Friction and wear reduction using ultrasonic lubrication

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Outline

• Background on ultrasonic lubrication

• Experiments
  - Stainless steel pin on aluminum disc
  - Ceramic & M50 steel pins on M50 steel disc
  - Steel on skin replica
  - Power mapping
  - Comparison between different lubrication methods

• Cube model

• Concluding remarks
**Ultrasonic Lubrication Principle**

**Ultrasonic lubrication**: the coefficient of dynamic friction between two surfaces decreases when ultrasonic vibrations are superimposed to the macroscopic sliding velocity.

- This form of friction reduction is “solid state” and **requires no greases or oils**.

- We use a **piezoelectric actuator** to create ultrasonic vibrations. Piezoelectric actuators are **extensively used** in consumer electronic products.

- Modulate the friction coefficient between “high friction” (**off state**) and “low friction” (**on state**) by driving the actuator at different voltages.

**Ultrasonic Lubrication Principle**

\[
\text{Friction ratio} = \frac{\text{Friction with ultrasonics}}{\text{Friction without ultrasonics}}
\]

\[
\text{Velocity ratio} = \frac{\text{Sliding velocity}}{\text{Vibration velocity}}
\]
State of the Art

Other Factors

- Friction type: dry sliding, lubricated sliding, and rolling
- Materials: steel, stainless steel, aluminum, copper, brake pad, glass, titanium, brass, Teflon, and rubber among others.

[References listed in appendix]
Applications

**Past**

**Metal forming:**
- Stamping
- Sheet rolling
- Wire drawing
- Compressing

*Sheet rolling*
Severdenko et al. (1974)

**Thermal stir welding:**
Reduce friction between workpiece and containment plates

**Future**

**Consumer products:**
Reduce friction to enhance user experience

**Vehicle applications:**
- Ball joints
- Seat rails
- Steering mechanisms
- Powertrain components

**Space mechanisms:**
Reduce friction and wear where traditional lubrication is not possible

Thermal stir welding:
Reduce friction between workpiece and containment plates

*HTTP://WWW.THANKSMAILCARRIER.COM/*

*HTTP://WWW.SPACETELESCOPES.COM/*
### Previous Experiments

<table>
<thead>
<tr>
<th>Setup</th>
<th>Velocity [mm/s]</th>
<th>Load [N]</th>
<th>Power [kW]</th>
<th>Max Friction Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>68</td>
<td>10</td>
<td>0.012</td>
<td>68</td>
</tr>
<tr>
<td>II</td>
<td>25</td>
<td>670</td>
<td>2.2</td>
<td>58</td>
</tr>
<tr>
<td>III-a</td>
<td>5810</td>
<td>40</td>
<td>2.2</td>
<td>22</td>
</tr>
<tr>
<td>III-b</td>
<td>5810</td>
<td>90</td>
<td>2.2</td>
<td>82.35</td>
</tr>
<tr>
<td>IV</td>
<td>5</td>
<td>60-240</td>
<td>2.2</td>
<td>100</td>
</tr>
</tbody>
</table>
Modified Pin-on-disc Tribometer

Weight (Normal load)

Load cell (Friction)

Sample disc

Chuck

Gymbal assembly

Piezo-actuator

Acorn nut

Front View

UIA 44th Annual Symposium, 20-22 April 2015, Washington DC
This study is conducted to investigate the relationship between wear reduction and **linear velocity**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group</strong></td>
<td>1 2 3</td>
</tr>
<tr>
<td><strong>Linear Velocity (mm/s)</strong></td>
<td>20.3 40.6 87</td>
</tr>
<tr>
<td><strong>Running time (h)</strong></td>
<td>4 2 0.93</td>
</tr>
<tr>
<td><strong>Distance travelled by pin (m)</strong></td>
<td>292.5</td>
</tr>
<tr>
<td><strong>Normal load</strong></td>
<td>3 N</td>
</tr>
<tr>
<td><strong>Revolutions</strong></td>
<td>1600</td>
</tr>
<tr>
<td><strong>Disc run out (mm)</strong></td>
<td>± 0.0286</td>
</tr>
<tr>
<td><strong>US frequency (kHz)</strong></td>
<td>22</td>
</tr>
<tr>
<td><strong>US amplitude (µm)</strong></td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Pin material</strong></td>
<td>Stainless steel 316</td>
</tr>
<tr>
<td><strong>Disc material</strong></td>
<td>Aluminum 2024</td>
</tr>
<tr>
<td><strong>Nominal groove diameter (mm)</strong></td>
<td>50</td>
</tr>
<tr>
<td><strong>Sampling frequency (Hz)</strong></td>
<td>400</td>
</tr>
</tbody>
</table>
Friction Reduction

- Reduction percentage is defined as
  \[ P_f = \frac{f_0 - f_1}{f_0} \times 100 \]
  where \( f_0 \) is the intrinsic friction and \( f_1 \) is the new (reduced) friction.

