

PERFORMANCE AND SAFETY IMPROVEMENT OF LARGE-SCALE HYDROSTATIC BEARINGS

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Supervisor specialist: Ing. Petr Šperka, Ph.D.

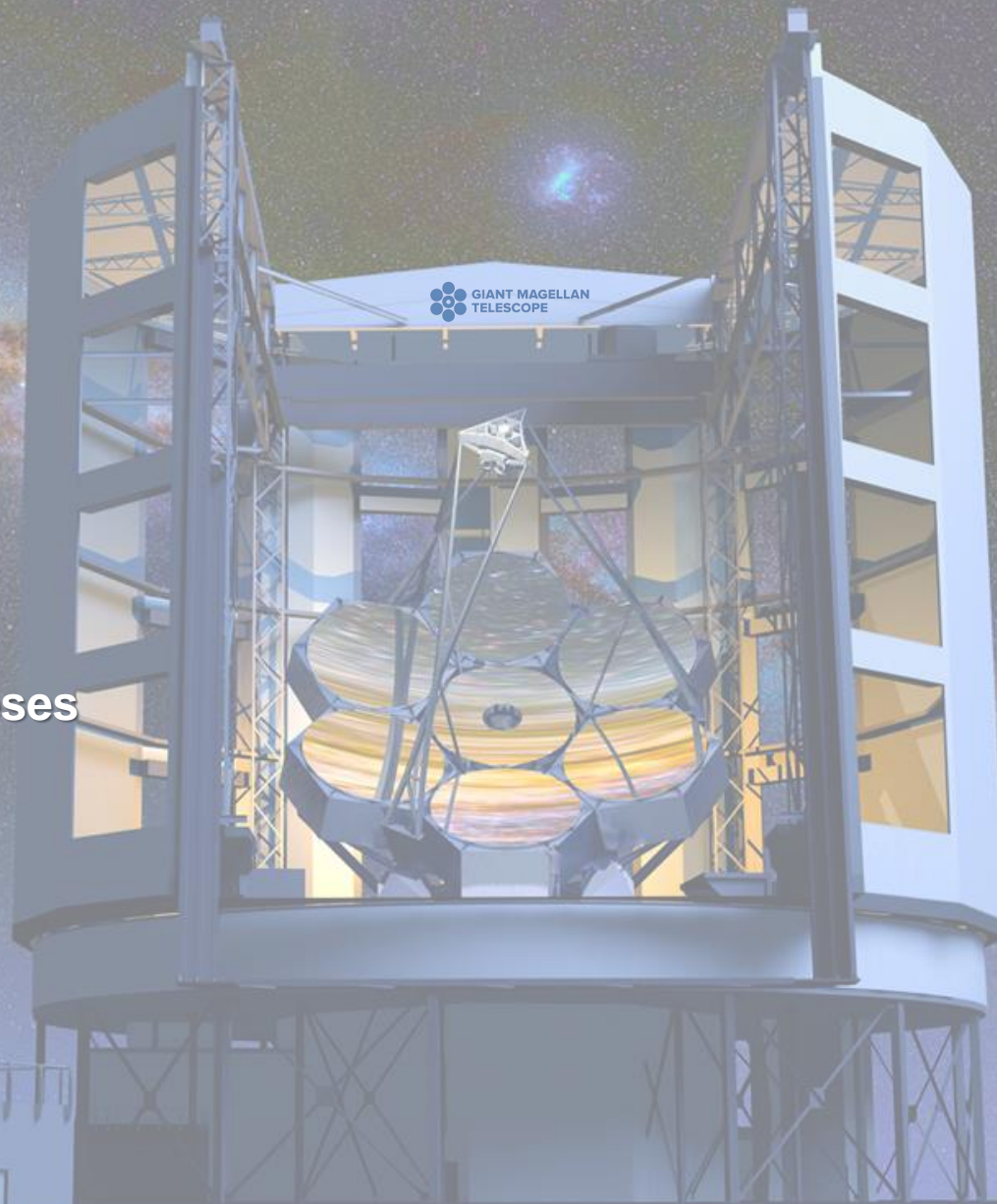
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN
Faculty of Mechanical Engineering
Brno University of Technology

Brno, 9.4.2024



INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN

- Introduction
- Motivation
- State of the art
- Problem analysis
- Goals of the thesis
- Scientific questions & hypotheses
- Material & methods
- Results & discussion
- Conclusion



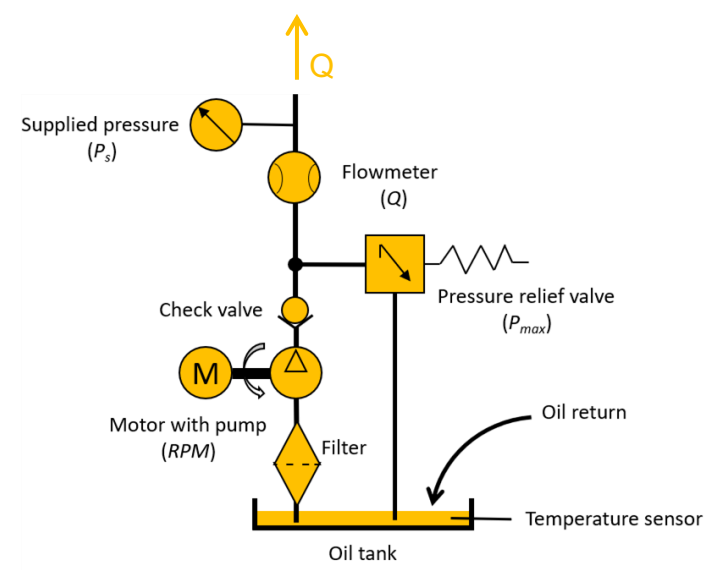
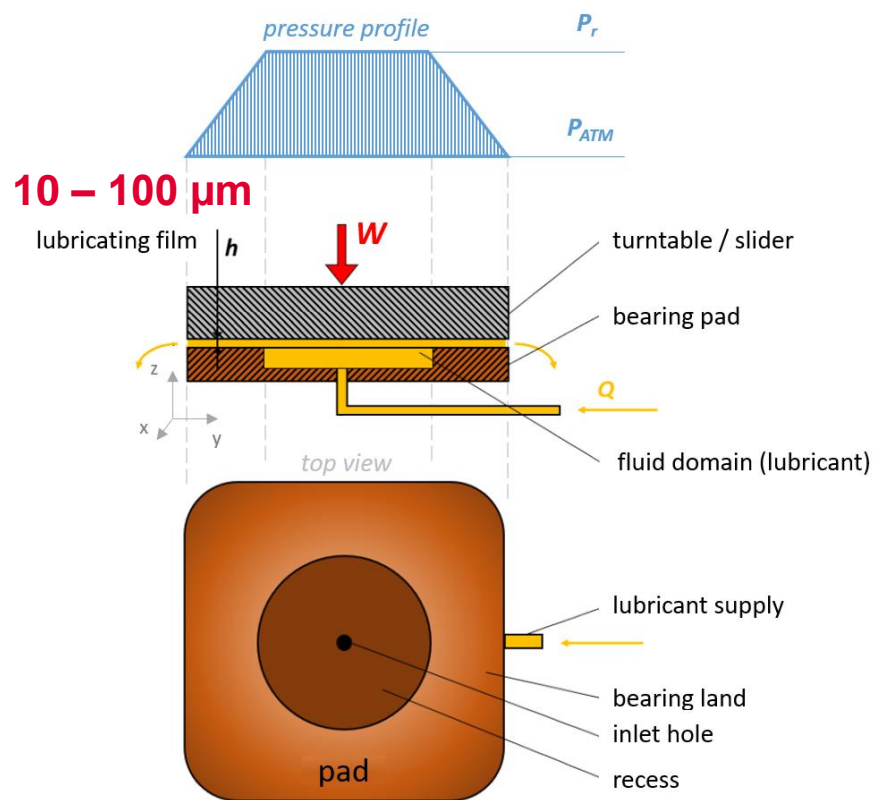
HYDROSTATIC BEARINGS

ADVANTAGES

- + low friction (COF up to 0.0001)
- + no wear of sliding surfaces
- + zero speed operation
- + precise & smooth movement
- + large load capacity
- + damping ability

DISADVANTAGES

- high cost
- continuous supply
- energy consumption
- misalignment sensitivity



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$$W = \frac{3\mu Q (R_2^2 - R_1^2)}{h^3}$$

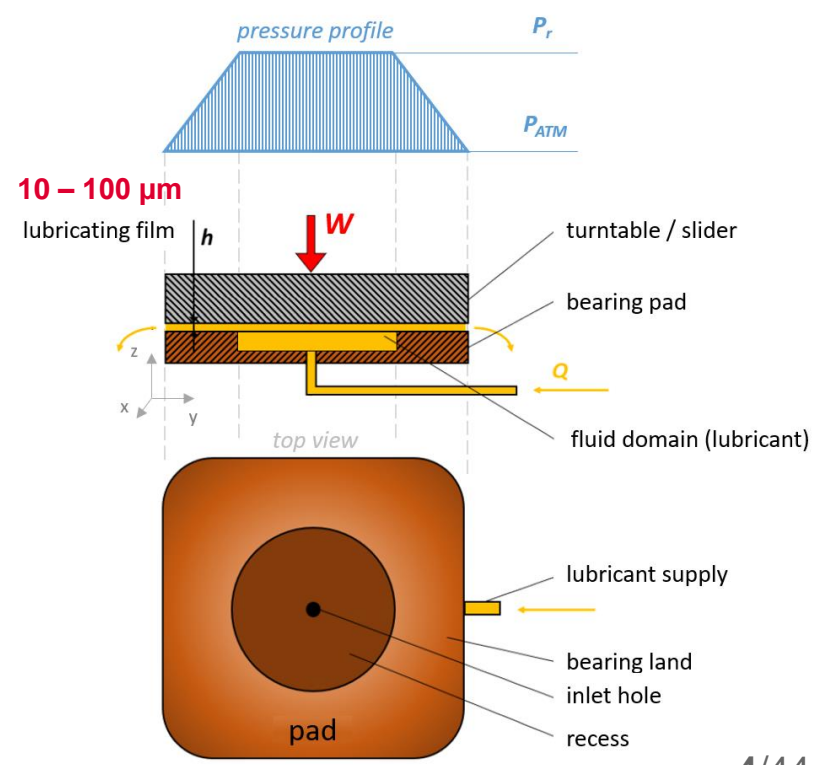
Load capacity W = $\frac{3\mu Q (R_2^2 - R_1^2)}{h^3}$

Dynamic viscosity μ

Supplied flow Q

Pad geometry $(R_2^2 - R_1^2)$

Film thickness h^3



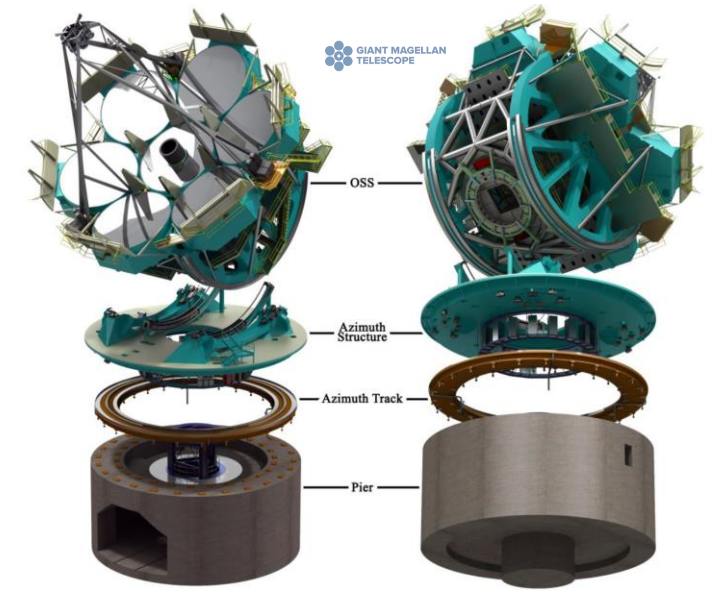
HYDROSTATIC BEARINGS

Applications:

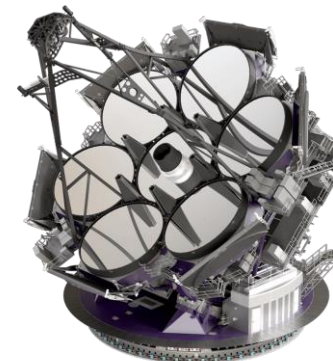
- Machining centres
- High-precision machines
- Turntables
- Industrial guideways
- Antennas & telescopes
- Potential use in high-demand areas (energetics, logistics, production,...)
- **Movement of large structures**



www.zollern.com



LARGE-SCALE HYDROSTATIC BEARINGS



www.giantmagellan.org



<https://elt.eso.org/>

	2 m	20 m	50 m	<i>bearing size</i>
	rotary table	GMT	ELT	
	30 t	900 t	3700 t	<i>load capacity</i>
	10 l/min	150 l/min	720 l/min	<i>flow rate</i>

LARGE-SCALE HYDROSTATIC BEARINGS

Challenges:

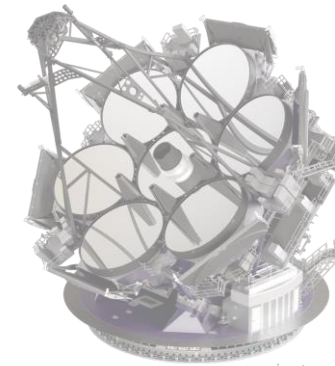
- High initial and **energetic demands** (ELT est. 100 000 € / year)
- High **maintenance costs** (HSB repair 1.15 milion €, NASA 2010)
- Limited **market availability**
- High potential for **megaprojects**



