

Defense of PhD thesis

BRNO, CZECH REPUBLIC | 2nd MARCH 2018

Elastohydrodynamic film study under impact loading and lateral vibrations

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AND INDUSTRIAL DESIGN

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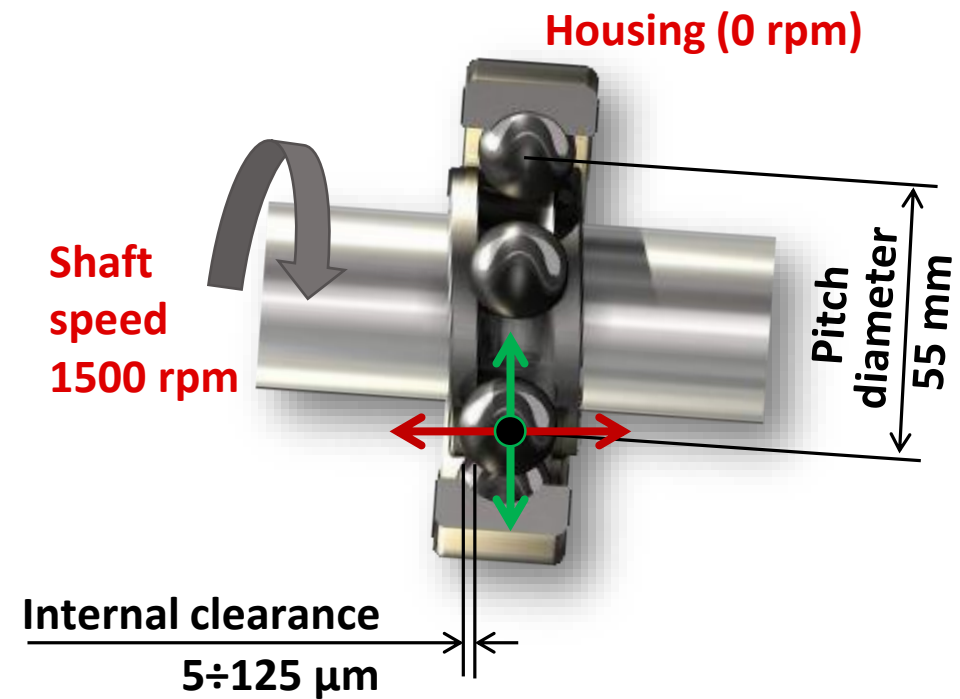
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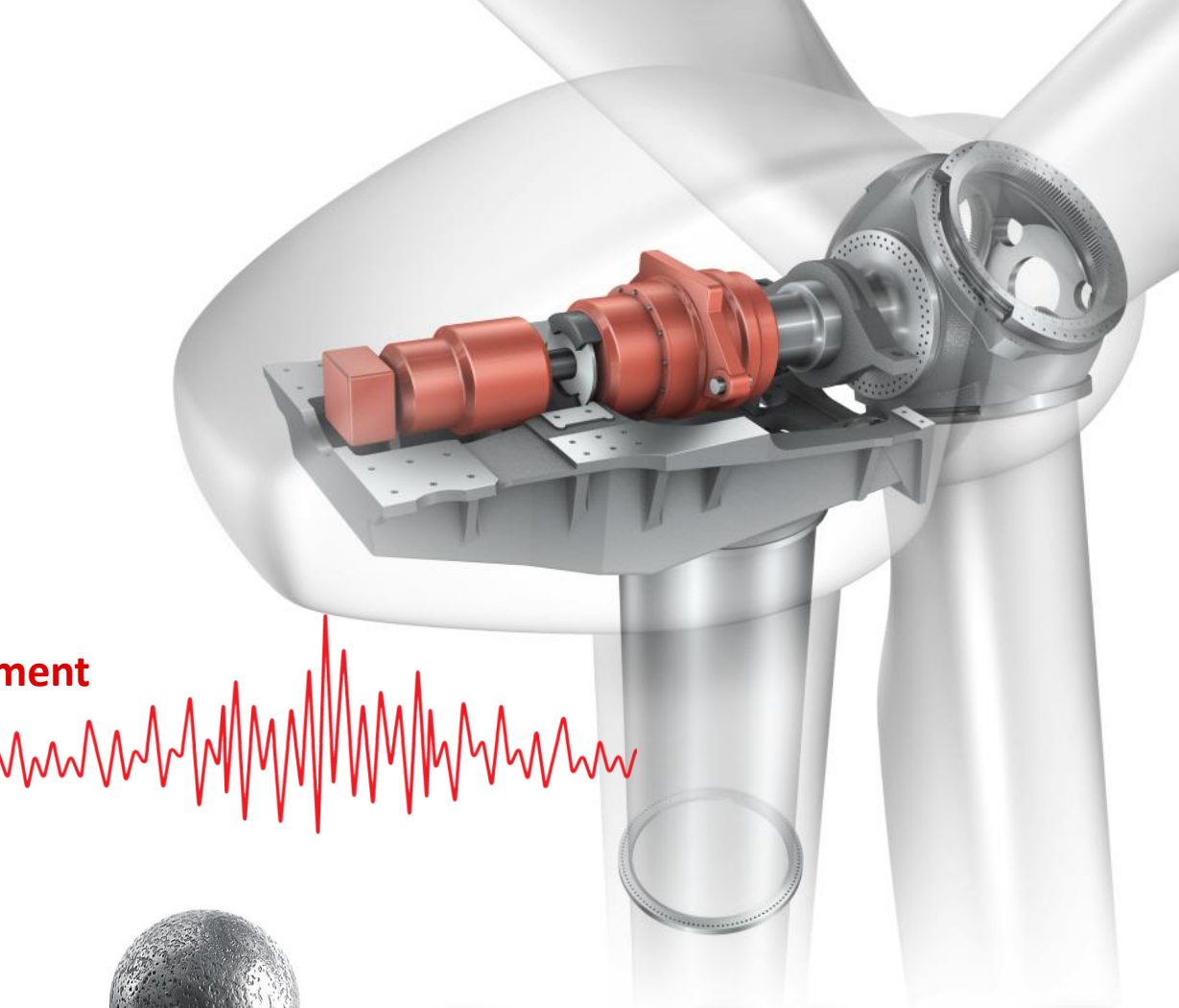


Introduction - Motivation

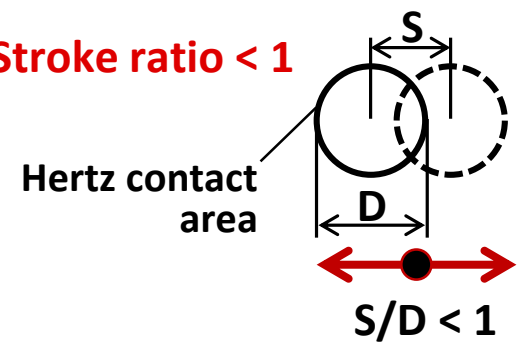
Vibrations in machine elements



Rolling element
frequency
>200 Hz



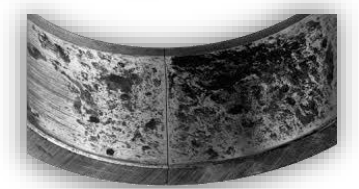
Stroke ratio < 1



Fatigue

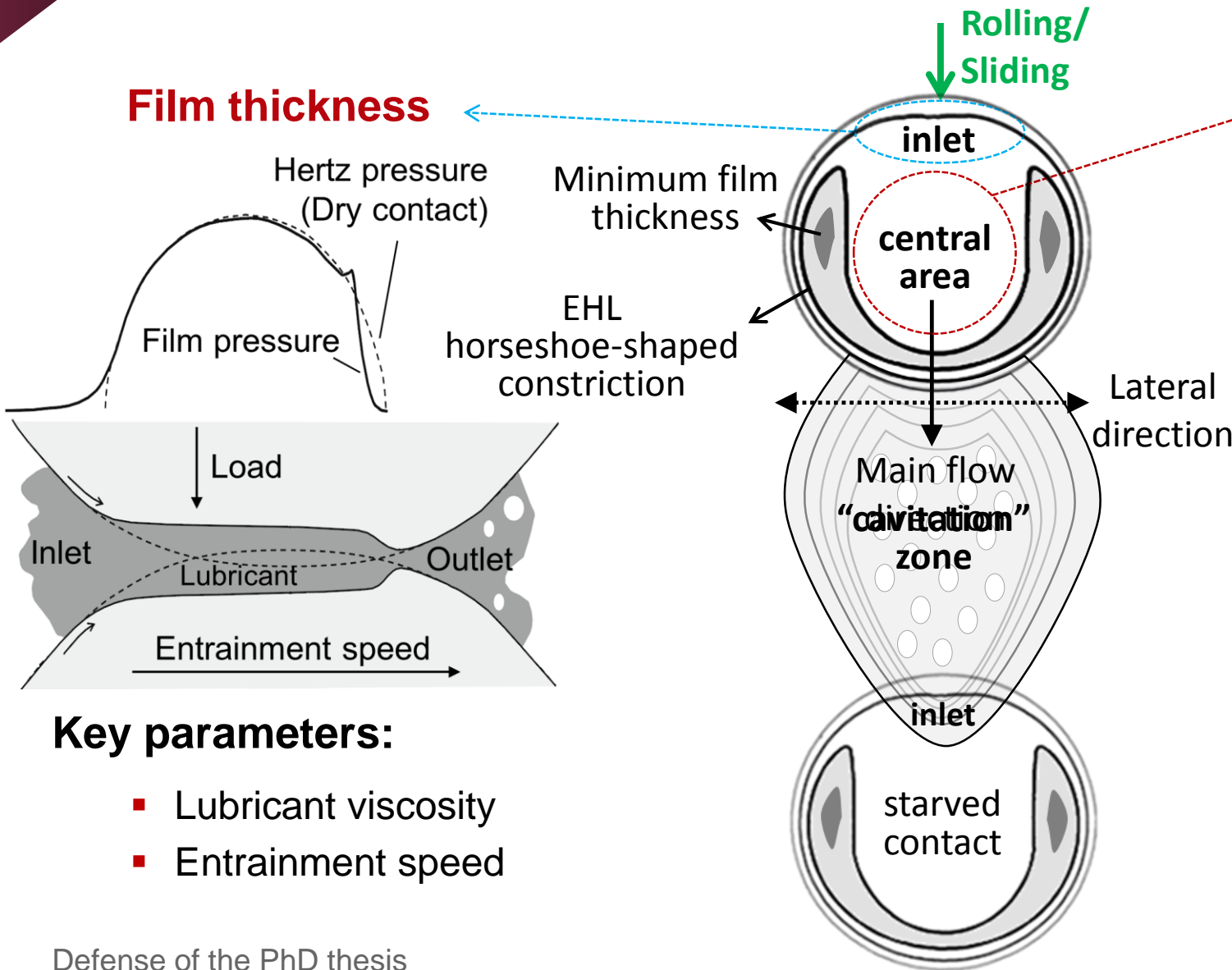


False brinelling



Fretting corrosion

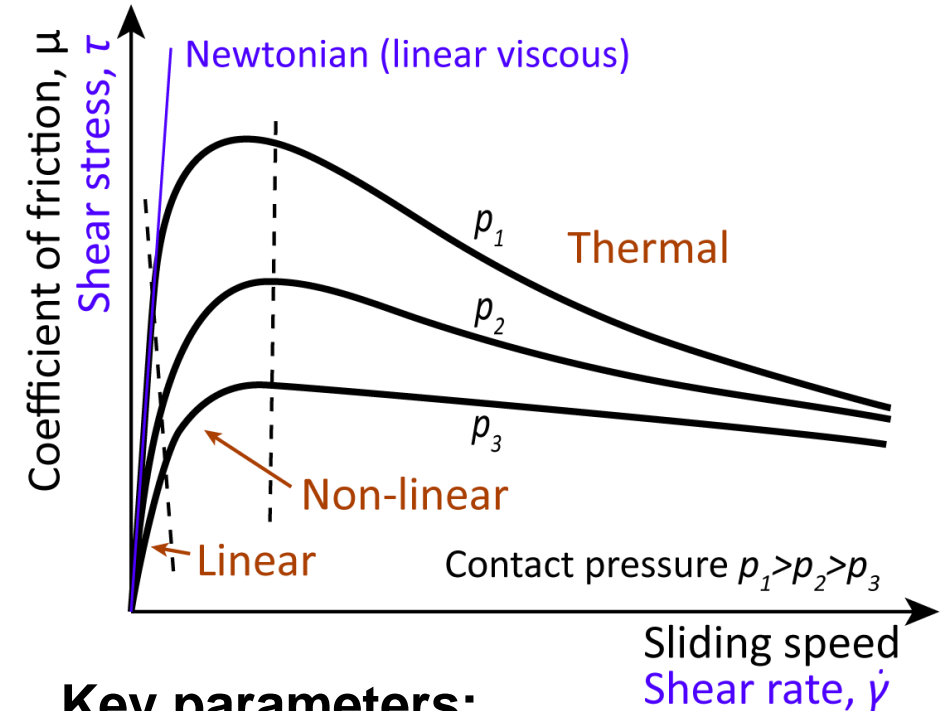
Introduction - Steady-state EHL contact



Key parameters:

- Lubricant viscosity
- Entrainment speed

Friction



Key parameters:

- Lubricant rheology
- Sliding speed (shear rate)
- Load (pressure)

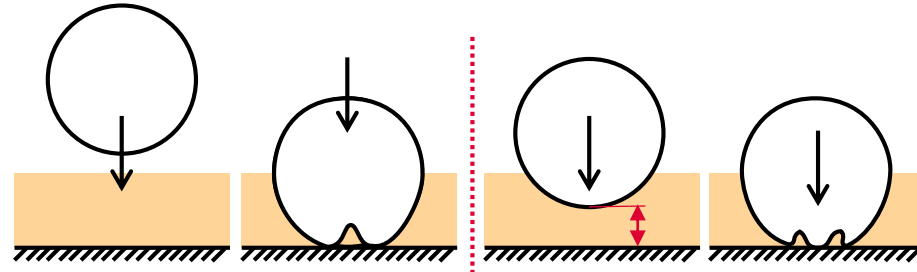
State of the art

Impact loading

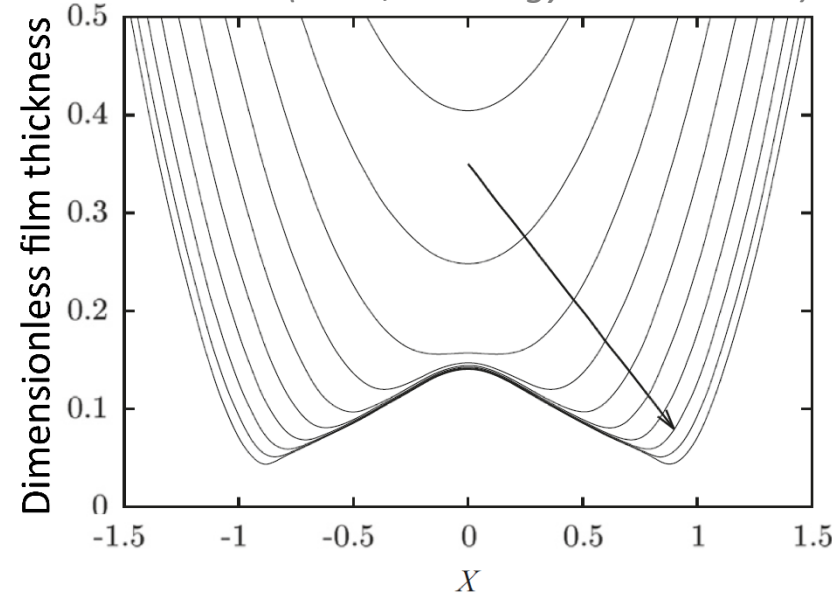
Transient motions

Lateral vibrations

Pure squeeze action



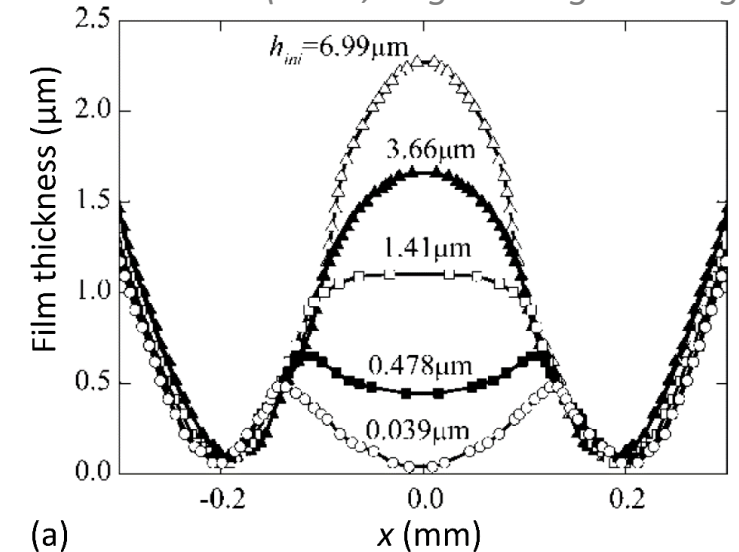
Venner (2016, Tribology International)