- All three groups show reduction of steady state friction force. Friction reduction decreases as velocity increases.
## Wear Reduction

<table>
<thead>
<tr>
<th>Linear velocity (mm/s)</th>
<th>Wear rate without US (mm³/m)</th>
<th>Wear rate with US (mm³/m)</th>
<th>Wear Reduction (mm³/m)</th>
<th>Number of Contacts</th>
<th>Wear Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.3</td>
<td>2.237×10⁻²</td>
<td>1.214×10⁻²</td>
<td>1.023×10⁻²</td>
<td>3.17×10⁸</td>
<td>45.76</td>
</tr>
<tr>
<td>40.6</td>
<td>2.581×10⁻²</td>
<td>1.338×10⁻²</td>
<td>1.243×10⁻²</td>
<td>1.58×10⁸</td>
<td>48.18</td>
</tr>
<tr>
<td>87</td>
<td>2.430×10⁻²</td>
<td>1.248×10⁻²</td>
<td>1.182×10⁻²</td>
<td>7.39×10⁷</td>
<td>48.63</td>
</tr>
</tbody>
</table>
Modified Pin-on-disc Tribometer for Power Mapping

- Gymbal assembly
- Weight (normal load)
- Load cell (friction)
- Hall-effect probe
- Gaussmeter
- Thermocouple
- Piezo-actuator
- Acorn nut
- Sample disc
- Platform
- Chuck
- Turntable thrust bearing
- Support frame (motor inside)
### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load (N)</td>
<td>3, 4, 5, 6, 7, 8, 9</td>
</tr>
<tr>
<td>Nominal contact area (mm²)</td>
<td>0.126</td>
</tr>
<tr>
<td>Nominal normal stress (MPa)</td>
<td>23, 32, 40, 48, 55, 63, 70</td>
</tr>
<tr>
<td>Rotational diameter (mm)</td>
<td>28, 48.3</td>
</tr>
<tr>
<td>Linear velocity (mm/s)</td>
<td>50-200</td>
</tr>
<tr>
<td>Peak-to-peak voltage (V)</td>
<td>0, 5.1, 10.3, 15.5, 20.7, 25.9</td>
</tr>
<tr>
<td>Actuator capacitance (nF)</td>
<td>360</td>
</tr>
<tr>
<td>Power consumed by the actuator (W)</td>
<td>0, 0.21, 0.84, 1.9, 3.39, 5.31</td>
</tr>
<tr>
<td>Nominal US amplitude (µm)</td>
<td>0, 0.46, 0.92, 1.38, 1.85, 2.31</td>
</tr>
<tr>
<td>US frequency (kHz)</td>
<td>22</td>
</tr>
<tr>
<td>Material</td>
<td>Uncoated steel for pin and disc</td>
</tr>
</tbody>
</table>

- 7 plates in total
- One stress assigned to one plate

![Sample plate](image)
Friction Reduction vs. Linear Velocity

Note: Noise and measurement errors cause some data markers to show greater than 100% friction reduction.
Relationship between Friction Reduction, Linear Velocity and Normal Stress

- Friction reduction peaks at 48 and 55 MPa normal stress, especially at low velocities.
- A dynamic model, incorporated with a “cube” model [15], is employed to explain the cause of the peaks.
Relationship between Friction Reduction, Linear Velocity, and Power Consumption

Normal stress = 23 MPa

Normal stress = 40 MPa

Normal stress = 55 MPa

Normal stress = 70 MPa
The efficiency coefficient can be used to:

(a) Estimate new (reduced) friction force for a given electrical power supply

\[ F_{t1} = F_{t0} - \frac{F_N (av_{rel} + b)}{v_{rel} A_n} \]

(b) Estimate power requirement for a given amount of friction reduction

\[ P_a = \frac{(F_{t0} - F_{t1})v_{rel} A_n}{F_N (av_{rel} + b)} \]

(c) Enable ultrasonic friction control

\[ \eta = av_{rel} + b \]
Comparison between Lubrication Methods

• US lubrication depends on velocity but not load; MK depends on load but not velocity; Both combined are mostly invariant with changing velocity or load

• **Region I**: Use US lubrication

• **Region II and III**: Use MK or MK + US depending on load

• **Region III**: Avoid US lubrication alone or increase US power

Electric power for US lubrication: 5.31 W
• The contact between two nominally flat surfaces in fact takes place between asperities

• A cube is used to represent the combined asperities. The height of the cube represents the average height of all the contacting asperities. The area of the top surface of the cube is equal to the actual contact area of two surfaces, which is much smaller than the nominal contact area

• The model takes plastic deformation of asperities into consideration

\[ F_t = K_t \delta \]

\[ K_t = \frac{E^* A_r^2}{d^3} \]

\[ \delta' = \delta + u_1 \]

\[ d' = d + u_3 \]

\[ F_t' = K_t' \delta' \]

*(Prime symbol denotes the value of parameters with ultrasonic vibrations)*

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Spring $k_1$ represents the stiffness of the contacting asperities.

It works when the displacement is within a certain range around equilibrium, and it has non-linear behavior.

The relationship is calculated from the “cube” model.

$$k^*_p = k_p + k_s$$

$$k_1 = \frac{E^* A_r}{d}$$
Total volume of the removed material in a cube can be calculated as

$$V = \frac{A_r d}{2}$$

where $A_r$ is the real contact area and $d$ is the height of the cube. When ultrasonic vibrations are applied, the volume of removed material is

$$V' = \frac{1}{2T} \int_0^T A_r' d' dt$$

The cube model is able to match the experimental data of friction and wear reduction with errors less than 15%.
Concluding Remarks

• Friction and wear reduction were investigated between various material combinations with conditions of various normal stresses and linear velocities

• Friction near 100% can be achieved under certain conditions

• Higher velocity results in lower friction reduction; normal stress has little effect on friction reduction

• Contour plots of power consumption, linear velocity, normal stress, and friction reduction were created from the experimental data

• A comparison between ultrasonic, traditional, and combined lubrication methods was conducted

• A cube model was proposed to explain and quantify ultrasonic friction and wear reduction
Thank you!
Additional Slides
References

References