2 m
rotary table

30 t

10 l/min

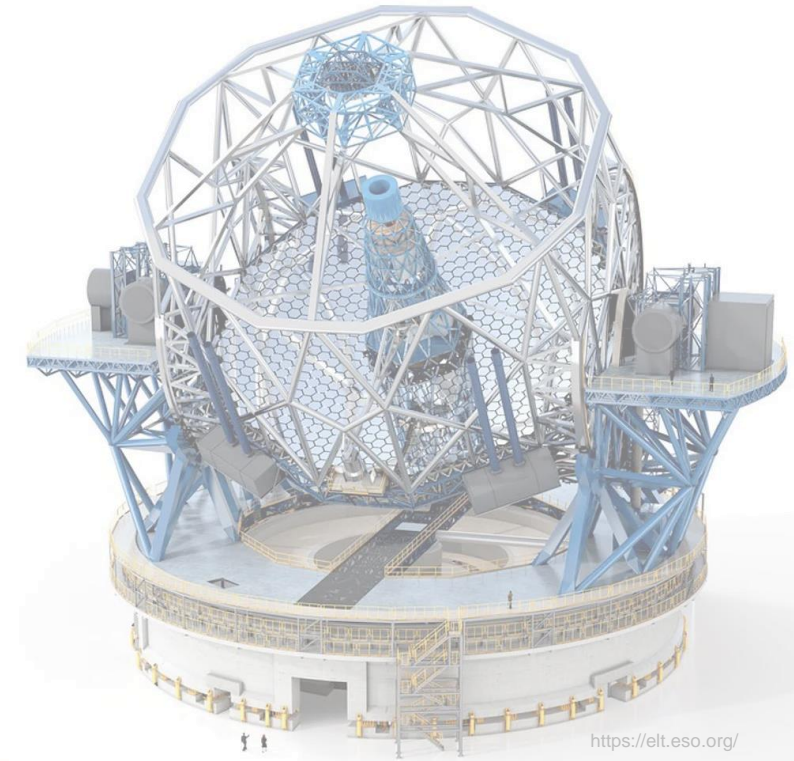


www.giantmagellan.org

20 m
GMT

900 t

150 l/min



<https://elt.eso.org/>

50 m
ELT

3700 t

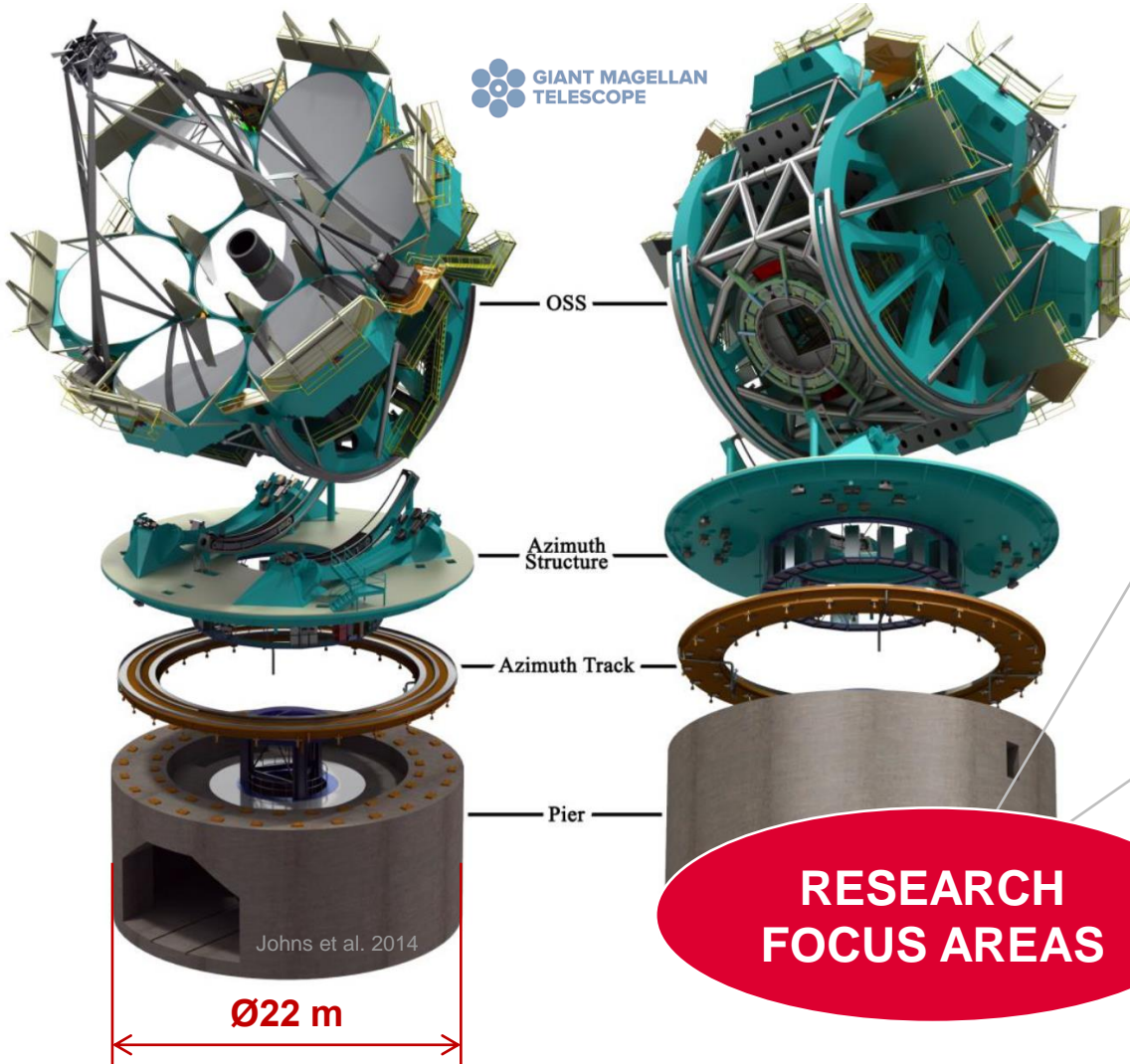
720 l/min

bearing size

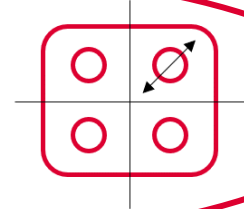
load capacity

flow rate

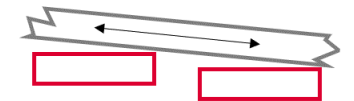
LARGE-SCALE HYDROSTATIC BEARINGS



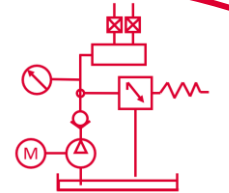
PAD GEOMETRY OPTIMIZATION



ALIGNMENT & MOVEMENT PRECISION

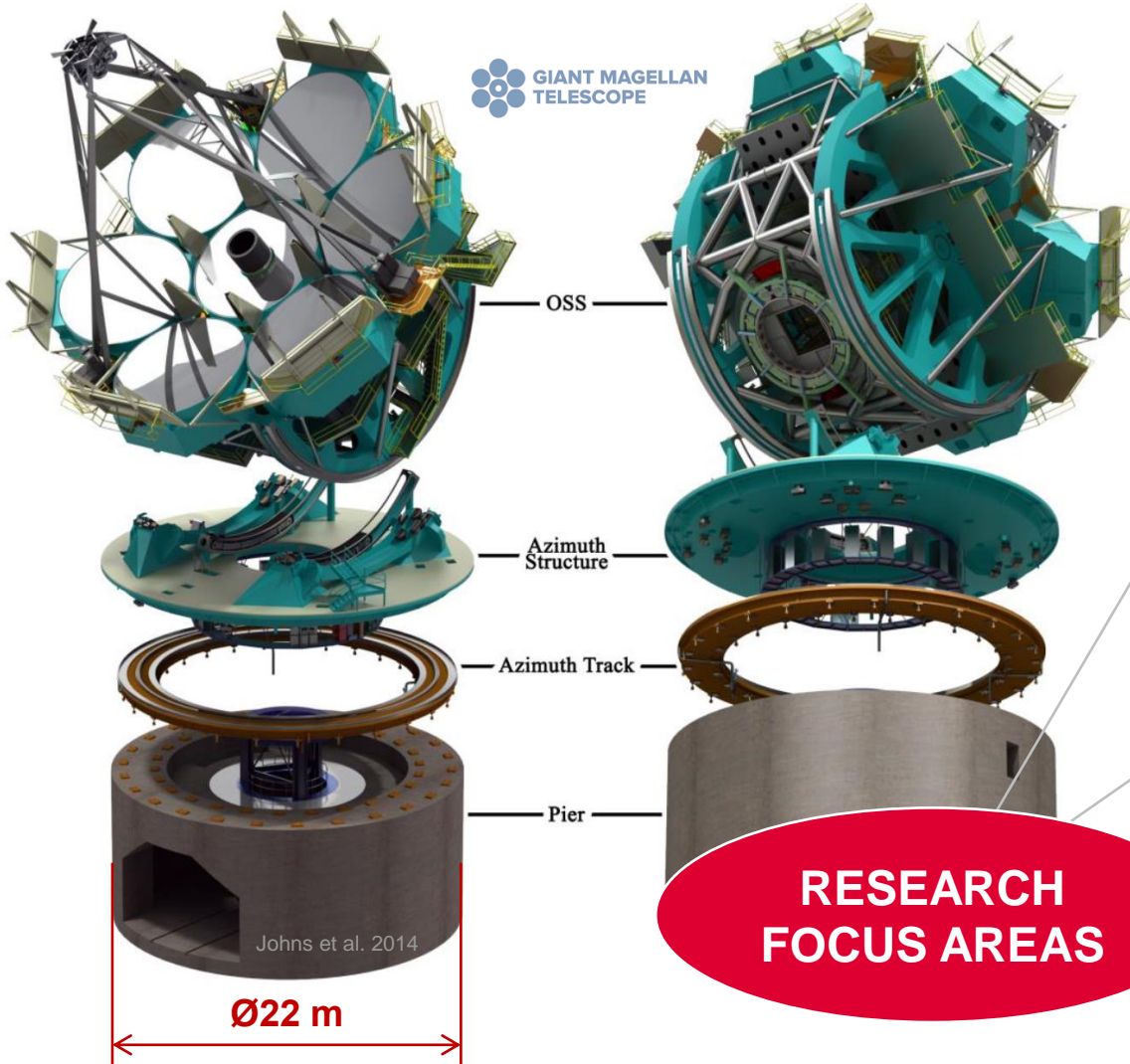


SUPPLY SYSTEM

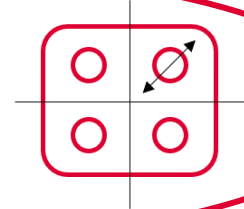


RESEARCH FOCUS AREAS

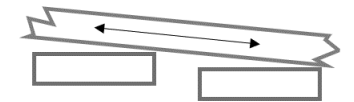
LARGE-SCALE HYDROSTATIC BEARINGS



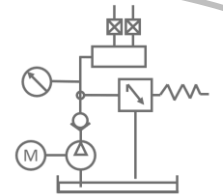
PAD GEOMETRY OPTIMIZATION



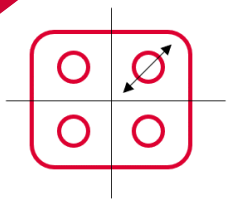
ALIGNMENT & MOVEMENT PRECISION



SUPPLY SYSTEM



RESEARCH FOCUS AREAS



PAD GEOMETRY OPTIMIZATION

Analytical approach

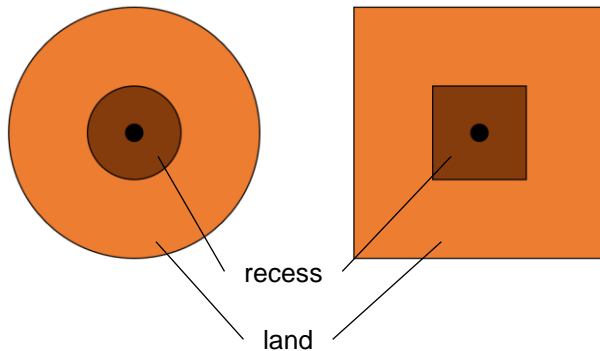
- Based on N -S equation
- Simplifications – Reynolds
- Only for simple geometry
- Recommended H/h (20-50x)
- Methodology on HSL design (Bassani & Piccigallo 1992)

Experimental approach

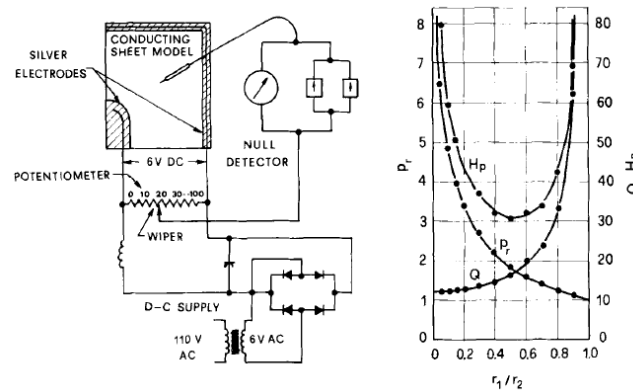
- Real behaviour of the bearing
- Validation of derived equations
- Demanding for time and cost
- Electric field analogy (Loeb, 1957)

Numerical approach

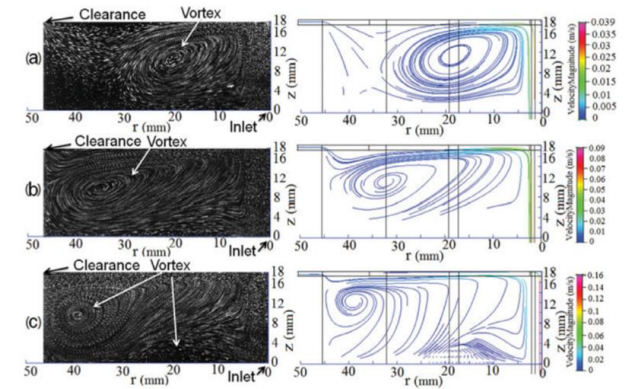
- Modelling of any geometry
- Time and cost efficient
- Reduction of development costs
- Model verification (Horvat, 2011)



Circular and rectangular pad geometry

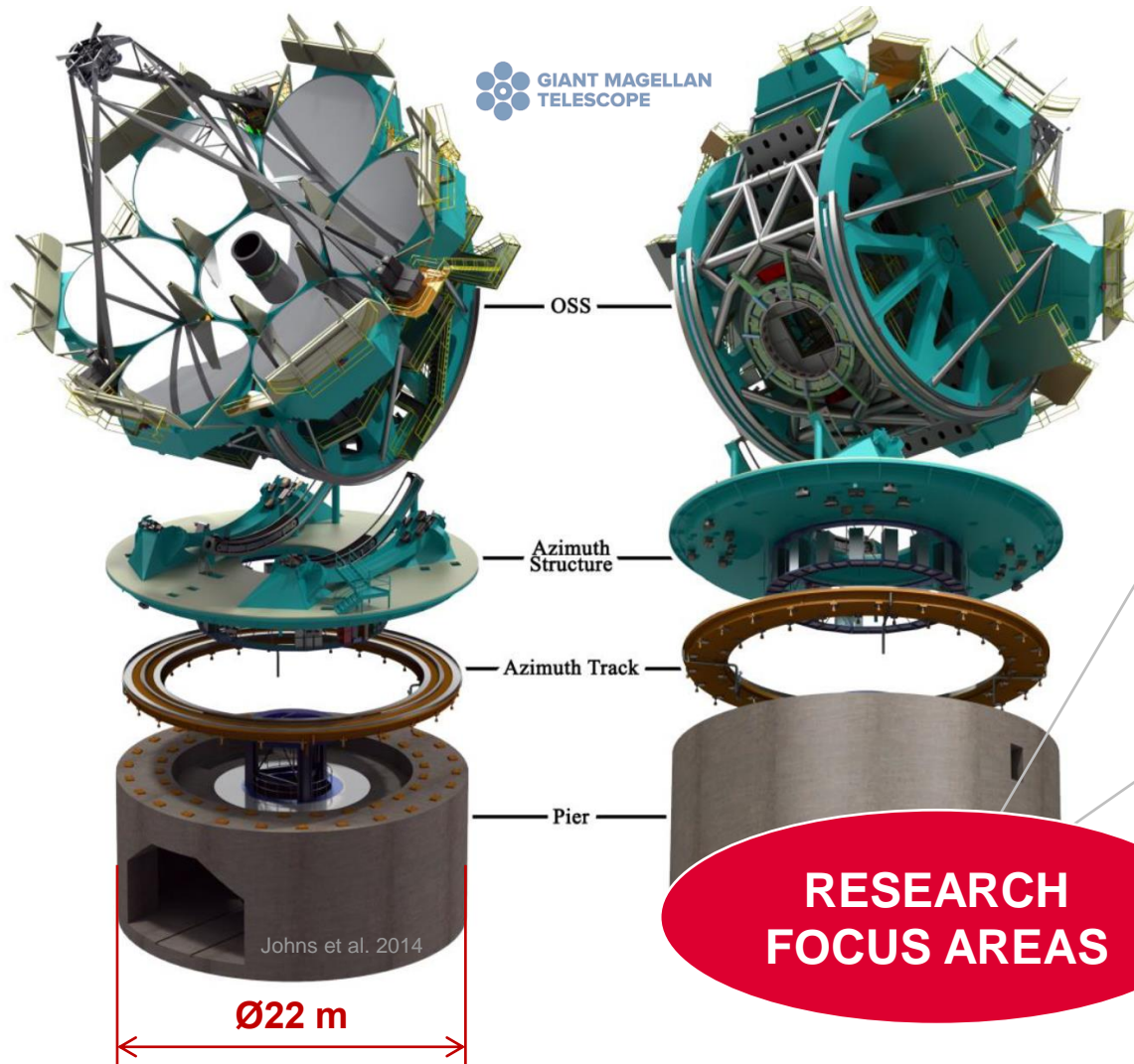


LOEB and RIPPEL (1958)

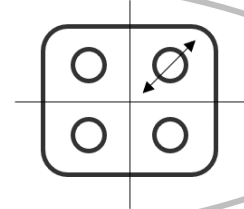


SHEN et al. (2014)

