Defense of PhD thesis

BRNO, CZECH REPUBLIC | 2nd MARCH 2018

Elastohydrodynamic film study under impact loading and lateral vibrations

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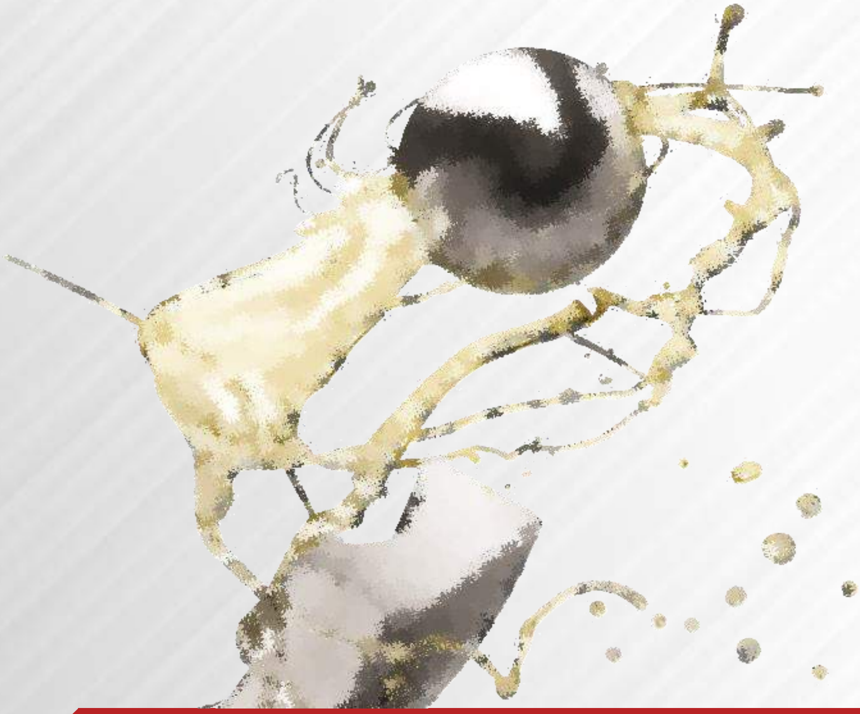
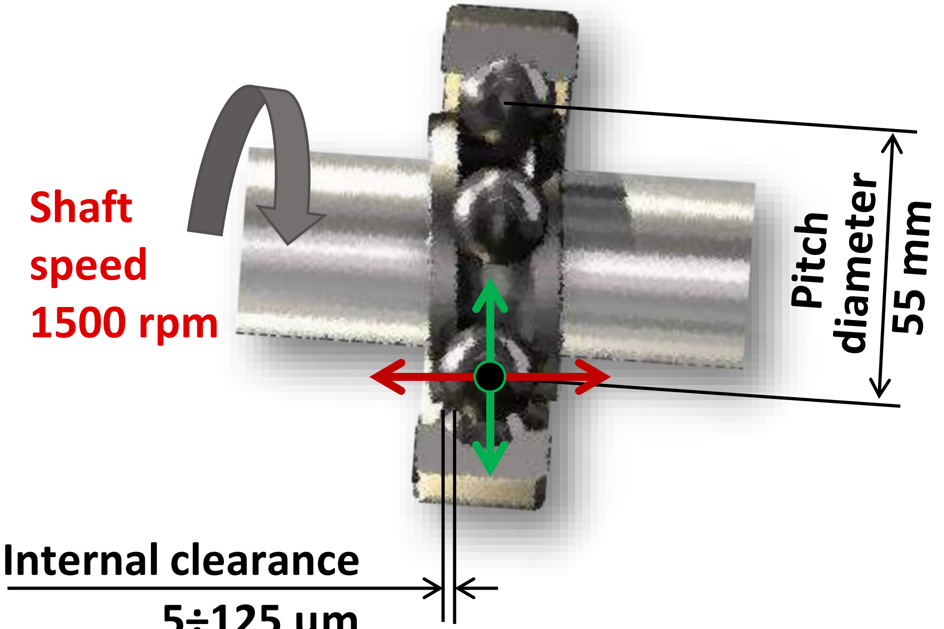


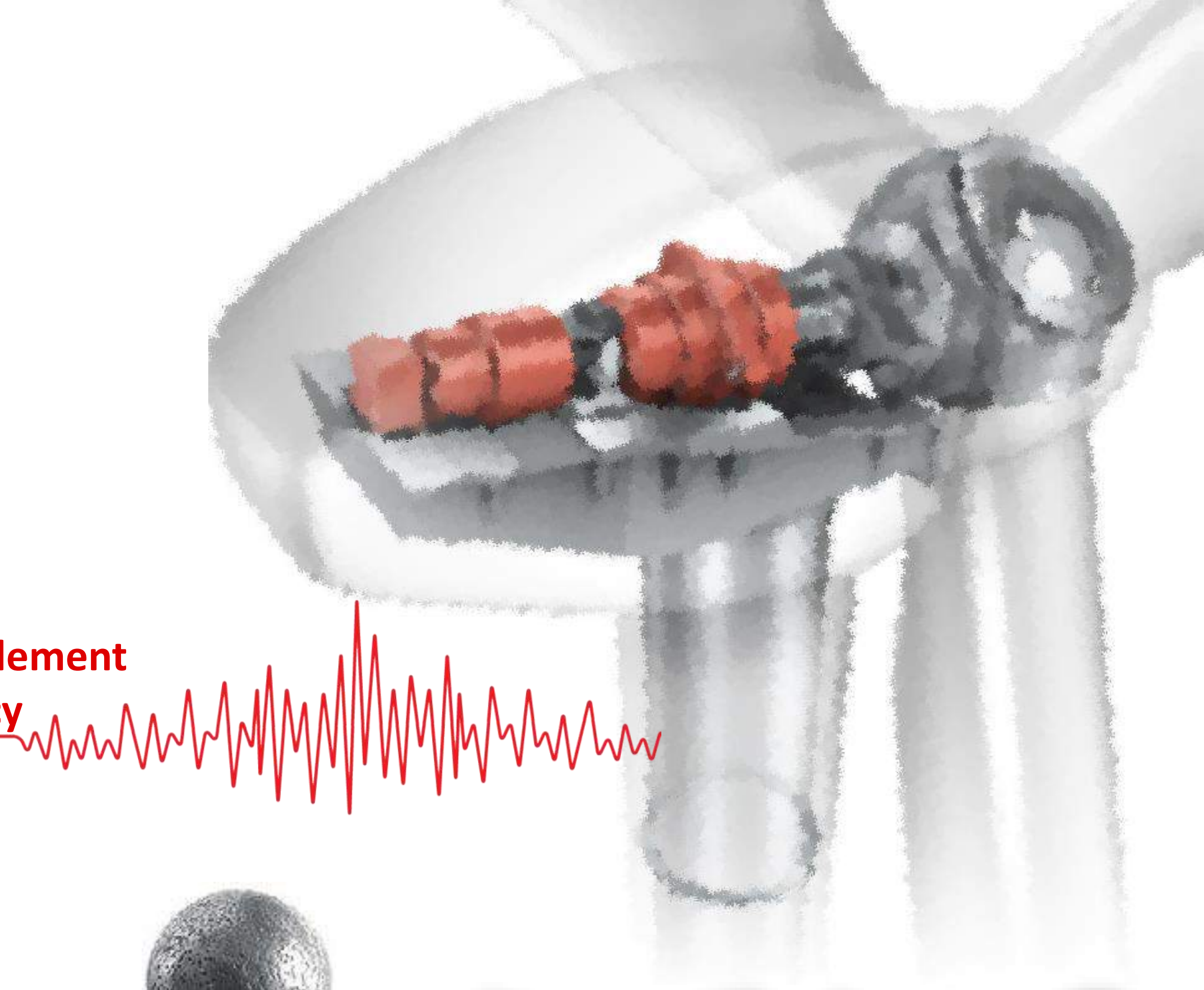
Contents

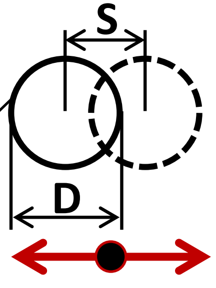
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

Introduction - Motivation

Vibrations in machine elements

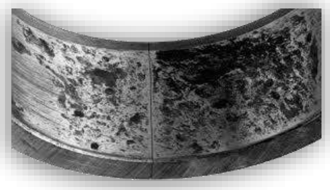






Fatigue

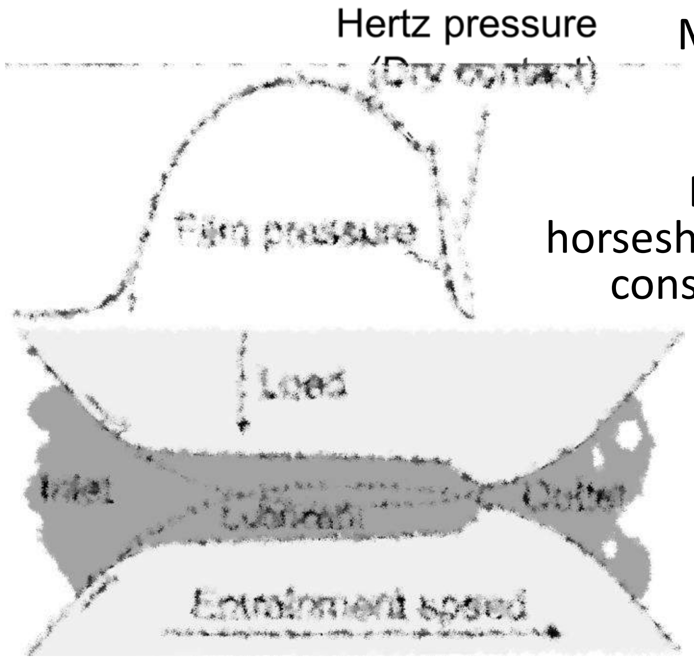
False brinelling



Fretting corrosion

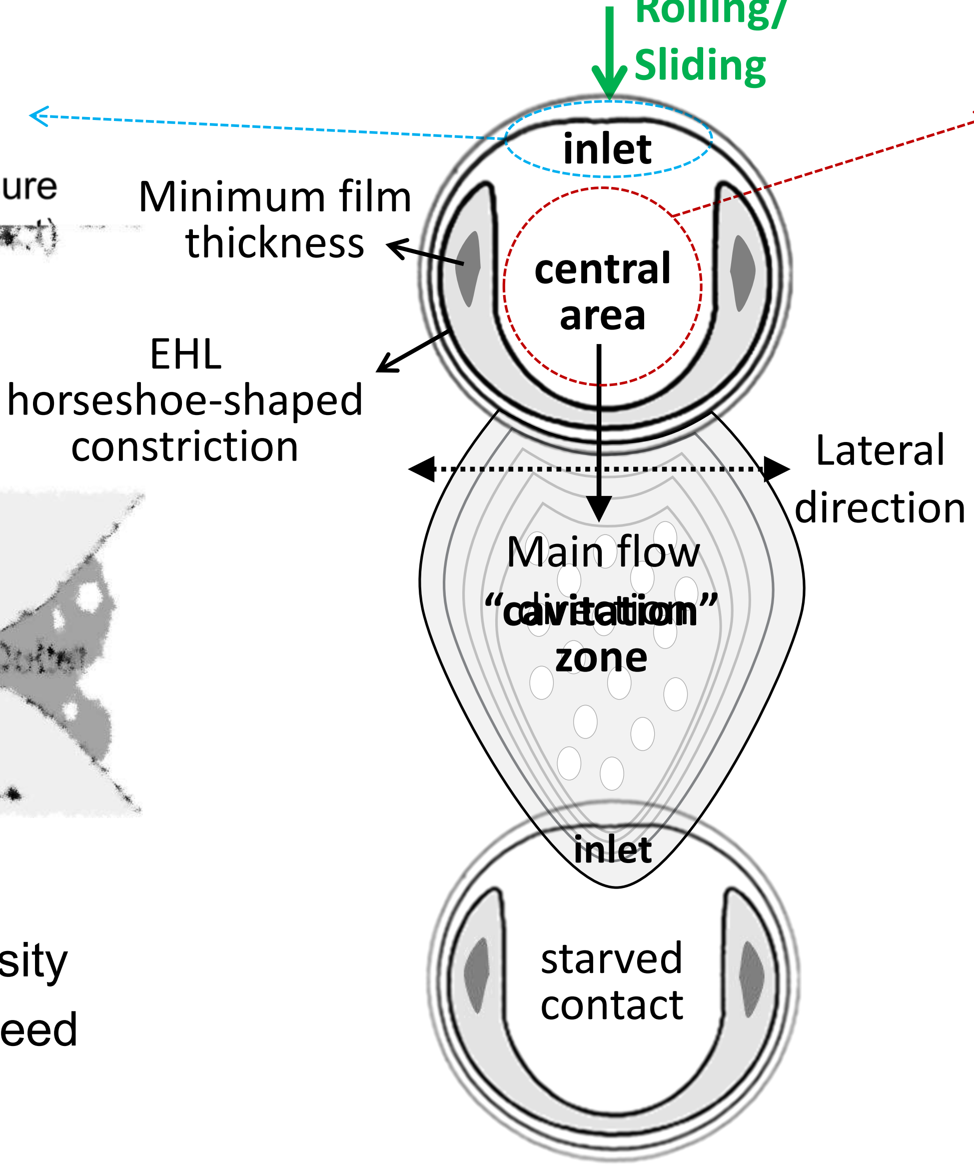
Introduction - Steady-state EHL contact

Film thickness

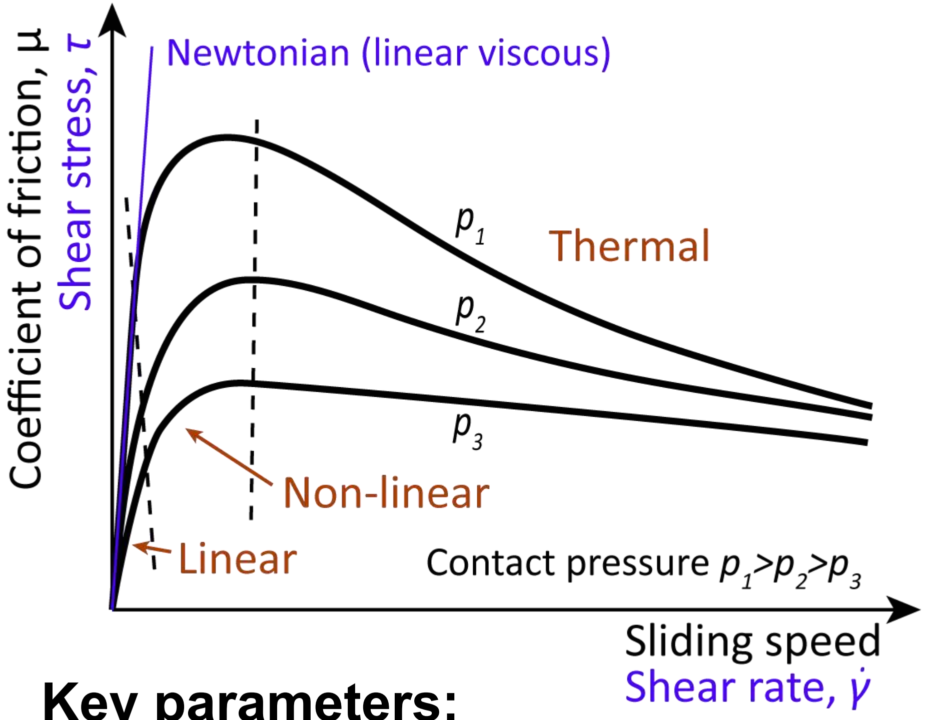


Key parameters:

- Lubricant viscosity
- Entrainment speed



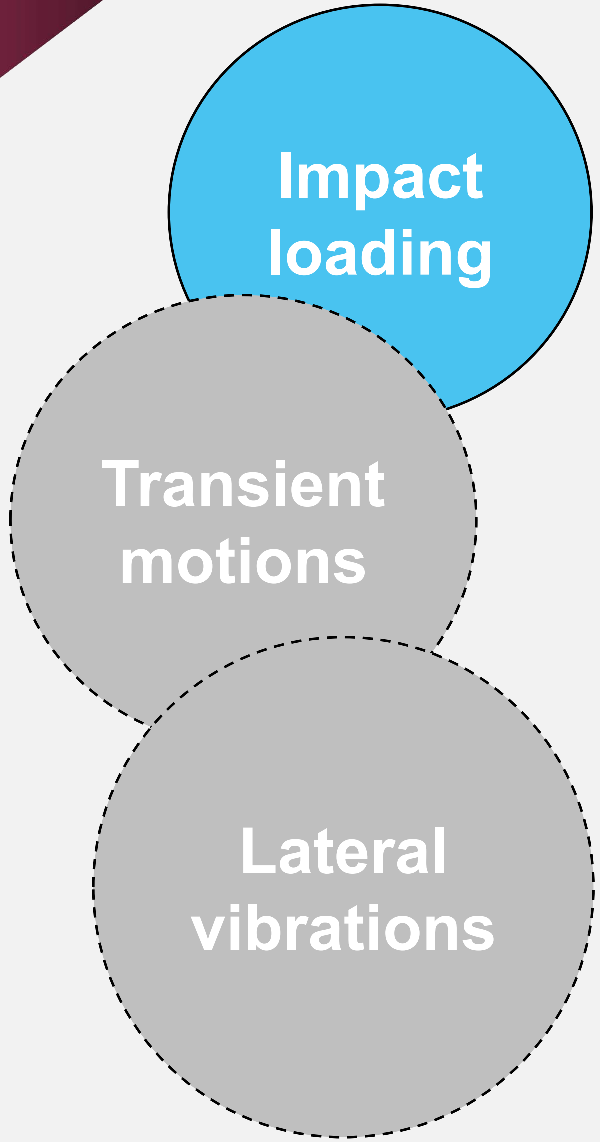
Friction



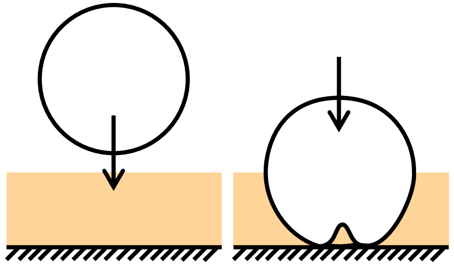
Key parameters:

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

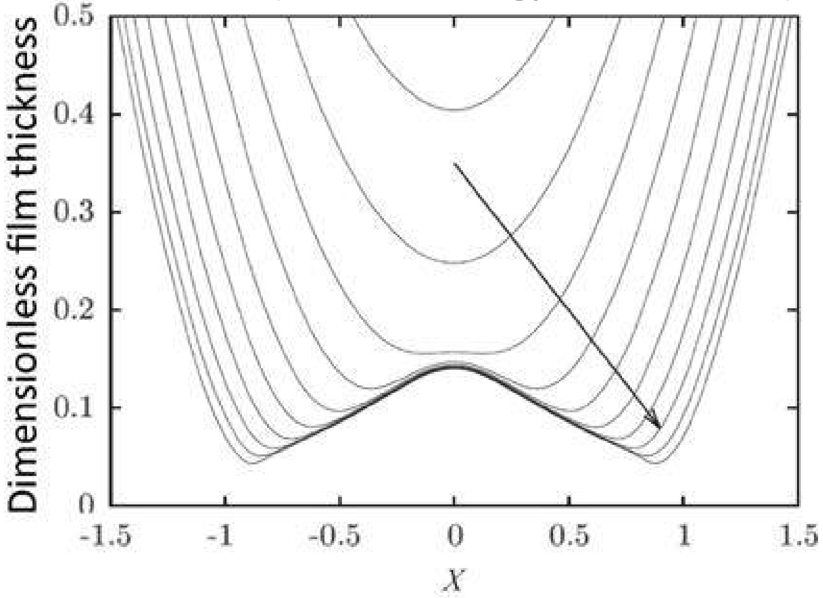
State of the art



Pure squeeze action



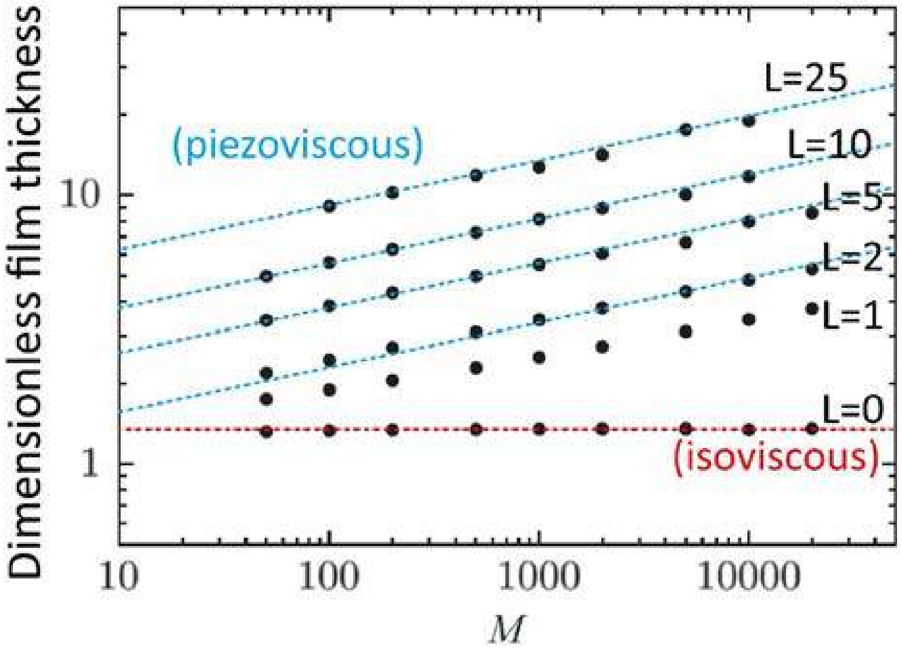
Venner (2016, Tribology International)



Key parameters:

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

Venner (2016, Tribology International)



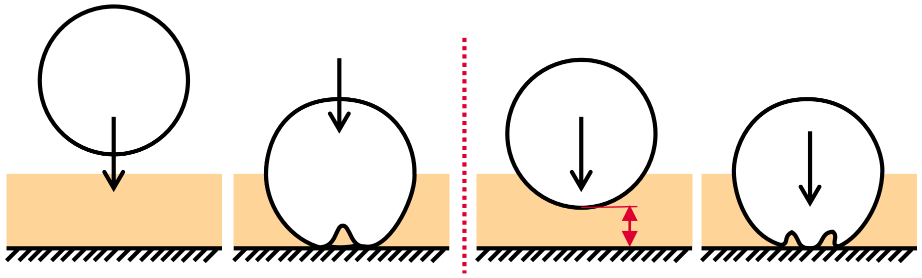
State of the art

Impact loading

Transient motions

Lateral vibrations

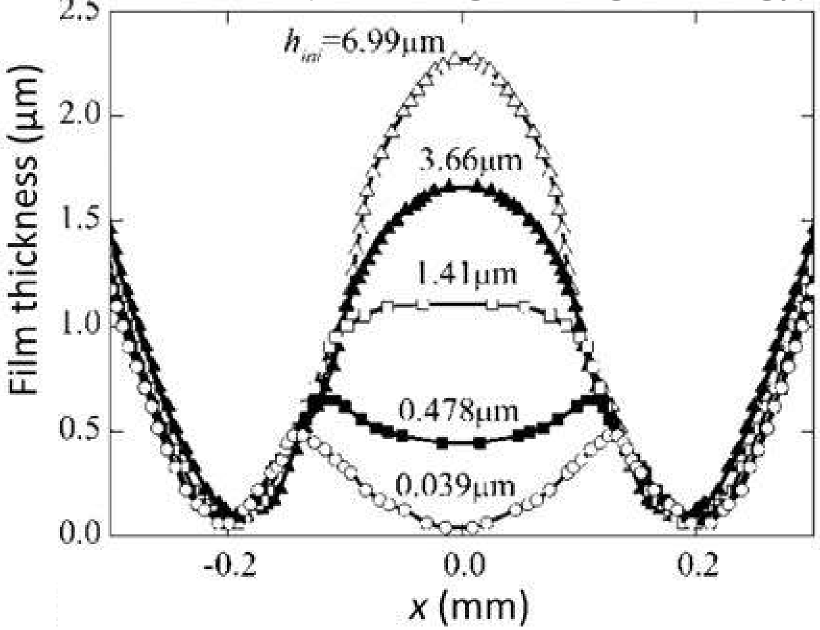
Pure squeeze action



Key parameters:

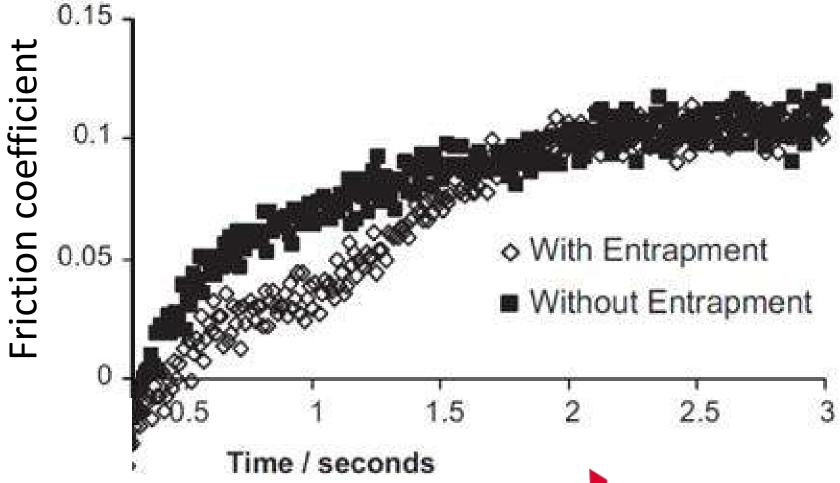
- Viscosity
- Pressure-viscosity coefficient
- Approaching speed (m/s)
- Loading speed (N/s)
- Initial impact gap

Kaneta (2007, Engineering Tribology)



Beginning of motion

Martini and Bair (2010, Tribology International)



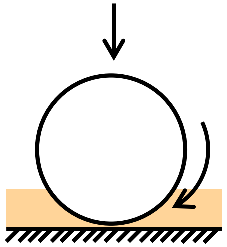
State of the art

Impact loading

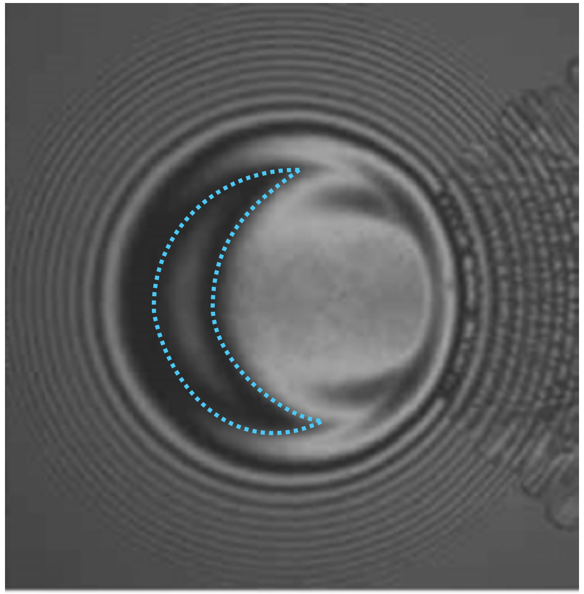
Transient motions

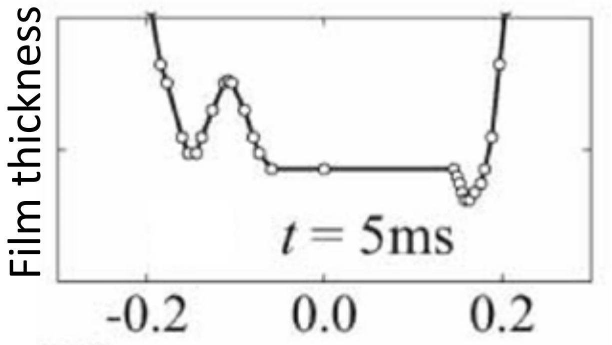
Lateral vibrations

Entrainment and squeeze action

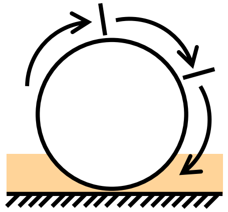


Kaneta (2007, Engineering Tribology)

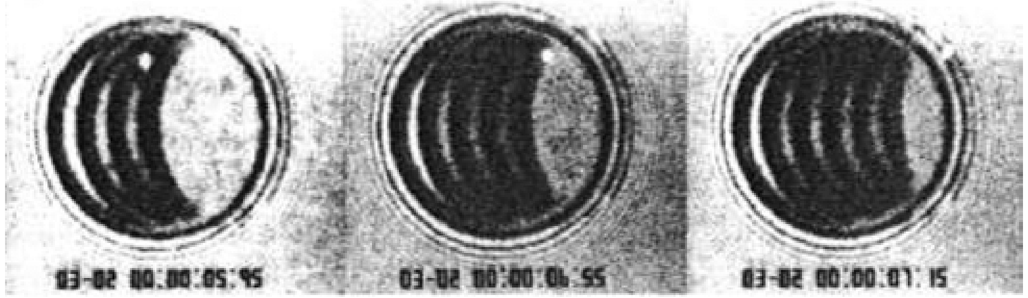




Start-stop motion



Kaneta (1990, Tribology-Transactions)



Key parameters:

- Deceleration

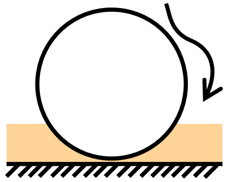
State of the art

Impact loading

Transient motions

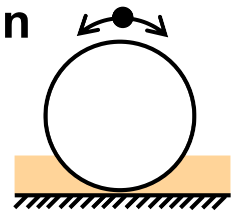
Lateral vibrations

Entrainment and squeeze action



Transient speed

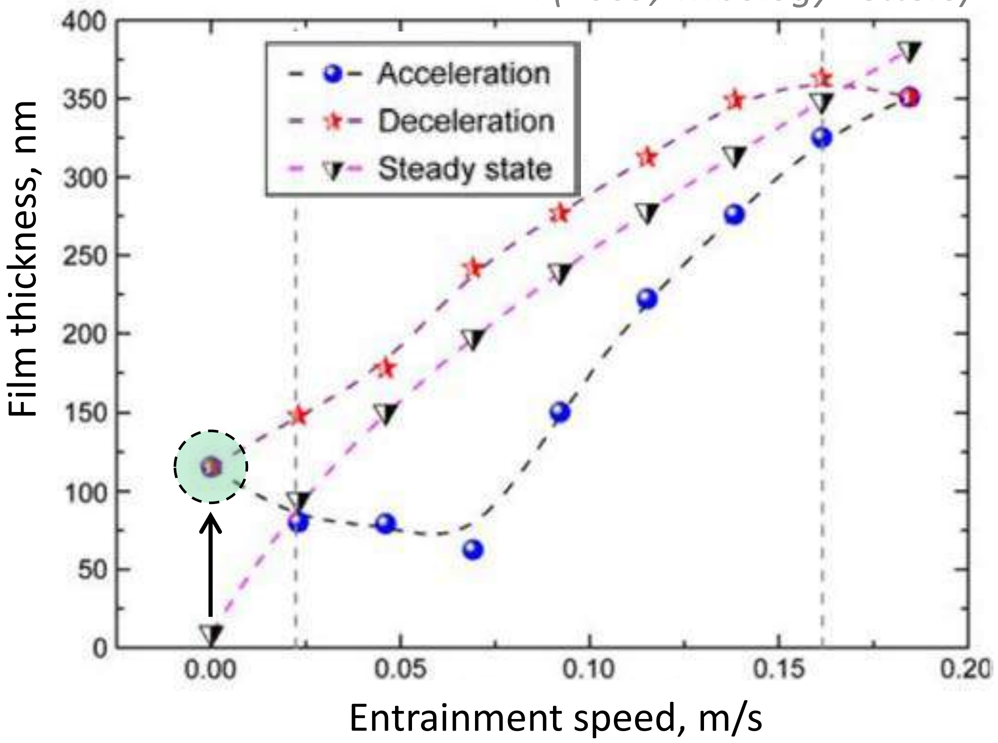
Reciprocation



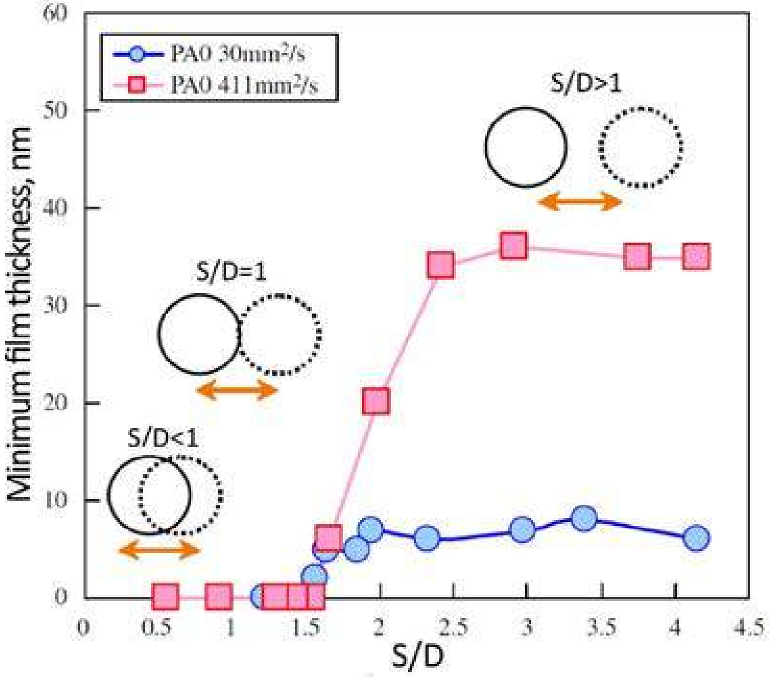
Key parameters:

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

Li (2009, Tribology Letters)



Maruyama (2010, Tribology International)



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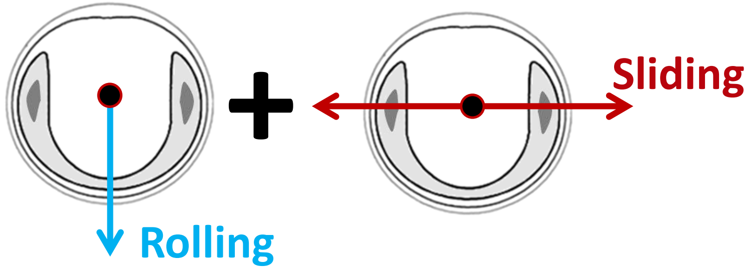
State of the art

Impact loading

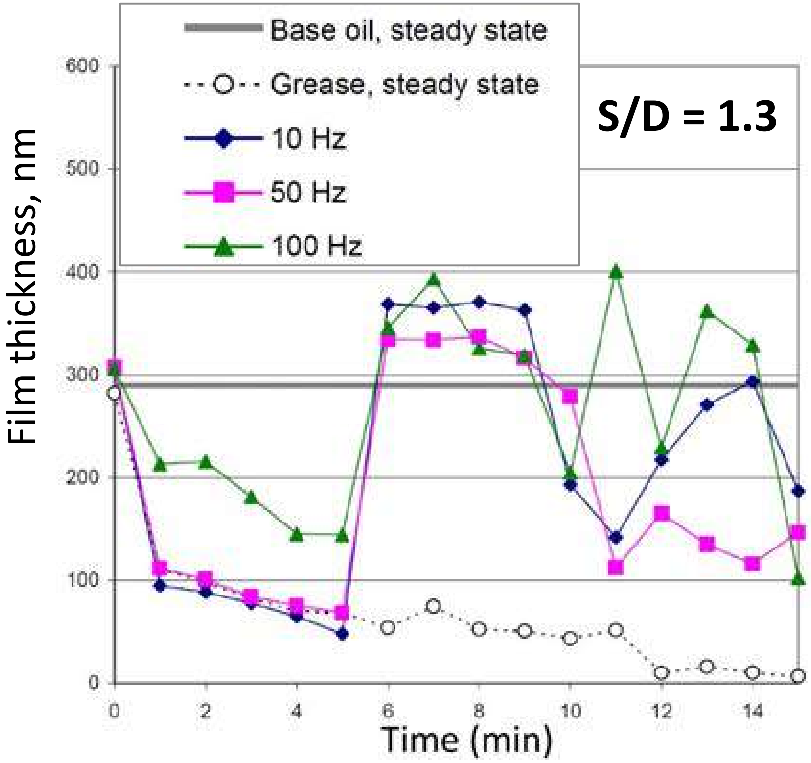
Transient motions

Lateral vibrations

Entrainment and squeeze action



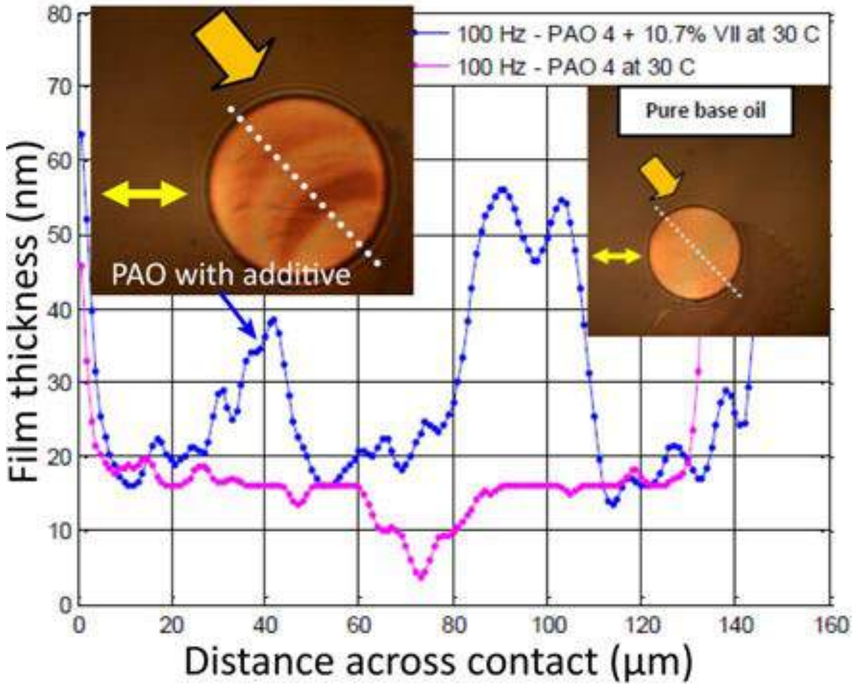
Kalogiannis (2013, Doctoral thesis)



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 shear flow?

Hypotheses

H1:

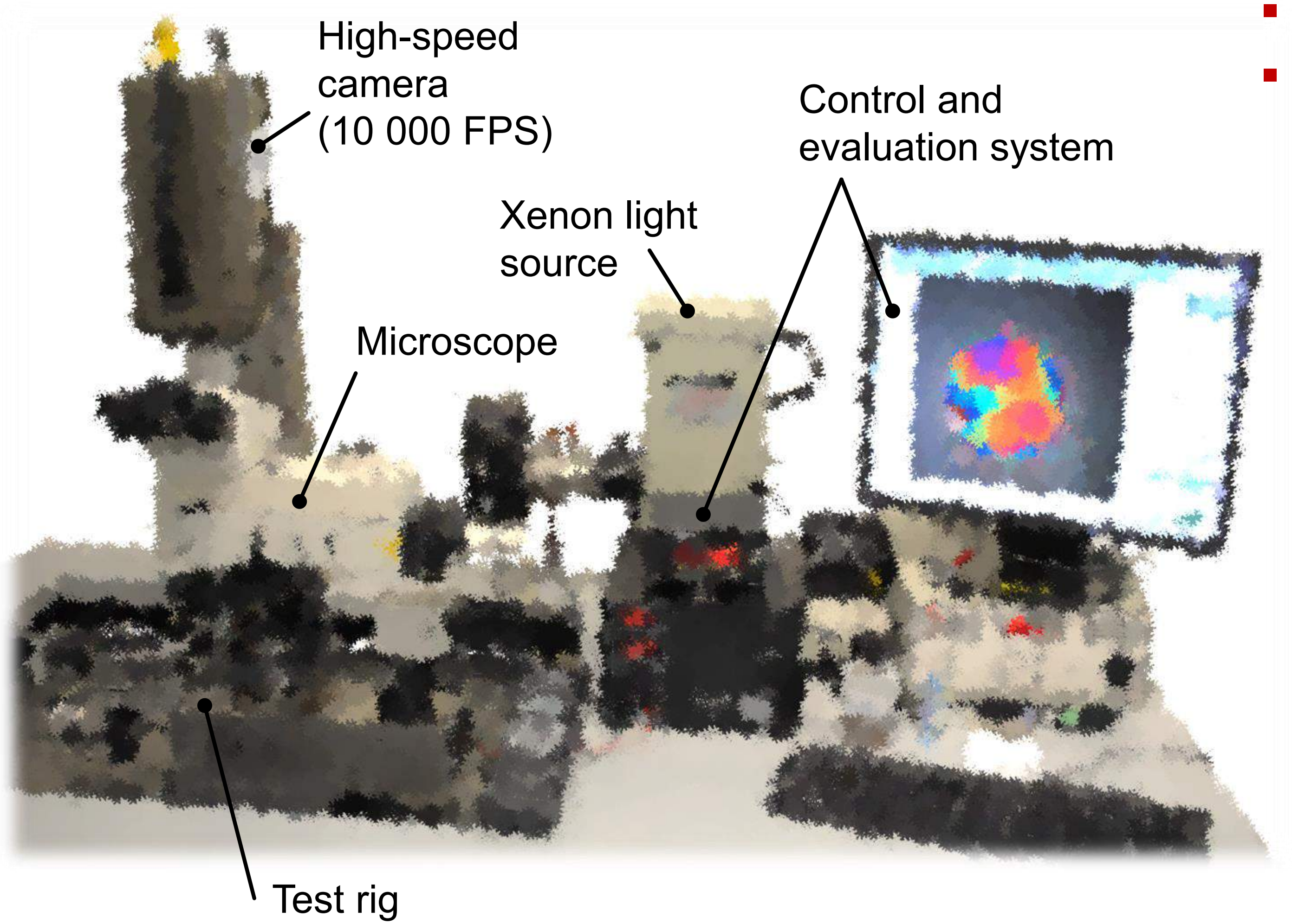
H2:

⋮

H6:

Materials and methods

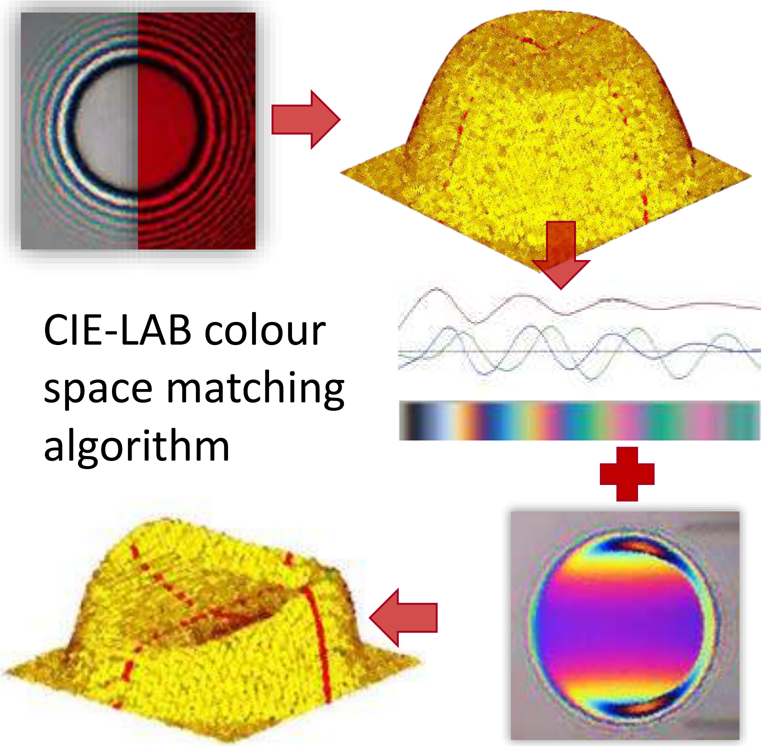
Experimental apparatus

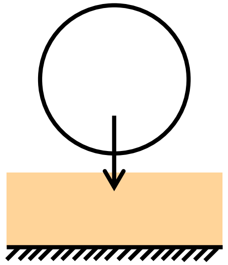


Thin film colorimetric interferometry

- Optical resolution 1 ÷ 900 nm
- Distinguishability ± 1 nm

Film thickness calibration

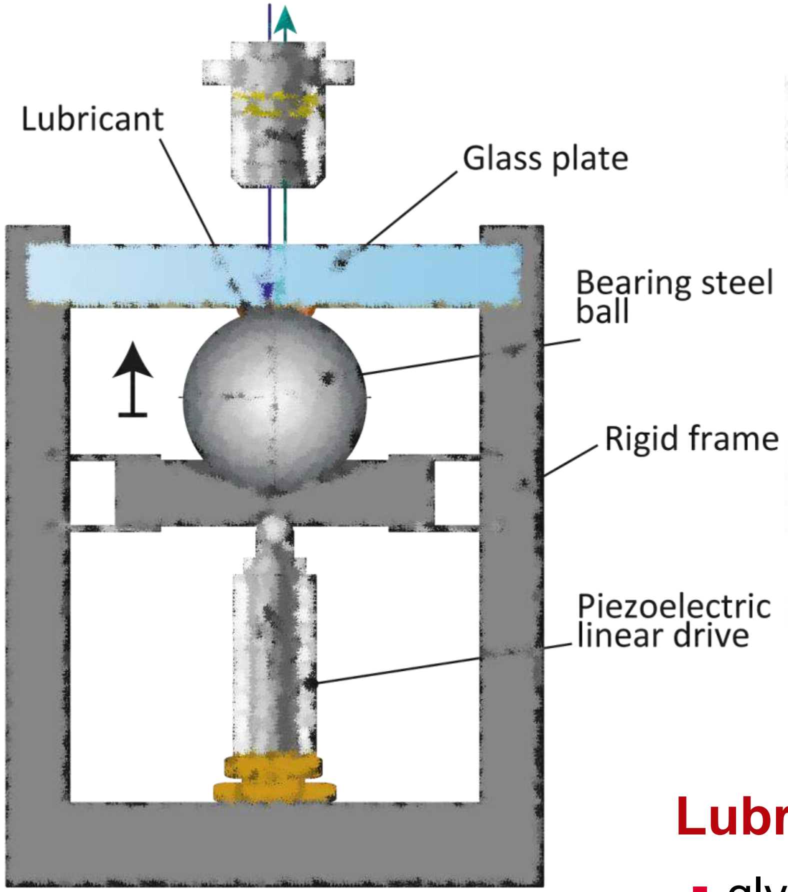




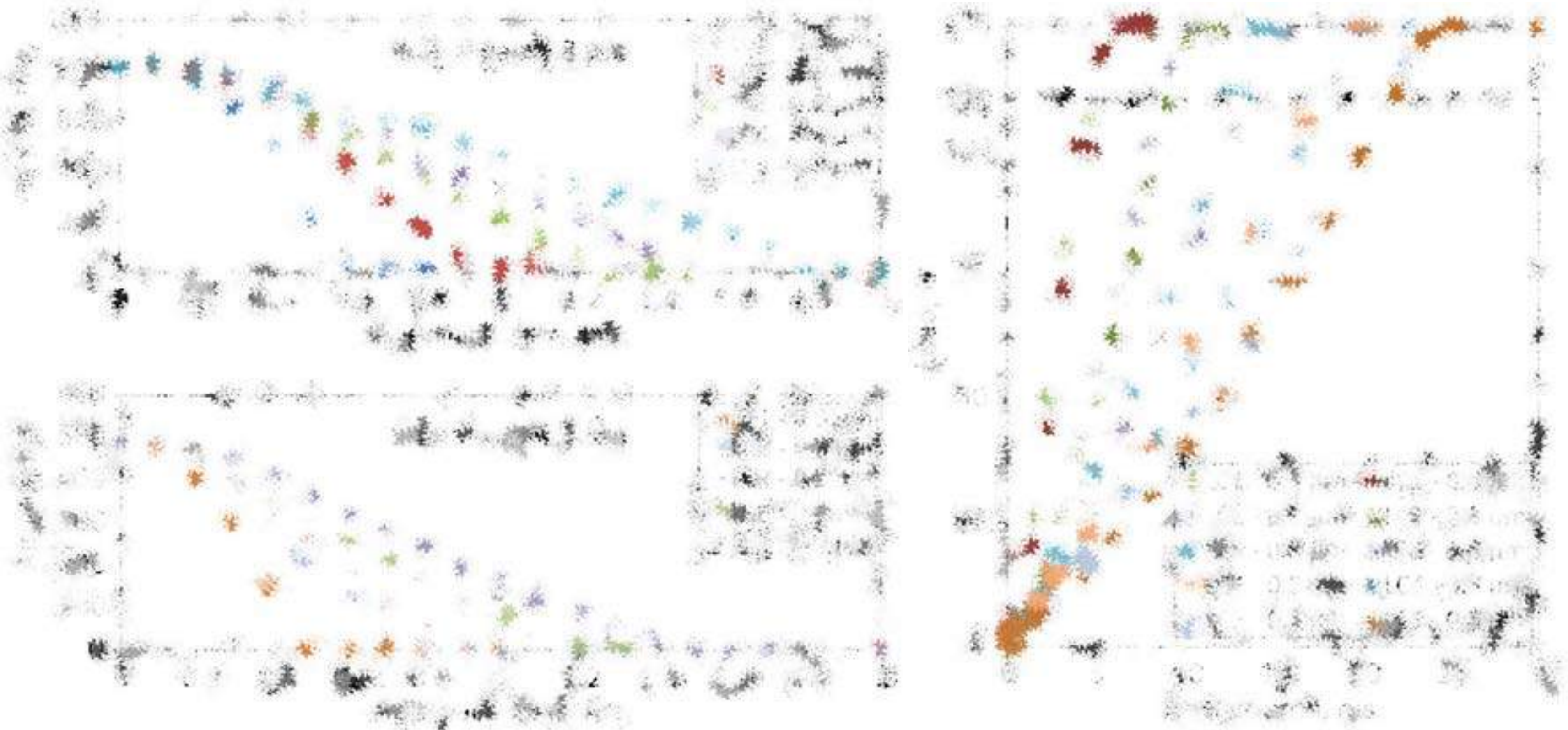
Materials and methods

Test rig – impact load

Film thickness



Approaching and loading curves (dry contact)



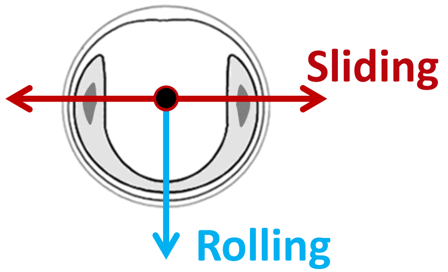
Lubricants:

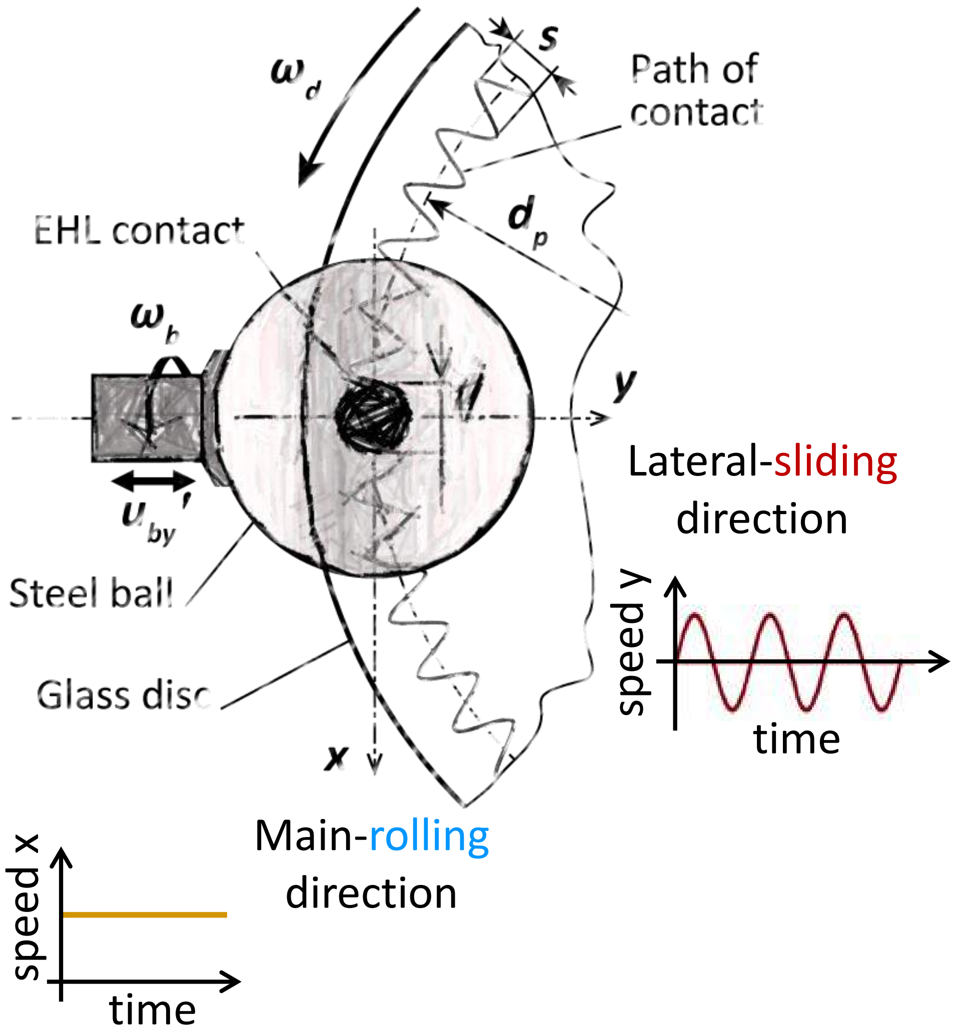
- glycerol
- squalane
- 2 poly-alfa-olefins
- bright stock oil
- silicone oil
- castor oil
- 3 paraffinic mineral oils
- traction fluid

Materials and methods

Test rig – lateral vibrations

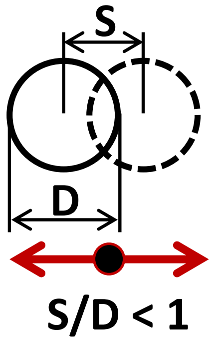
Film thickness | Friction





Operating conditions (over 200 combinations)

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



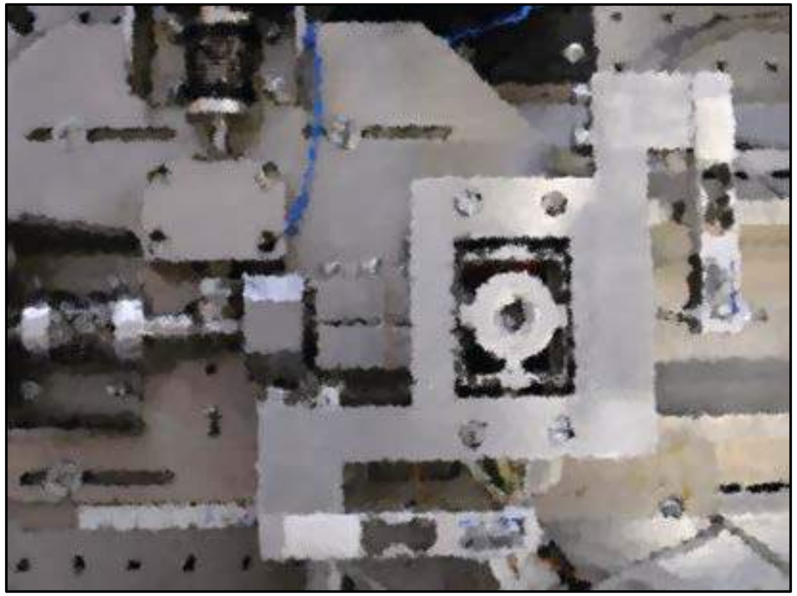
Lubricants and mixtures:

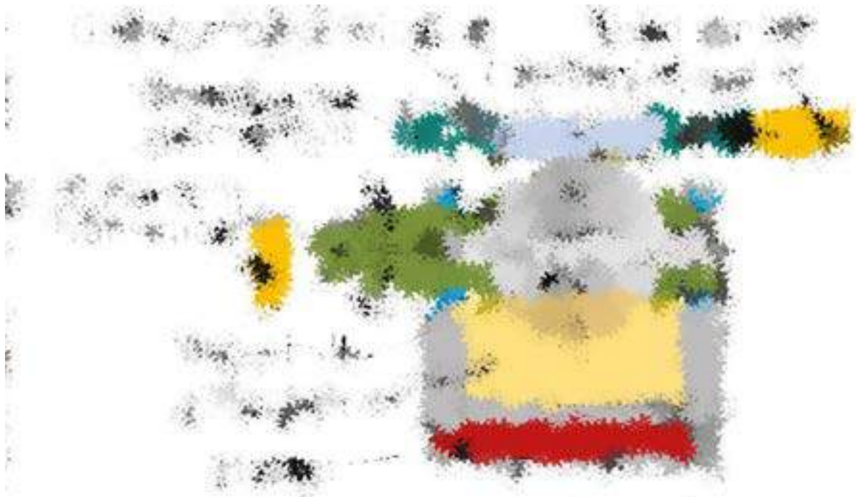
- castor oil (Newtonian)
- paraffinic mineral oil (Newtonian)
- polyglycol (non-Newtonian)
- 2 mixtures (non-Newtonian)

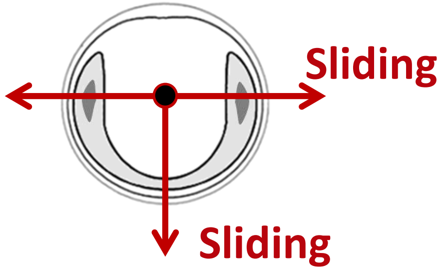
Materials and methods

Test rig – lateral vibrations

Film thickness | **Friction**







Materials:

- Glass / sapphire window
- Steel ball roughness Ra ≤ 7 nm

Lubricant:

- bright stock oil (Newtonian)

Friction coefficient (COF) measurement

- COF range 0.005 ÷ 0.2
- COF uncertainty 0.0005

Operating conditions (≈100 combinations)

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

Impact loading

Film thickness

Role of approaching/loading speed?

Impact of lubricant rheology?

Lateral vibrations

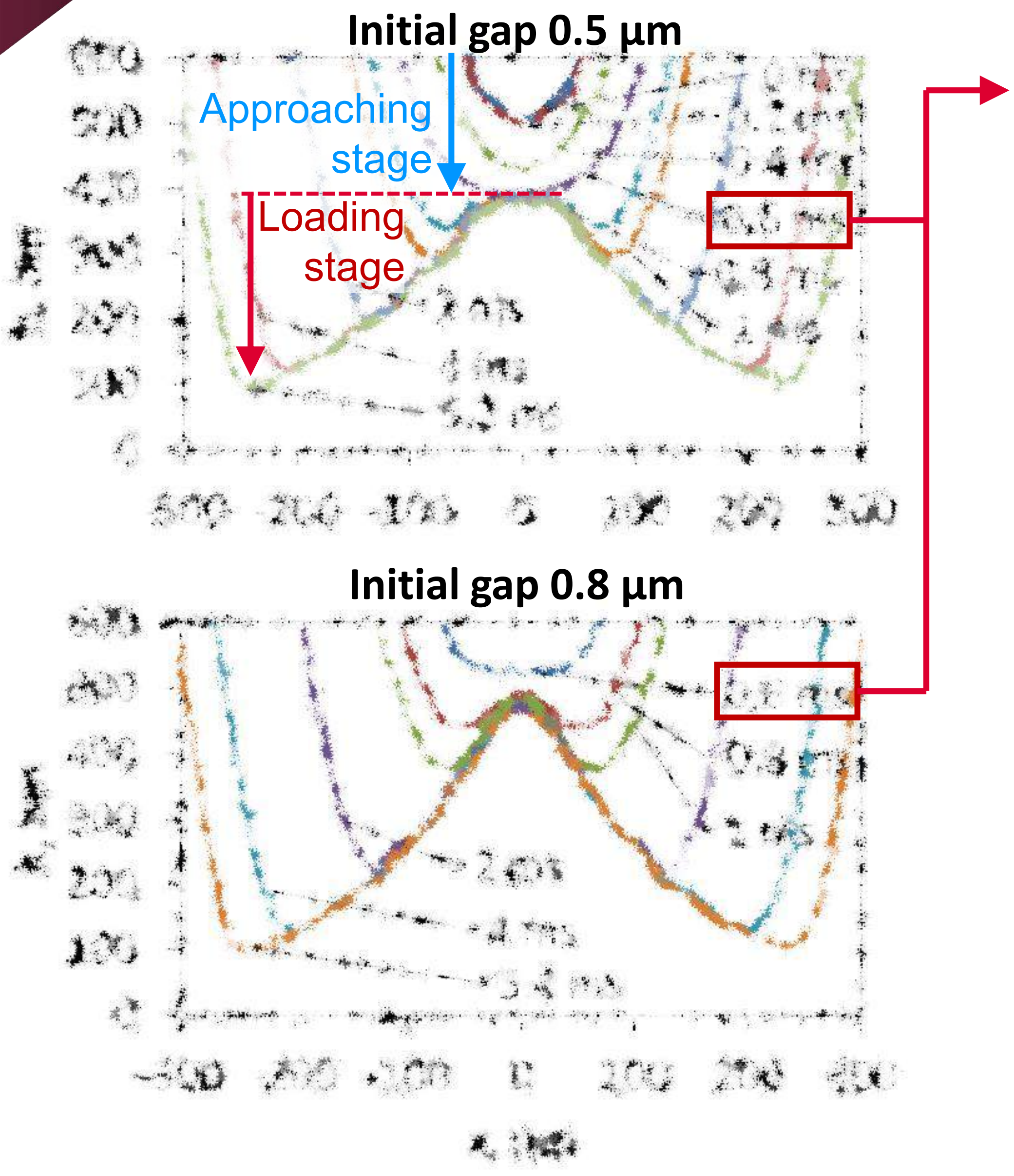
Film thickness

Friction

Effect of vibrations on film thickness?