Key parameters:

- Viscosity
- Pressure-viscosity coefficient
- Approaching speed (m/s)
- Loading speed (N/s)
- Initial impact gap

Kaneta (2007, Engineering Tribology)



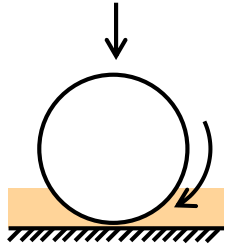
State of the art

Impact loading

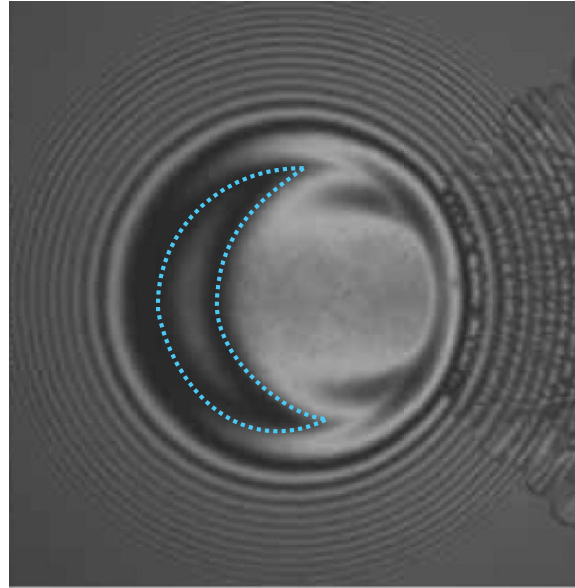
Transient motions

Lateral vibrations

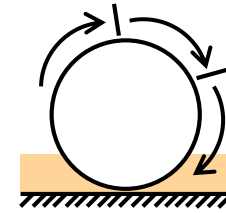
Entrainment and squeeze action



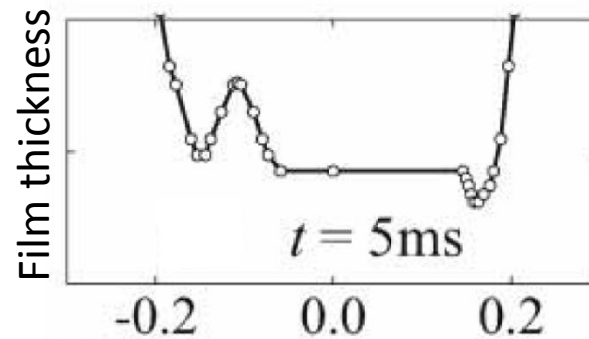
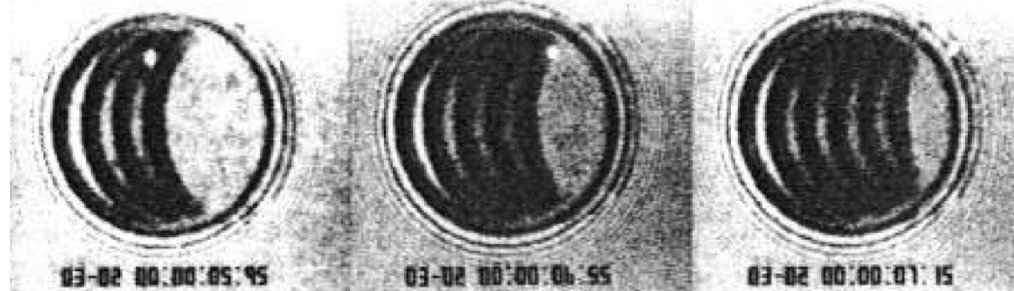
Kaneta (2007, Engineering Tribology)



Start-stop motion



Kaneta (1990, Tribology-Transactions)



Key parameters:

- Deceleration

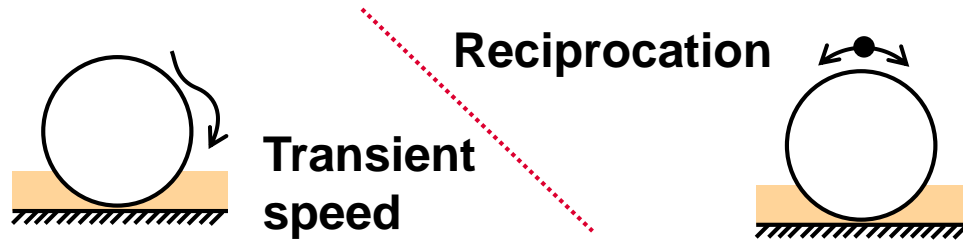
State of the art

Impact loading

Transient motions

Lateral vibrations

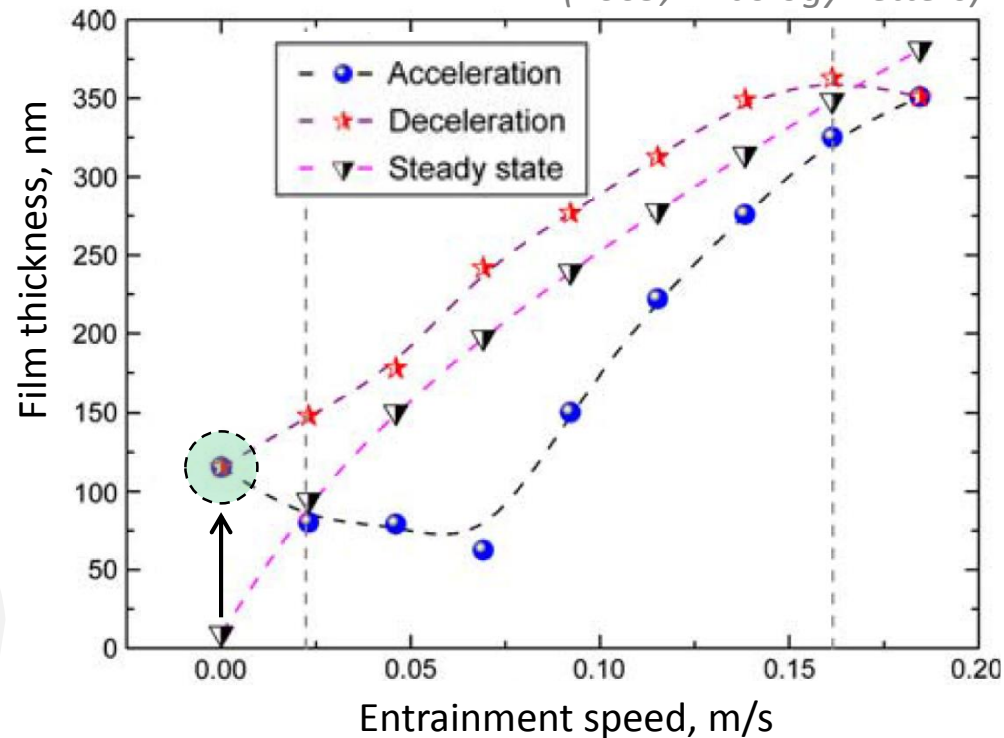
Entrainment and squeeze action



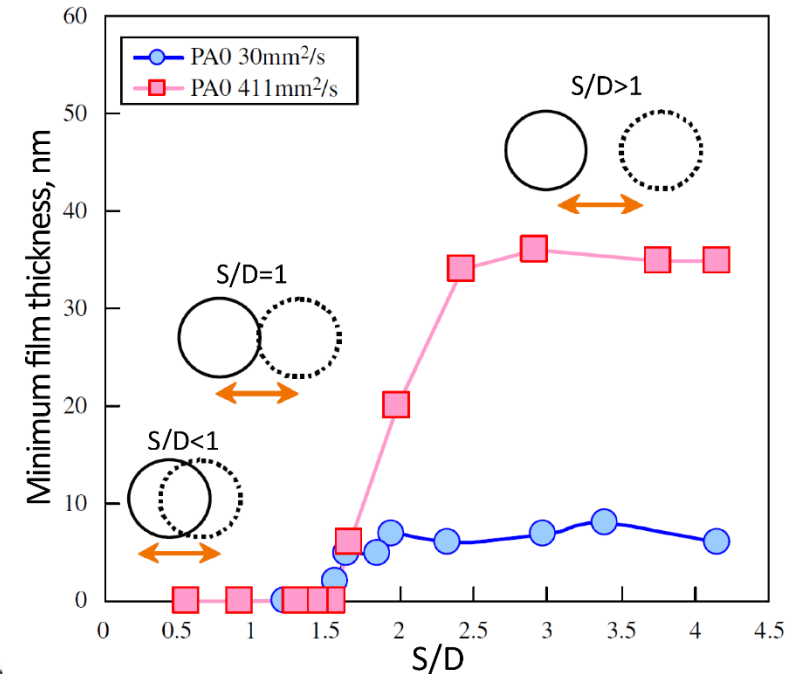
Key parameters:

- Acceleration/Deceleration
- Frequency
- S/D ratio (stroke length)

Li (2009, Tribology Letters)



Maruyama (2010, Tribology International)



State of the art

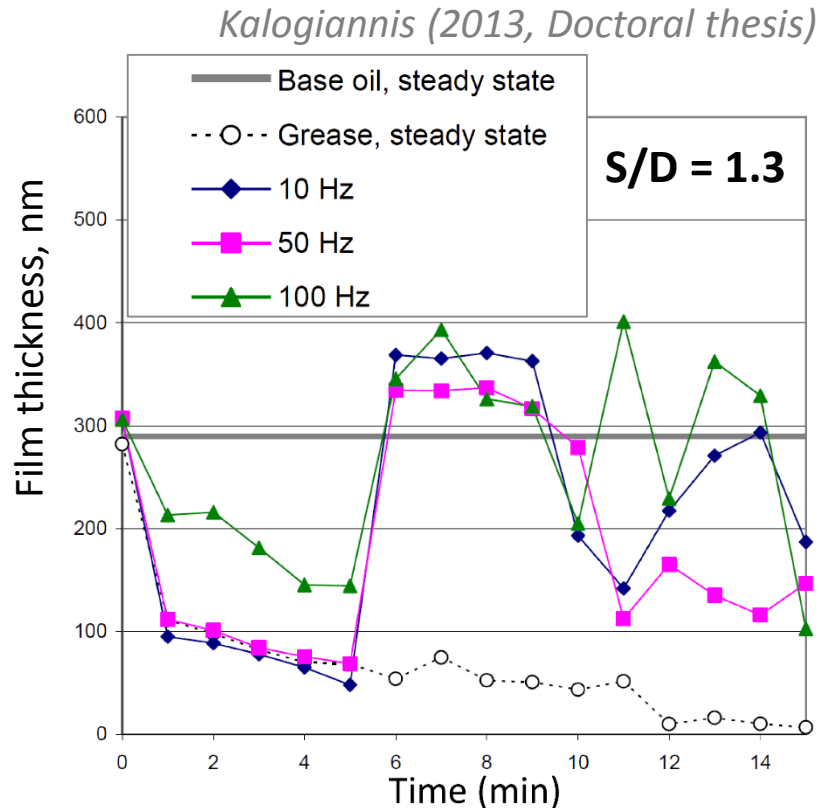
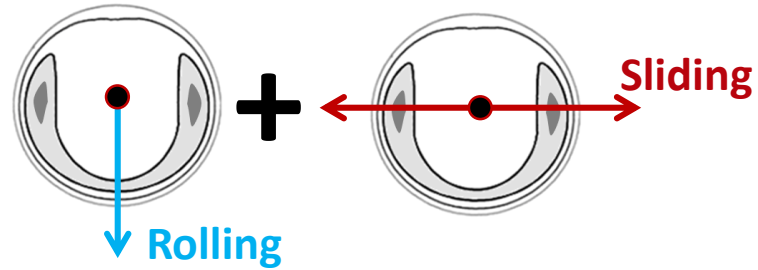
Impact loading

Transient motions

Lateral vibrations

Defense of the PhD thesis

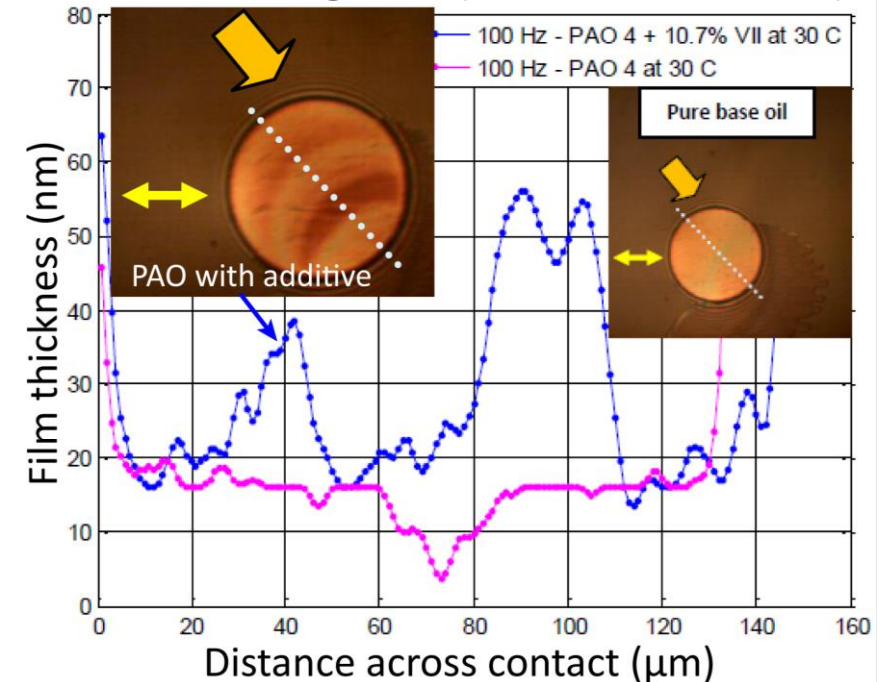
Entrainment and squeeze action



Key parameters:

- S/D ratio (replenishment)
- Lubricant rheology
- Main/lateral speed ratio

Kalogiannis (2013, Doctoral thesis)



Critical summary of literature review

Impact loading

Role of key parameters on entrapment?