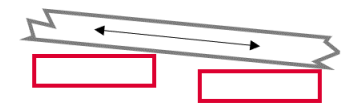
LARGE-SCALE HYDROSTATIC BEARINGS



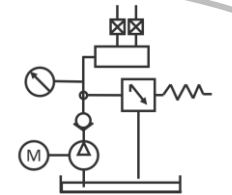
PAD GEOMETRY OPTIMIZATION

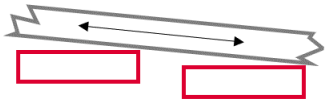


ALIGNMENT & MOVEMENT PRECISION



SUPPLY SYSTEM





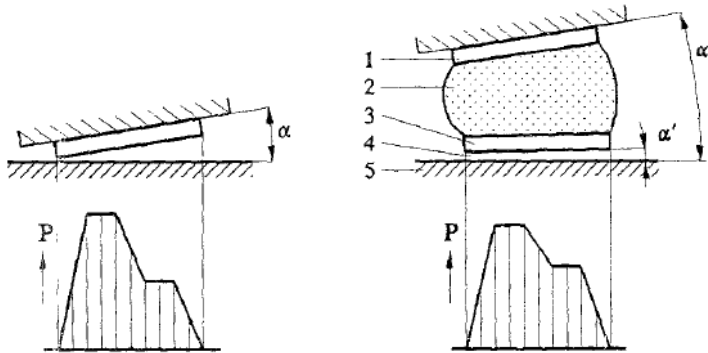
ALIGNMENT & MOVEMENT PRECISION

- Challenging manufacturing, transportation & assembly
- Film thickness in range **20-100 μm**
- Pad misalignment might lead to surface damage & seizure

SELF-ALIGNING

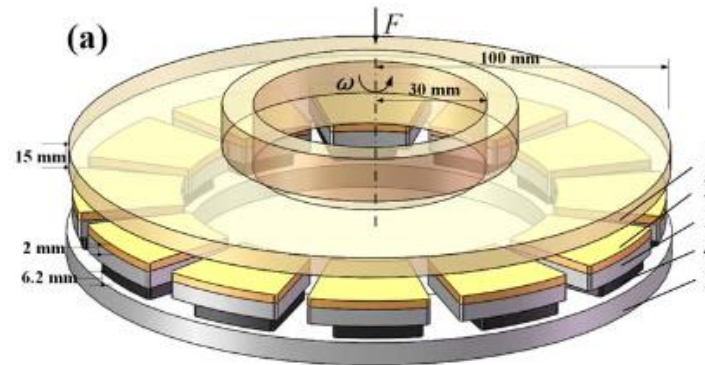
Van Beek et al. (1996)

- Numerical model
- More uniform pressure distribution



Liang et al. (2019)

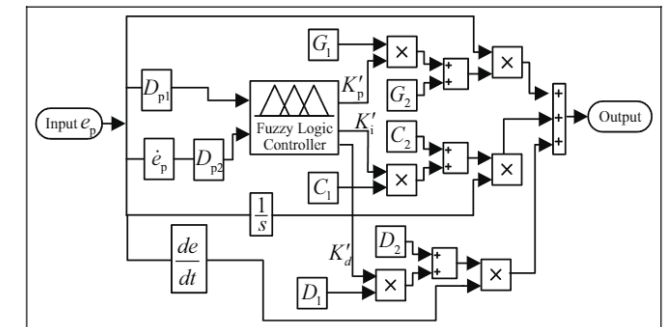
- Numerical & experimental model
- HD pad compliant support



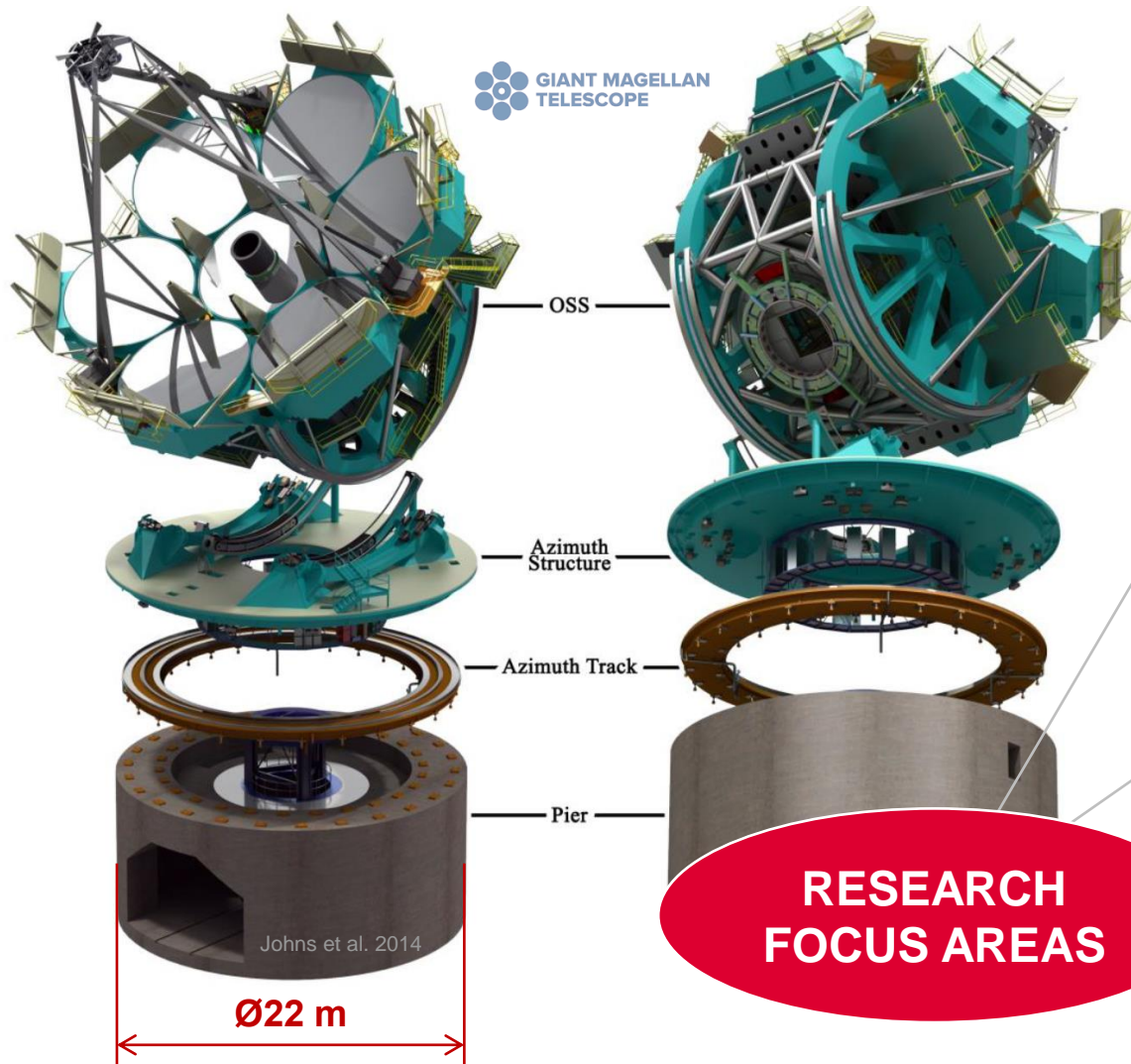
FEEDBACK CONTROL

Rehman et al. (2019)

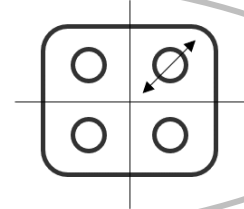
- Experimentally verified
- Higher precision than PID controller



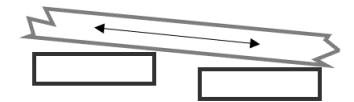
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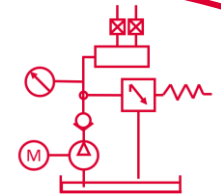
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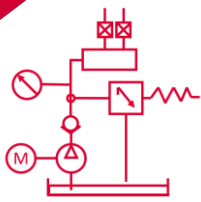


ALIGNMENT & MOVEMENT PRECISION

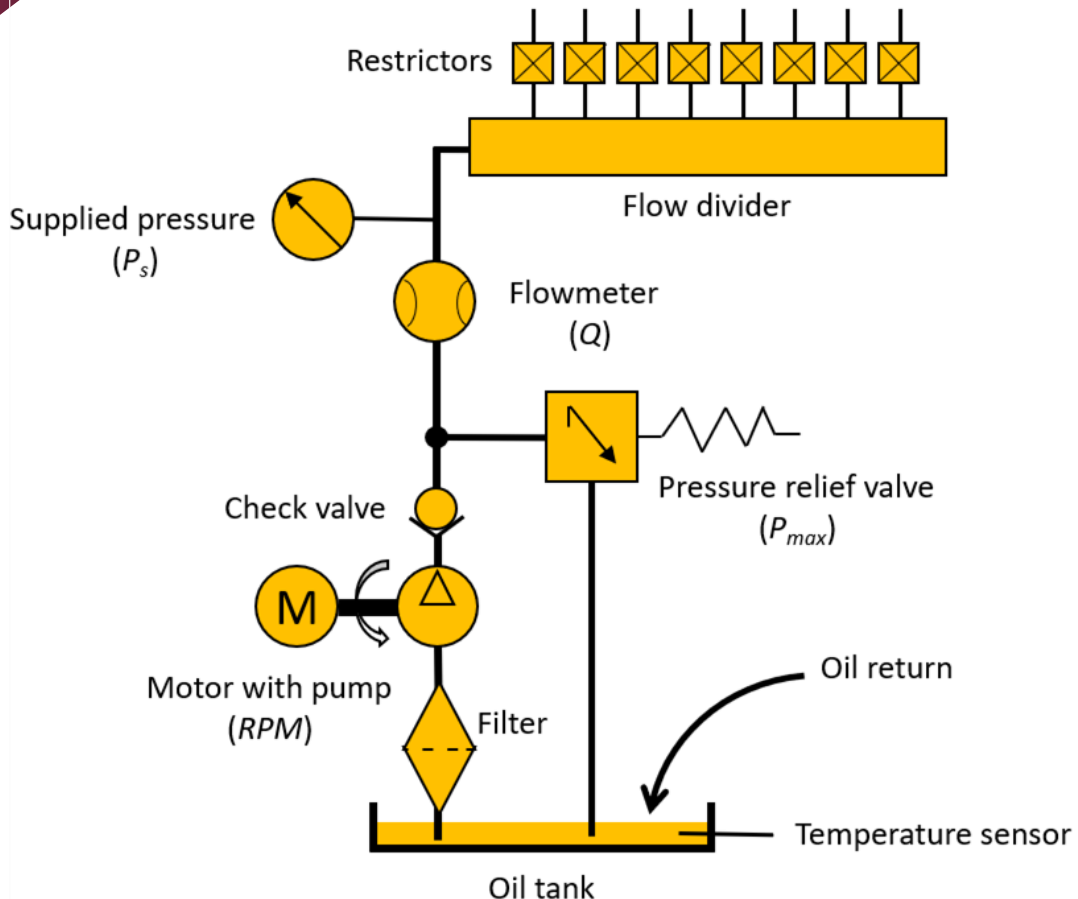


SUPPLY SYSTEM





HYDROSTATIC BEARING LUBRICATION SYSTEM



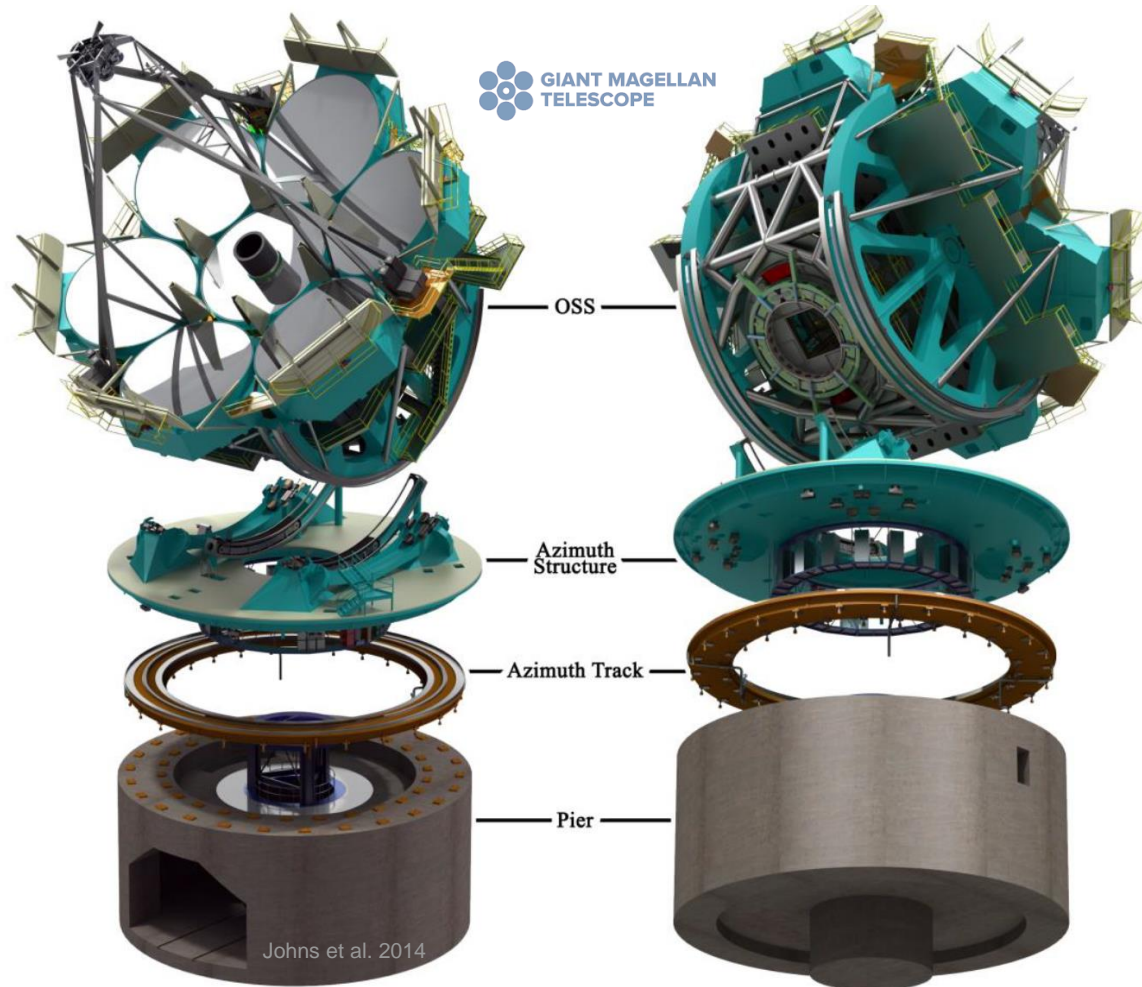
PRESSURIZED OIL SUPPLY

- Continuous supply of pressurized lubricant
- Flow control & adjustment (Rehman 2021)
- Research mainly focused on restrictors (Childs 2019)

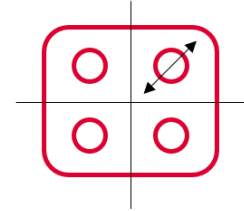
RESTRICTORS

- Most common types (Bassani & Piccigallo 1992):
 - Fixed:** Orifice, capillary
 - Variable – passive:** compliant elements, control valves
 - Variable – active:** EM valves
- Necessary in multi-pad single-pump HSB systems (Khonsari 2017)

SUMMARY OF LITERATURE REVIEW

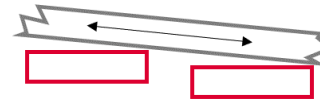


Pad geometry optimization



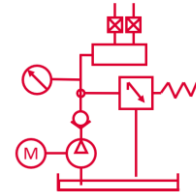
- ✓ Optimization methods
- ✓ Multi-criteria optimization
- ✗ Multi-parametric shape optimization

Alignment & movement precision



- ✓ Surface topography influence
- ✗ Compliant support experiments
- ✗ Assembly error tolerancing

Supply system



- ✓ Flow control devices
- ✓ Feedback systems
- ✗ Energy consumption reduction

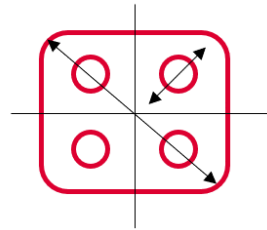
AIM OF THE THESIS



Introduce **performance** and **safety** improvements to the large-scale hydrostatic bearing design methodology.

