

OPERATIONAL SAFETY AND RELIABILITY ENHANCEMENT OF LARGE-SCALE HYDROSTATIC BEARINGS

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Brno University of Technology

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**INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN**



CONTENT

Motivation

Introduction

State of the art

Aim

Scientific questions and hypotheses

Material and methods

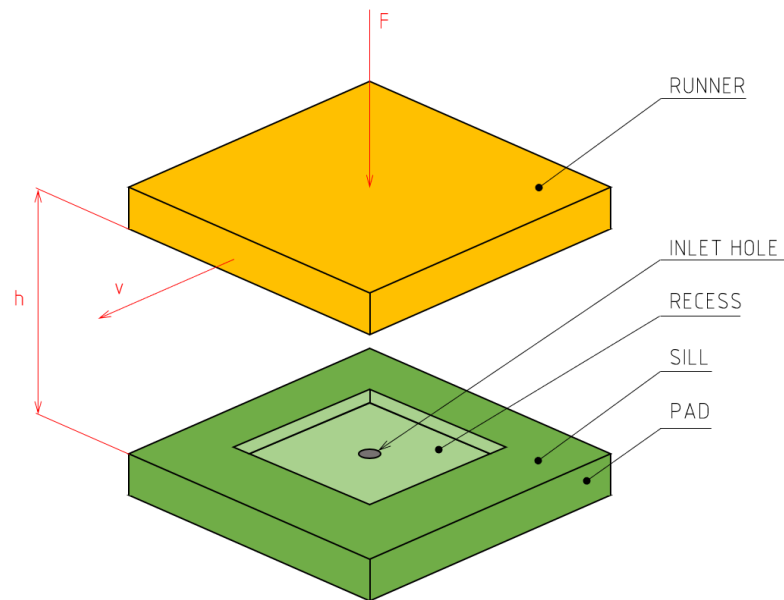
Results

Conclusion

INTRODUCTION

HYDROSTATIC BEARINGS

- Sliding bearings
- Externally pressurized



$$h = \sqrt[3]{\frac{Q \cdot A \cdot \mu}{F \cdot q_f}}$$

ADVANTAGES

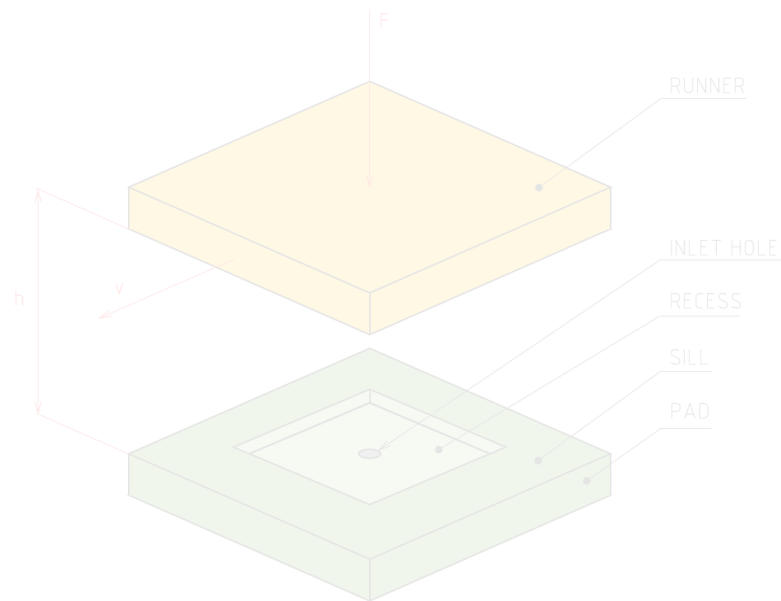
- Zero speed operation
- Large loads
- Low friction



INTRODUCTION

HYDROSTATIC BEARINGS

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- Externally pressurized



$$h = \sqrt[3]{\frac{Q \cdot A \cdot \mu}{F \cdot q_f}}$$

ADVANTAGES

- Zero speed operation
- Large loads
- Low friction



MOTIVATION

- Large-scale applications
- Precision of bearing
- High maintenance costs



Ø 34 m



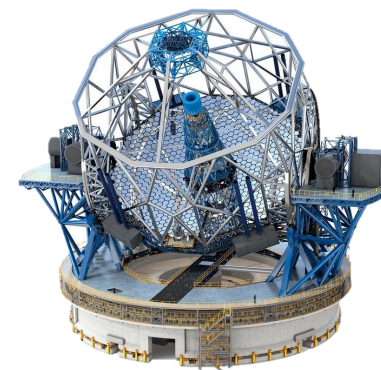
Antenna Goldstone, California
(www.jpl.nasa.gov)