- Theoretical studies - Approaching speed (m/s)
- Experimental studies - Loading speed (N/s)

Experimental studies

- Limited number of lubricants / specific lubricant
 - Unrealistically large initial gaps (over 1 μm)
-

Lateral vibrations

Effect of vibrations on film thickness?

- No qualitative or quantitative description
- $S/D > 1$

Frictional response under vibrations?

- No study

Aim of PhD thesis

To experimentally determine the **effects of operating parameters** on the EHL film behaviour in the point contact under **impact load** and **lateral vibrations**

Scientific questions

- Which parameters determine a thickness and shape of squeezed film?
- What is the dependence of film thickness on the rate of lateral vibrations?
- What is the relation between friction responses in different directions of contact?

Hypotheses

H1:

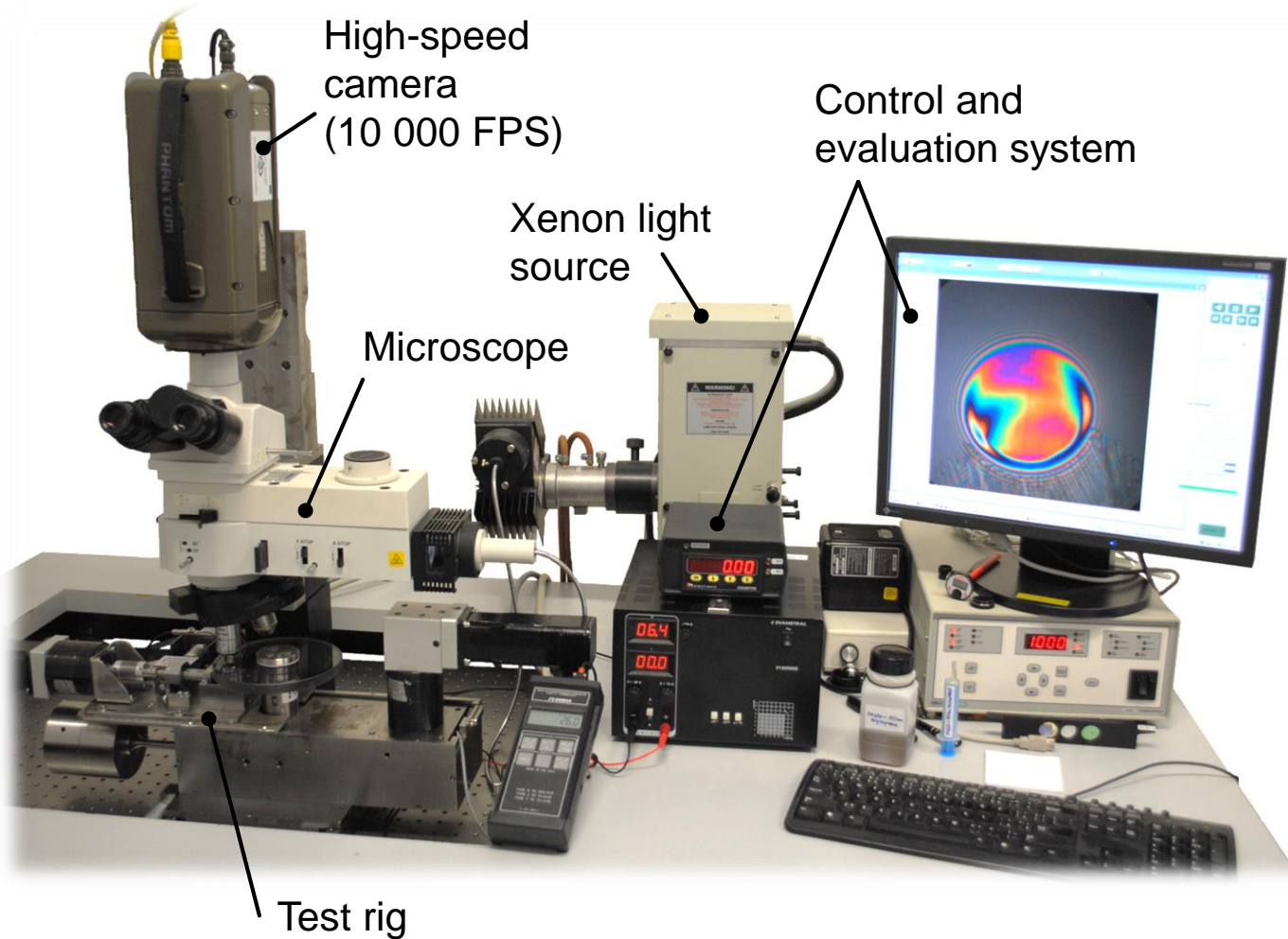
H2:

⋮

H6:

Materials and methods

Experimental apparatus

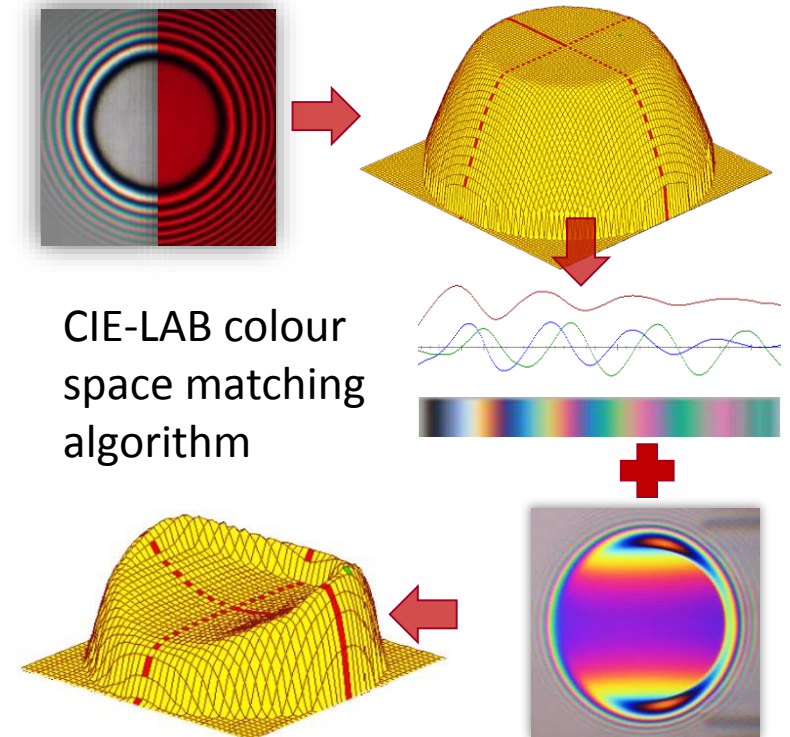


Defense of the PhD thesis

Thin film colorimetric interferometry

- Range 1 ÷ 900 nm
- Resolution ± 1 nm

Film thickness calibration

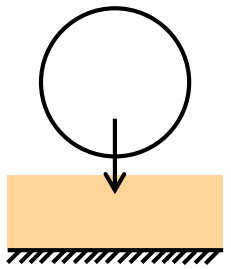


11/31

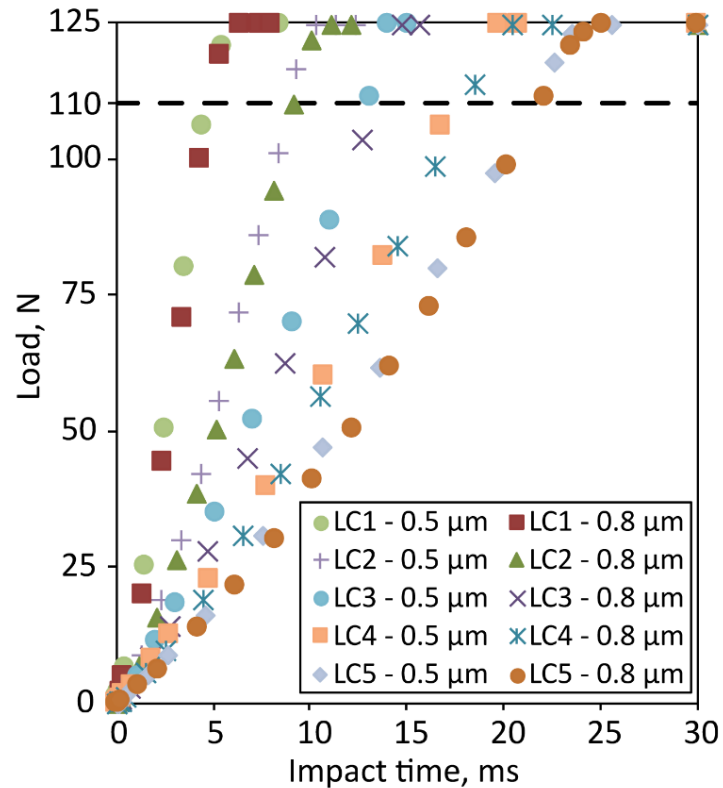
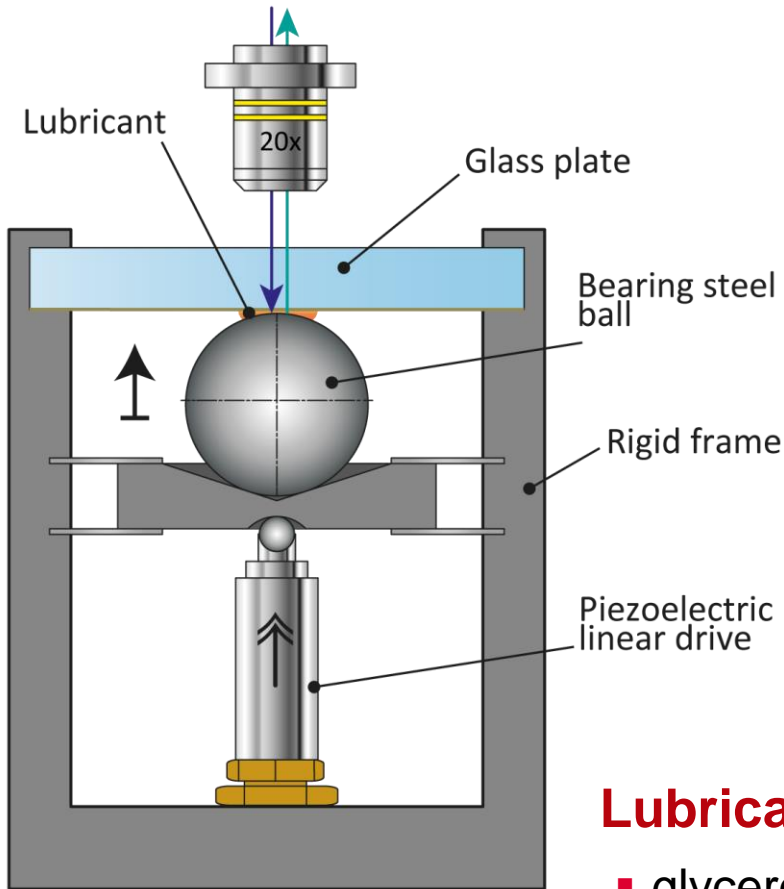
Materials and methods

Test rig – impact load

Film thickness



Approaching and loading speeds (dry contact)



Load curve	Initial gap (μm)	Approach. speed (μm/ms)	Loading speed (N/ms)
LC1	0.5	1.358	24.6
	0.8	2.170	22.9
LC5	0.5	0.409	5.1
	0.8	0.473	5.0

Lubricants:

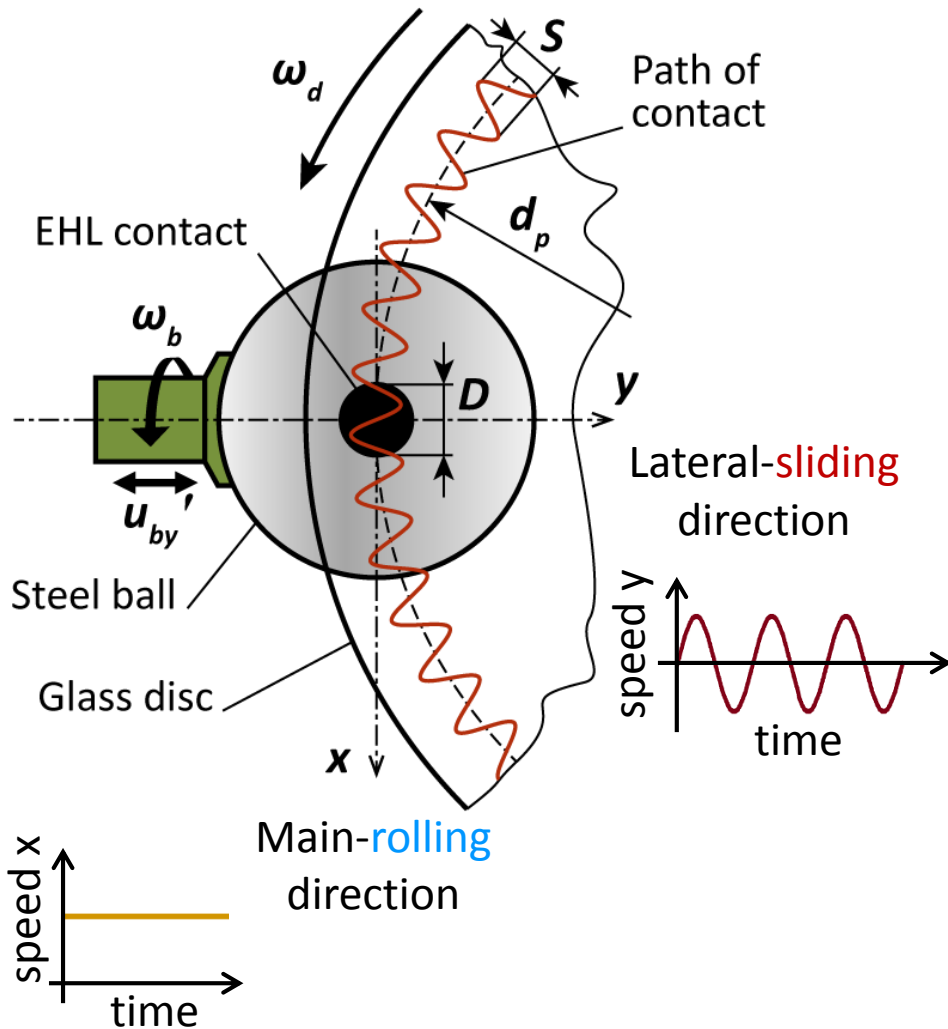
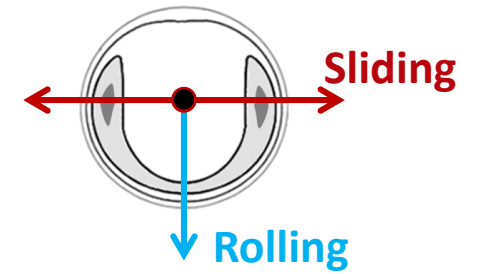
- glycerol
- 2 poly-alfa-olefins
- silicone oil
- 3 paraffinic mineral oils
- squalane
- bright stock oil
- castor oil
- traction fluid

Materials and methods

Test rig – lateral vibrations

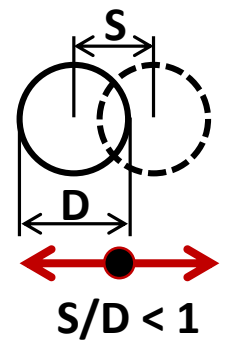
Film thickness

Friction



Operating conditions

Parameter	Min	Max
Entrainment speed u_e' (m/s)	0.006	0.55
Slide-to-roll ratio (SRR) Σ' (1)	0	-1.99
Frequency f (Hz)	0	300
Stroke length S (μm)	80	400
Entrainment acceleration a_e' (m/s^2)	0	250
S/D ratio (1)	0.1	0.9
Contact pressure p_h (GPa)	0.45	0.88