Frictional response under vibrations?

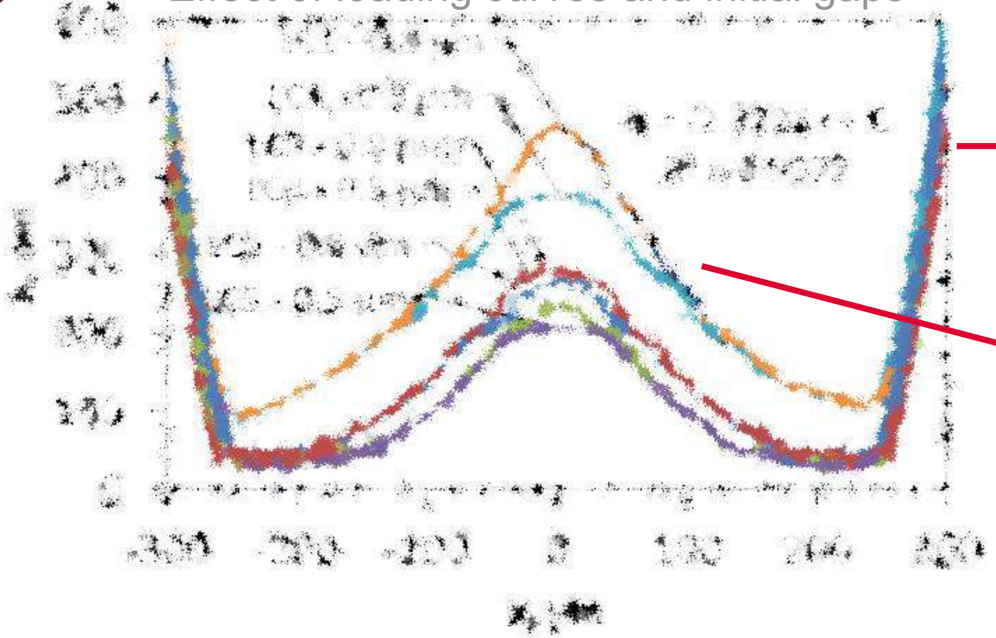
Results and discussion – Role of approaching/loading speed



- Central film thickness defined by residual film at specific time

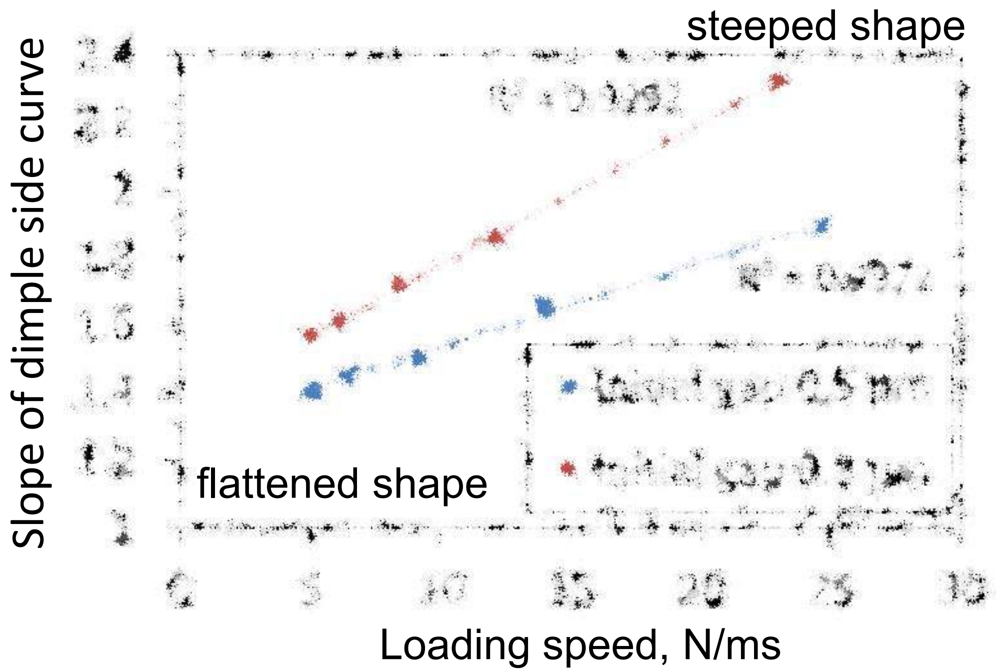
Results and discussion – Role of approaching/loading speed

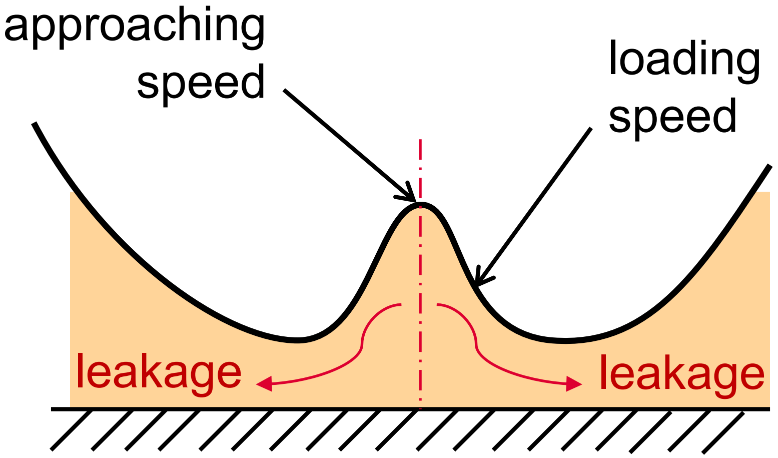
Effect of loading curves and initial gaps



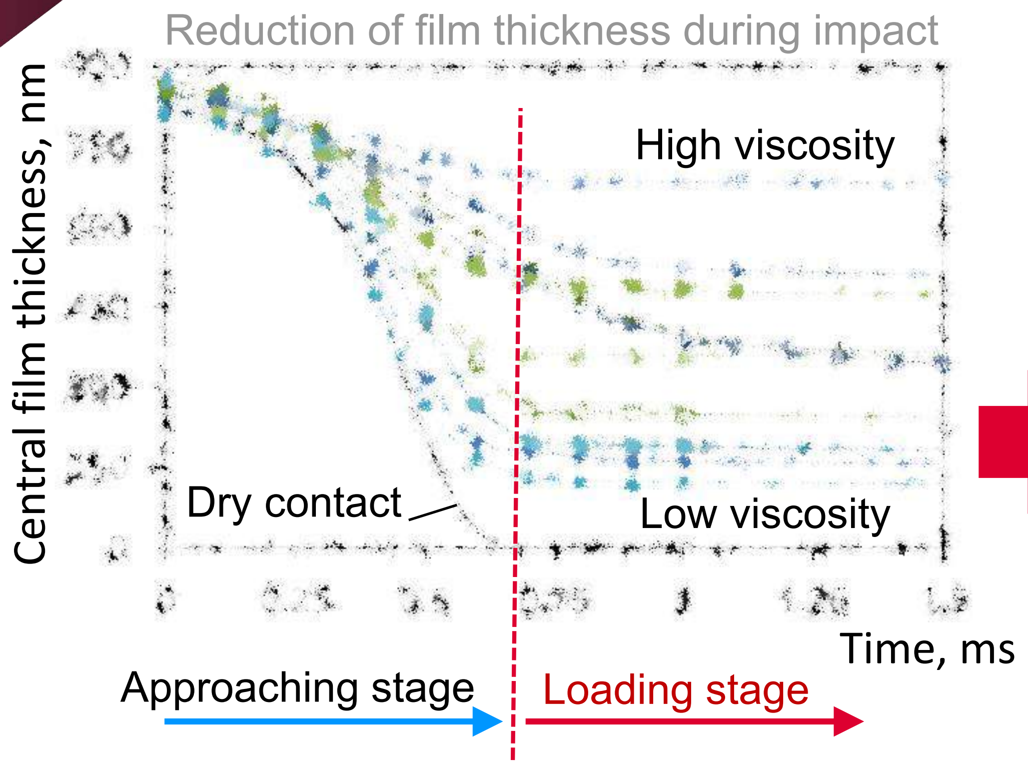
- Central film thickness defined by residual film at specific time
- Changes in central thickness follow differences in approaching speed

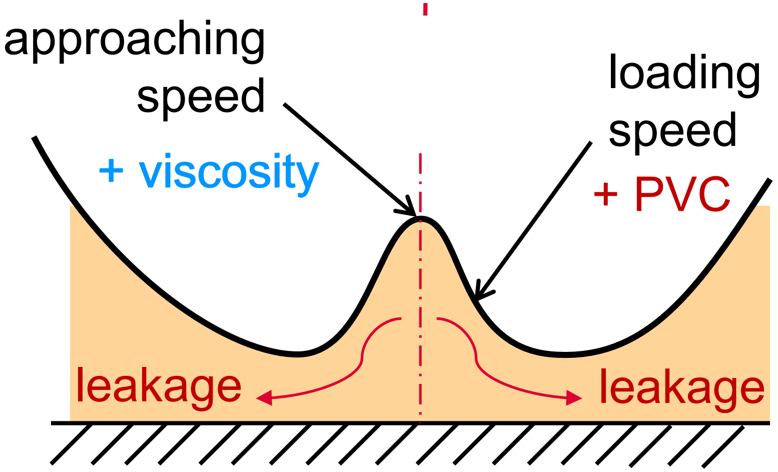
Effect of loading speed



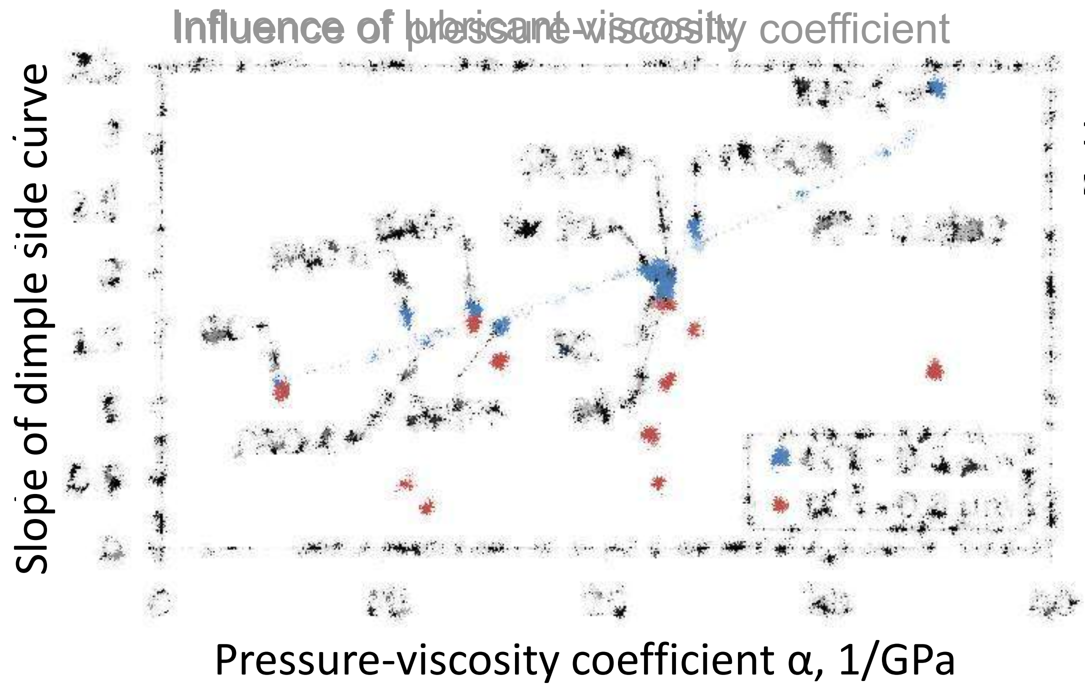


Results and discussion – Effect of lubricant rheology





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



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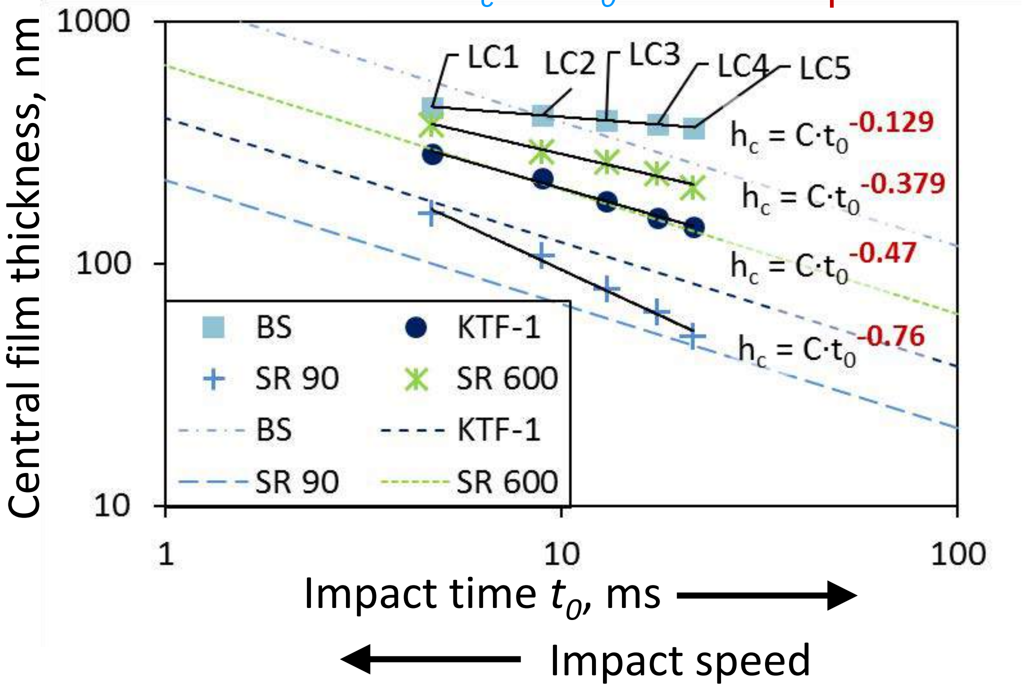
Results and discussion – Comparison with prediction

Venner (2016, Tribology International)

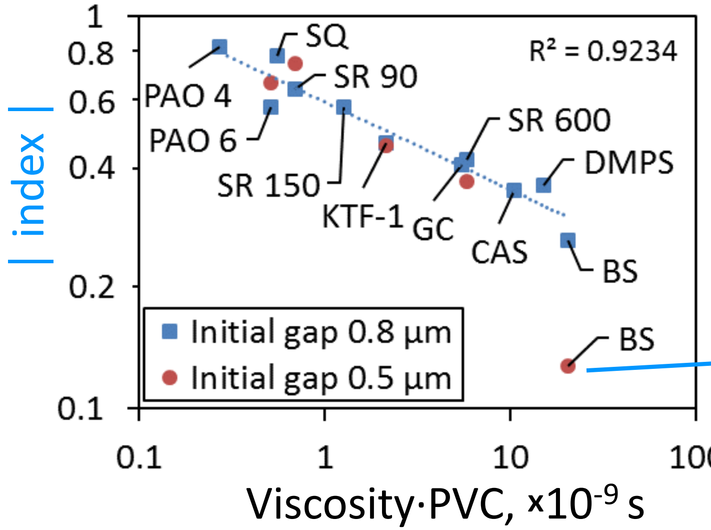
- Underestimated thickness by 32% (viscosity-pressure relationship)
- Different trend (index) representing effect of impact time / speed

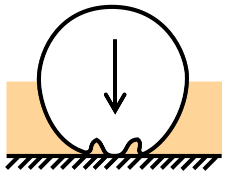
--- Prediction $h_c = C \cdot t_0^{-0.5125}$ Experiment



- Lubricant rheology affects impact time / speed

$$index = \pm 0.6053(\eta_0 \cdot \alpha \cdot C_1)^{-0.224}$$





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

Results and discussion

Impact loading

Film thickness

Role of approaching/loading speed?