SCIENTIFIC QUESTIONS:

1. What is the influence of hydrostatic bearing recess position and size on the bearing performance?



2. How is the hydrostatic lubricating film affected by assembly errors of the bearing bodies?

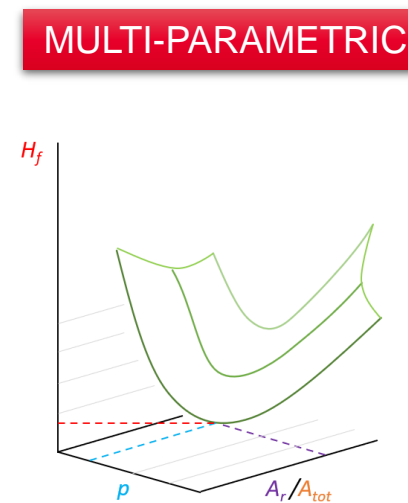
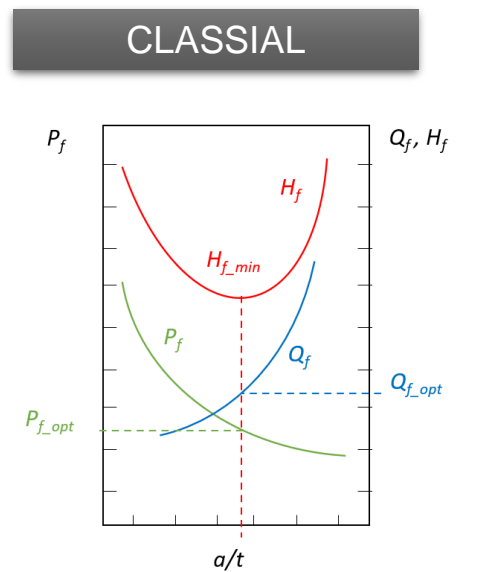
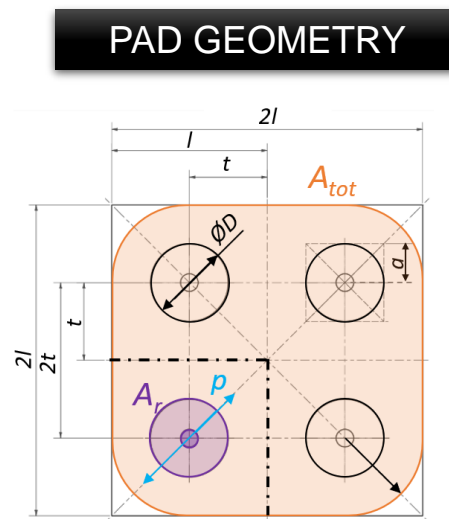
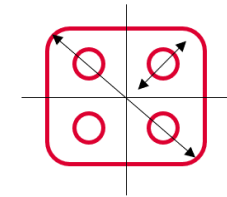


SCIENTIFIC QUESTIONS

1. What is the influence of hydrostatic bearing recess position and size on the bearing performance?

HYPOTHESIS 1 (SQ 1):

Recess size and layout optimization are usually done according to one parameter classical approach, in which the geometric parameters are linked together. Separating the two parameters, size and layout, can lead to improved pad performance and lower energetic losses.



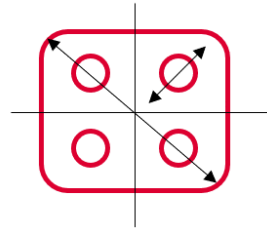
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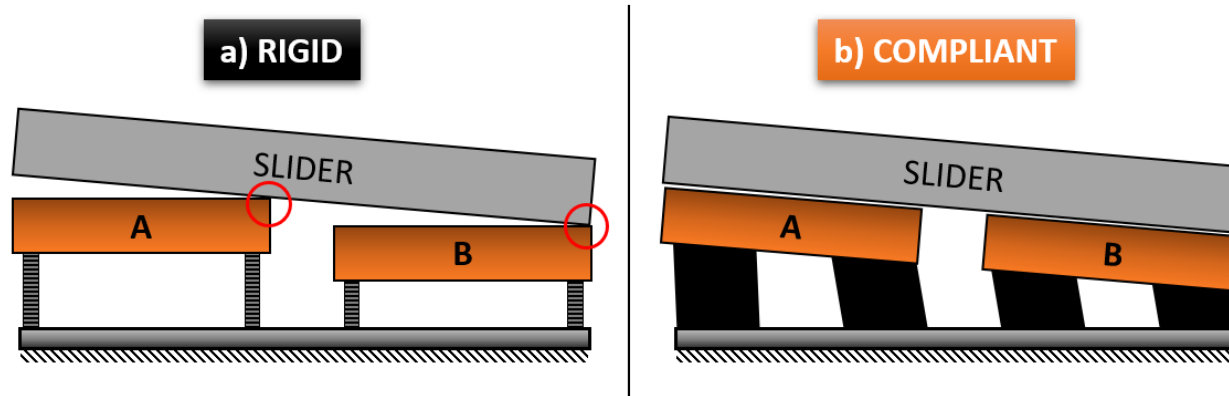
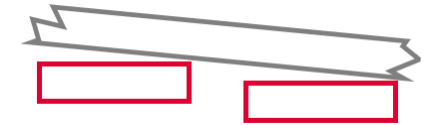


SCIENTIFIC QUESTIONS

2. How is the hydrostatic lubricating film affected by assembly errors of the bearing bodies?

HYPOTHESIS 2 (SQ 2):

Pad misalignment can significantly affect the generation and uniformity of the HS lubricating film. The lubricating film is able to compensate certain magnitude of pad misalignment. The bearing performance during eccentric loading can be improved using a compliant member. But the compliant support is also able to compensate larger misalignment compared to rigid support.



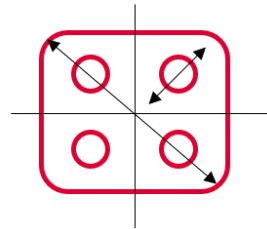
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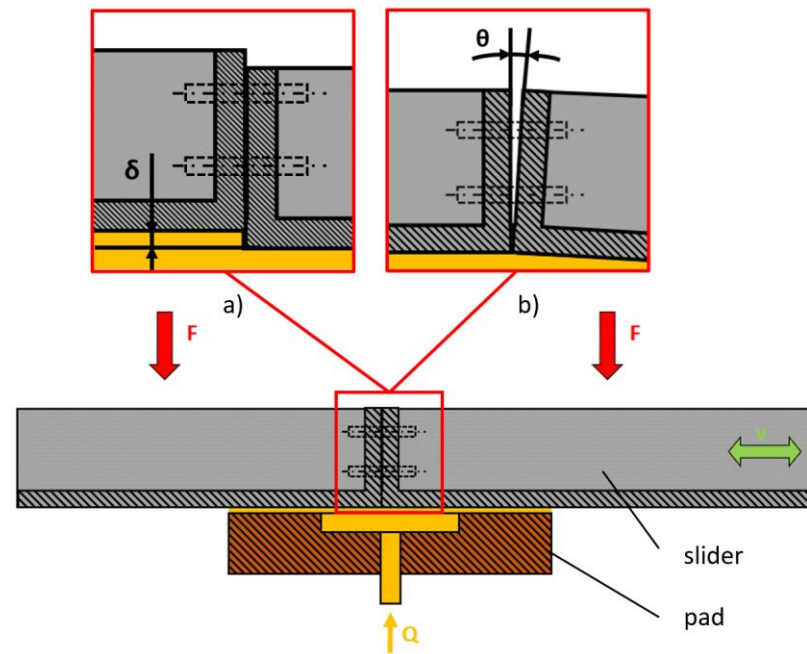
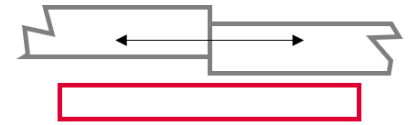


SCIENTIFIC QUESTIONS

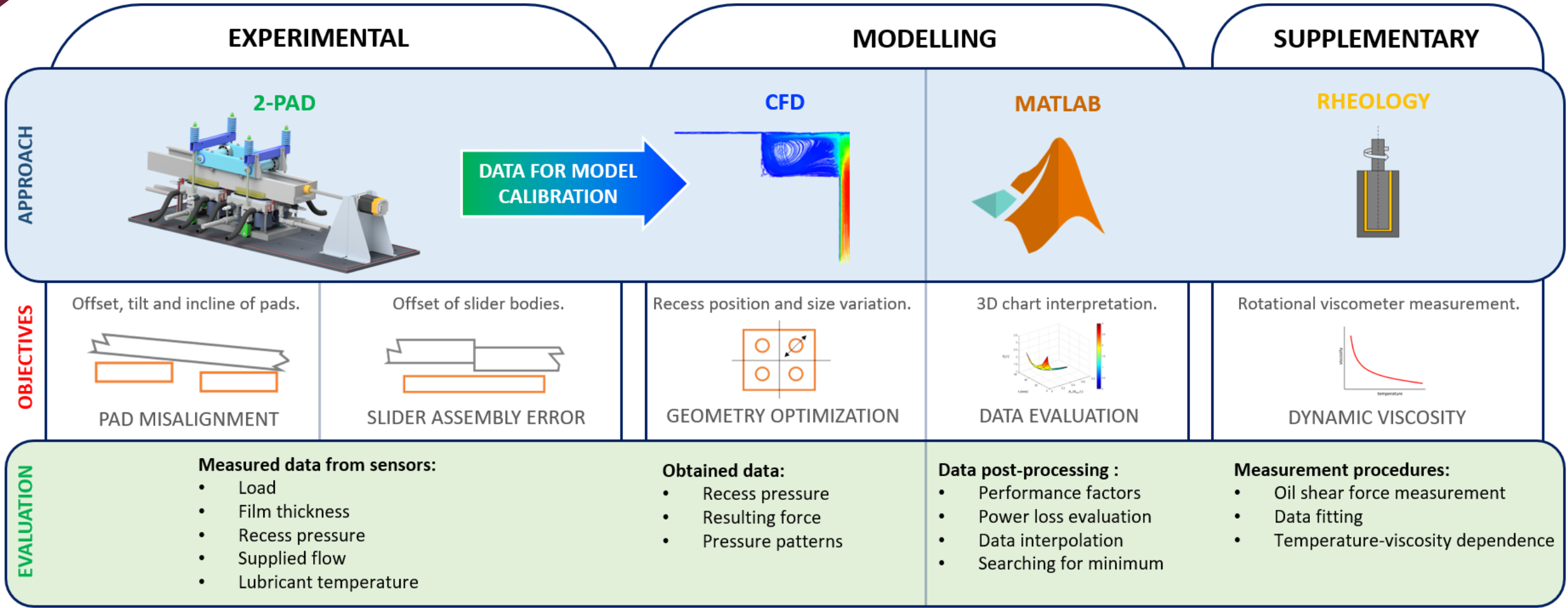
2. How is the hydrostatic lubricating film affected by assembly errors of the bearing bodies?

HYPOTHESIS 3 (SQ 2):

Assembly errors of segmented sliders were not studied, even though HS bearings have a great potential in large-scale applications. Assembly errors of a segmented slider can lead to HS lubricating film non-uniformity and disruption. The maximal allowed error of the segmented sliders must be smaller than the film thickness to secure safe operation of the bearing.



MATERIALS & METHODS

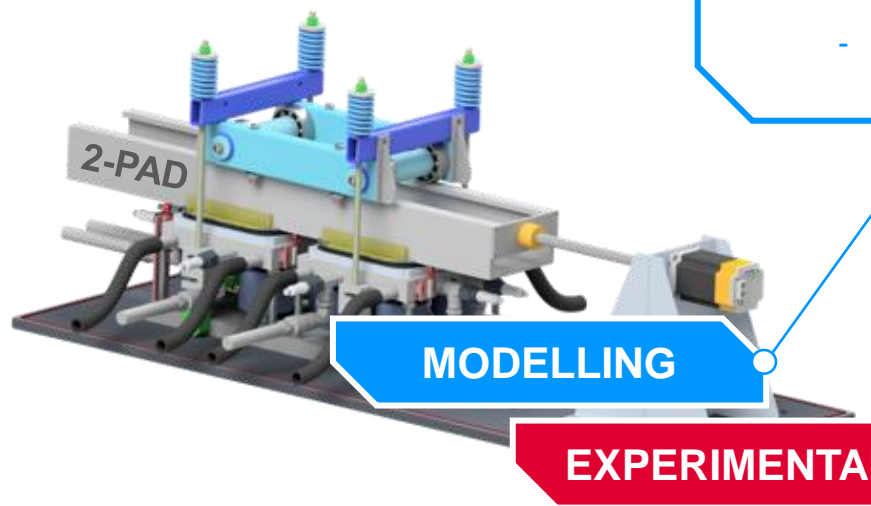
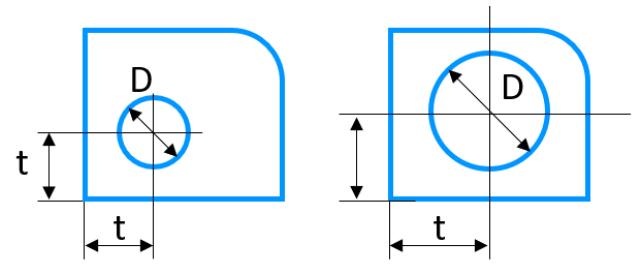


SOLUTION METHODOLOGY

BEARING EFFICIENCY

PAD GEOMETRY OPTIMIZATION

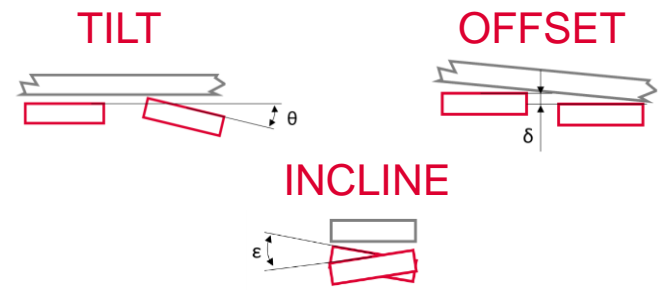
- STATIC



CFD MODEL VALIDATION

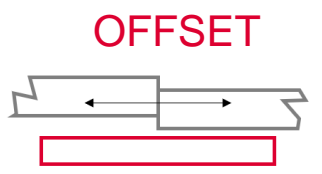
PAD MISALIGNMENT

- STATIC



BEARING SAFETY

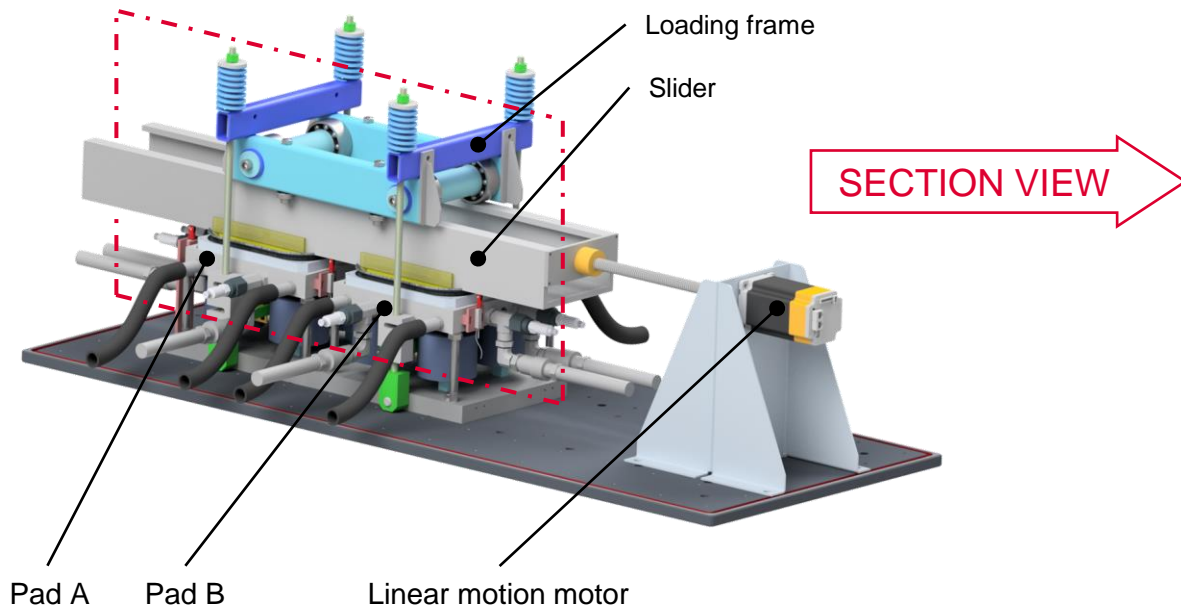
SLIDER ASSEMBLY ERROR



- STATIC
- LOW-SPEED
(38 mm/s)