1,5 year of preparations

7 months realization

10 tuns one HS pad

1,25 mil USD



Ø D

50 m



20 m



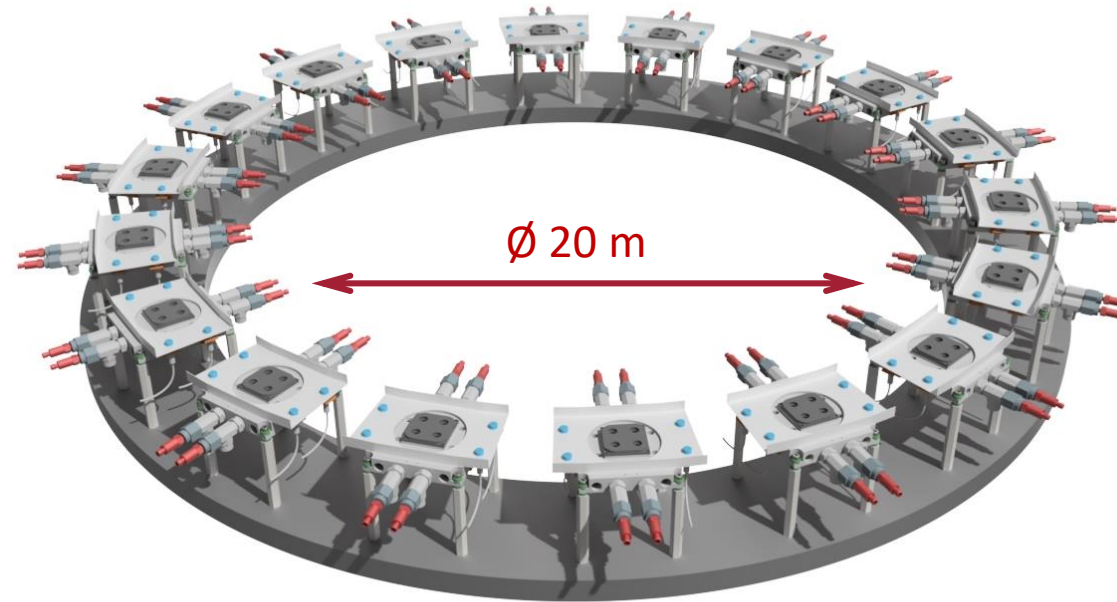
8 m



0,1 m

STATE OF THE ART

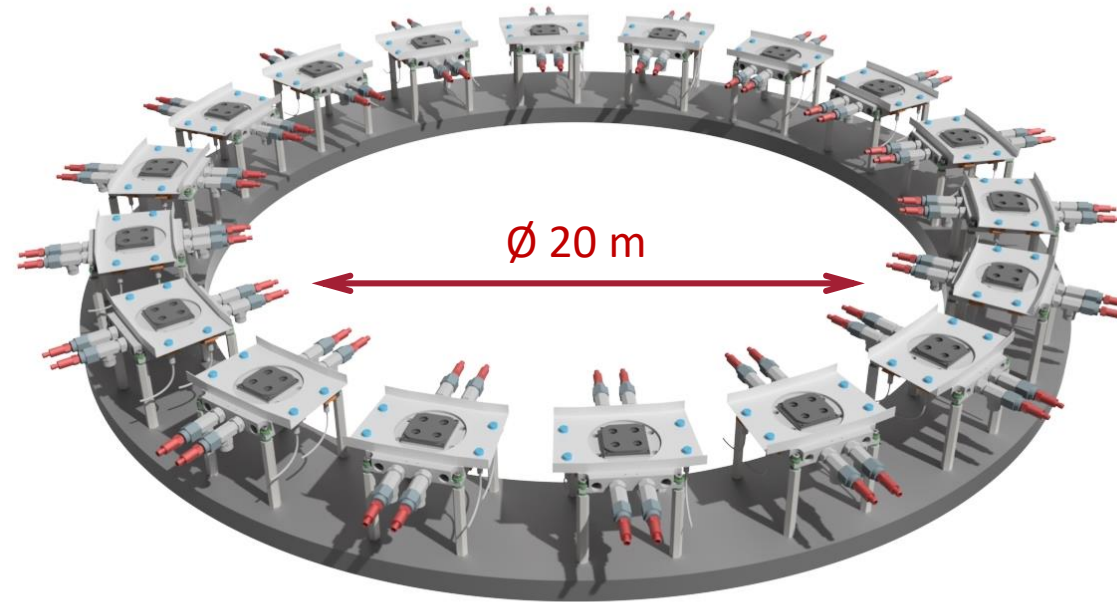
LARGE-
SCALE
BEARINGS



SAFETY

STATE OF THE ART

LARGE-
SCALE
BEARINGS



SAFETY

STATE OF THE ART

LARGE-SCALE BEARINGS

DEEP SPACE NETWORK (DSN)

- HS azimuth bearing 34 m diameter
- 3 rectangular pads with 6 recesses
- Supply pressure 28 MPa
- Expected thickness 127 – 254 μm



NASA, *DSN antennas*

VERY LARGE TELESCOPE (VLT)

- 2 azimuthal rings: 8 m and 20 m
- 16 square pads with 4 recesses
- Supply pressure 8.5 MPa
- Thickness measured 2x a year
- Expected thickness 40 – 60 μm



GIANT MAGELLAN TELESCOPE (GMT)

- HS azimuth bearing 21 m diameter
- Recess pressure 3.5 MPa
- Expected thickness 65 – 70 μm



Giantmagellan.org

STATE OF THE ART

LARGE-SCALE BEARINGS

DEEP SPACE NETWORK (DSN)

- HS azimuth bearing 64 m diameter
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NASA, DSN antennas

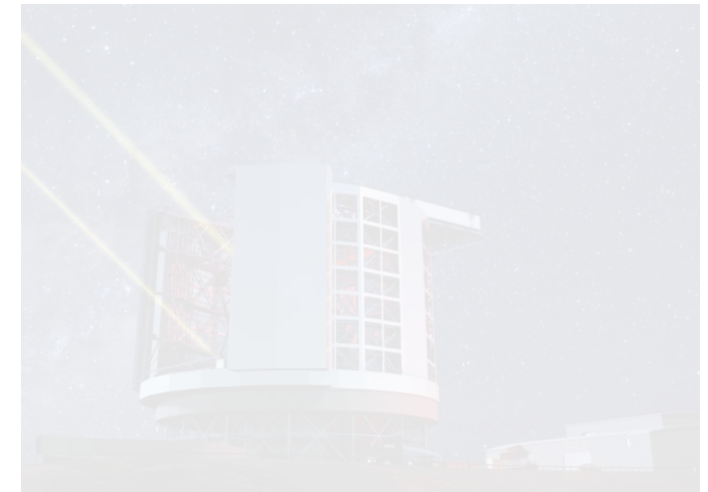
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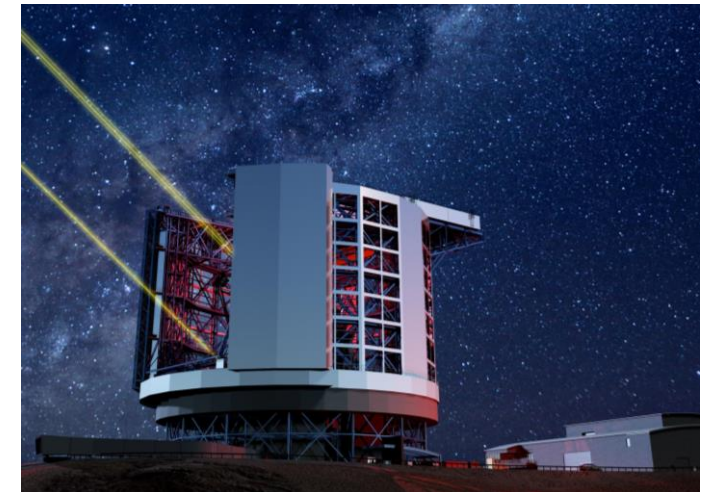
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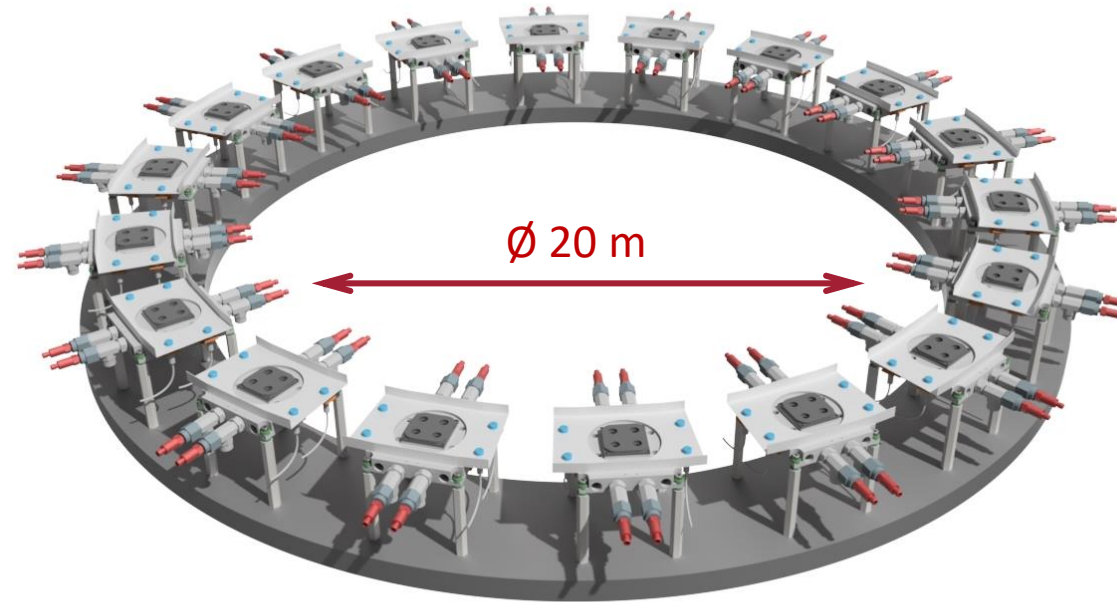
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STATE OF THE ART