Impact of lubricant rheology?

Lateral vibrations

Film thickness

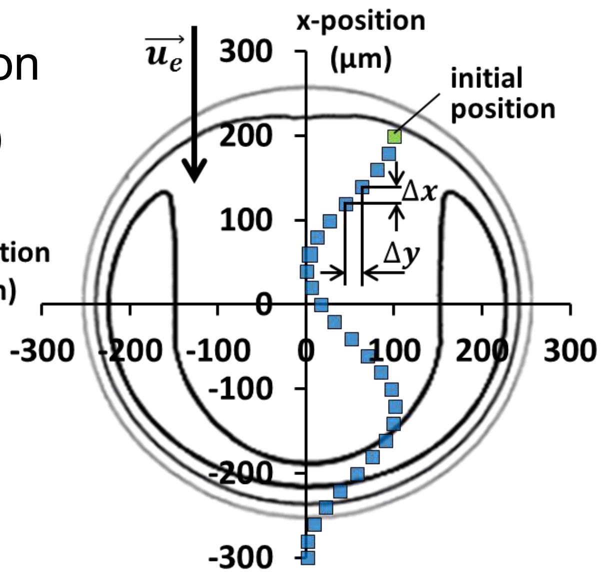
Friction

Effect of vibrations on film thickness?

Frictional response under vibrations?

Results and discussion – Mechanism of lubricant passage

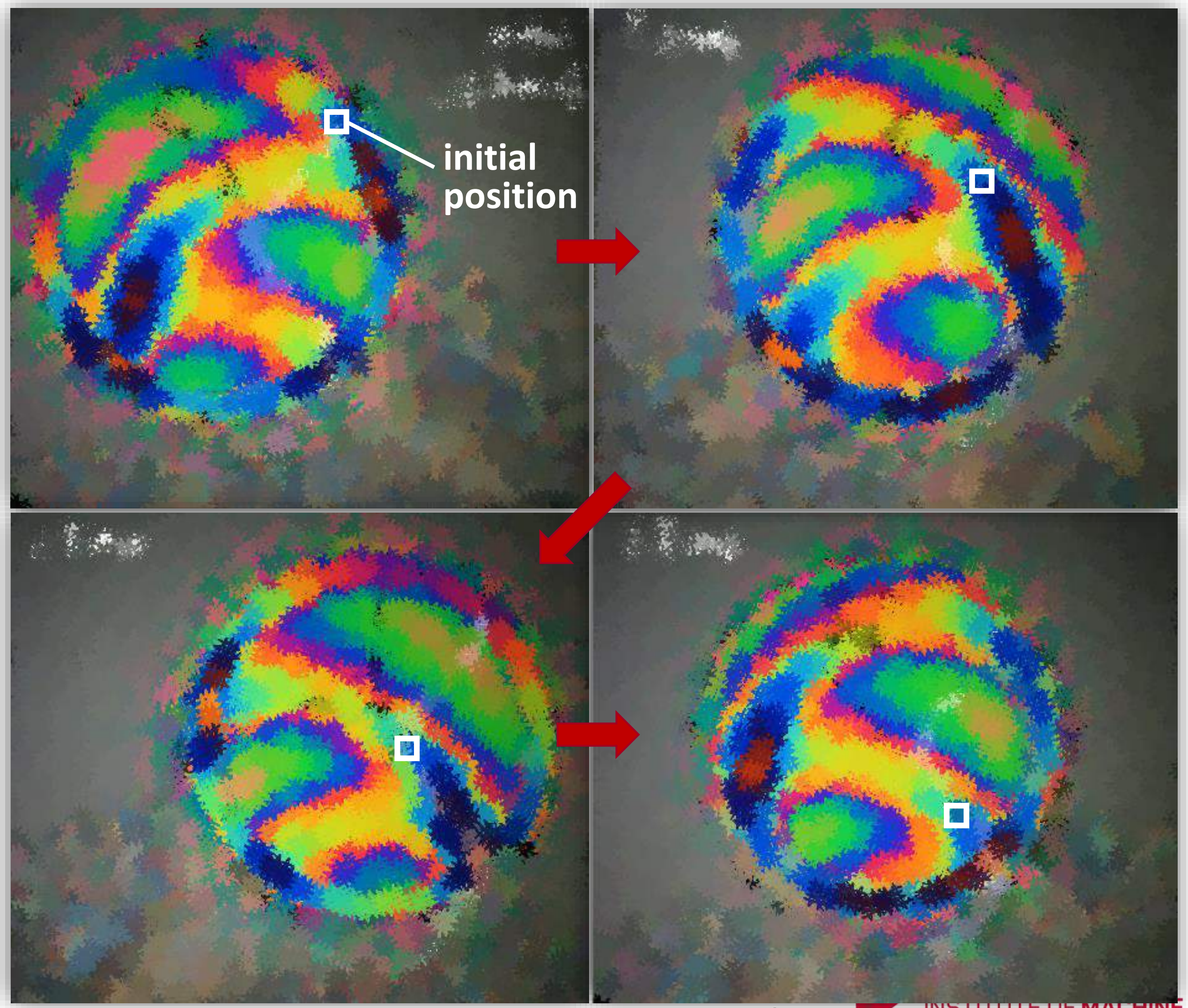
- Theoretical estimation (based on kinematics)



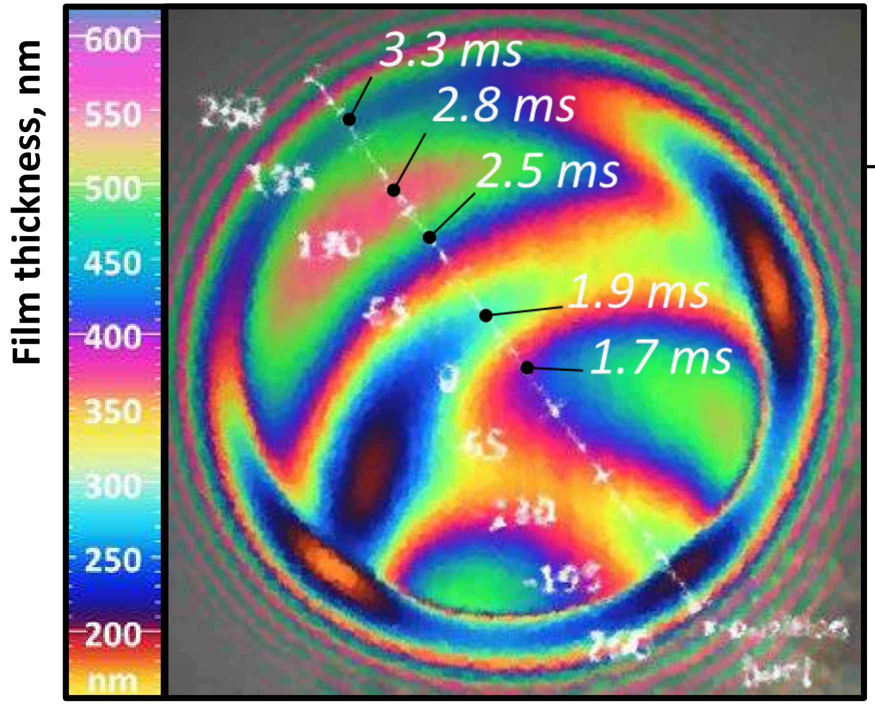
- In-situ observation

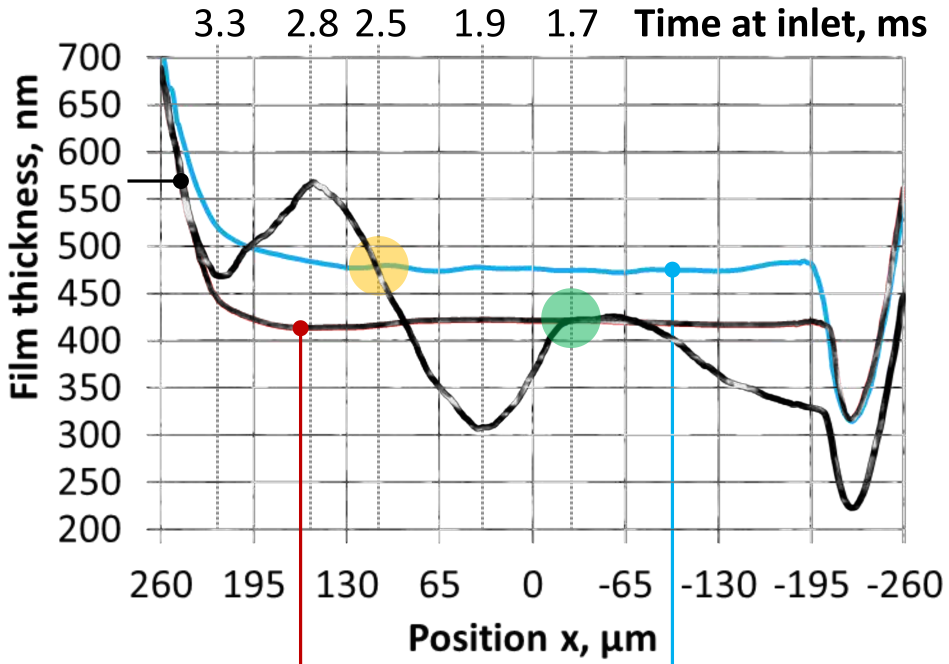
SN650 + PIP, 0.1 m/s,
300 Hz x 200 µm, 0.7 GPa

- Passage driven by vector of entrainment velocity

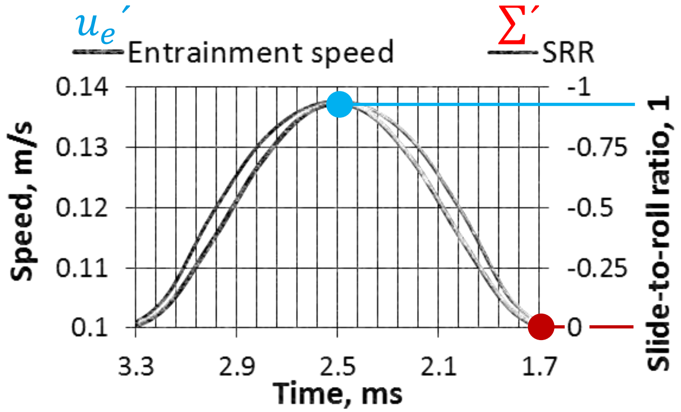


Results and discussion – Origin of film thickness distribution

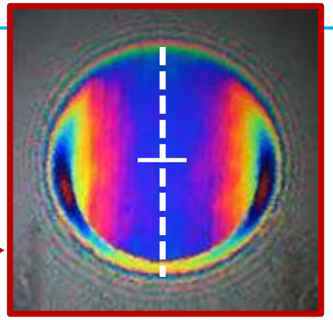




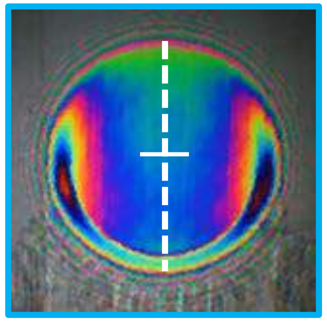
Corresponding steady-state conditions:



u_{ex}=0.1 m/s, ∑=0



u_{ex}=0.137 m/s, ∑=-0.94



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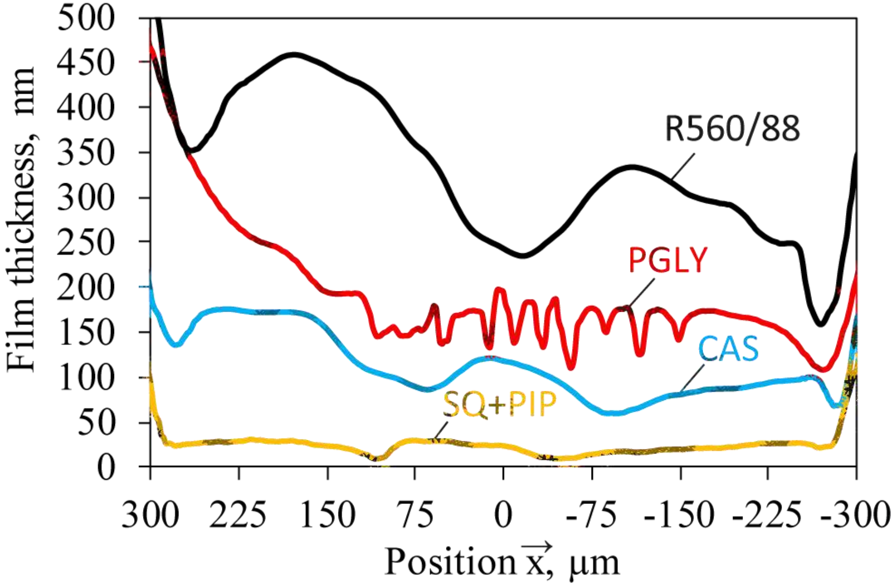
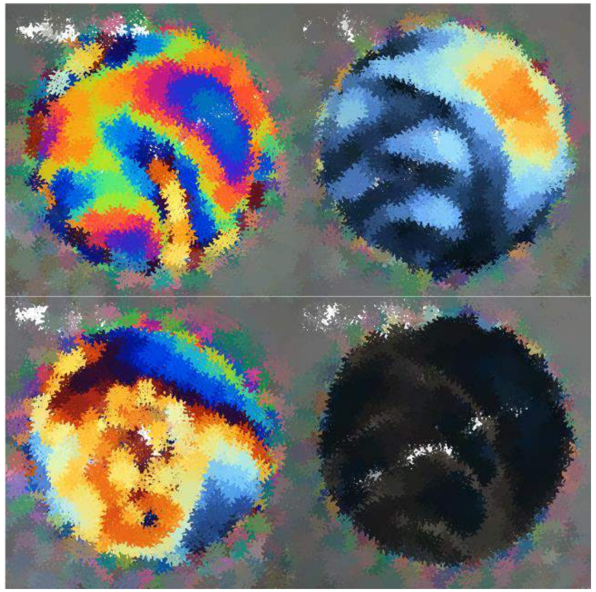
Results and discussion – Effect of vibrations on film thickness

