of a steel-steel-couple, oscillation frequency of 45 kHz and the oscillation amplitudes: (1) 0.023 μm , (2) 0.056 μm , (3) 0.095 μm , (4) 0.131 μm , (5) 0.211 μm , (6) 0.319 μm

Oscillations Normal to the Sliding Direction



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- Each end of the sample has the oscillation velocity
  $v = \frac{\Delta l}{2} \omega \cos \omega t = \hat{v} \cos \omega t$
- v_0: Sliding velocity of the disc
- $F_r = 2F_{sl} \cos \varphi = \mu_0 F_N \cos \varphi$
- $\tan \varphi = \frac{v}{v_0}$

Oscillations Normal to the Sliding Direction

$$\mu = \frac{1}{2\pi}\int_0^{2\pi} \frac{F_r}{F_N} \mathrm{d}\xi \quad \text{with } \xi = \omega t$$

$$= \frac{\mu_0}{2\pi}\int_0^{2\pi} \cos(\arctan\frac{v}{v_0}) \mathrm{d}\xi$$

$$= \frac{\mu_0}{2\pi}\int_0^{2\pi} \frac{1}{1+(\frac{v}{v_0})^2} \mathrm{d}\xi$$

$$= \frac{\mu_0}{2\pi}\int_0^{2\pi} \frac{1}{1+(\frac{\hat{v}}{v_0}\cos\xi)^2} \mathrm{d}\xi$$

Note: μ only dependents on the ratio $\frac{v_0}{\hat{v}}$

Oscillations normal to the Sliding Direction

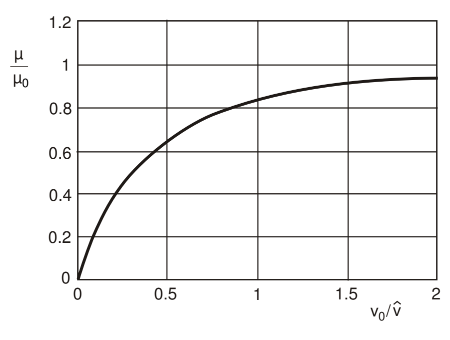

Fig.: Theoretical graph of the coefficient of friction dependent on the sliding velocity. This graph was first introduced in [1]

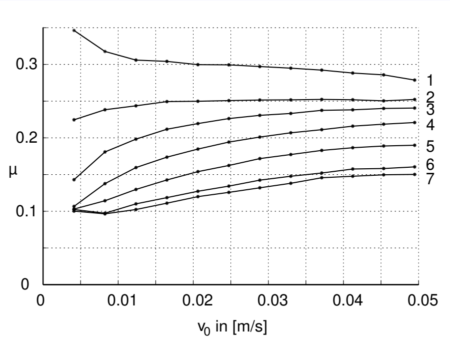

Fig.: Experimental data of the coefficient of friction of a steel-steel-couple,oscillation frequency of 45 kHz and the oscillation amplitudes: (1) 0.0, μm , (2) 0.026 μm , (3) 0.05 μm , (4) 0.076 μm , (5) 0.114 μm , (6) 0.182 μm, (7) 0.244 μm

[1] Littmann, Storck, Wallaschek, *Reibung bei Ultraschallschwingungen*, VDI-Berichte NR. 1736, 2002

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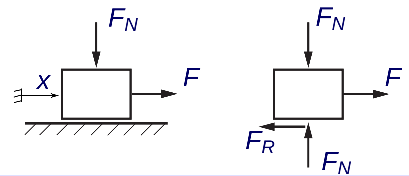


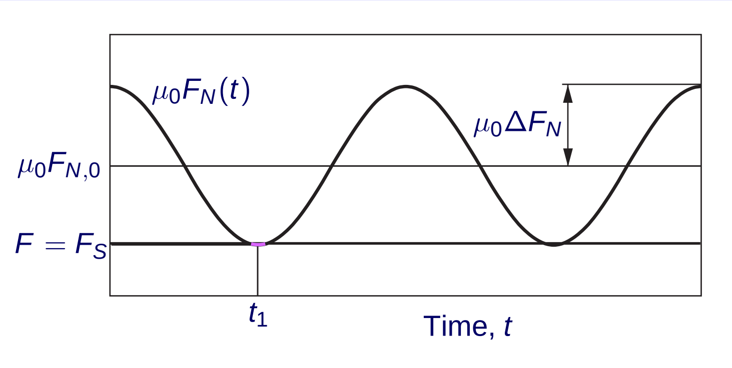
Oscillation due to normal force:

$$F_N = F_{N,0} + \Delta F_N \cos \omega t$$

Equation of motion:

$$m\ddot{x} = F - \mu_0 (F_{N,0} + \Delta F_N \cos \omega t)$$

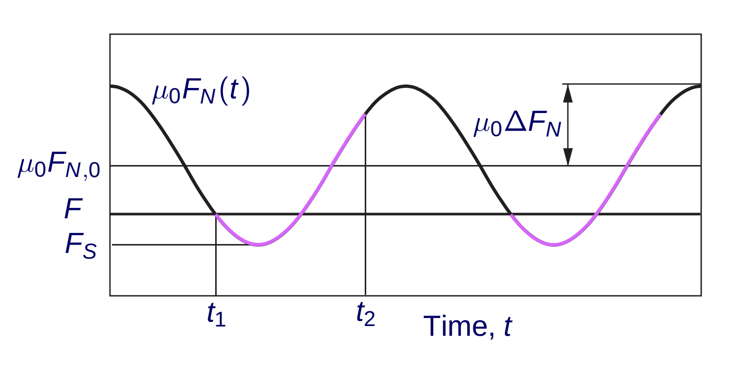
Stick Motion



$$F = F_S = \mu_0(F_{N,0} - \Delta F_N) \quad \Leftrightarrow \quad t_1 = t_2$$

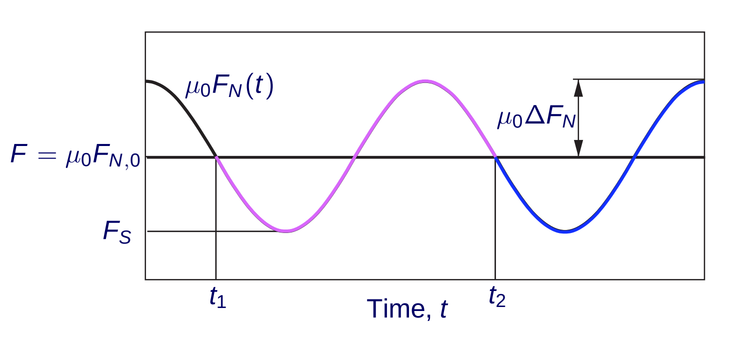
Out-of-Plane Oscillations

Stick-Slip Motion



$$F > \mu_0(F_{N,0} - \Delta F_N) \quad \Leftrightarrow \quad t_2 > t_1$$

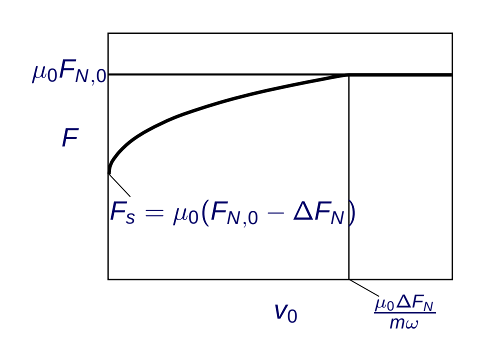
Slip Motion



$$F = \mu_0 F_{N,0} \quad \Leftrightarrow \quad t_2 = t_1 + T$$

Out-of-Plane Oscillations

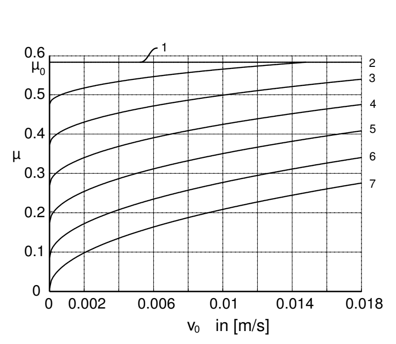
Analytical/Numerical solution:



Approximative solution:

$$F = \mu_0 \left(F_{N,0} - \Delta F_N\right) + \mu_0 \Delta F_N \left[\sqrt{\frac{4\pi}{9} \frac{m\omega}{\mu_0 \Delta F_N} v_0} + \left(1 - \sqrt{\frac{4\pi}{9}}\right) \left(\frac{m\omega}{\mu_0 \Delta F_N} v_0\right)^{1.2}\right]$$

Out-of-Plane Oscillations



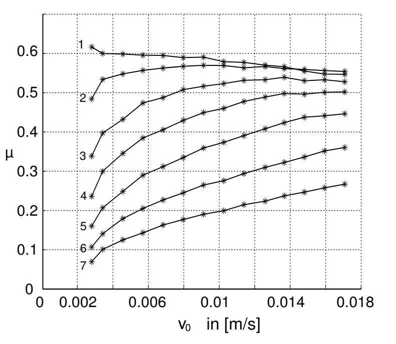


Fig.: Experimental dependence of the coefficient of friction $\mu = F/F_{N,0}$ on the average sliding velocity v_0 for the ratios of $\Delta F_N/F_{N,0}$: (1) 0, (2) 0.18, (3) 0.36, (4) 0.53, (5) 0.70, (6) 0.85, (7) 1.

Conclusions

For dry friction for all three oscillation directions the overall effects are the same!

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- Without oscillation the coefficient of friction is a monotonically **decreasing** function with respect to the velocity
- With oscillations the coefficient of friction is a monotonically **increasing** function with respect to the velocity

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$\Rightarrow$ The effect known to cause friction induced instabilities (e.g. braking noise) is reversed!

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$\Rightarrow$ The effect known to cause friction induced instabilities (e.g. braking noise) is reversed!

- μ is highly reduced
- Largest effect for small velocities and large oscillation amplitudes
- We showed that even simple theoretical considerations succesfully predict the main features

Thank you for your attention !