LARGE-
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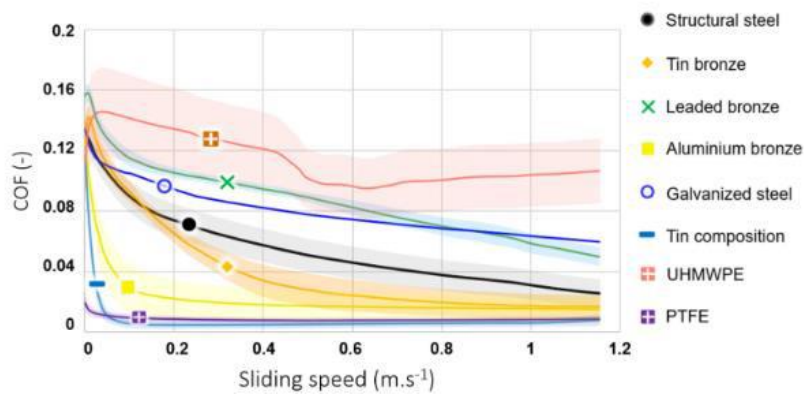
SAFETY

STATE OF THE ART

SAFETY OF OIL FILM

MATERIAL INFLUANCE

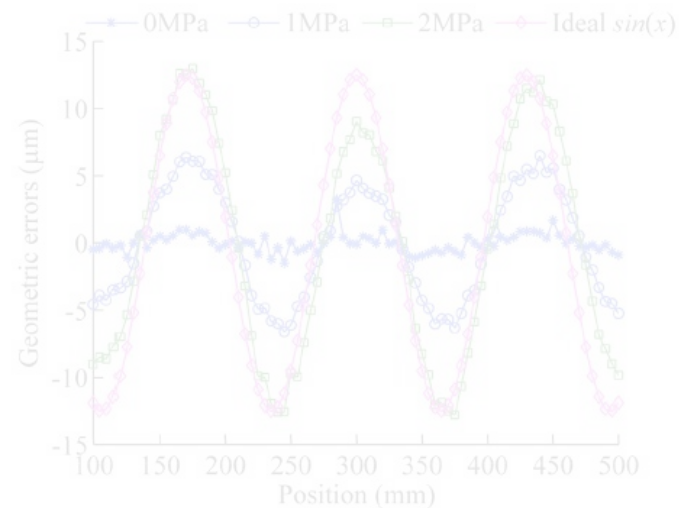
- Risk of abrasive particles
- Beneficial material combinations



MICHALEC, M. et. al. *Adv Eng Mater* (2024)

GEOMETRIC ERRORS

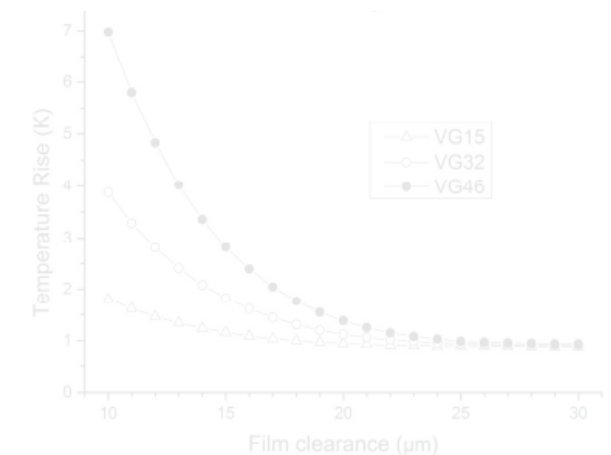
- Influence of manufacturing on pressure distribution
- Decrease of stiffness and precision



Zhang, P. et. al. *Int J Mach Tools Manuf* (2018)

TEMPERATURE CHANGES

- Shear in small clearances
- Changes during night and day



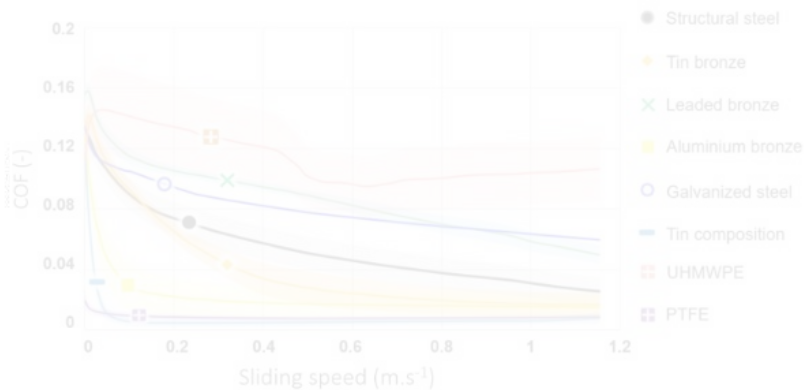
Huang, H.C. et. al. *Lubricants* (2022)