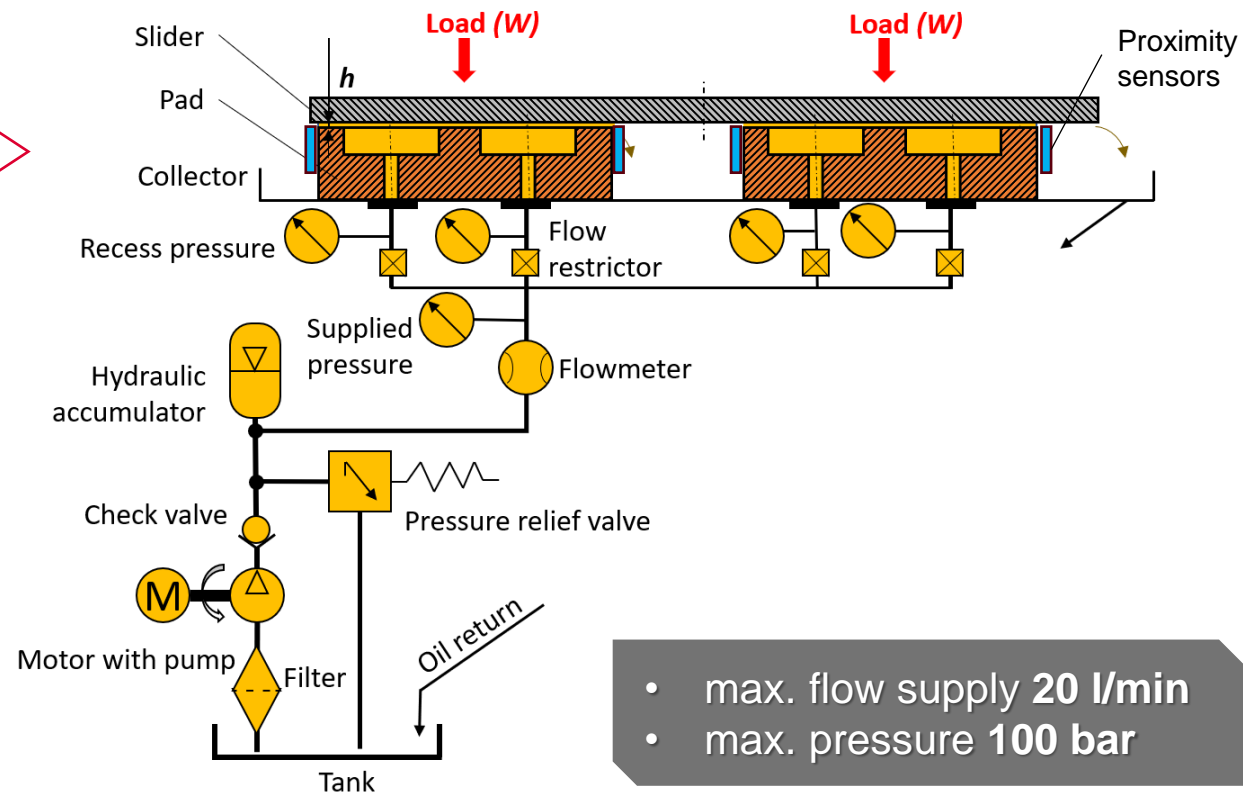
EXPERIMENTAL DEVICE – 2PAD

THE BEARING



- in-gap oil temperature measurement
- four-recess configuration
- max. load 40 kN
- distance sensors 0 – 3 mm (0.005 mm res.)

HYDRAULIC CIRCUIT



- max. flow supply 20 l/min
- max. pressure 100 bar

- max. flow supply 20 l/min
- max. pressure 100 bar

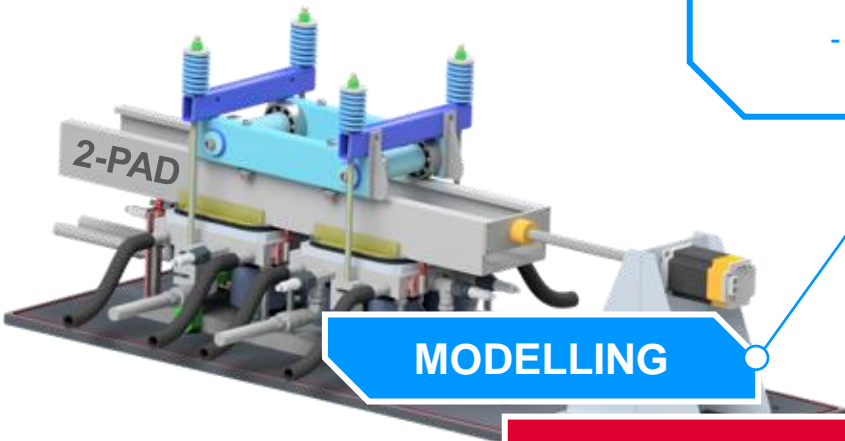
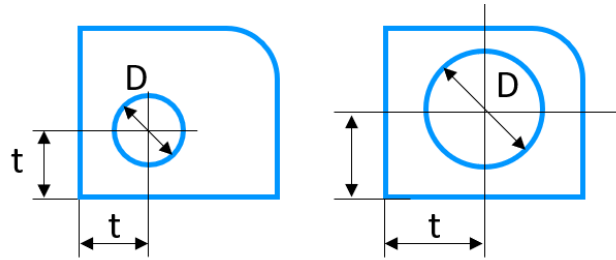
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SOLUTION METHODOLOGY

BEARING EFFICIENCY

PAD GEOMETRY OPTIMIZATION

- STATIC



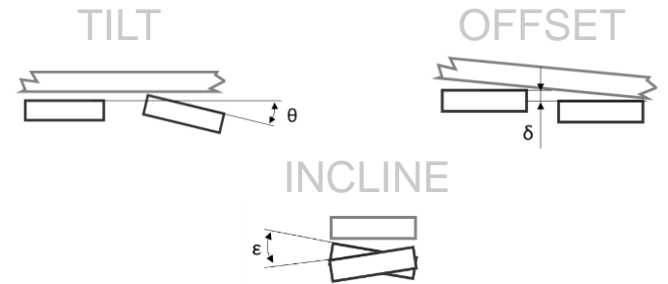
MODELLING

EXPERIMENTAL

CFD MODEL VALIDATION

PAD MISALIGNMENT

- STATIC

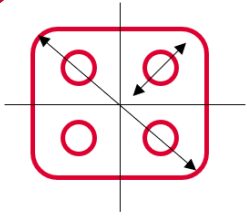


BEARING SAFETY

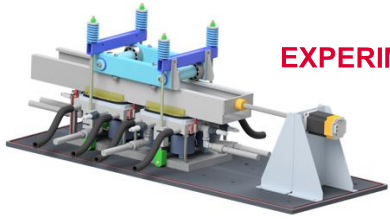
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- STATIC
- LOW-SPEED
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PAD GEOMETRY OPTIMIZATION

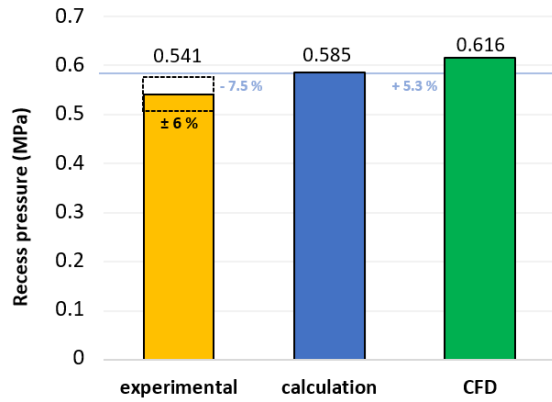
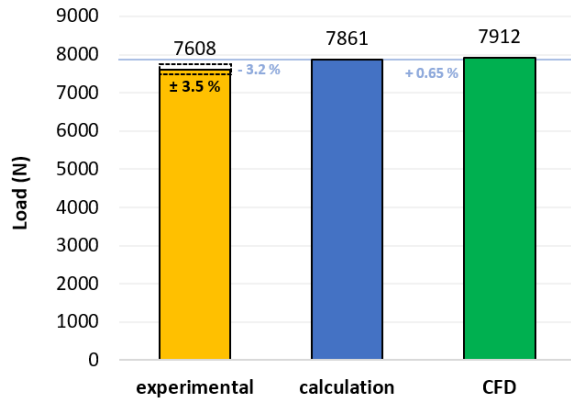


EXPERIMENTAL DATA

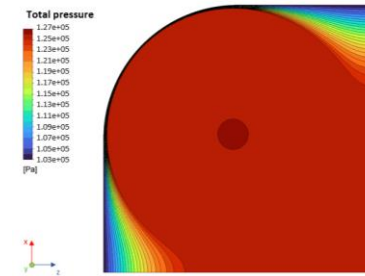
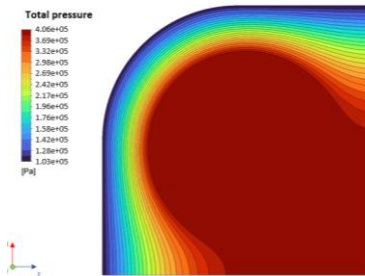
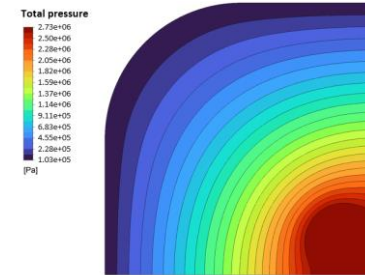
PARAMETRIZATION



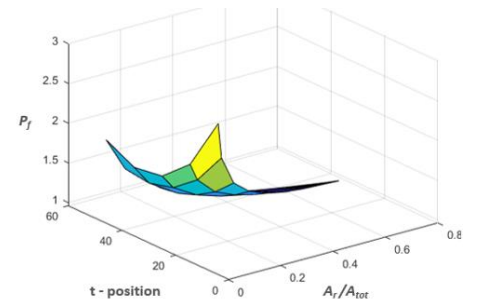
- Static conditions
- Total load: 16 kN
- Film thickness: 0.197 mm
- Total supplied flow: 8.5 l/min



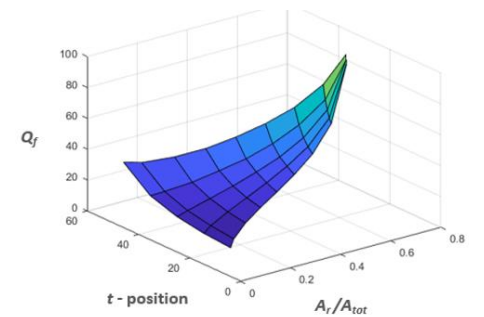
Comparison of results for initial pad geometry.



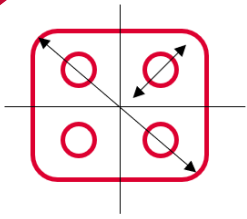
PRESSURE FACTOR



FLOW FACTOR



Pad geometry variations of recess size and position.



PAD GEOMETRY OPTIMIZATION

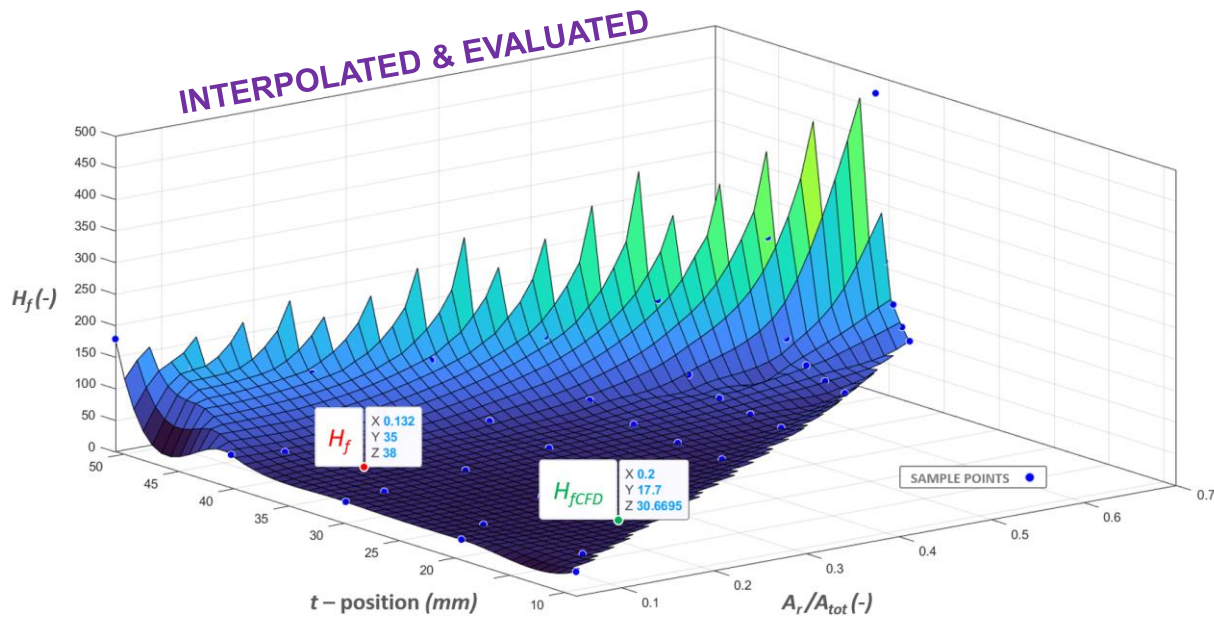
SIMULATION RESULTS



PERFORMANCE FACTORS

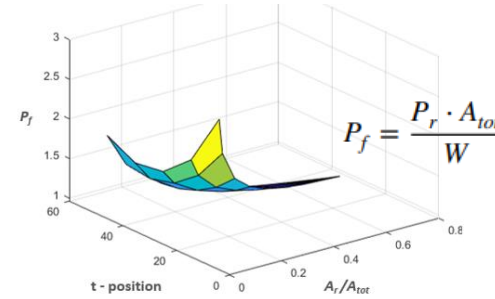


CALCULATION & INTERPOLATION

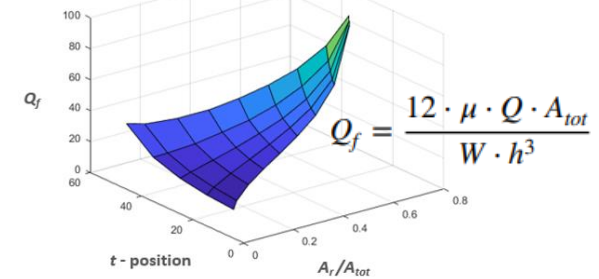


Interpolated power loss factor data with optimal recess size and position using novel and classical approaches.