Lubricants and mixtures:

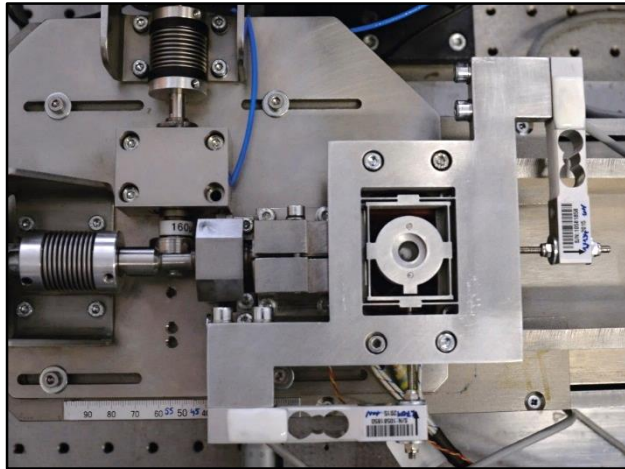
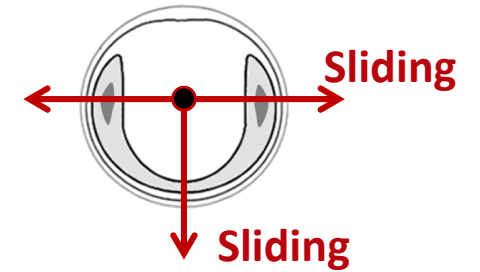
- castor oil (Newtonian)
- paraffinic mineral oil (Newtonian)
- polyglycol (non-Newtonian)
- 2 mixtures (non-Newtonian)

Materials and methods

Test rig – lateral vibrations

Film thickness

Friction



Materials:

- Glass / sapphire window
- Steel ball roughness $R_a \leq 7$ nm

Lubricant:

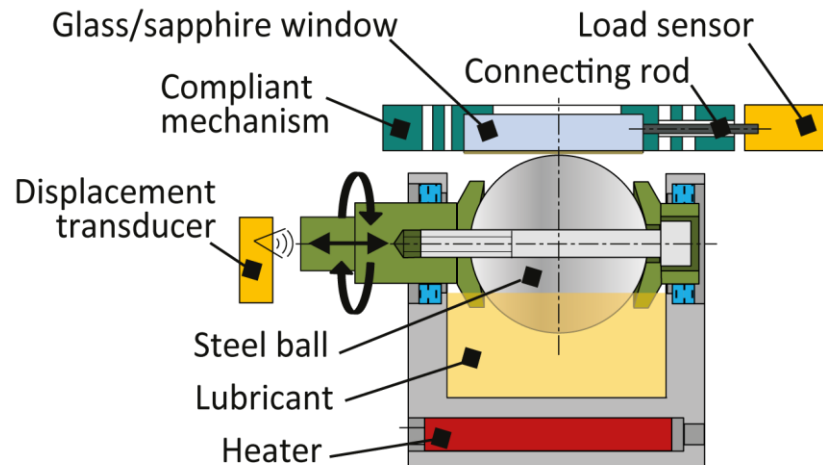
- bright stock oil (Newtonian)

Friction coefficient (COF) measurement

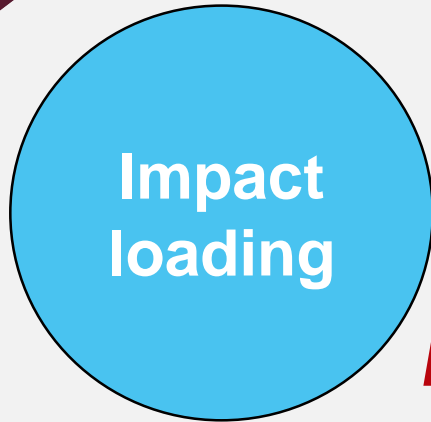
- COF range $0.005 \div 0.2$
- COF uncertainty 0.0005

Operating conditions

Parameter	Min	Max
Main sliding speed u_{sx} (m/s)	0.1	0.1
Frequency f (Hz)	0	100
Stroke length S (μm)	30	220
S/D ratio (1)	0.06	0.62
Contact pressure p_h (GPa)	0.53	1.32



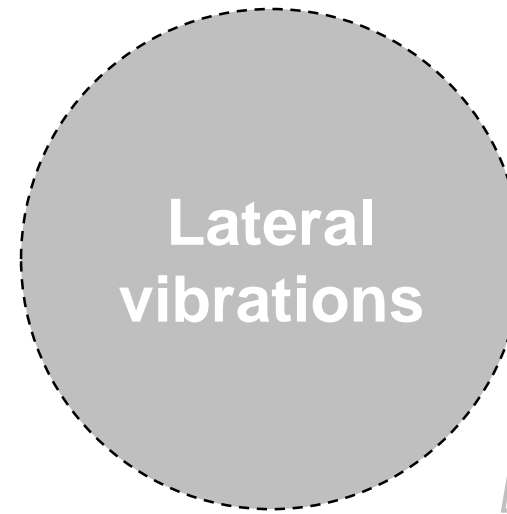
Results and discussion



Film thickness

Role of approaching/loading speed?

Impact of lubricant rheology?



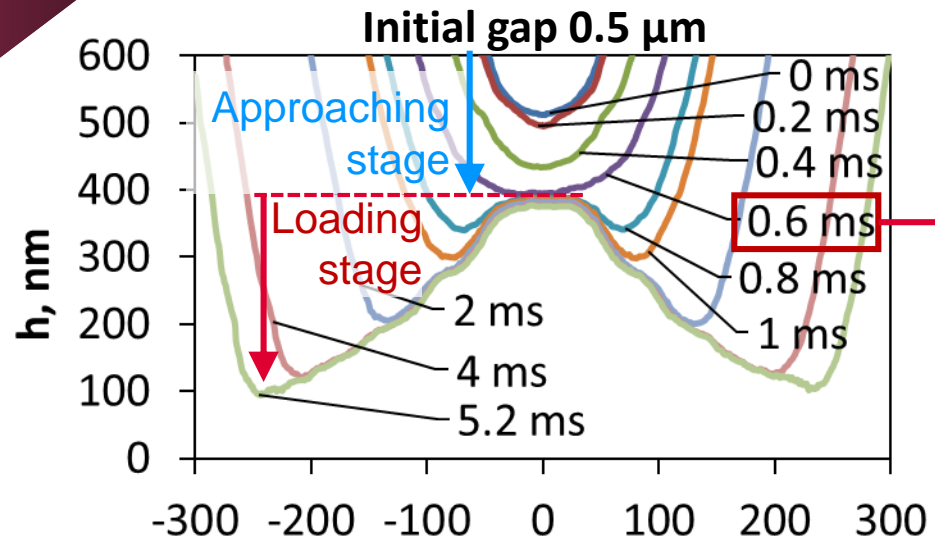
Film thickness

Friction

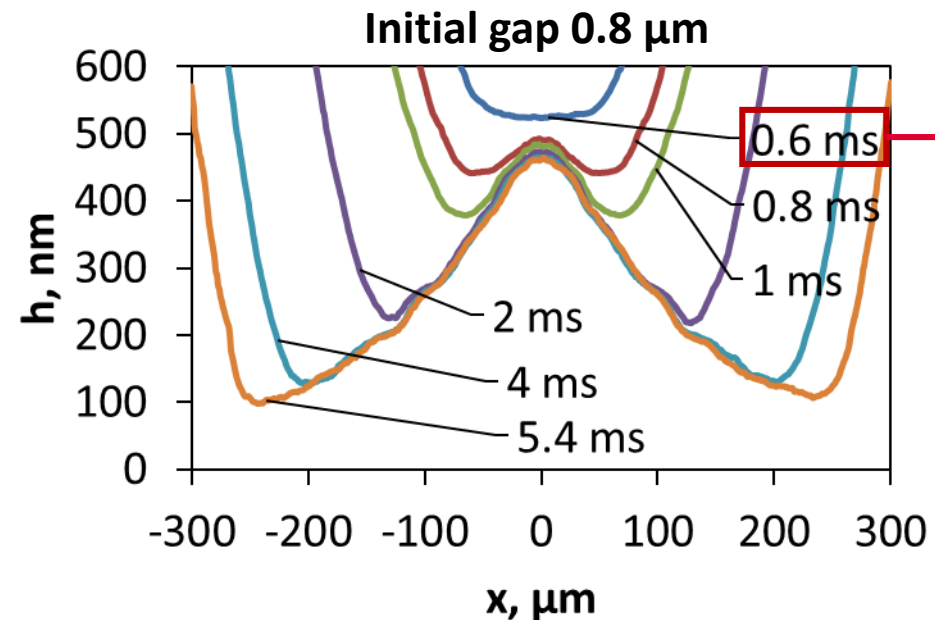
Effect of vibrations on film thickness?

Frictional response under vibrations?

Results and discussion – Role of approaching/loading speed

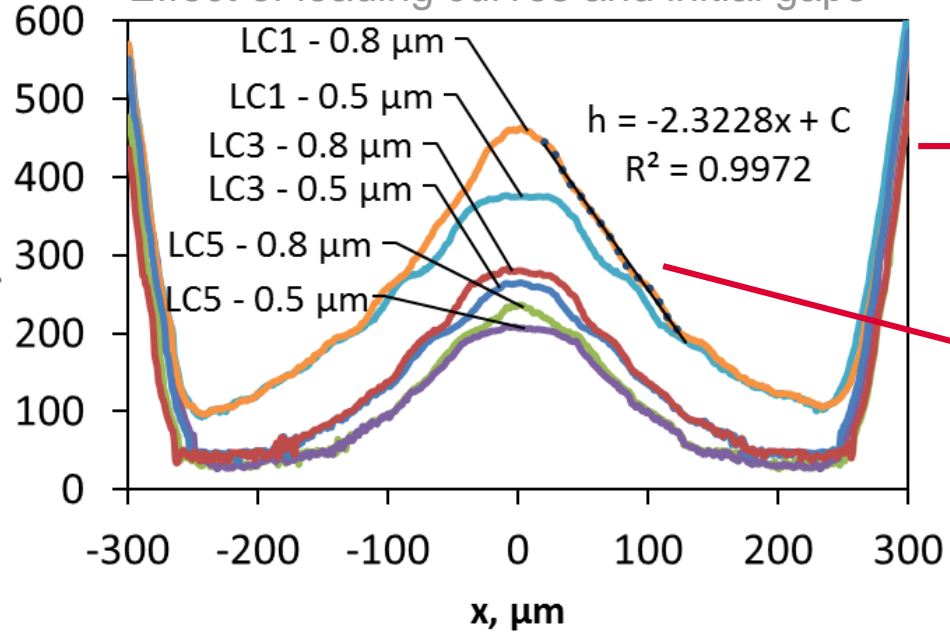


- Central film thickness defined by residual film at specific time



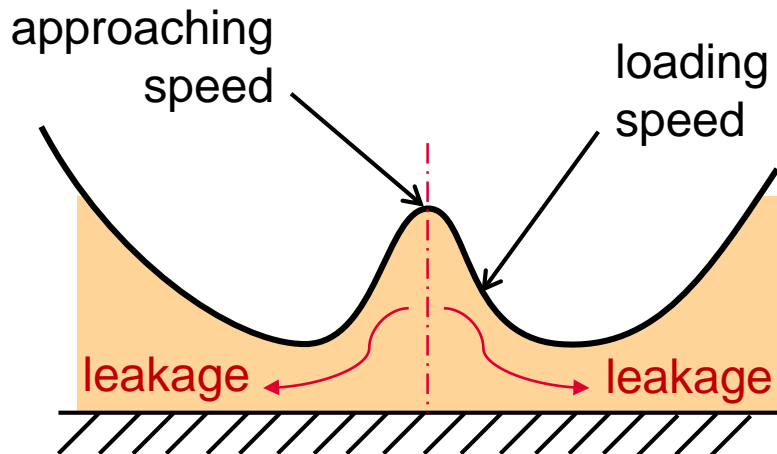
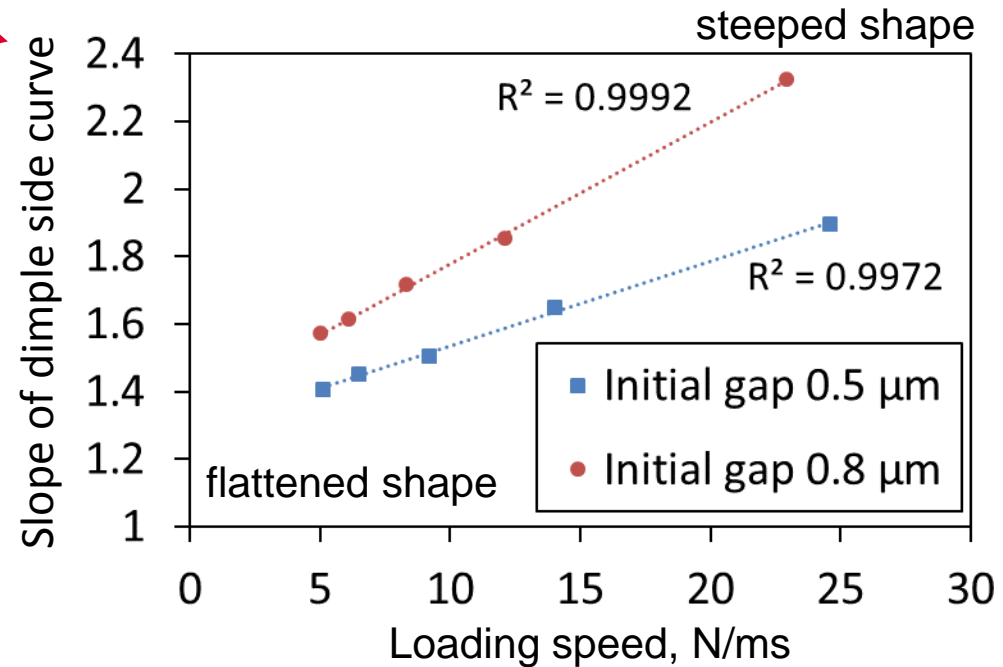
Results and discussion – Role of approaching/loading speed