STATE OF THE ART

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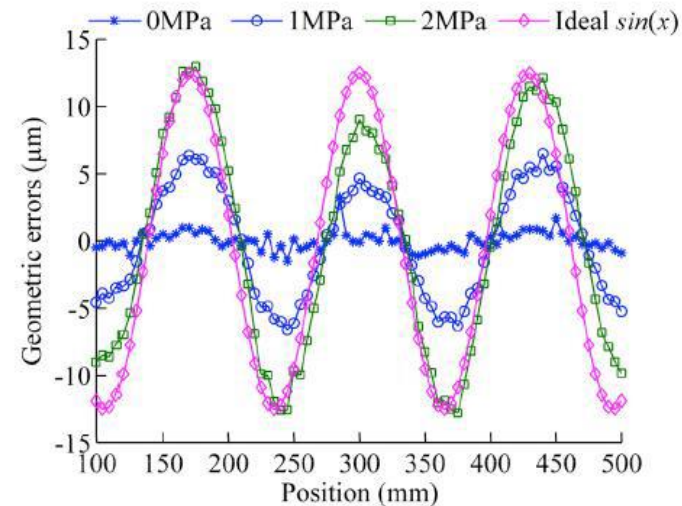
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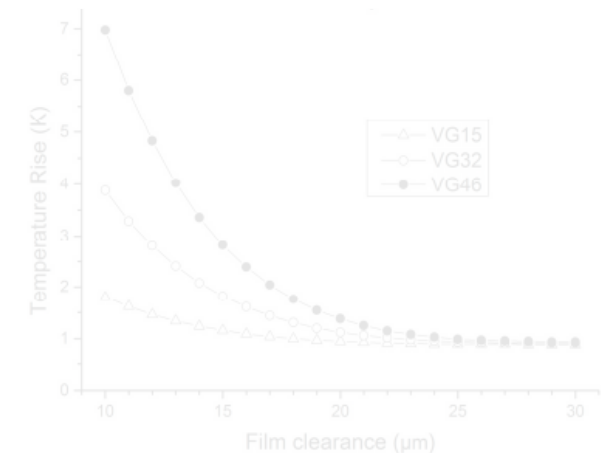
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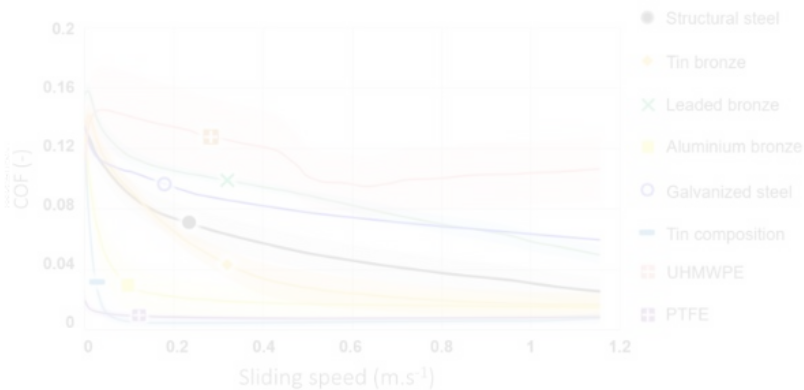
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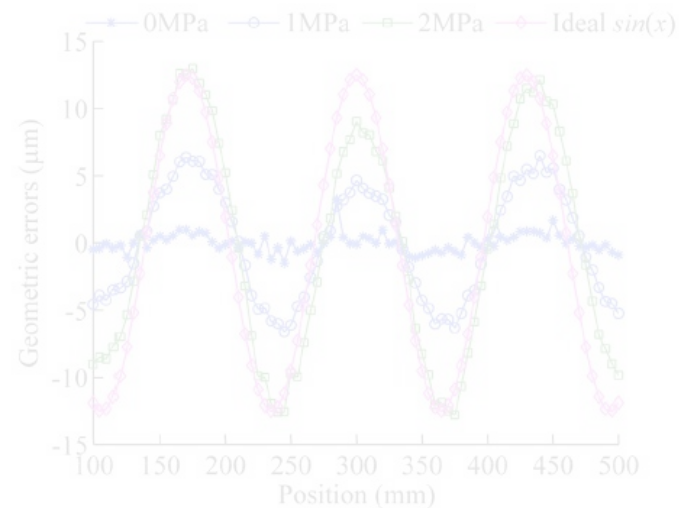
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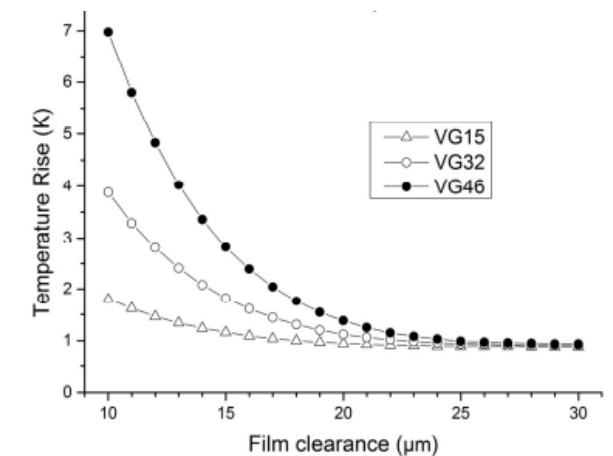
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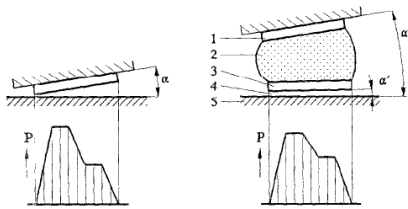
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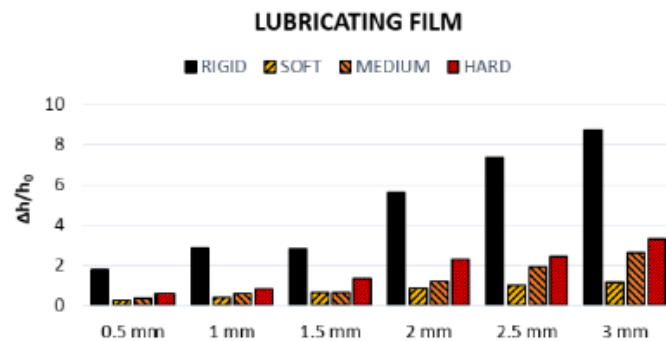
SAFETY OF OIL FILM

COMPLIANT SUPPORT

- Stiffness is not key parameter
- Can adapt to imperfections



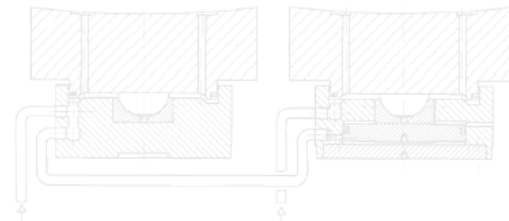
VAN BEEK, A. et. al. *Tribology International* (1997)