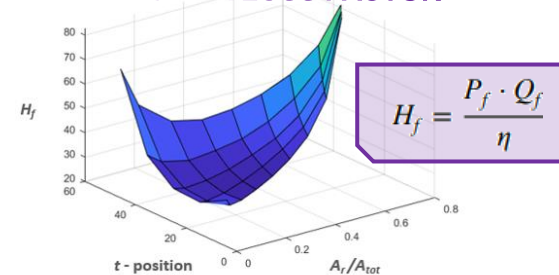
PRESSURE FACTOR

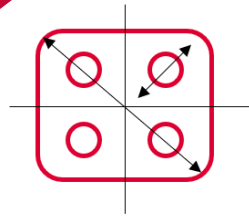


FLOW FACTOR



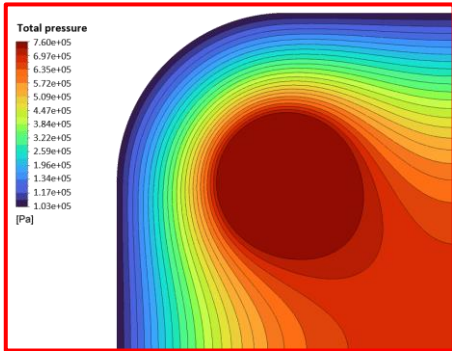
POWER LOSS FACTOR



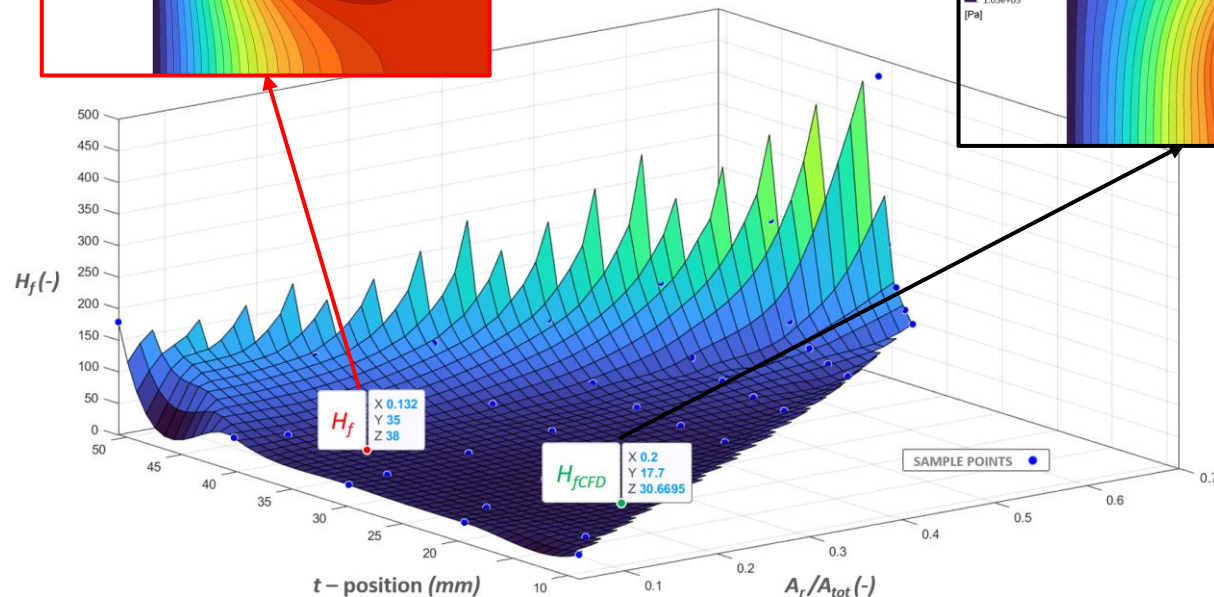
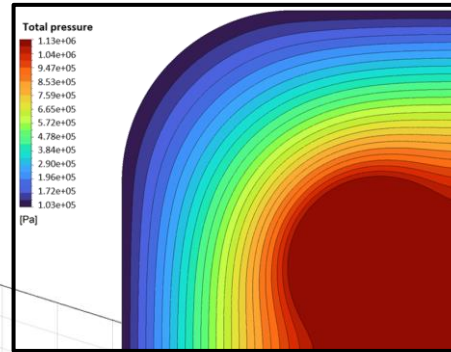


PAD GEOMETRY OPTIMIZATION

CLASSICAL



NEW APPROACH



PROS:

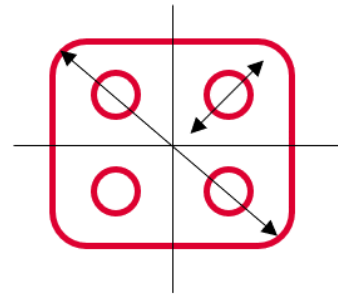
- + 20 % lower power loss
- + Uniform pressure distribution
- + Usable for any shape
- + Suitable for any software

CONS:

- Higher misalignment sensitivity
- Requires decent hardware

Interpolated power loss factor data with optimal recess size and position using novel and classical approaches.

SQ1 – HYPOTHESES 1



Q1: „What is the influence of hydrostatic bearing recess position and size on the bearing performance?“

H1 (Q1): „Recess size and layout optimization are usually done according to one parameter classical approach, in which the geometric parameters are linked together. Separating the two parameters, size and layout, can lead to improved pad performance and lower energetic losses.“

VERIFIED

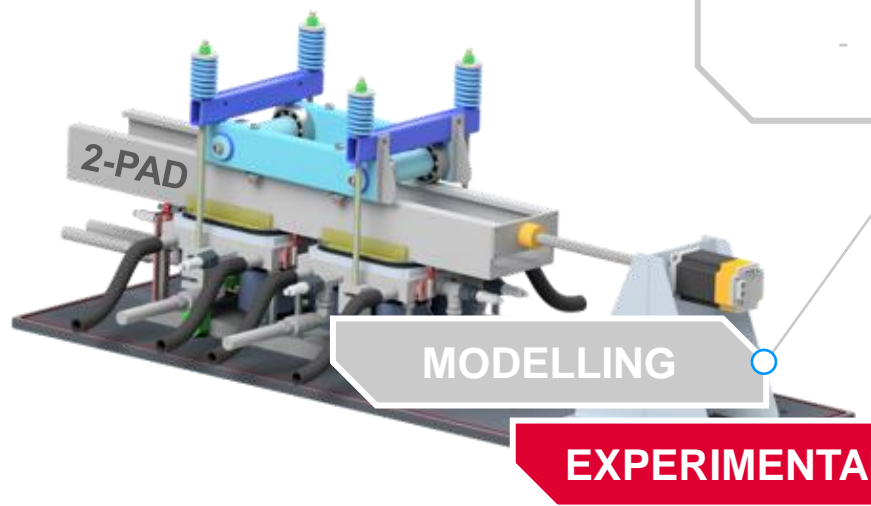
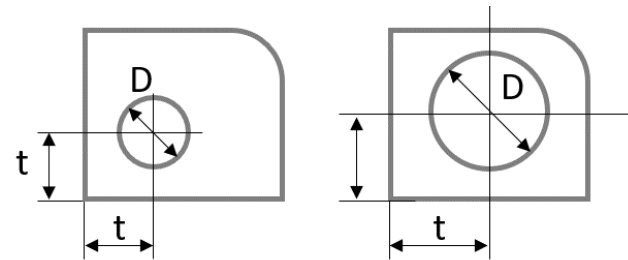
„HSB pad geometry is one of the key parameters influencing its performance. The proposed two parameter method shows that by adjusting recess size and position separately can reduce energy losses up to 20 %, compared to the classical approach.“

SOLUTION METHODOLOGY

BEARING EFFICIENCY

PAD GEOMETRY OPTIMIZATION

- STATIC



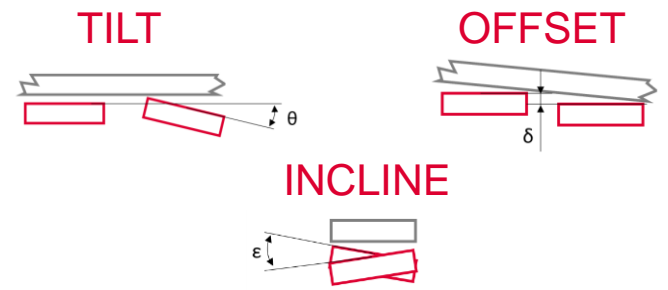
MODELLING

EXPERIMENTAL

CFD MODEL VALIDATION

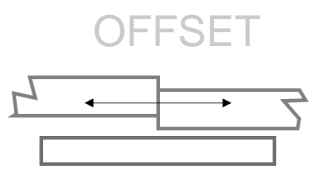
PAD MISALIGNMENT

- STATIC



BEARING SAFETY

SLIDER ASSEMBLY ERROR



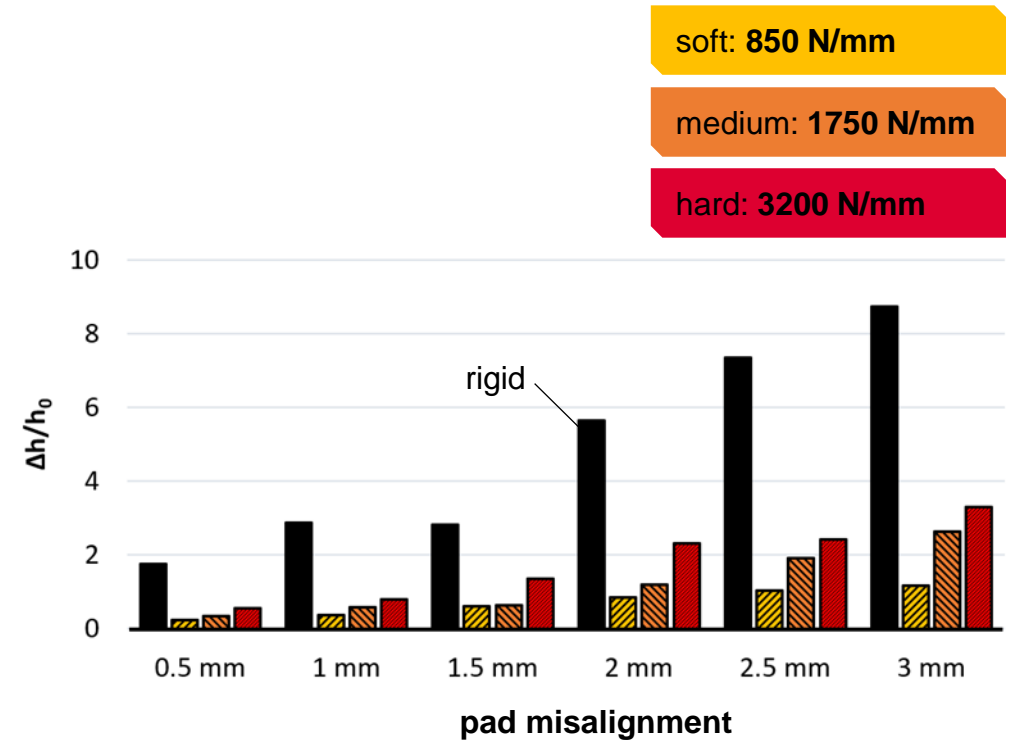
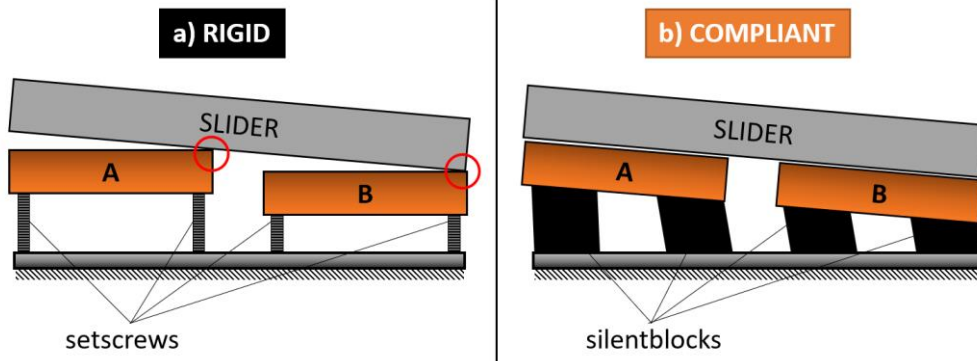
- STATIC
- LOW-SPEED
(38 mm/s)

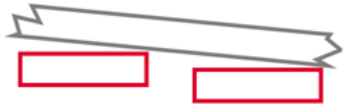


PAD MISALIGNMENT – SUPPORT STIFFNESS

COMPLIANT SUPPORT STIFFNESS

- Slider adjustment to the misalignment
- Relative change in film thickness
- Film stiffness: **17 kN/mm**

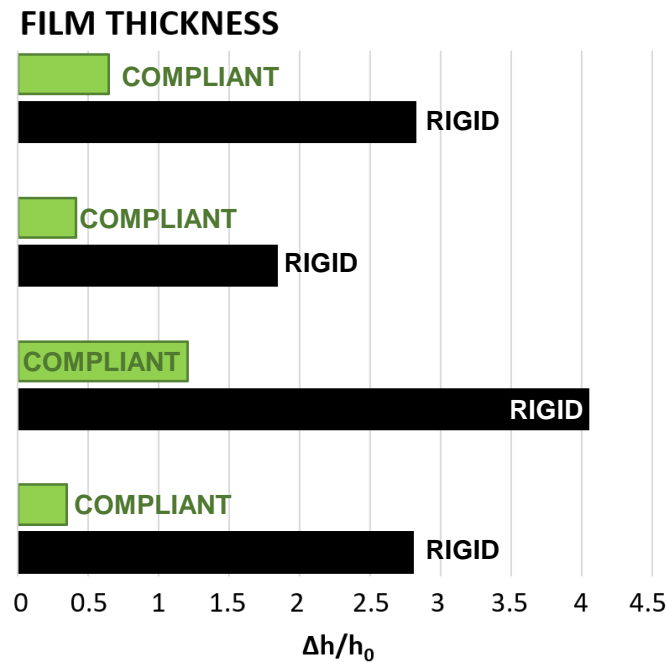
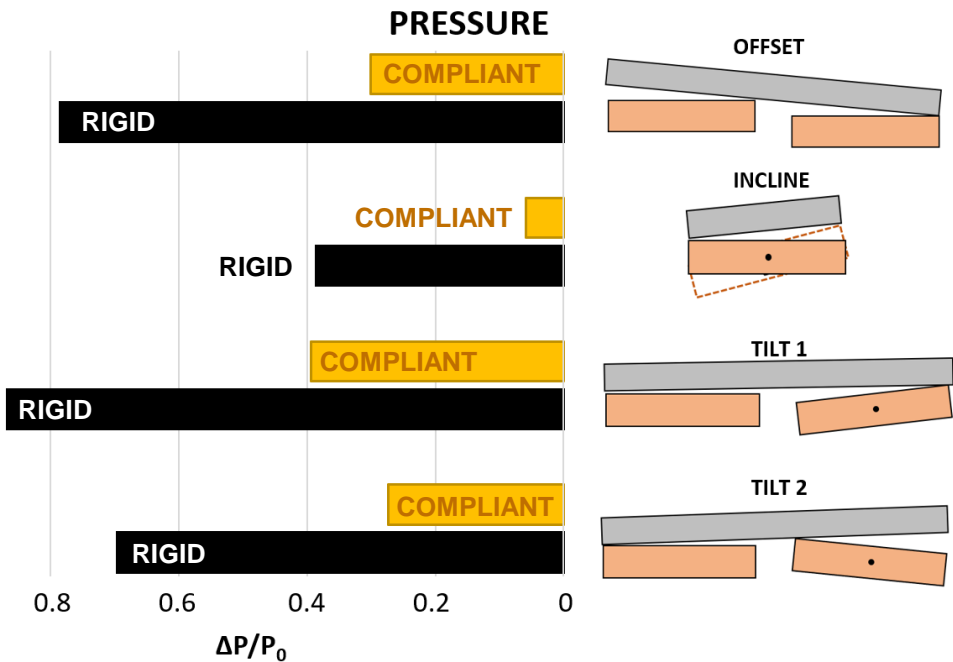
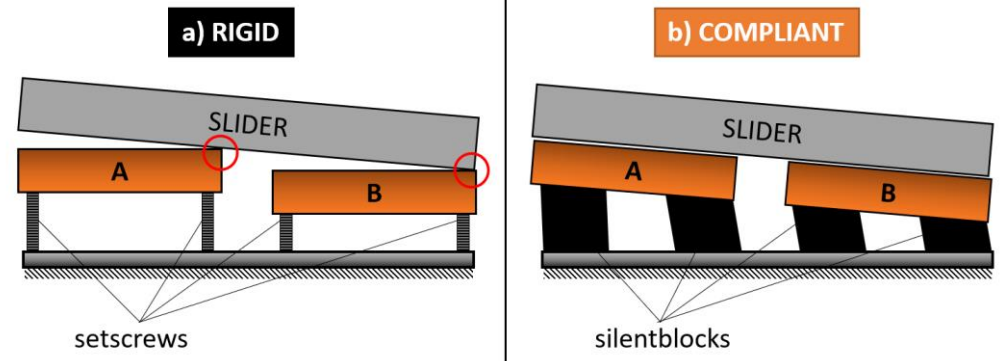




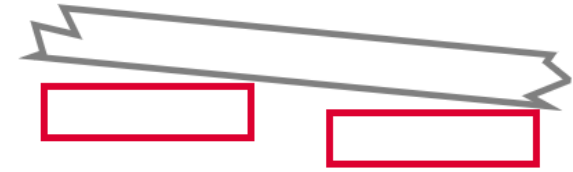
PAD MISALIGNMENT - ASSESSMENT

COMPLIANT SUPPORT

- Self-aligning
- 4-6x better performance
- Not suitable for high-precision apps



SQ2 – HYPOTHESIS 2



Q2: „How is the hydrostatic lubricating film affected by assembly errors of the bearing bodies?“

H2 (Q2): Pad misalignment can significantly affect the generation and uniformity of the HS lubricating film. The lubricating film is able to compensate certain magnitude of pad misalignment. The bearing performance during eccentric loading can be improved using a compliant member. But the compliant support is also able to compensate larger misalignment compared to rigid support.