Effect of loading curves and initial gaps

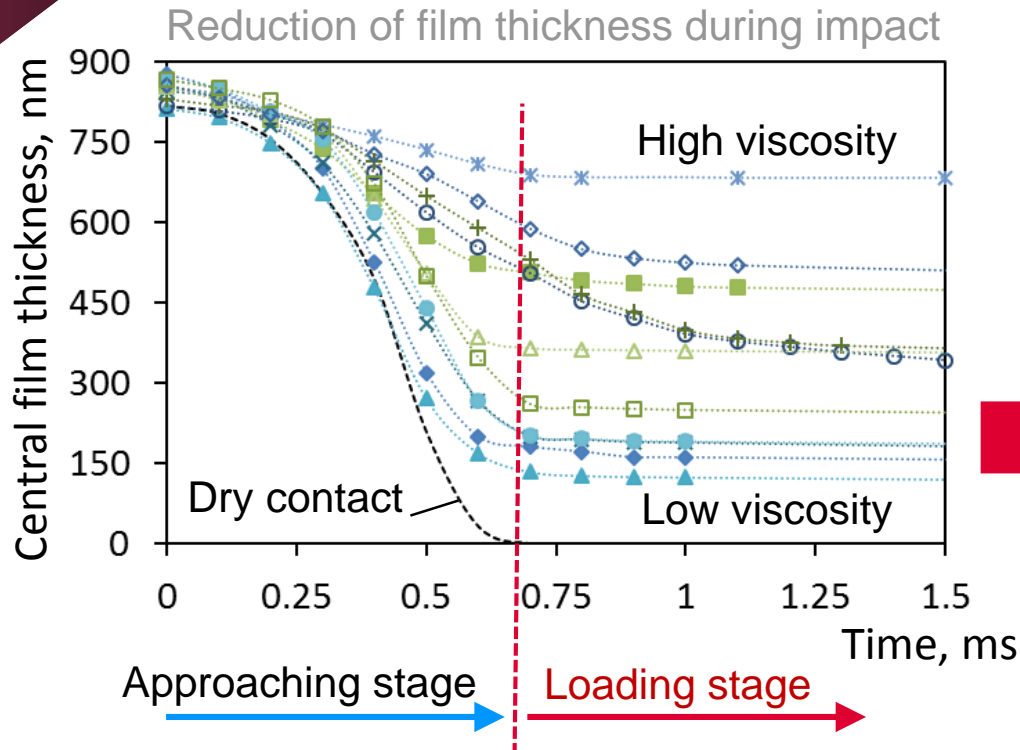


- Central film thickness defined by residual film at specific time
- Changes in central thickness follow differences in approaching speed

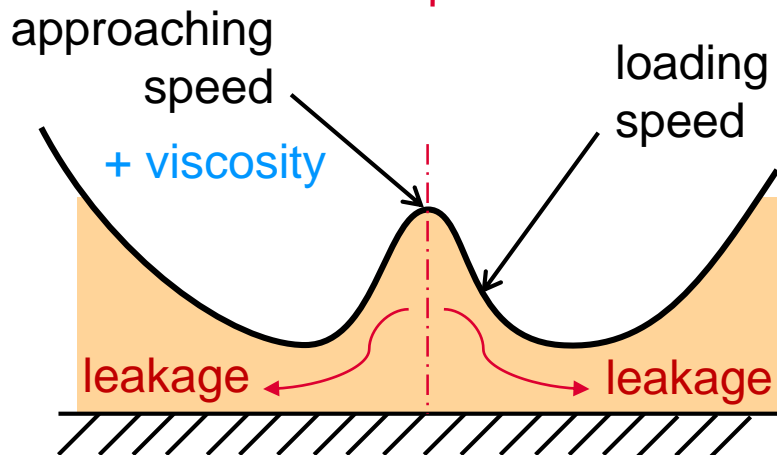
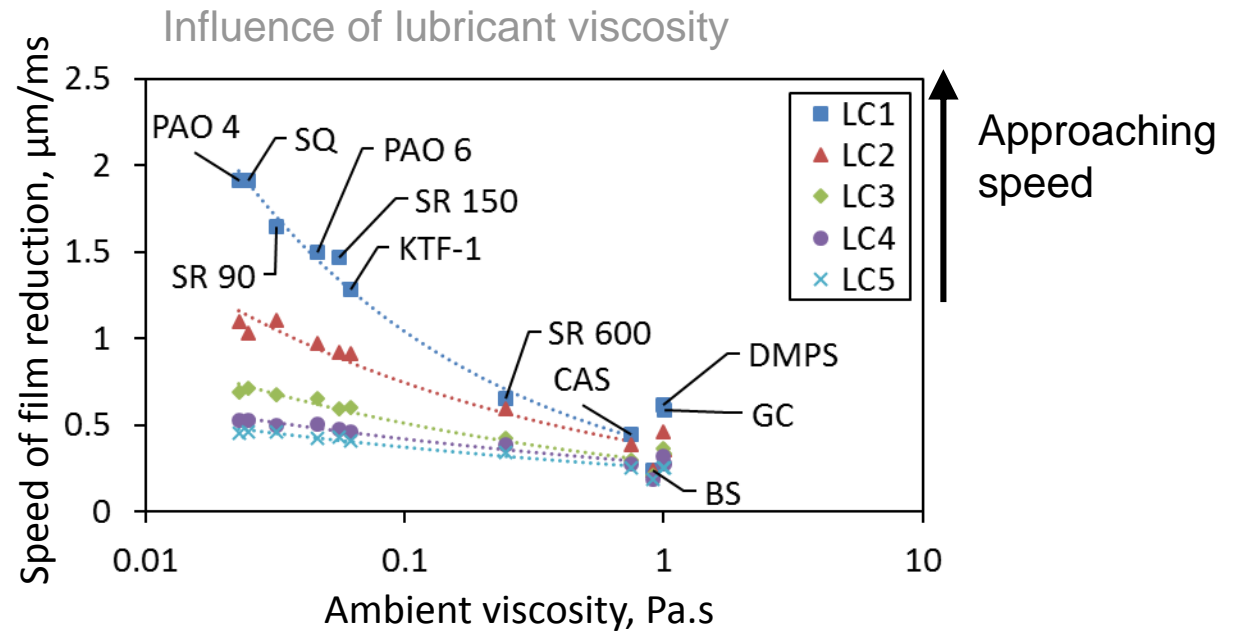
Effect of loading speed



Results and discussion – Effect of lubricant rheology



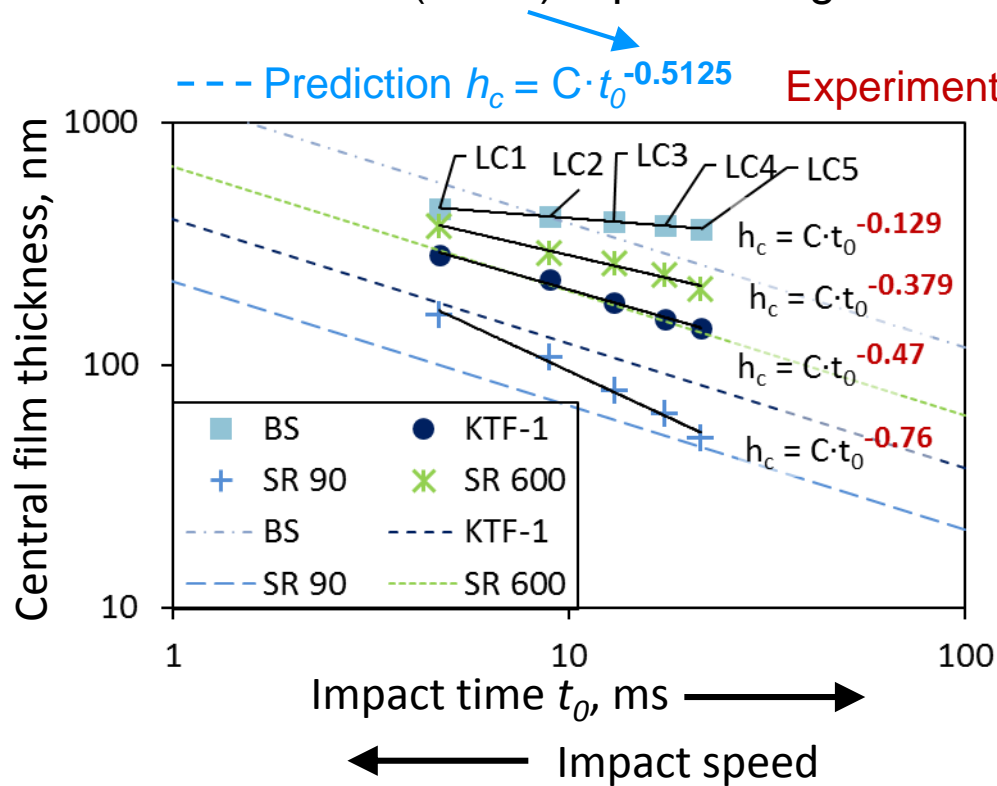
- Viscosity at ambient pressure
- Pressure-viscosity coefficient (PVC)



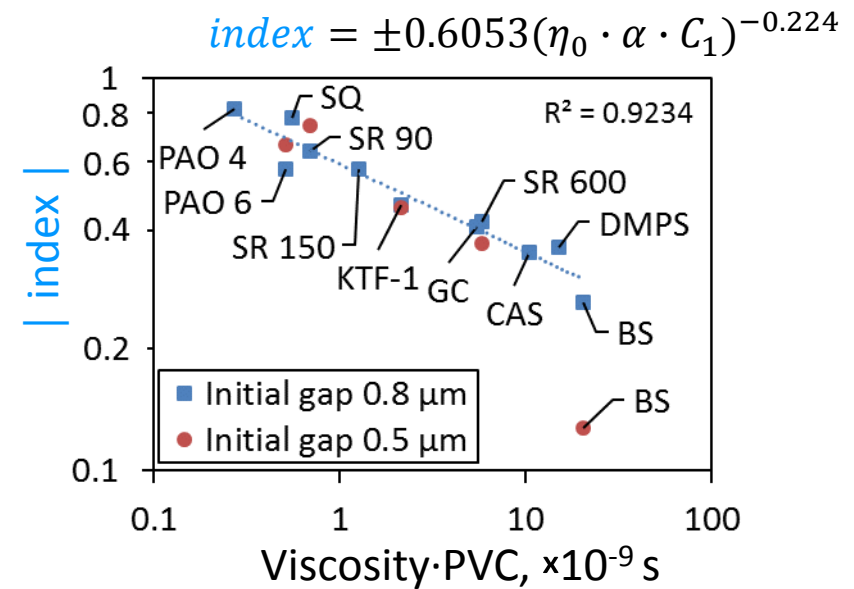
Results and discussion – Comparison with prediction

Venner (2016, Tribology International)

- Underestimated thickness by 32%
- Different trend (*index*) representing effect of impact time / speed



- Lubricant rheology affects impact time / speed



- Influence of impact times/speeds on film thickness can be estimated from basic rheological properties of lubricants

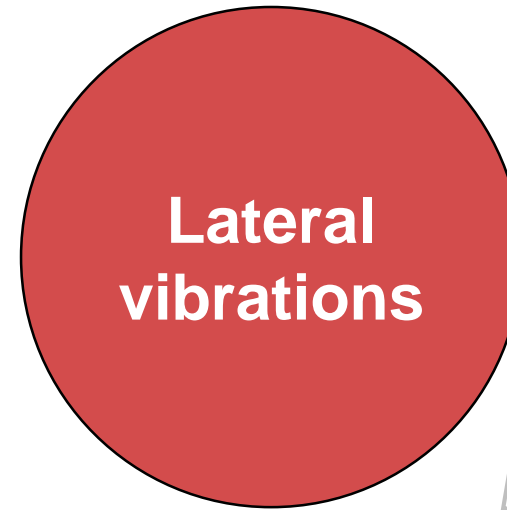
Results and discussion



Film thickness

Role of approaching/loading speed?

Impact of lubricant rheology?



Film thickness

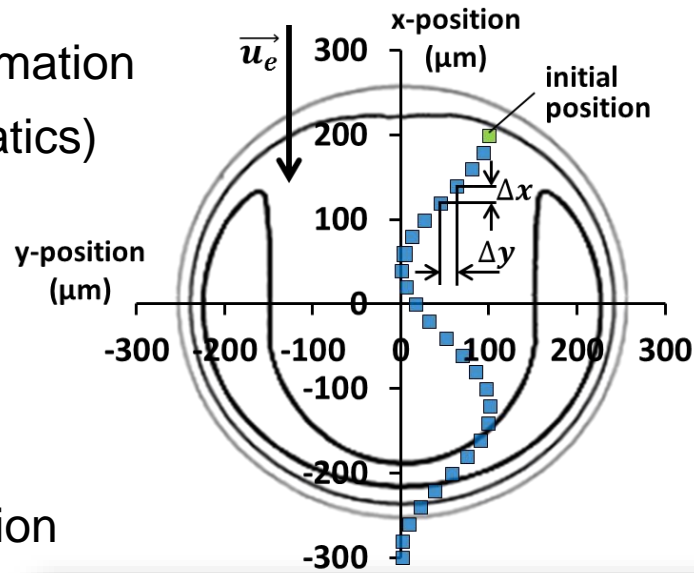
Friction

Effect of vibrations on film thickness?

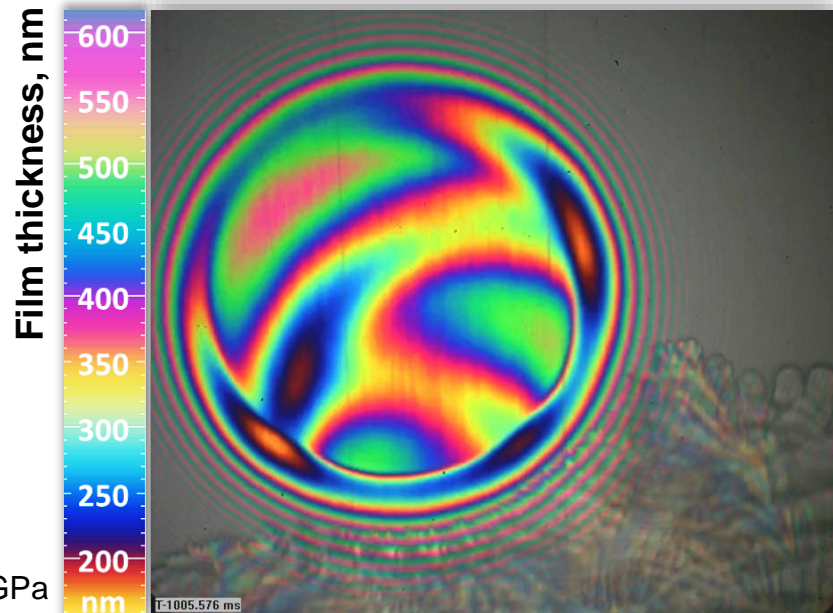
Frictional response under vibrations?