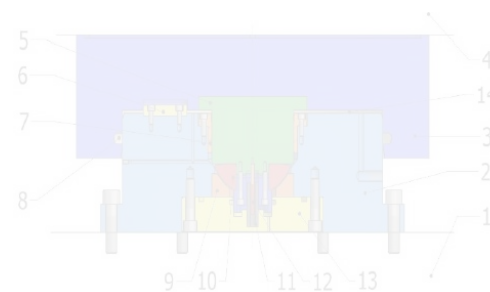
MICHALEC, M. et. al. *Precision Engineering* (2022)

TILTING SUPPORT

- Demanding for manufacturing
- Angular and height adjustments



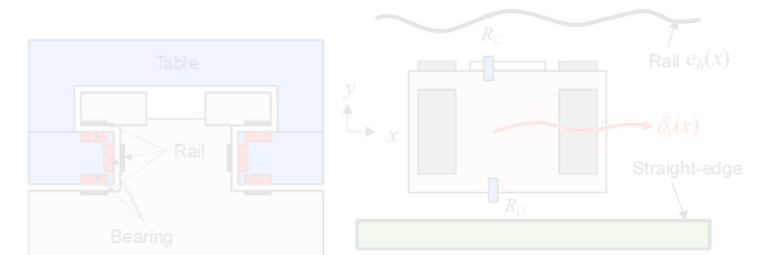
BASSANI, R. et. al. *Hydrostatic lubrication* (1992)



MARCHIORI, G. et. al. *SPIE* (2018)

ALIGNMENT

- Linear HS guideway
- Probe with negative shape of HS support
- Precision $\pm 0,001$ mm



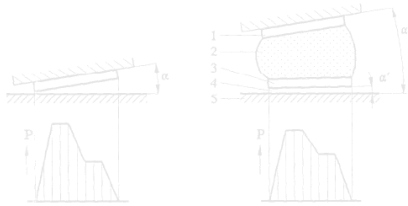
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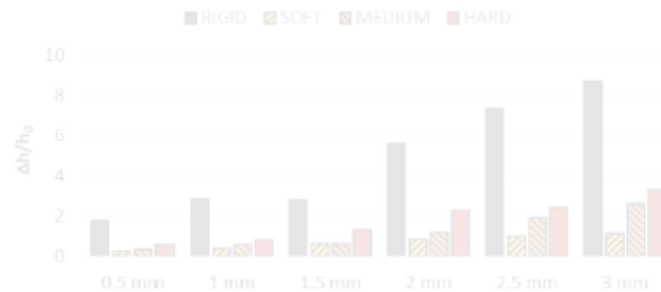
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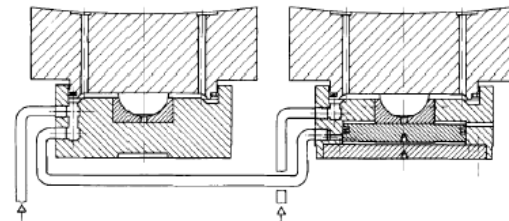
LUBRICATING FILM



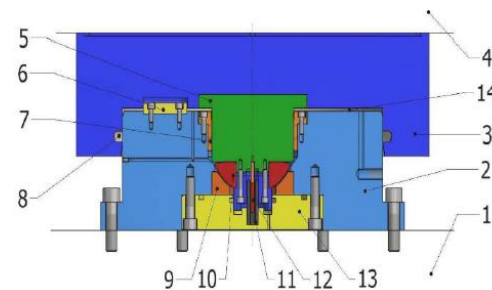
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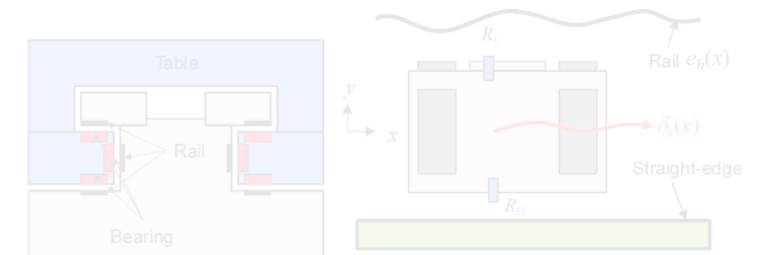
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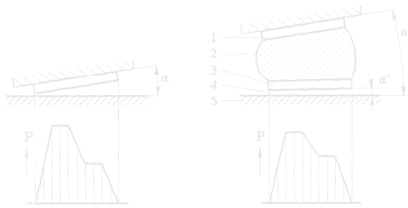
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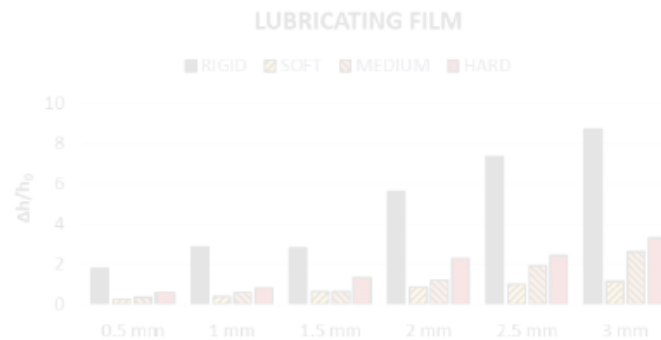
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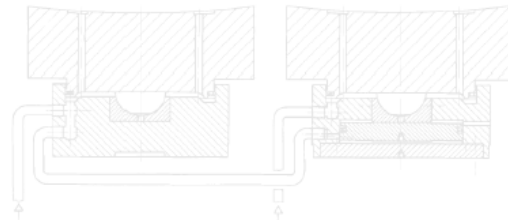
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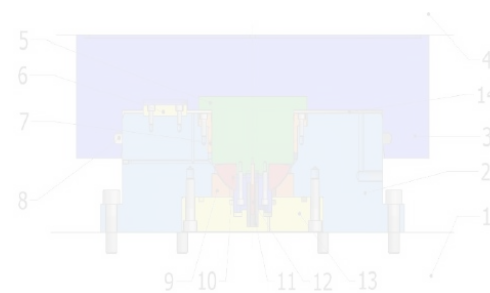
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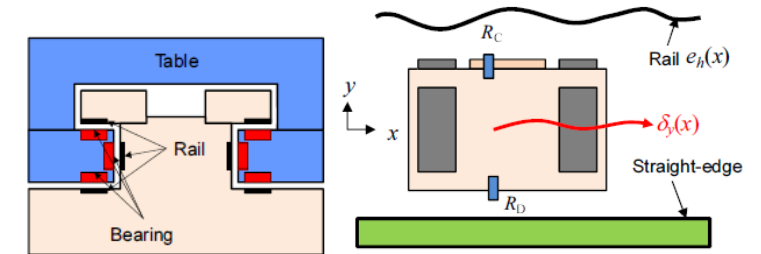
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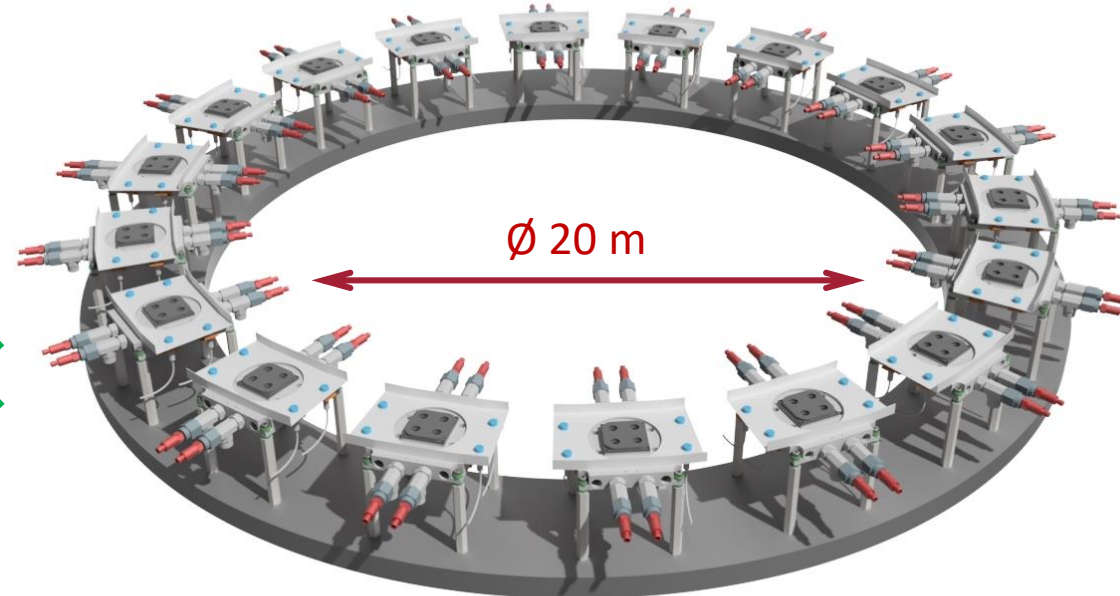