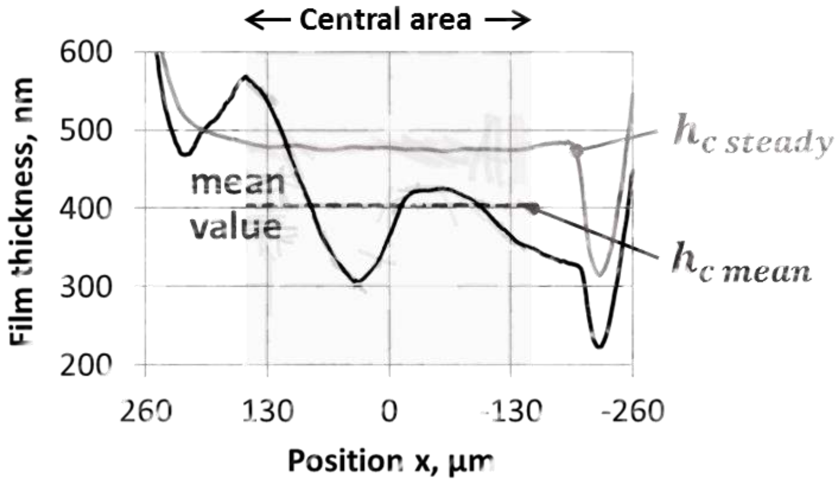
The same conditions, different lubricants





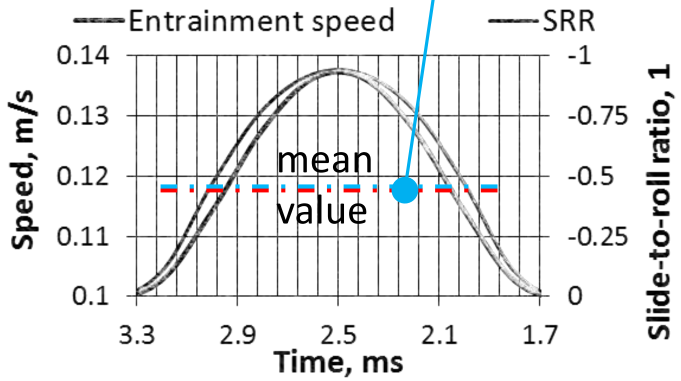
0.05 m/s, 300 Hz x 310 µm, 0.88 GPa

Unification using dimensionless number



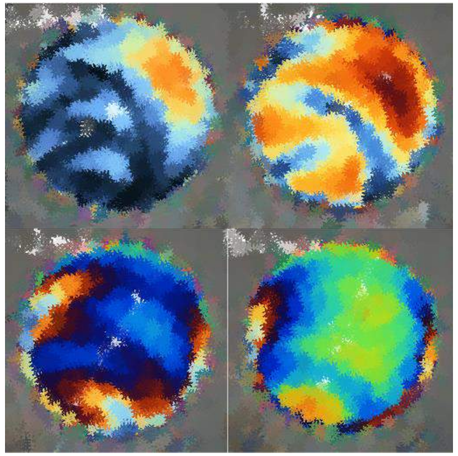
Relative mean thickness

$$H_{mean} = h_{c\ mean} / h_{c\ steady} \approx 0.57$$

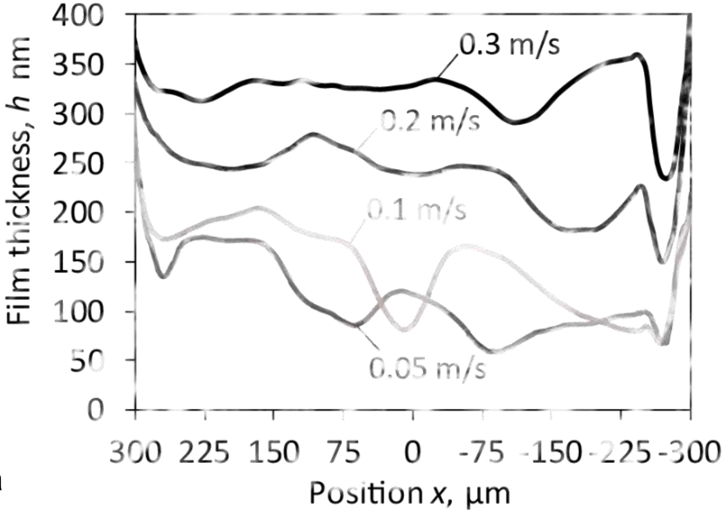


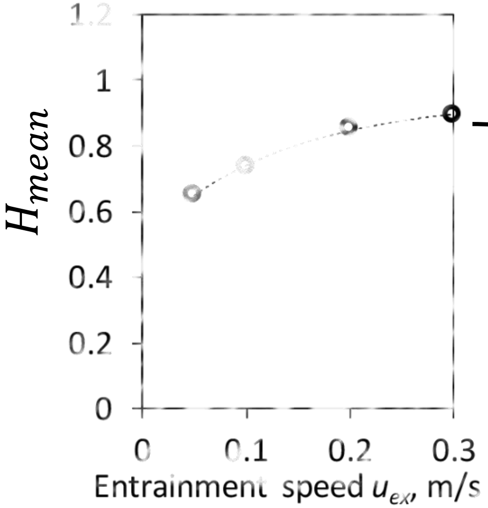
Results and discussion – Effect of vibrations on film thickness

The same lubricant, different main entrainment speed

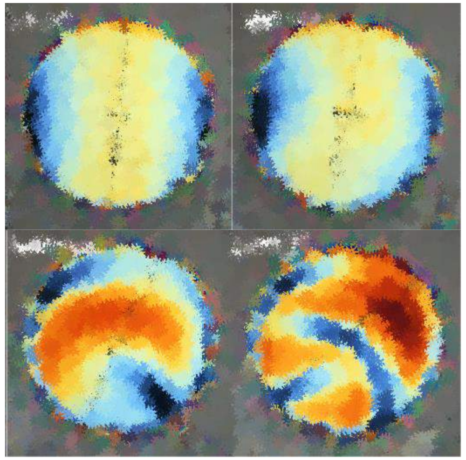


CAS, 300 Hz, 310 µm, 0.88 GPa

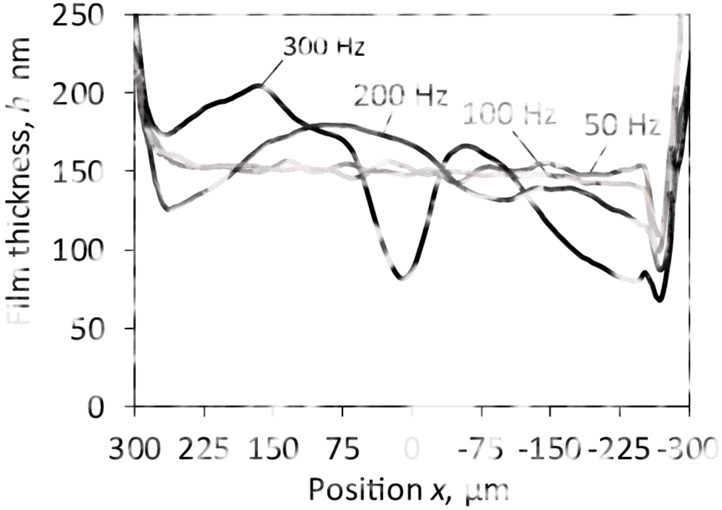


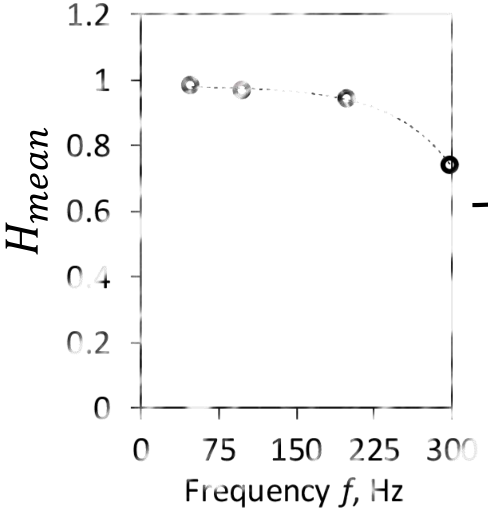


The same lubricant, different lateral entrainment speed (frequency)



CAS, 0.1 m/s, 310 µm, 0.88 GPa

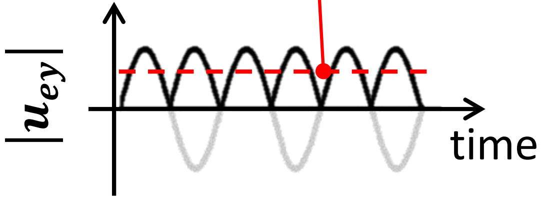




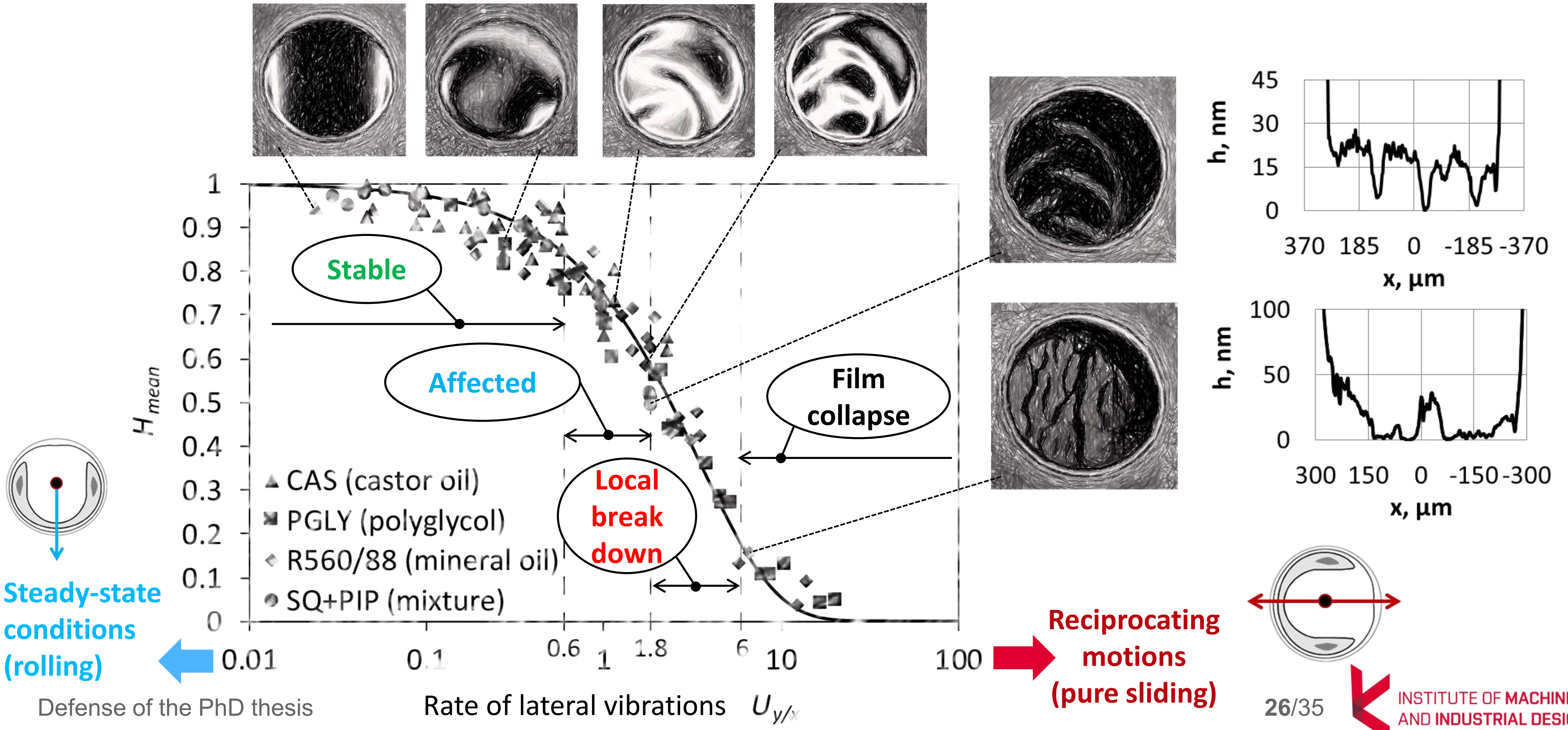
Unification using dimensionless number

Rate of lateral vibrations

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



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

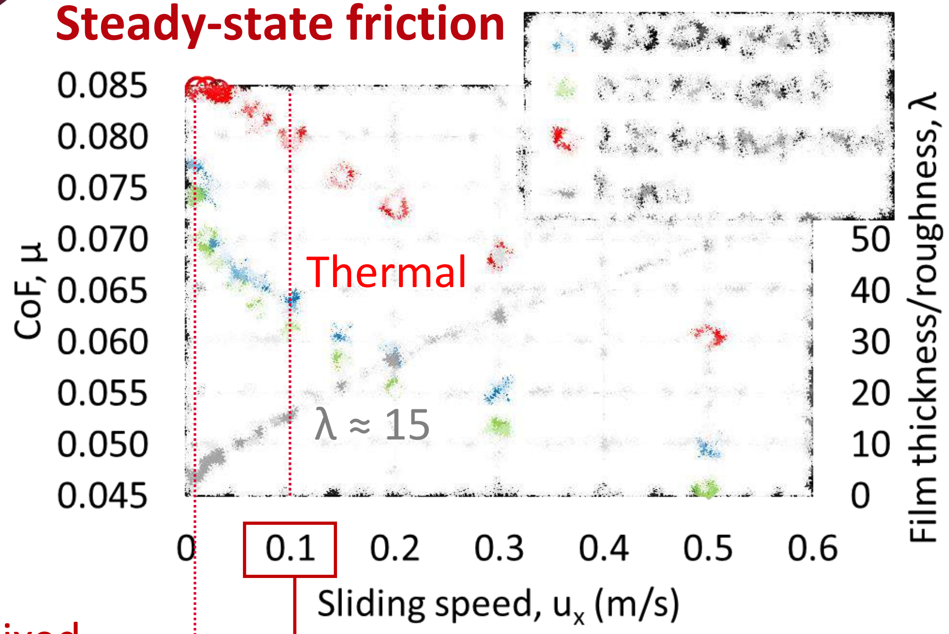
Friction

Effect of vibrations on film thickness?

Frictional response under vibrations?