VERIFIED

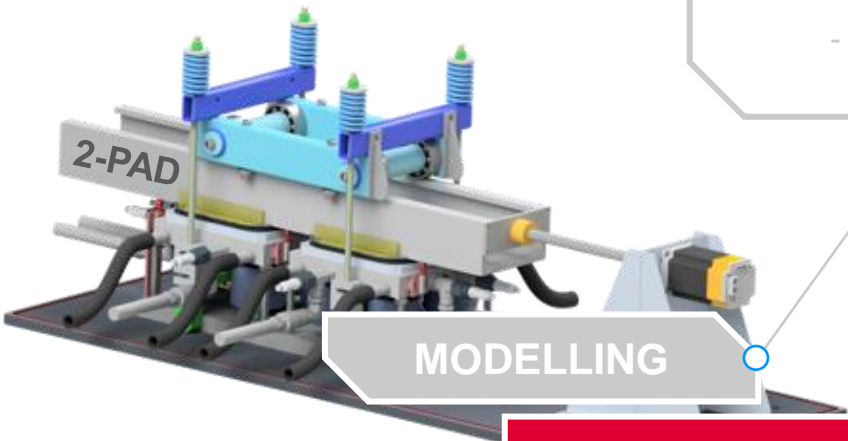
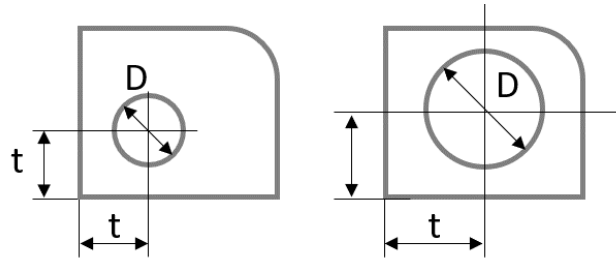
„Compared to a rigid support, compliant pad support for multi-pad HSB allows 4 to 6 times larger misalignment depending on the misalignment type.“

SOLUTION METHODOLOGY

BEARING EFFICIENCY

PAD GEOMETRY OPTIMIZATION

- STATIC



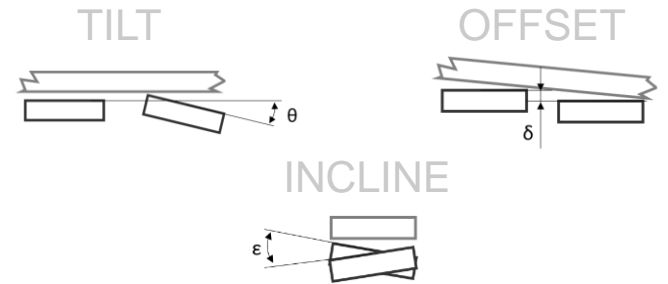
MODELLING

EXPERIMENTAL

CFD MODEL VALIDATION

PAD MISALIGNMENT

- STATIC



BEARING SAFETY

SLIDER ASSEMBLY ERROR

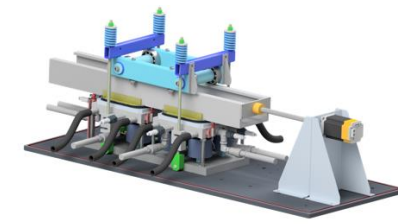
OFFSET



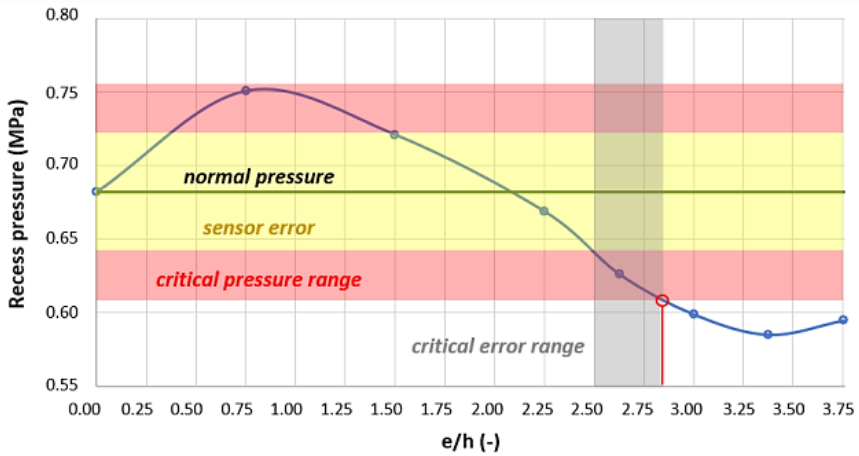
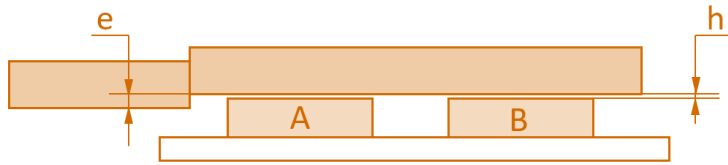
- STATIC
- LOW-SPEED (38 mm/s)



SLIDER MISALIGNMENT - STATIC

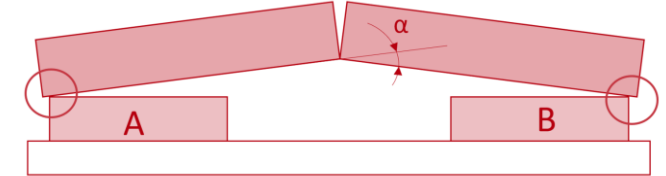
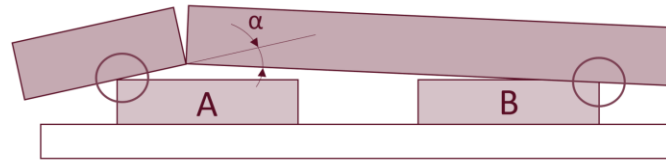


OFFSET

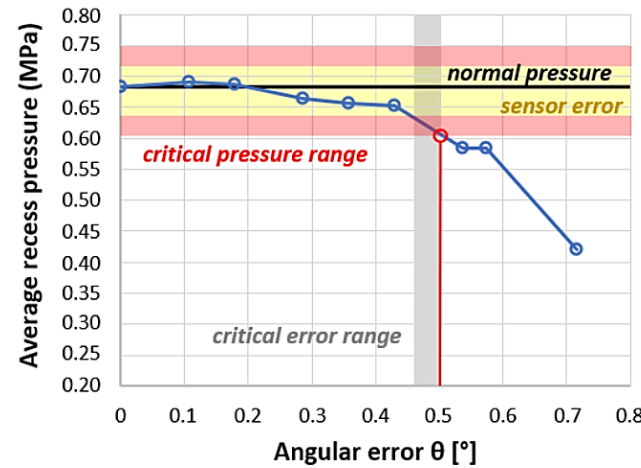


- Critical $e/h = 2.75$
- Dependent on connection position

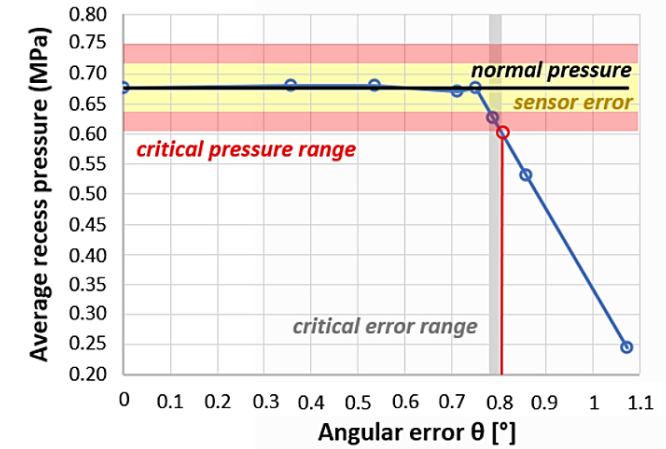
TILT



A) mid-pad



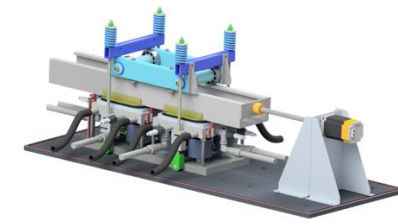
B) mid-bearing



- Limit error 0.46°
- Dependent on pad distance



SLIDER MISALIGNMENT - DYNAMIC

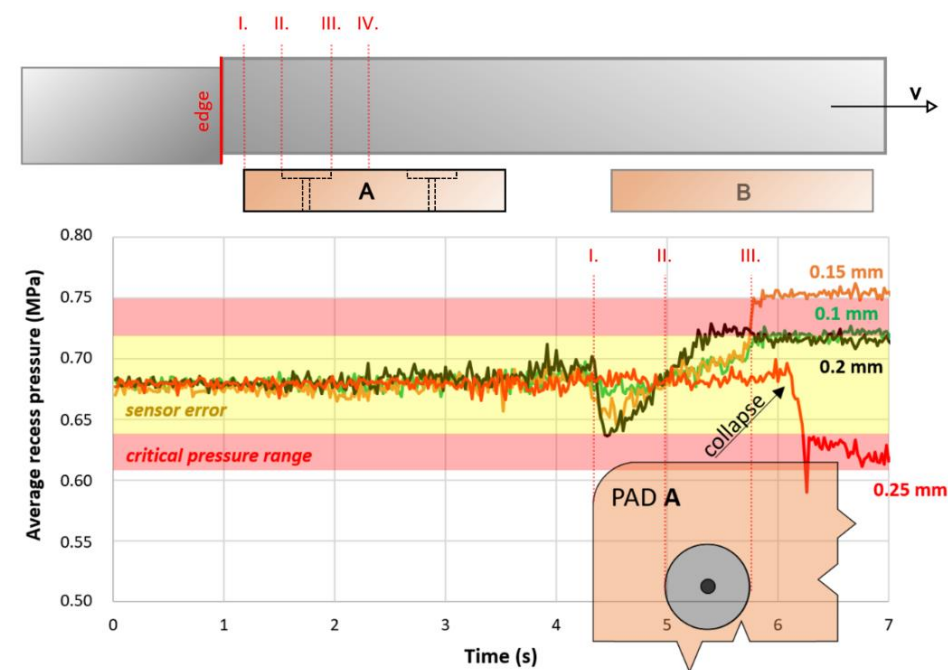
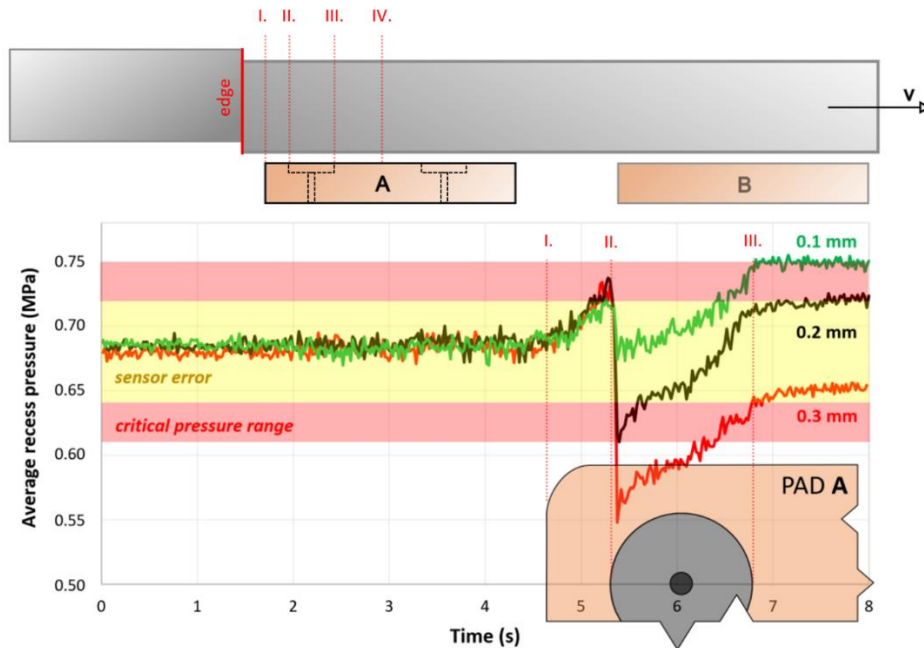


STEP-UP

- Critical $e/h = 1.5$
- Gradual loss of load-carrying ability

STEP-DOWN

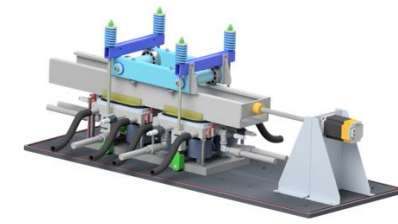
- Critical $e/h = 1$
- High risk of collision