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SUMMARY OF LITERATURE REVIEW

LARGE-SCALE BEARINGS

- Pressure approach ✓
- High precision demand ✓
- Film thickness diagnostics ✗



SAFETY

- Compliant supports ✓
- Erosion effects ✗
- Large-scale alignment ✗

AIM OF THE THESIS

- Analyse the influence of geometric imperfections, hydraulic disturbances, and operating conditions on the minimum lubricating film thickness.
- Establish lubricating film thickness as safety-relevant parameter.

Output:

safety assessment based on lubricating film thickness and its distribution

SCIENTIFIC QUESTIONS AND HYPOTHESES

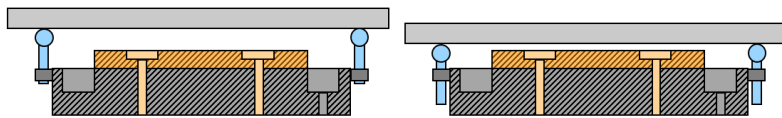
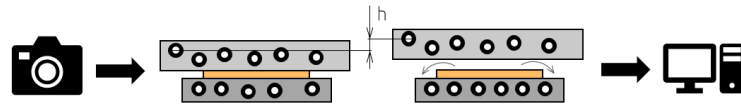
QUESTION 1

How optical methods improve safety of lubricating film?

H1

Optical measurements enable precise evaluation of film thickness under real operating conditions.

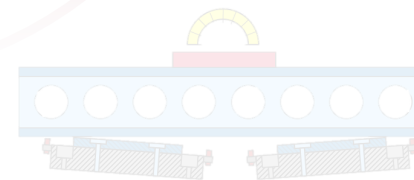
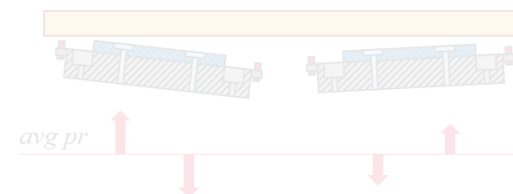
Thickness measurement precision



H2

Optical alignment improves the positioning of pads, leading to a more uniform lubricating film.

Alignment precision



SCIENTIFIC QUESTIONS AND HYPOTHESES

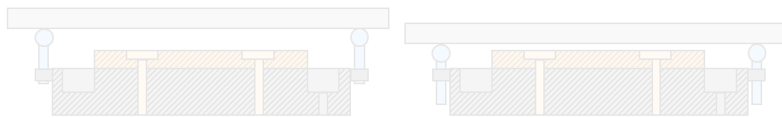
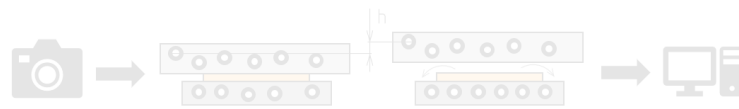
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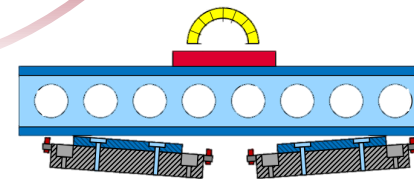
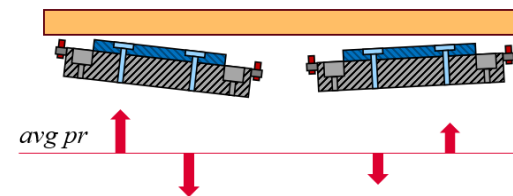
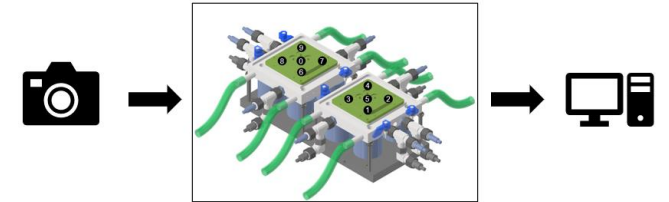
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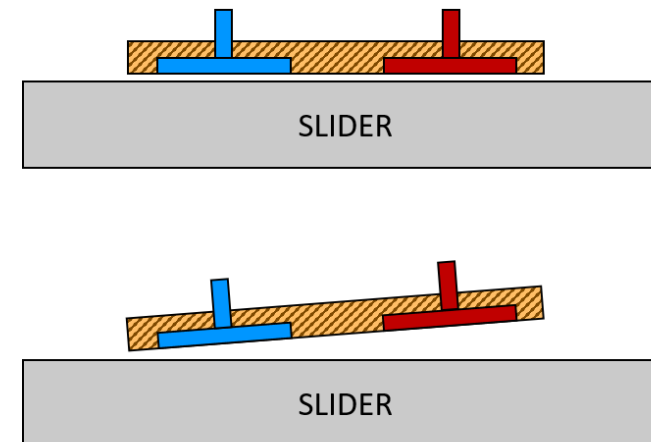
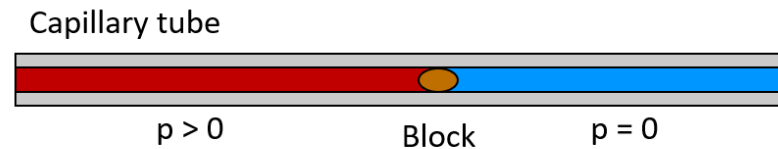
SCIENTIFIC QUESTIONS AND HYPOTHESES