Results and discussion – Mechanism of lubricant passage

- Theoretical estimation (based on kinematics)

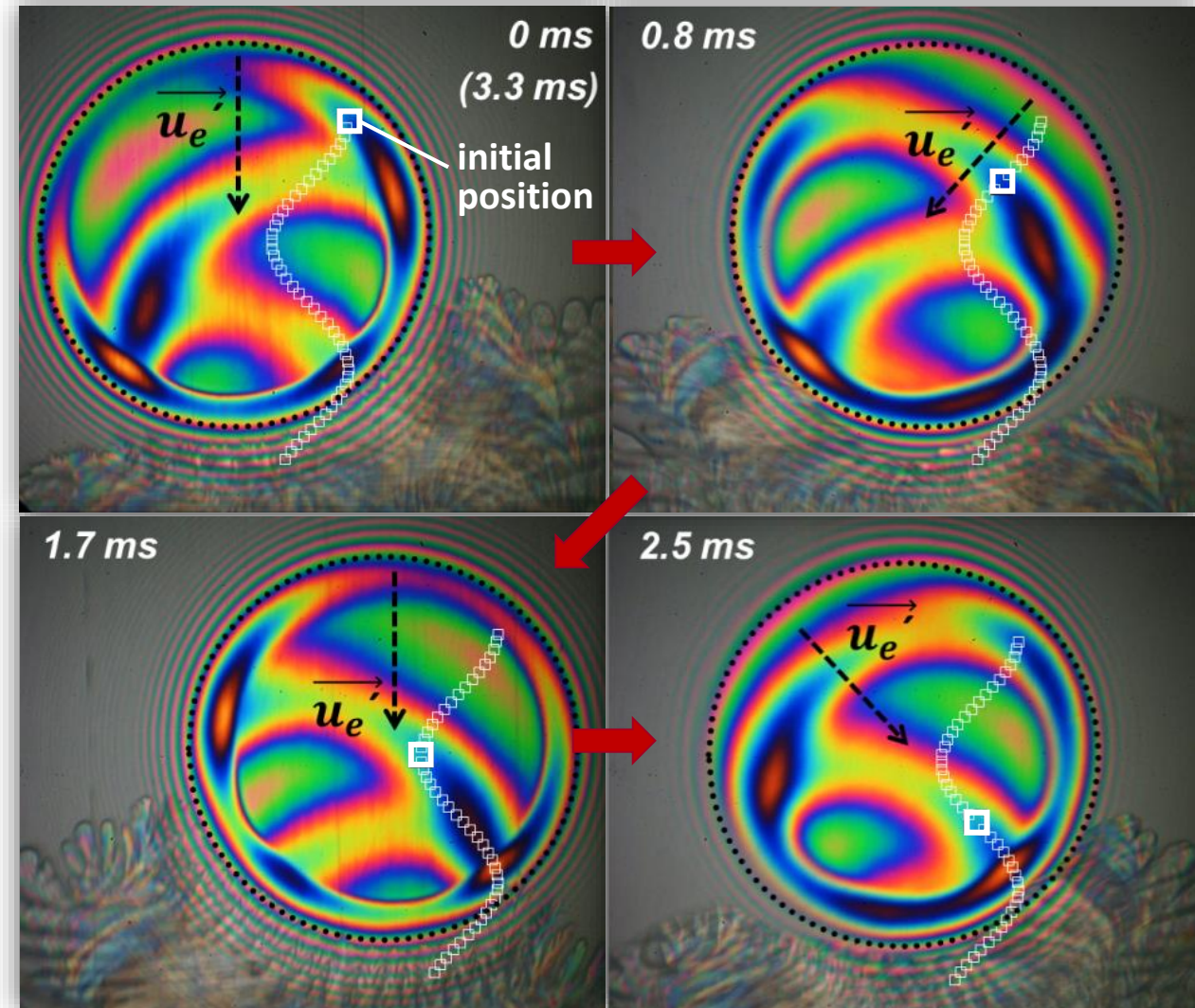


- In-situ observation

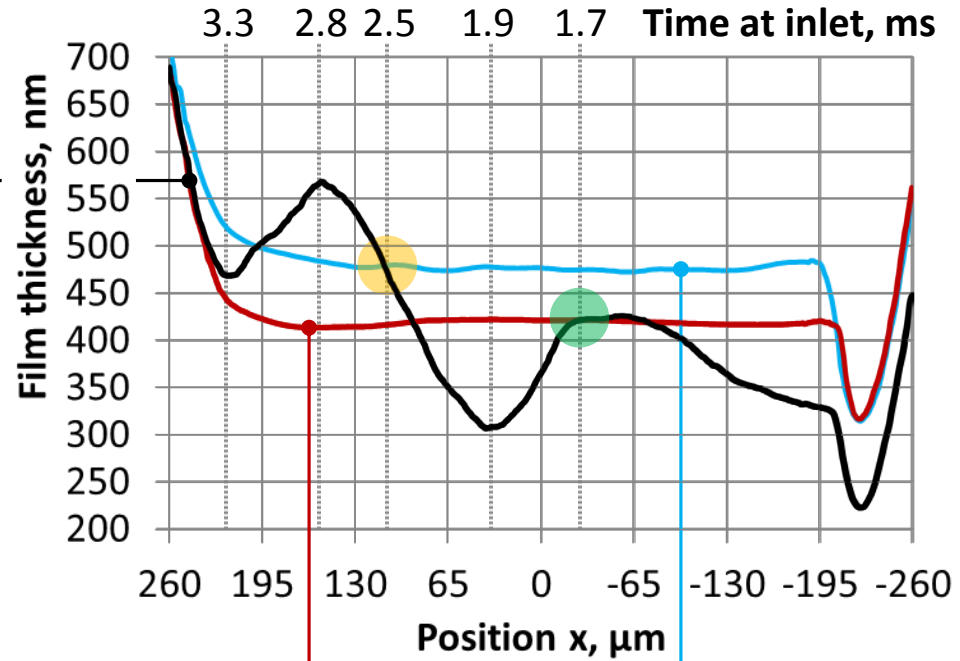
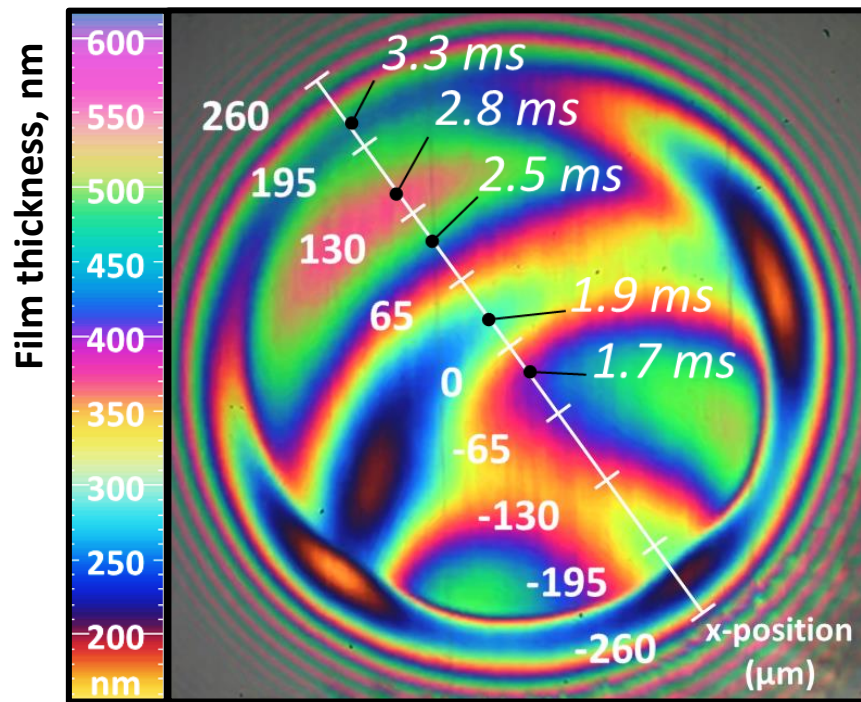


SN650 + PIP, 0.1 m/s,
300 Hz x 200 μm , 0.7 GPa

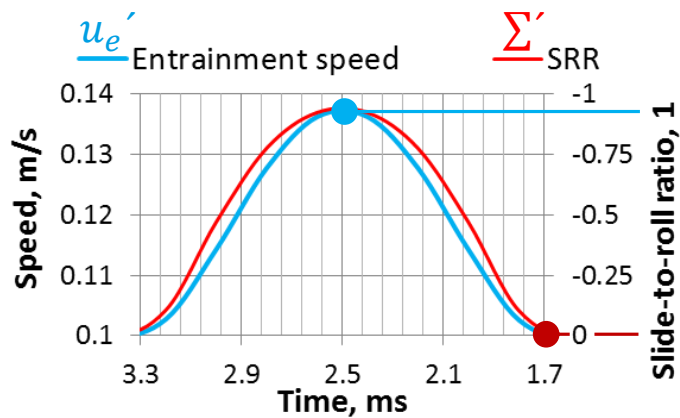
- Passage driven by vector of entrainment velocity



Results and discussion – Origin of film thickness distribution

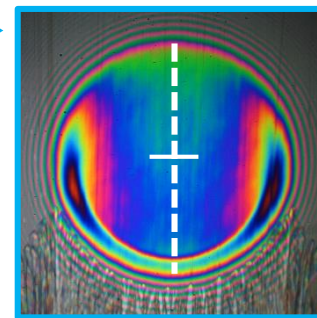
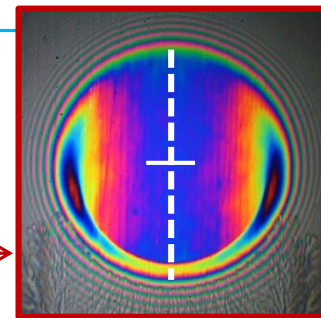


Corresponding steady-state conditions:



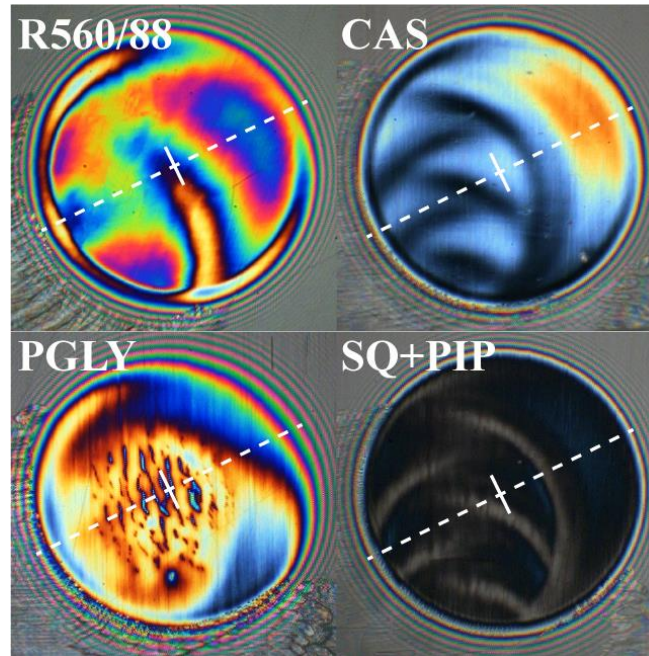
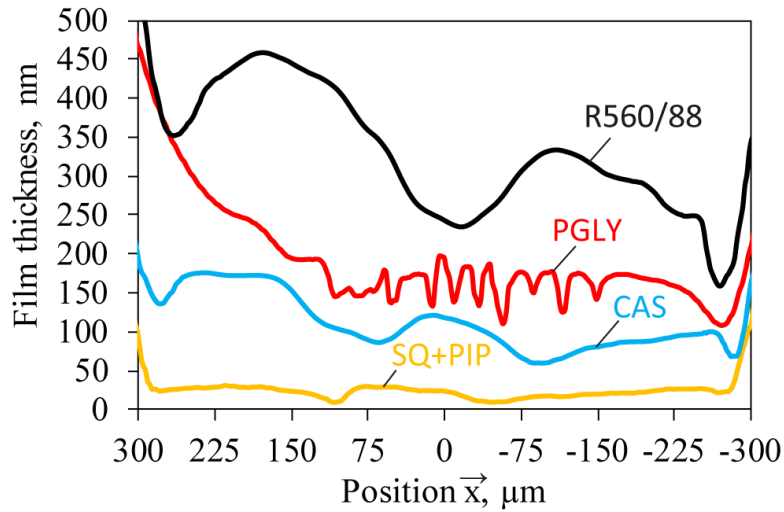
$u_{ex} = 0.1 \text{ m/s}, \Sigma = 0$

$u_{ex} = 0.137 \text{ m/s}, \Sigma = -0.94$



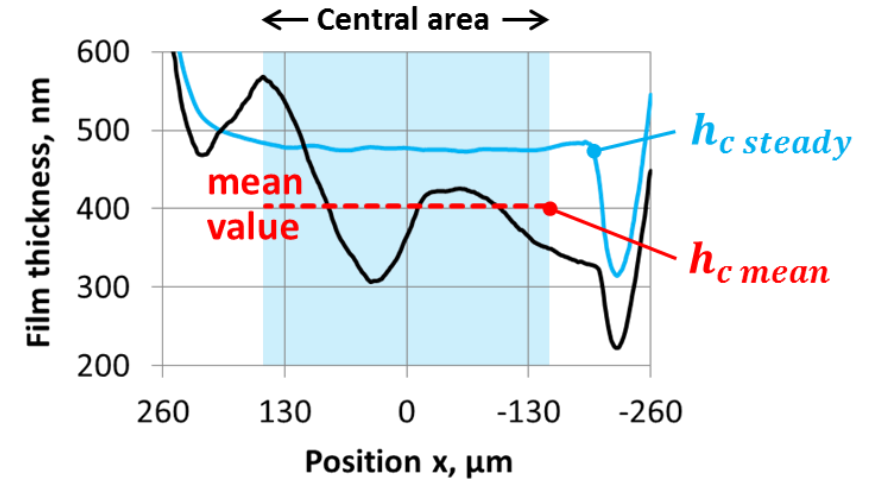
Results and discussion – Effect of vibrations on film thickness

The same conditions, different lubricants



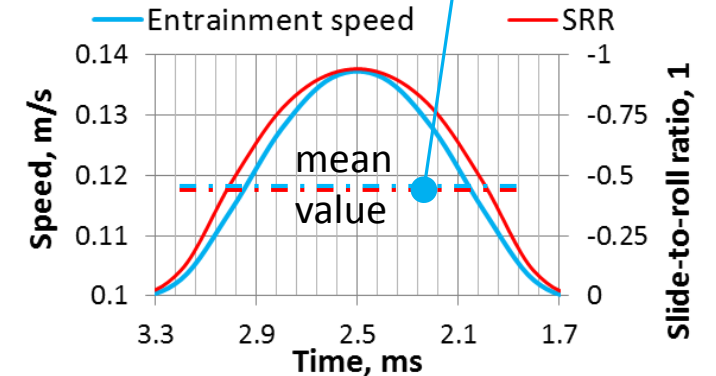
0.05 m/s, 300 Hz x 310 μm, 0.88 GPa

Unification using dimensionless number



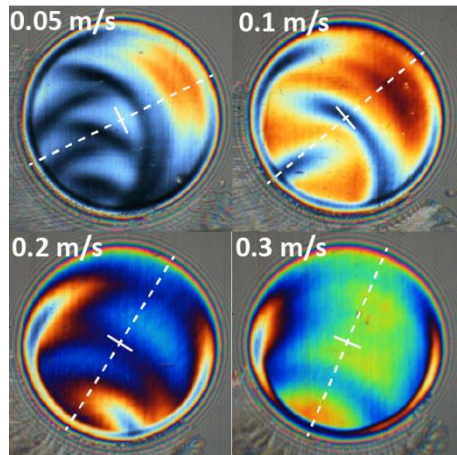
Relative mean thickness

$$H_{mean} = h_{c\ mean} / h_{c\ steady}$$

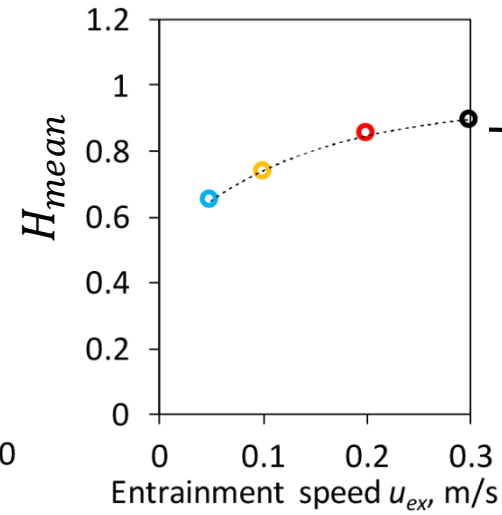
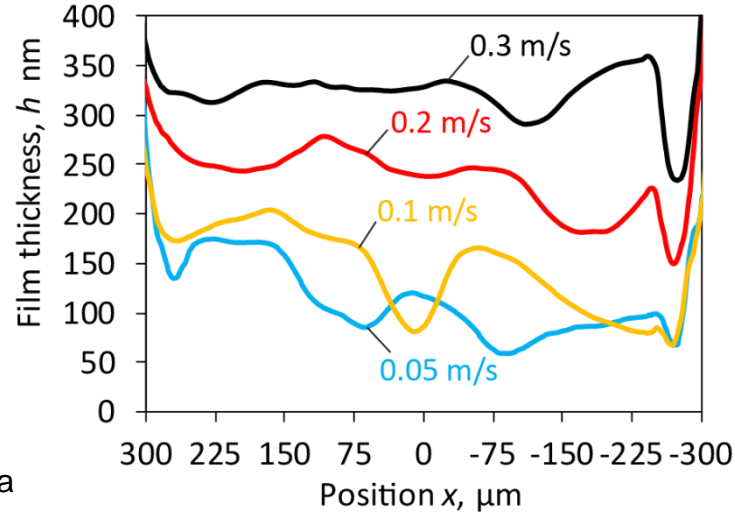