$h = 0,14 \text{ mm}$



SLIDER MISALIGNMENT - DYNAMIC

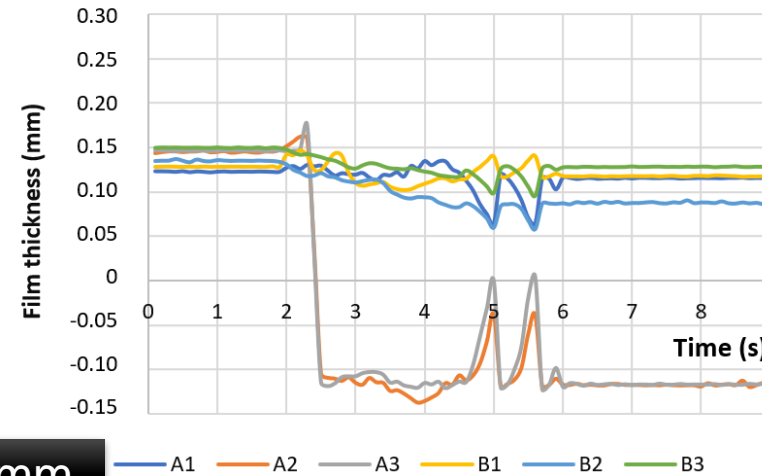
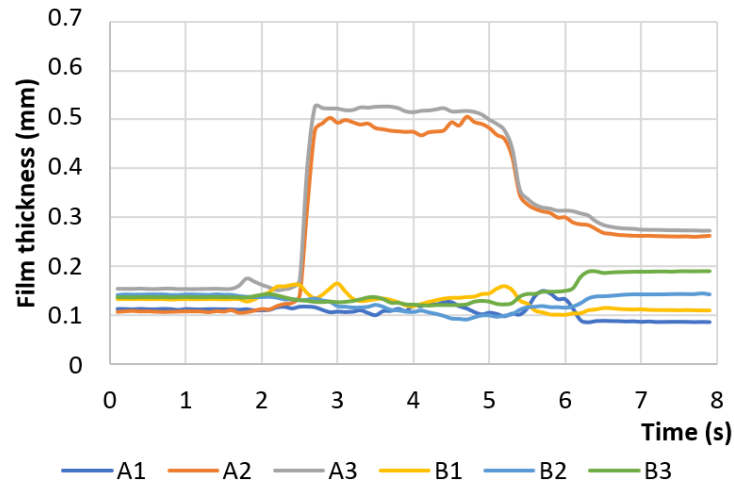
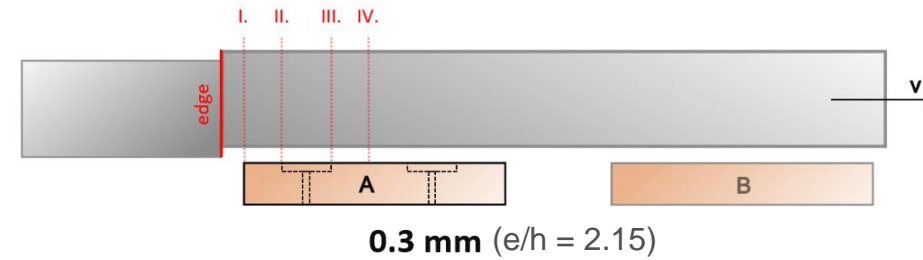
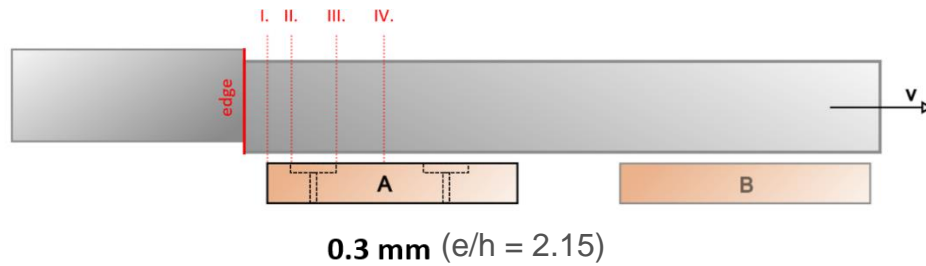


STEP-UP

- Critical $e/h = 1.5$
- Gradual loss of load-carrying ability

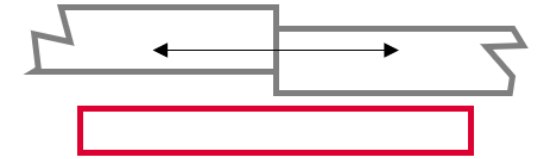
STEP-DOWN

- Critical $e/h = 1$
- High risk of collision



$h = 0,14 \text{ mm}$

SQ2 – HYPOTHESIS 3



Q2: „How is the hydrostatic lubricating film affected by assembly errors of the bearing bodies?“

H3 (Q2): Assembly errors were not studied, even though HS bearings have a great potential in large-scale applications. Assembly errors of a segmented slider can lead to HS lubricating film non-uniformity and disruption. The maximal allowed error of the segmented sliders must be smaller than the film thickness to secure safe operation of the bearing.

VERIFIED

The maximal allowed error of slider segmented bodies to avoid collision must be smaller than the film thickness.

THESIS LAYOUT

Literature review

2021

A Review of the Design and Optimization of Large-scale Hydrostatic Bearing Systems



IF: 5.7 (Q1)
AIS: 0.789 (Q2)

STATE-OF-THE-ART

New experimental device & compliant support experiments

2022

The prediction of large-scale hydrostatic bearing pad misalignment error and its compensation using compliant support



IF: 3.6 (Q2)
AIS: 0.665 (Q2)

CFD pad geometry optimization

2023

A novel geometry optimization approach for multi-recess hydrostatic bearing pad operating in static and low-speed conditions using CFD simulation



IF: 3.2 (Q1)
AIS: 1.02 (Q2)

BEARING EFFICIENCY

BEARING SAFETY

Segmented slider assembly errors

2023

Assembly error tolerance estimation for large-scale hydrostatic bearing segmented sliders under static and low-speed conditions



IF: 2.60 (Q2)
AIS: 0.64 (Q3)

LIST OF PUBLICATIONS

Related to the thesis topic:



MICHALEC, M., P. SVOBODA, I. KŘUPKA, M. HARTL. A Review of the Design and Optimization of Large-scale Hydrostatic Bearing Systems. *Engineering Science and Technology, an International Journal*, 2021, vol. 24, issue 4, s. 936-958. ISSN: 2215-0986. [IF = 5.155] (Author's contribution 70 %)



MICHALEC, M., V. POLNICKÝ, J. FOLTÝN, P. SVOBODA, P. ŠPERKA, J. HURNÍK. The prediction of large-scale hydrostatic bearing pad misalignment error and its compensation using compliant support. *Precision engineering*. Elsevier, 2022, vol. 75, 67-79. doi:10.1016/j.precisioneng.2022.01.011. [IF = 3.315] (Author's contribution 40 %)



MICHALEC, M., J. HURNÍK, J. FOLTÝN, P. SVOBODA. Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 2022, vol. 237, issue 1, 1-9. doi.org/10.1177/13506501221108138. [IF = 1.674] (Author's contribution 40 %)



MICHALEC, M., T. DRYML, D. JAVORSKÝ, L. SNOPEK, M. ČUPR, J. FOLTÝN, P. SVOBODA. Assembly error tolerance estimation for large-scale hydrostatic bearing segmented sliders under static and low-speed conditions. *Machines*. MDPI, 2023, vol. 75, 67-79. doi:10.1016/j.precisioneng.2022.01.011 [IF = 2.6] (Author's contribution 60 %)



MICHALEC, M., M. ONDRA, M. SVOBODA, J. CHMELÍK, P. ZEMAN, P. SVOBODA, R. L. JACKSON. A novel geometry optimization approach for multi-recess hydrostatic bearing pad operating in static and low-speed conditions using CFD simulation. *Tribology Letters*. Elsevier, 2023, vol. 71, issue 52, 14pp. doi.org/10.1007/s11249-023-01726-3 [IF = 3.327] (Author's contribution 65 %)

Other publications:



MICHALEC, M., P. SVOBODA, I. KŘUPKA, M. HARTL. Tribological behaviour of smart fluids influenced by magnetic and electric field – A review. *Tribology in Industry*, 2018, vol. 40, issue 4, pp. 515-528. ISSN: 0354-8996. [Citescore = 2.4] (Author's contribution 65 %)



MICHALEC, M., P. SVOBODA, I. KRUPKA, M. HARTL a A. VENCL. Investigation of the tribological performance of ionic liquids in non-conformal EHL contacts under electric field activation. *Friction*, 2020, 8(5), 982-994. ISSN 2223-7690. Available from: doi:10.1007/s40544-019-0342-y [IF = 5.662] (Author's contribution 65 %)



VENCL, A., M. KANDEVA, E. ZADOROZHAYA, P. SVOBODA, M. MICHALEC, A. MILIVOJEVIĆ a U. TRDAN. Studies on structural, mechanical and erosive wear properties of ZA-27 alloy-based micro-nanocomposites. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 2021. https://doi.org/10.1177/1464420721994870. [IF = 2.311] (Author's contribution 5 %)



ČERNÁK, M., M. MICHALEC, M. VALENA, M. RANUŠA. Inlet shape optimization of pneumobil engine pneumatic cylinder using CFD analysis. *Journal of Physics: Conference Series* 1935. *Journal of Physics: Conference Series*, 2021. ISBN: 1742-6588. [Citescore = 0.7] (Author's contribution 30 %)

OTHER RESULTS



UTILITY MODEL

SVOBODA, P.; V. POLNICKÝ, M. MICHALEC, D. ROBENEK. Brno University of Technology, Antonínská 548/1, 60200 Brno, Veveří, Czech Republic, IČ: 216305 (40 %) Bosch Rexroth, spol. s r.o., Těžební 1238/2, 62700 Brno, Černovice, Czech Republic (60 %): Device for testing the operating conditions of segmental axial hydrostatic bearings. 35880, utility model (2022).




FUNCTIONAL SAMPLE


POLNICKÝ, V.; M. MICHALEC, P. SVOBODA, D. ROBENEK: Experimental stand for testing hydrostatic bearing of large structures in the area of special equipment. Laboratory A3/109 Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2 616 69 Brno, functional sample (2020).

CONFERENCE POSTER


- WTC 2022, Lyon, FR



WTC 2022
WORLD TECHNOLOGICAL CONGRESS



BRNO FACULTY
UNIVERSITY OF MECHANICAL
OF TECHNOLOGY ENGINEERING



INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN

Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method

Michal Michalec* (Michal.Michalec@vut.cz), Jakub Humík, Jan Foltýn, Petr Svoboda

1 Motivation

- Investigation of the applicability of optical methods for hydrostatic (HS) bearing lubricating film thickness measurement.

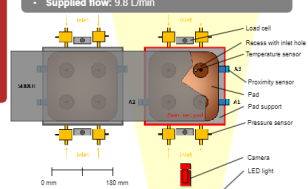
2 Background

- Previous research indicated challenges connected with large-scale HS bearings levelling and big data evaluation from a huge number of sensors.
- A versatile method with sufficient precision could help simplifying the assembly process, or investigate the bearing performance during operation of the bearing.
- Optical methods based on point tracking measurement have already been presented. However, none of them have aimed at HS bearing film thickness measurement.
- The present study aims at the use of optical point tracking method to evaluate hydrostatic bearing lubricating layer thickness.

3 Methods

2-PAD (Dual pad HS bearing experimental rig):

- Load: 16 kN
- Supplied flow: 9.8 L/min



Film thickness prediction formula:

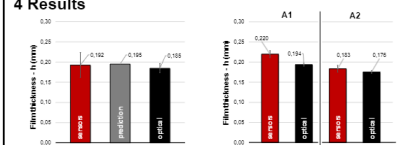
$$h = \sqrt{\frac{12 \cdot Q \cdot \mu \cdot A}{F - q_f}}$$

OPT (Optical point tracking method):

Camera:

- Monochromatic ZWO ASI 1600 MM
- 16 Mpx CMOS
- 35 mm Zeiss Interlock Compact lens

4 Results




Reference image and current image showing movement compensation and overlapping images.

5 Conclusions

- Achieved **good agreement** of predicted and measured film thickness by sensors and OPT.
- The OPT method provides data with **smaller deviation** compared to sensors.
- Potential precision of OPT **up to 0.001 mm**.
- Suitable also for deformation investigation **after method customization**.
- Field measurements** might prove the versatility of the proposed OPT method.

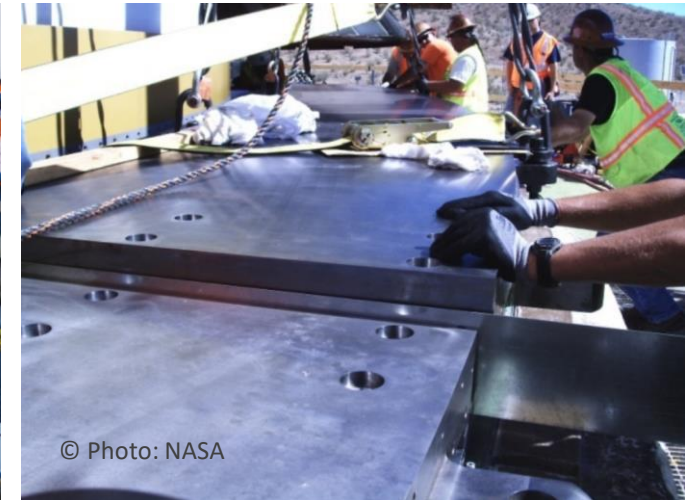
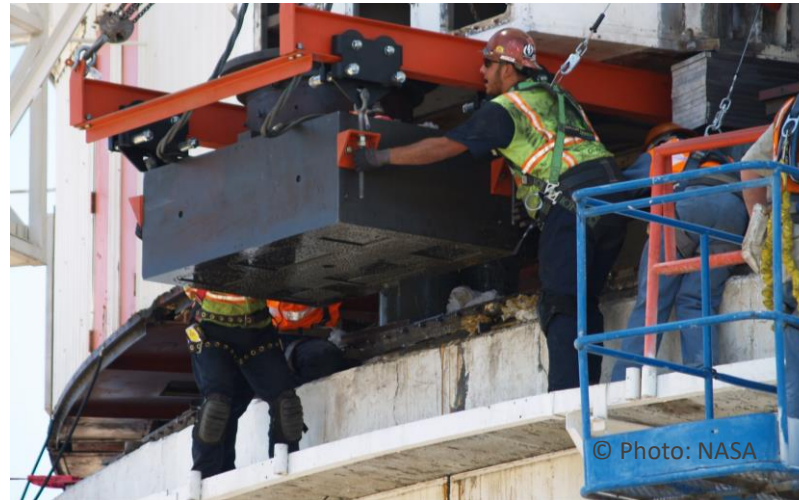
T A This research was carried out under the project FW03010357 with financial support from the state budget by the Technology Agency of the Czech Republic (www.tacr.cz) and the Ministry of Industry and Trade within the TREND Programme. The research was co-funded by Faculty of Mechanical Engineering, Brno University of Technology internal specific project F01-S-20-ICW.

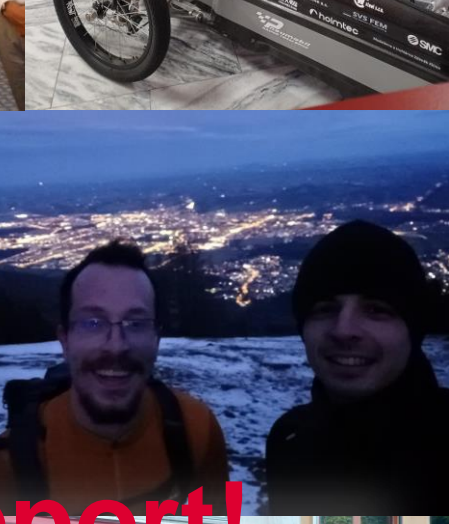
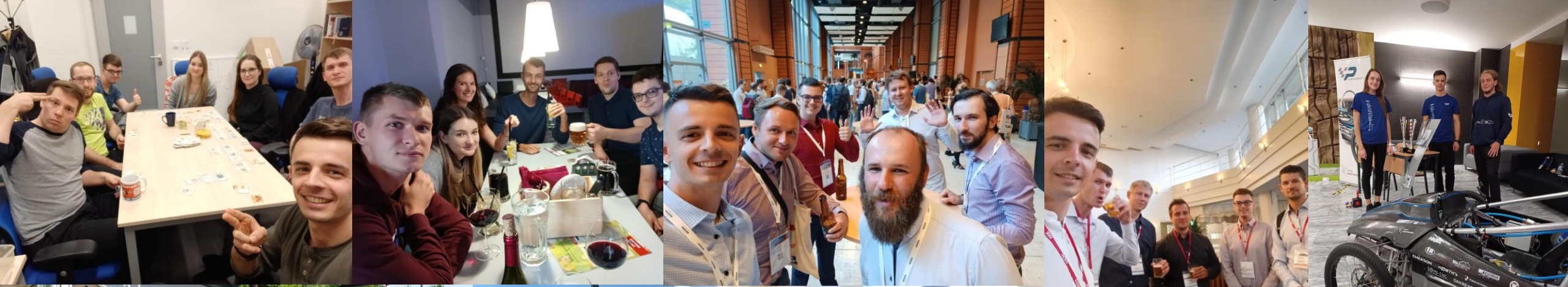


PRACTICAL APPLICATIONS OF RESULTS

Potential improvements of large-scale HSL bearings based on obtained results:

- Reduced power consumption by **20 %** → **20 000 €** (at est. ELT operation 100 000 € / year)
- Simplified design and assembly process – **limits of pad & segmented slider assembly errors**
- **Improved safety** (HS bearing repair cost 1.15 million €, made by NASA in 2010)





Thank you for your company, help & support!