QUESTION 2

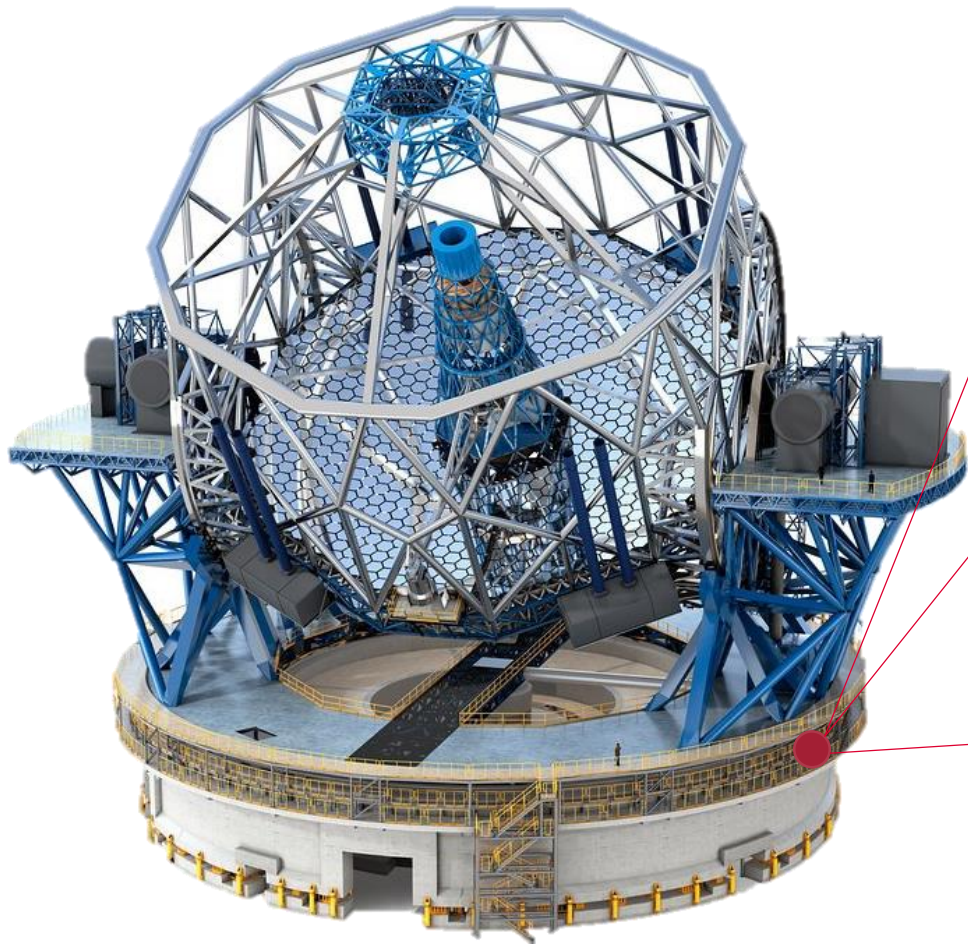
How restrictor failure affect safety of lubricating film?

H3

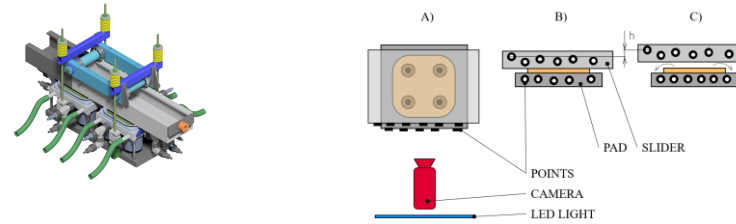
Blockage of a capillary restrictor in a multi-recess hydrostatic bearing causes a measurable decrease in local film thickness and creating a safety-critical condition.