Results and discussion – Effect of vibrations on film thickness

The same lubricant, different main entrainment speed



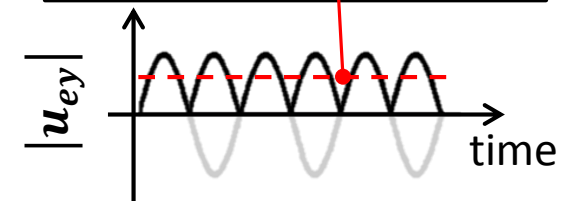
CAS, 300 Hz, 310 μm, 0.88 GPa



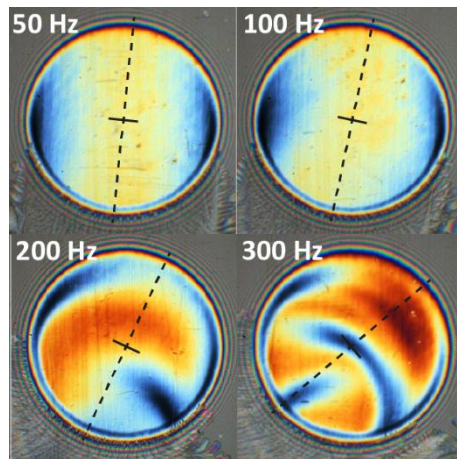
Unification using dimensionless number

Rate of lateral vibrations

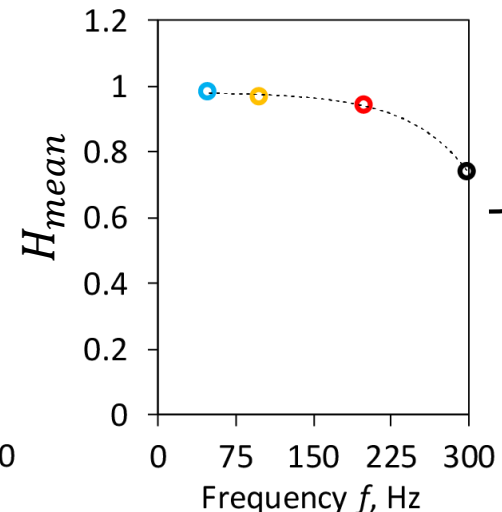
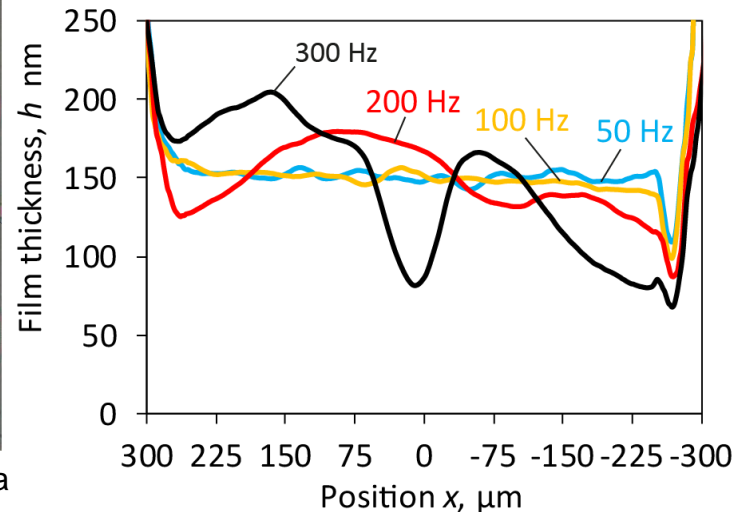
$$U_{y/x} = |u_{ey}|_{mean} / u_{ex}$$



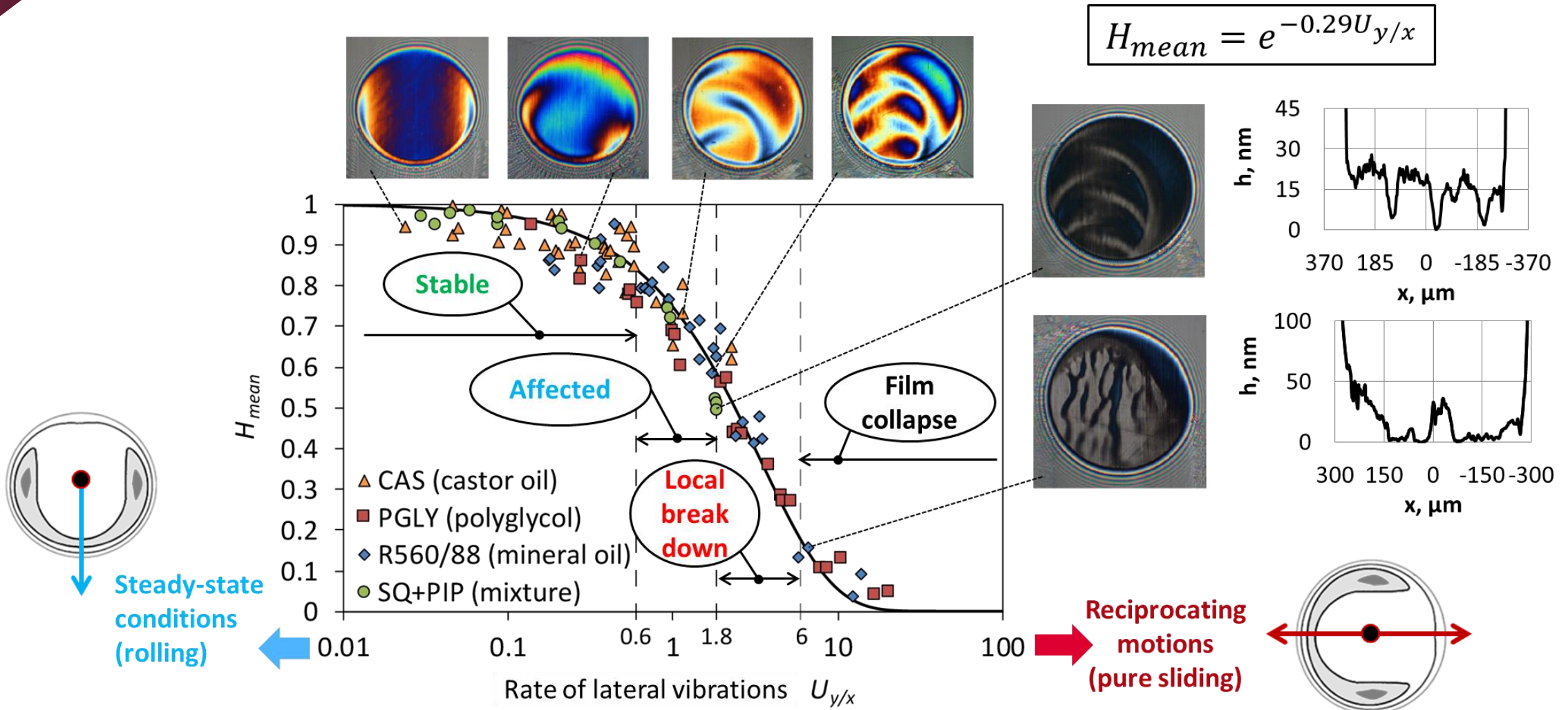
The same lubricant, different lateral entrainment speed (frequency)



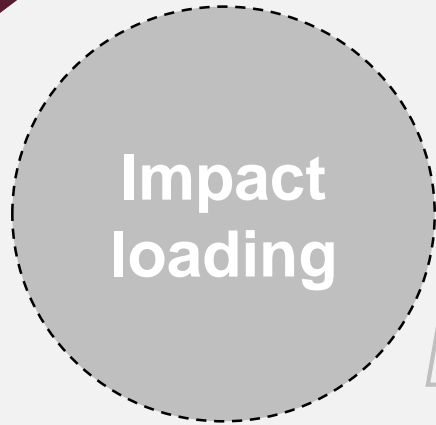
CAS, 0.1 m/s, 310 μm, 0.88 GPa



Results and discussion – Effect of vibrations on film thickness



Results and discussion

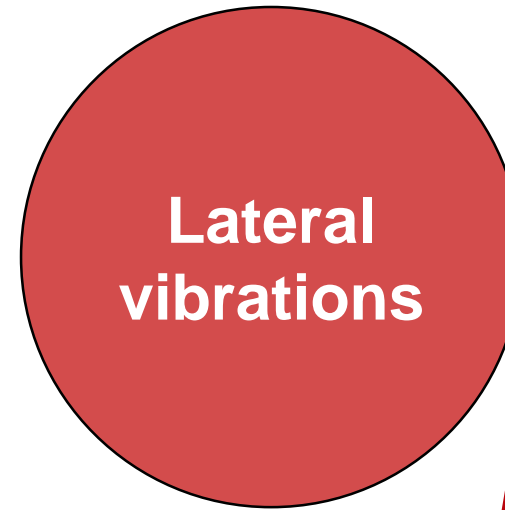


Impact
loading

Film thickness

Role of approaching/loading speed?

Impact of lubricant rheology?



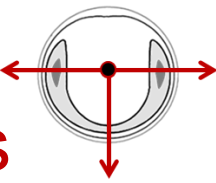
Lateral
vibrations

Film thickness

Friction

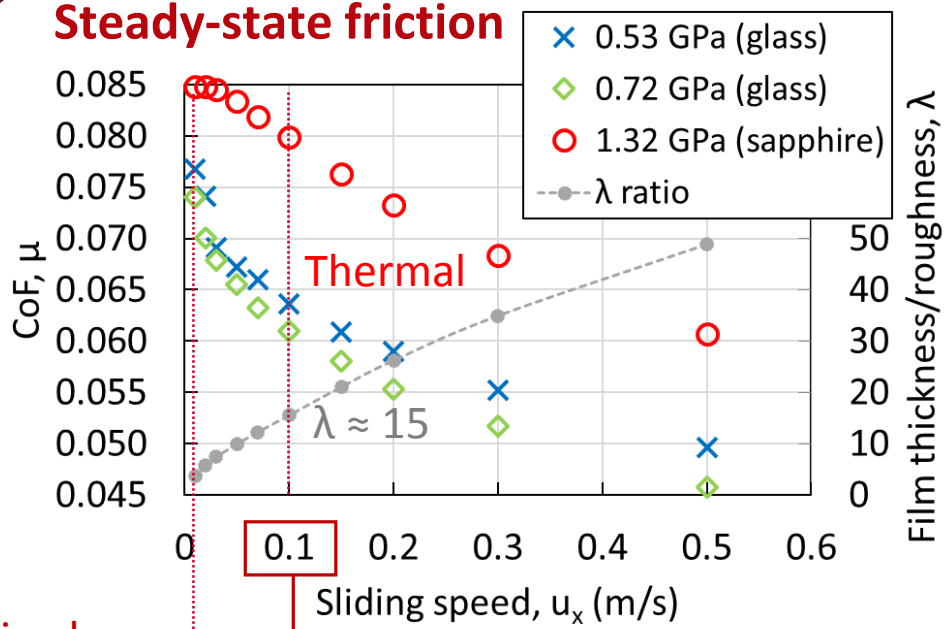
Effect of vibrations on film thickness?

Frictional response under vibrations?



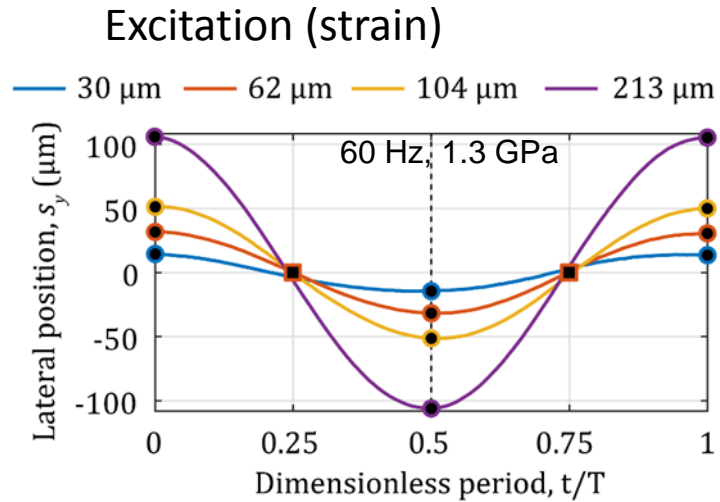
Results and discussion – Friction under lateral vibrations

Steady-state friction

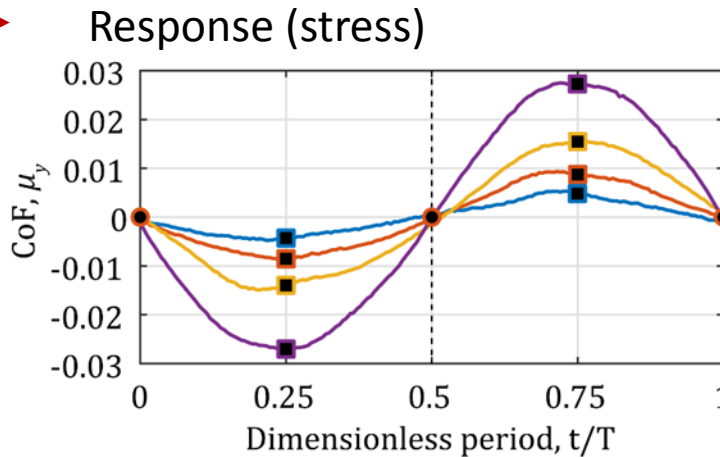


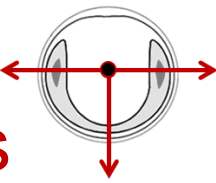
Mixed lubrication ← EHL lubrication →
 $\lambda \approx 3.5$

Friction in the lateral direction of contact under vibrations



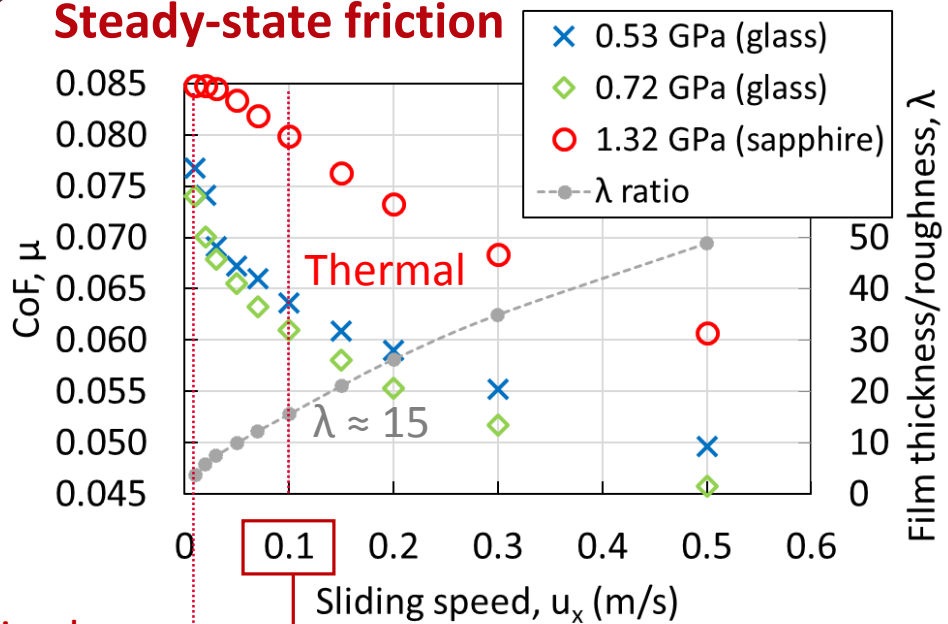
- position-independent COF
- purely viscous response