Results and discussion – Friction under lateral vibrations

Steady-state friction



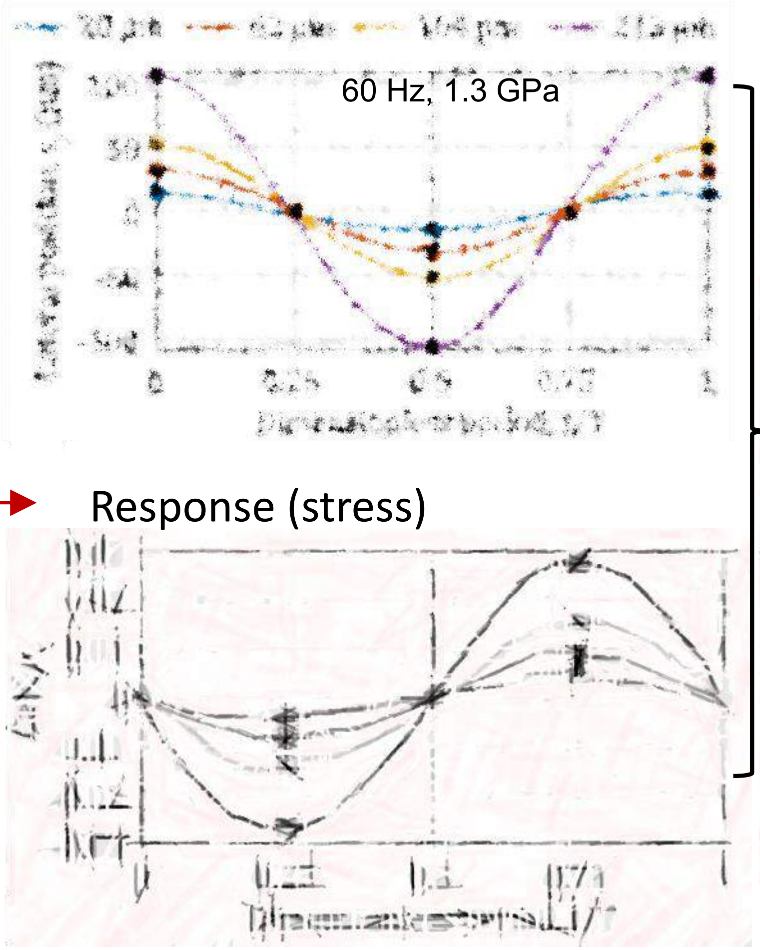
Mixed lubrication

EHL lubrication

λ ≈ 3.5

Friction in the lateral direction of contact under vibrations

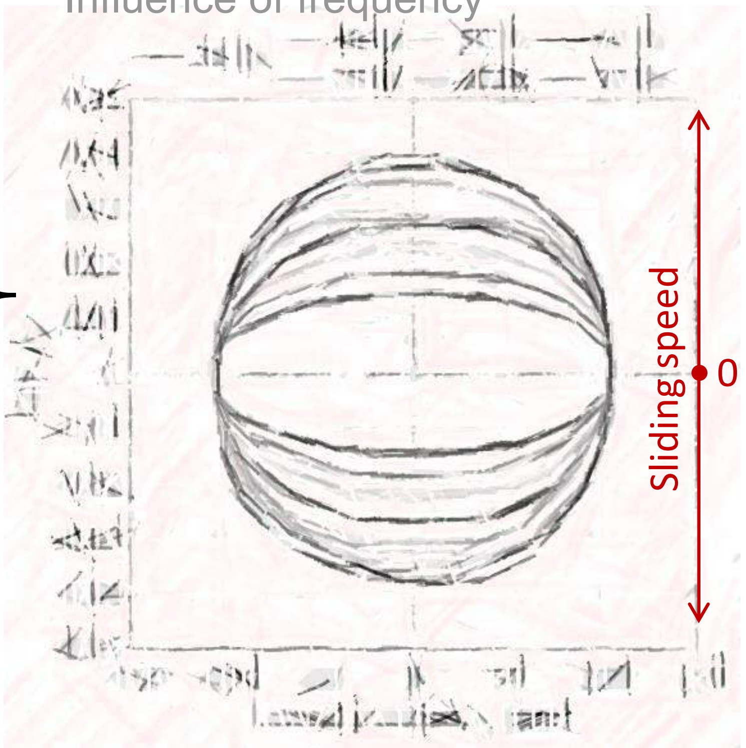
Excitation (strain)



Response (stress)

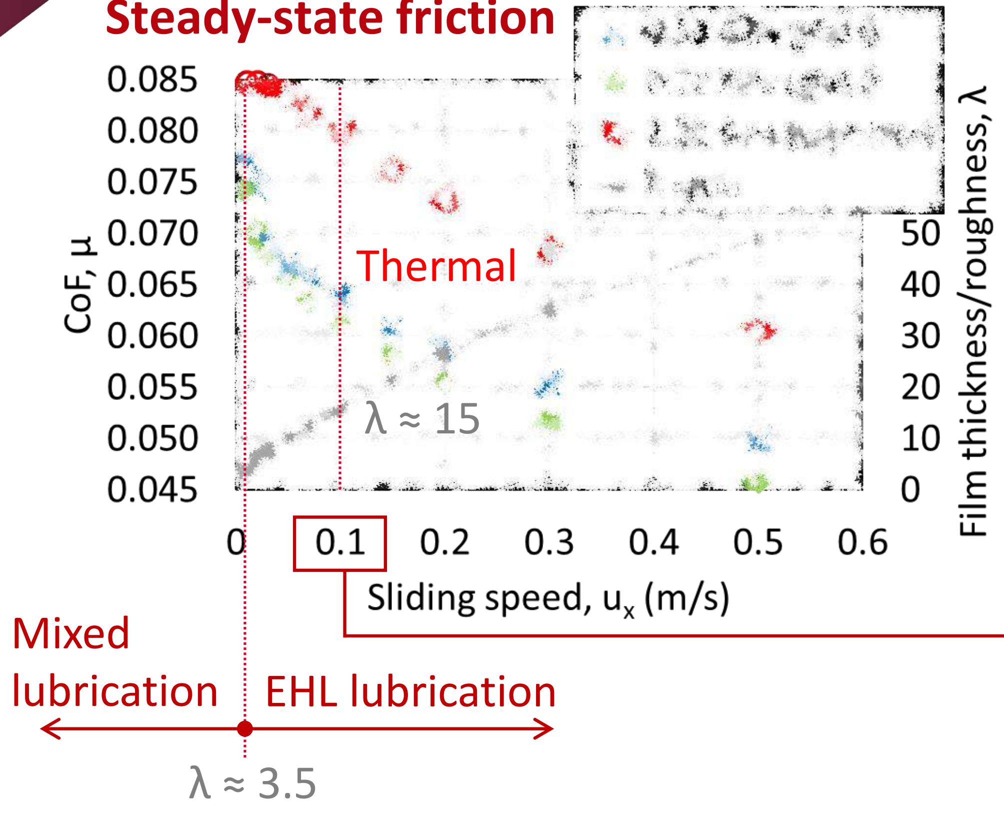
- position-independent COF
- purely viscous response

Influence of frequency



Results and discussion – Friction under lateral vibrations

Steady-state friction

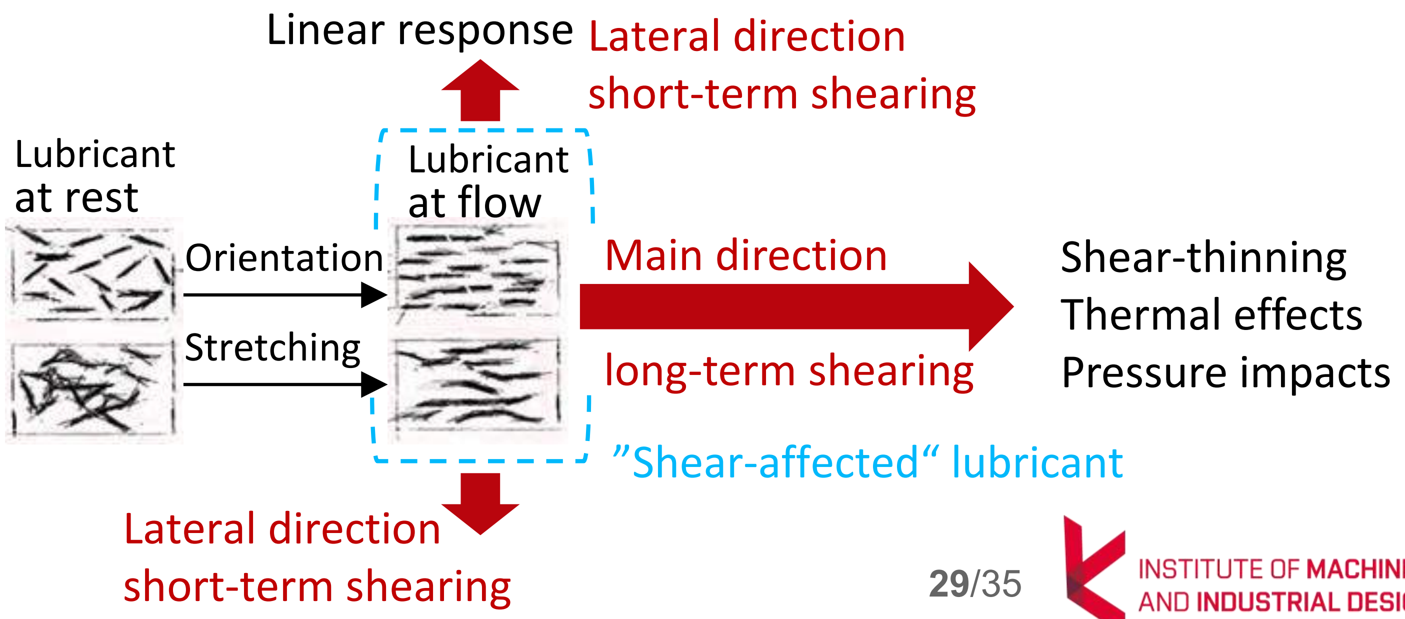


Friction in the lateral direction of contact under vibrations

No visible effects of:

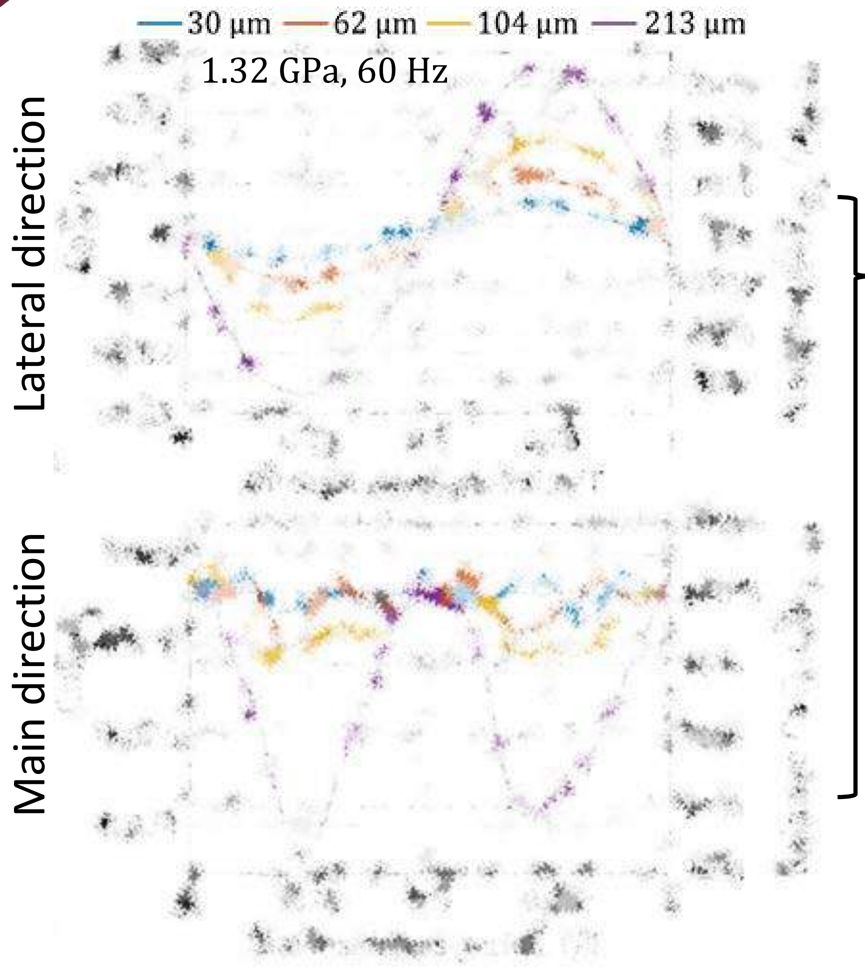
- Pressure
- Shear-thinning
- Shear heating

Structural arrangement of lubricant

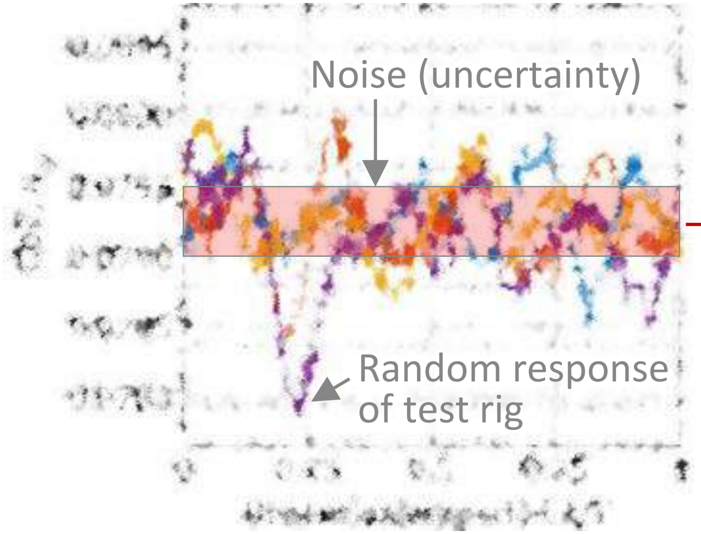


Results and discussion – Friction under lateral vibrations

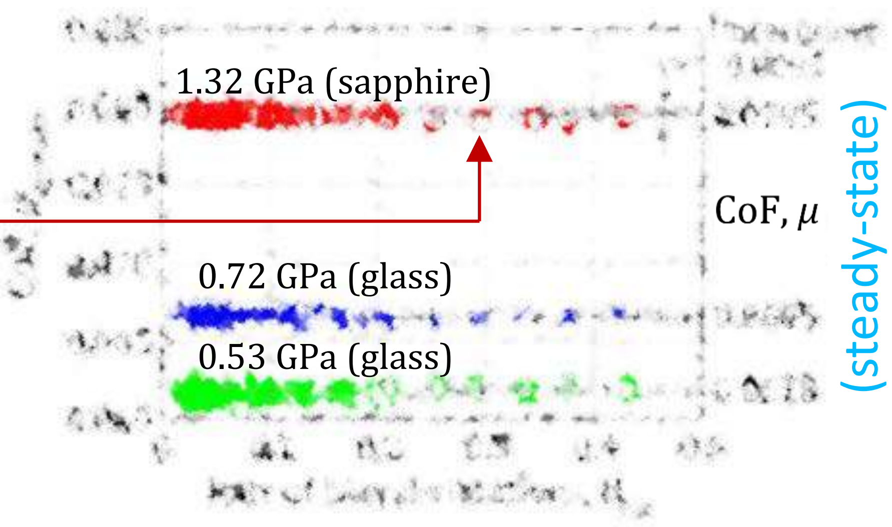
Total friction and its components



Sliding speed direction



Effect of lateral vibrations



- Lateral friction affects main friction but not vice versa

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

  (valid only for used conditions)

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

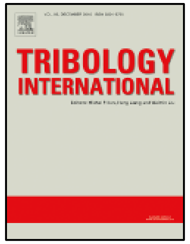
Lateral vibrations

- Relationship describing reduction in the relative mean film thickness with increase in the rate of vibrations was established.
- Thresholds for a local film breakdown and film collapse were found.
- Friction in the direction perpendicular to the main shear flow reveals a natural, unaffected, response of the lubricant originating from the perturbation of its structural arrangement.
- Link between frictional responses with respect to the main shear flow was discussed.

Conclusions of the PhD thesis

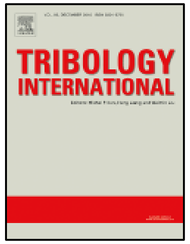
Impact loading

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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