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

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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
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Oscillations in Sliding Direction

Fig.: Geometrical Set-Up

\[ l = l_0 + \Delta l \sin \omega t \implies \frac{dl}{dt} = \Delta l \omega \cos \omega t \]

Each end of the sample has the oscillation velocity
\[ v = \frac{\Delta l}{2} \omega \cos \omega t = \hat{v} \cos \omega t \]

\( \Theta \): Opening angle between plate center and sample end

Coulomb's friction law:
\[ F = \mu_0 F_N \text{sgn}(v_{rel}) \]

\( v_0 \): 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

$\mu$: Coefficient of friction averaged over one oscillation period

\[
\mu = \frac{1}{2\pi} \int_{0}^{2\pi} \frac{F}{F_N} d\xi \quad \text{with} \quad \xi = \omega t
\]

\[
= \frac{1}{2\pi} \int_{0}^{2\pi} \frac{\mu_0}{F_N} \left( \frac{F_N}{2} \left| \frac{v_{rel,1}}{v_{rel,1}} \right| + \frac{F_N}{2} \left| \frac{v_{rel,2}}{v_{rel,2}} \right| \right) d\xi
\]

\[
= \frac{\mu_0}{2\pi} \int_{0}^{2\pi} \frac{v_0 \cos \Theta - \hat{v} \cos \xi}{\sqrt{v_0^2 + \hat{v}^2 \cos^2 \xi - 2v_0 \hat{v} \cos \Theta \cos \xi}} d\xi
\]

\textbf{Note:} $\mu$ 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 $\mu m$, (2) 0.056 $\mu m$, (3) 0.095 $\mu m$, (4) 0.131 $\mu m$, (5) 0.211 $\mu m$, (6) 0.319 $\mu m$
Oscillations Normal to the Sliding Direction

\[ l = l_0 + \Delta l \sin \omega t \Rightarrow \frac{dl}{dt} = \Delta l \omega \cos \omega t \]

- Each end of the sample has the oscillation velocity
  \[ v = \frac{\Delta l}{2} \omega \cos \omega t = \hat{v} \cos \omega t \]
- \( \nu_0 \): Sliding velocity of the disc
- \( F_r = 2F_{sl} \cos \varphi = \mu_0 F_N \cos \varphi \)
- \( \tan \varphi = \frac{v}{v_0} \)

Fig.: Geometrical Set-Up
Oscillations Normal to the Sliding Direction

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

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

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

\[ = \frac{\mu_0}{2\pi} \int_0^{2\pi} \frac{1}{1 + (\frac{\dot{v}}{v_0} \cos \xi)^2} d\xi \]

**Note:** \( \mu \) only dependents on the ratio \( \frac{v_0}{\dot{v}} \)
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

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Oscillation due to normal force:

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

Equation of motion:

\[ m \ddot{x} = F - \mu_0(F_{N,0} + \Delta F_N \cos \omega t) \]
Out-of-Plane Oscillations

Stick Motion

\[ F = F_S = \mu_0(F_{N,0} - \Delta F_N) \iff t_1 = t_2 \]
Out-of-Plane Oscillations

Stick-Slip Motion

\[ F > \mu_0(F_{N,0} - \Delta F_N) \iff t_2 > t_1 \]
Out-of-Plane Oscillations

Slip Motion

\[ F = \mu_0 F_{N,0} \]

\[ F = \mu_0 F_N(t) \]

\[ F_S = \mu_0 \Delta F_N \]

\[ F = \mu_0 F_{N,0} \iff t_2 = t_1 + T \]
Out-of-Plane Oscillations

Analytical/Numerical solution:

\[ F_s = \mu_0 (F_{N,0} - \Delta F_N) \]

Approximative solution:

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

⇒ The effect known to cause friction induced instabilities (e.g. braking noise) is reversed!
Conclusions

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

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

- $\mu$ is highly reduced.
- Largest effect for small velocities and large oscillation amplitudes.
- We showed that even simple theoretical considerations successfully predict the main features.
Thank you for your attention!