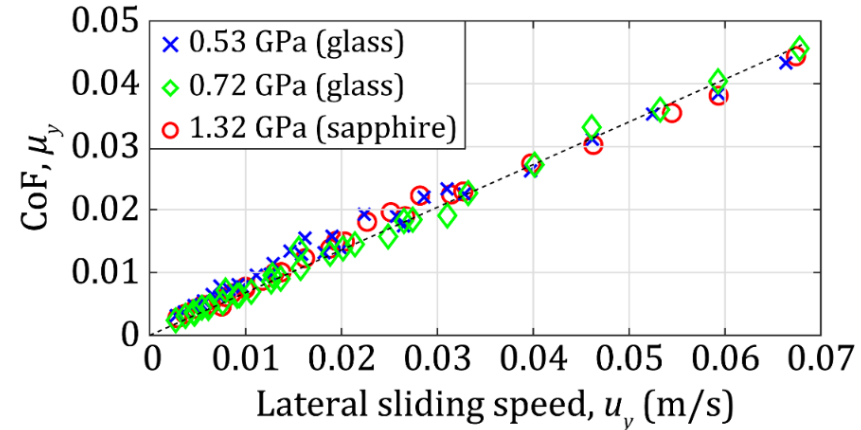


Results and discussion – Friction under lateral vibrations

Steady-state friction



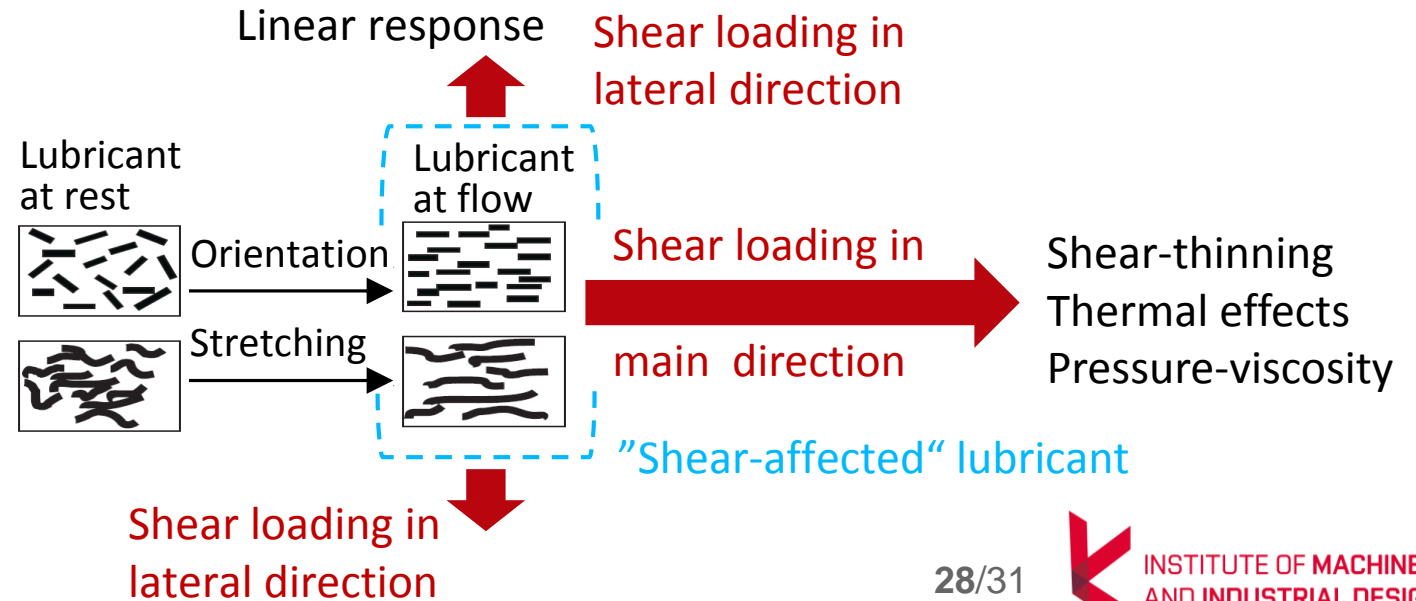
Friction in the lateral direction of contact under vibrations



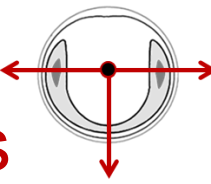
No visible effects of:

- Pressure
- Shear-thinning
- Shear heating

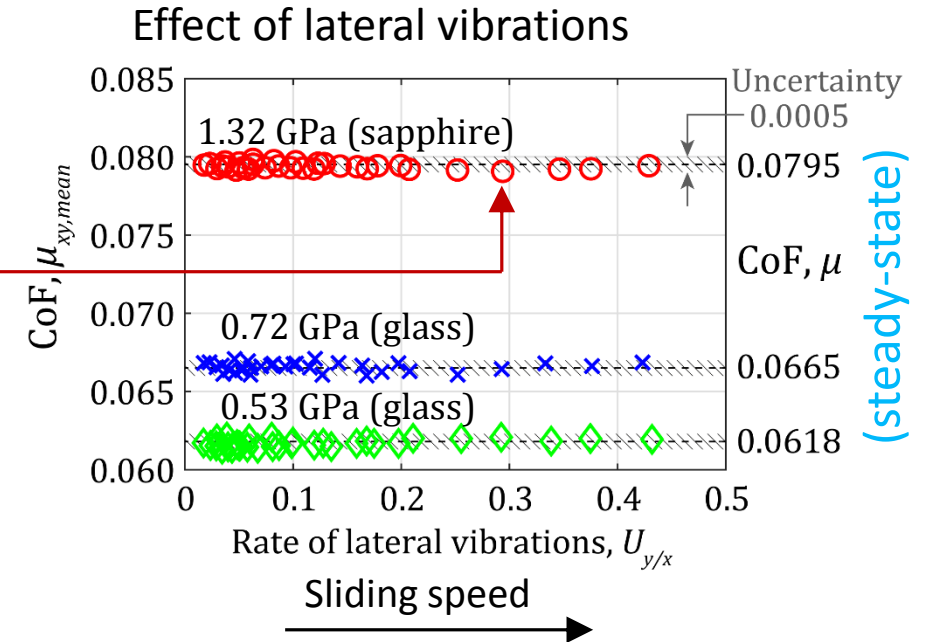
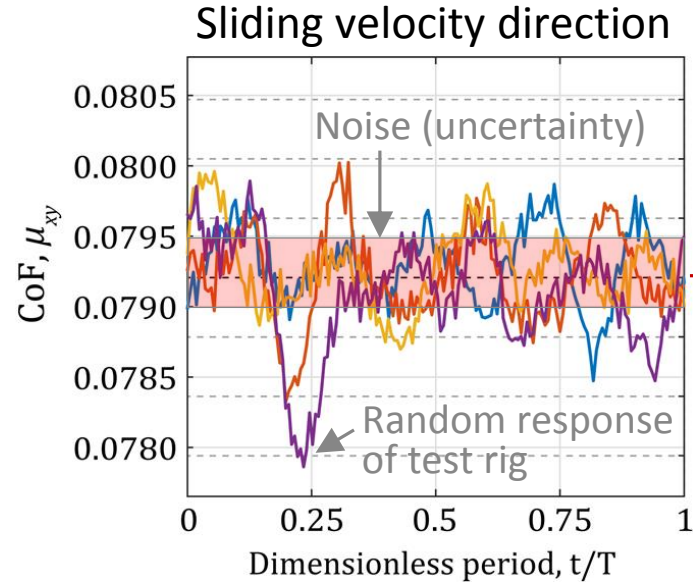
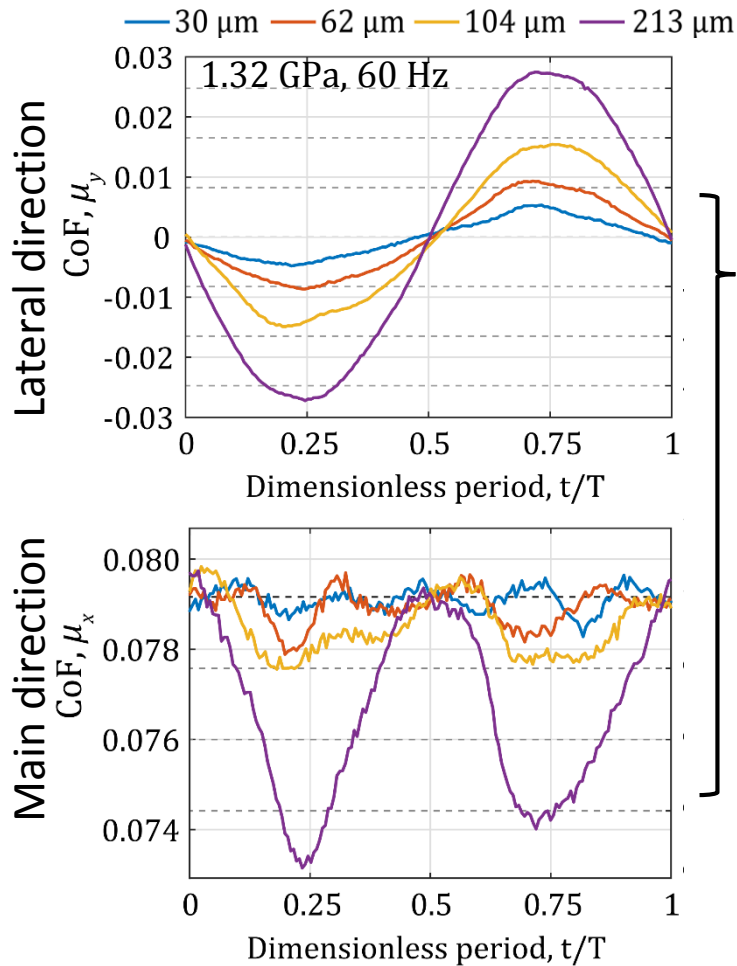
Structural arrangement of lubricant



Results and discussion – Friction under lateral vibrations



Total friction and its components



- Limiting shear stress reached
- No visible effect of vibrations on friction

Conclusions of the PhD thesis

Impact loading

- The role of **approaching** and **loading speed** on dimple film shape formation and resulting film thickness was clarified.

Lateral vibrations

- Relationship describing reduction in film thickness with increase in **the rate of lateral vibrations** was established.
- Thresholds for a local **film breakdown and film collapse** were found.
- **Friction** should not be treated as isotropic.

Conclusions of the PhD thesis

Impact
loading

- A. FRYZA, J., P. SPERKA, M. KANETA, I. KRUPKA and M. HARTL. Effects of lubricant rheology and impact speed on EHL film thickness at pure squeeze action. *Tribology International*. 2017, vol. 106, p. 1-9.

Journal impact factor = 2.903, Quartile Q1, CiteScore = 3.16

Author's contribution 60%



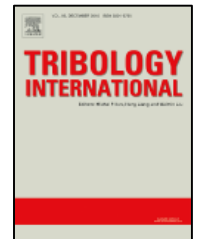
Lateral
vibrations

Thickness

- B. FRYZA, J., P. SPERKA, I. KRUPKA and M. HARTL. Effects of lateral harmonic vibrations on film thickness in EHL point contacts. *Tribology International*. 2018, vol. 117, p. 236-249.

Journal impact factor = 2.903, Quartile Q1, CiteScore = 3.16

Author's contribution 75%



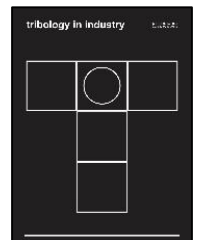
Lateral
vibrations

Friction

- C. FRYZA, J., P. SPERKA, I. KRUPKA and M. HARTL. Frictional response of lubricant in EHL contact under transient bi-directional shear loading. *Tribology in Industry*. 2017, vol. 39, no. 4, p. 506-518.

CiteScore = 1.32

Author's contribution 70%



List of publications

journals
with impact
factor

FRYZA, J., P. SPERKA, I. KRUPKA and M. HARTL. Effects of lateral harmonic vibrations on film thickness in EHL point contacts. *Tribology International*. 2018, vol. 117, p. 236-249.

FRYZA, J., P. SPERKA, M. KANETA, I. KRUPKA, et al. Effects of lubricant rheology and impact speed on EHL film thickness at pure squeeze action. *Tribology International*. 2017, vol. 106, p. 1-9

peer-reviewed
journal

FRYZA, J., P. SPERKA, I. KRUPKA and M. HARTL. Frictional response of lubricant in EHL contact under transient bi-directional shear loading. *Tribology in Industry*. 2017, vol. 39, no. 4, p. 506-518.

conference
proceedings

FRYZA, J. and M. OMASTA. The Experimental Determination of the Grease Amount to Effective Wear Reduction in the Wheel-Rail Contact. In *The Latest Methods of Construction Design*. Cham: Springer International Publishing, 2016, p. 127-132.

FRYZA, J.; SPERKA, P.; KRUPKA, I.; HARTL, M. Behaviour of EHL Films under Lateral Vibrations. In *Book of Proceedings of 56th International Conference of Machine Design Departments*. Nitra: Slovak University of Agriculture in Nitra, 2015. p. 349-352.

OMASTA, M.; FRYZA, J.; HARTL, M.; KRUPKA, I. Study of Effects of Wheel Flange/ Rail Gauge Contact Lubrication. In *Proceedings of World Tribology Congress 2013*. Torino: Politecnico di Torino (DIMEAS), 2013. p. 3007-3009.

OMASTA, M.; FRYZA, J.; HARTL, M.; KRUPKA, I. An experimental approach to the study of rail wheel/flange lubrication. In *STLE Annual Meeting & Exhibition 2013 / Proceedings of a meeting held 5-9 May 2013*. Detroit, Michigan, USA: Society of Tribologists and Lubrication Engineers, 2013. p. 1-3.

List of publications

conference
abstracts

FRYZA, J.; SPERKA, P.; KRUPKA, I.; HARTL, M. Viscoelastic response of lubricant in an EHL contact under transient bi-directional shear loading. *STLE 72nd Annual Meeting & Exhibition*. 2017. Atlanta, Georgia, USA.

FRYZA, J.; SPERKA, P.; KRUPKA, I.; HARTL, M. Effects of lateral vibrations on film thickness distribution in a point EHL contact. *The 17th Nordic Symposium on Tribology - NORDTRIB 2016*. 2016. Hämeenlinna, Finland.

FRYZA, J.; SPERKA, P.; KRUPKA, I.; HARTL, M. Roughness Effects in Impact EHL of Elliptical Contacts. *International Tribology Conference*. 2015. Tokyo, Japan.

Thank you for attention

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