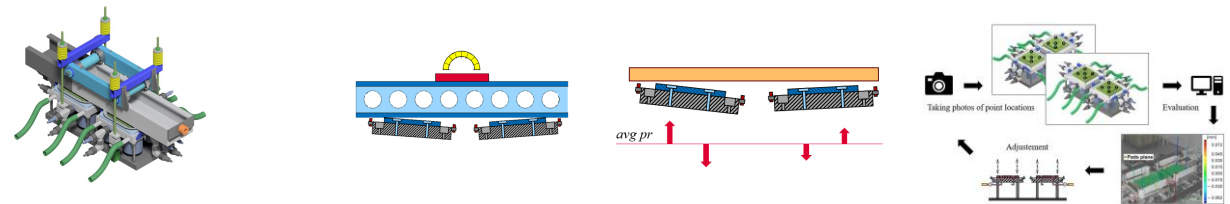
THESIS LAYOUT



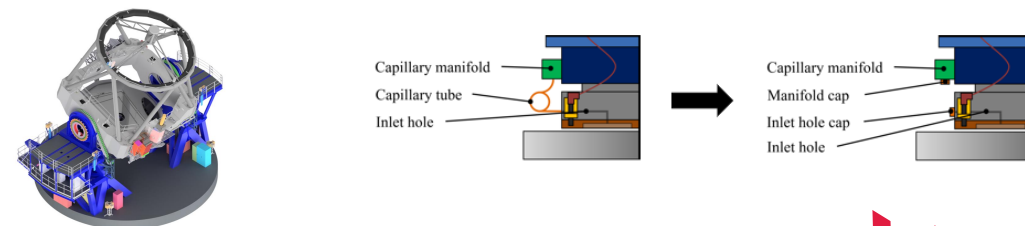
FILM THICKNESS MEASUREMENT



ALIGNMENT



SAFETY PROCEDURE

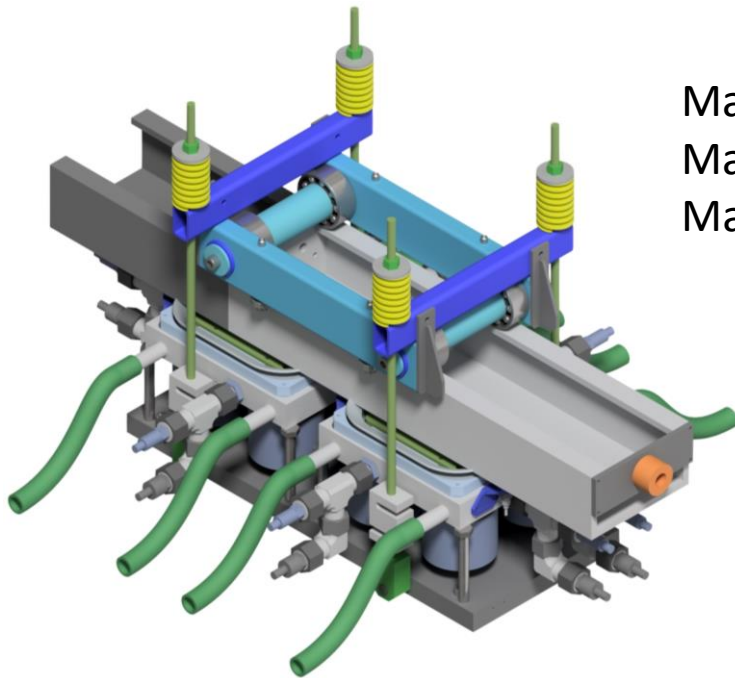


MATERIAL AND METHODS

EXPERIMENTAL OBJECTS

Experimental hydrostatic bearing – 2PAD

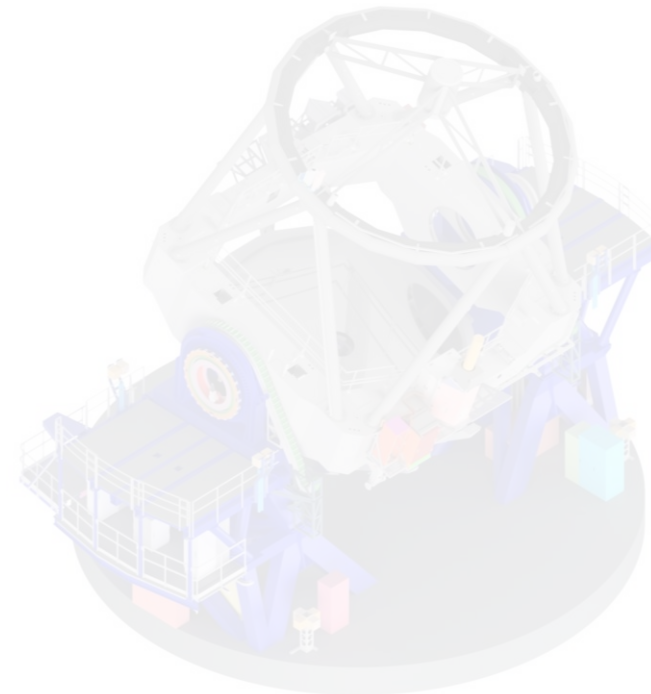
- Linear hydrostatic bearing
- 2 pads with 4 circular recesses



Max. load: **40 kN**
Max. pressure: **100 bar**
Max. flow: **20 l/min**

Very Large Telescope - VLT

- Azimuth hydrostatic bearing of 20 meters diameter
- 16 pads with 4 square recesses



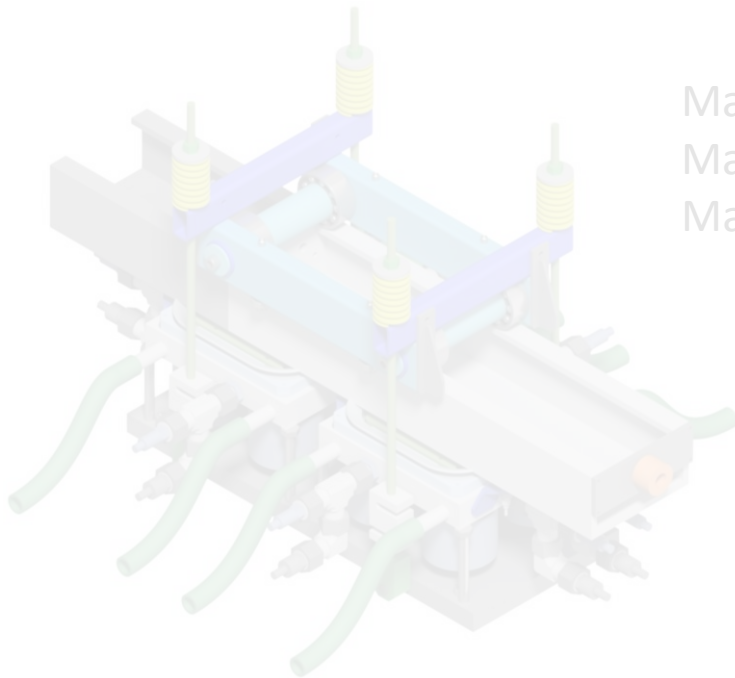
Load: **4 900 kN**
Max. pressure: **85 bar**
Max. flow: **16 l/min**

MATERIAL AND METHODS

EXPERIMENTAL OBJECTS

Experimental hydrostatic bearing – 2PAD

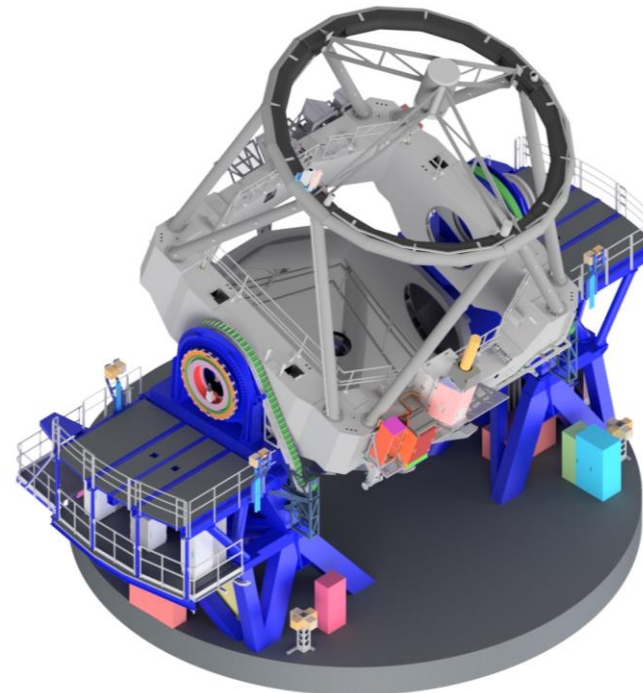
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- 16 pads of azimuth with 4 square recesses



Load: 4 900 kN
Max. pressure: 85 bar
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MATERIAL AND METHODS

FILM THICKNESS MEASUREMENT

DIAL INDICATORS

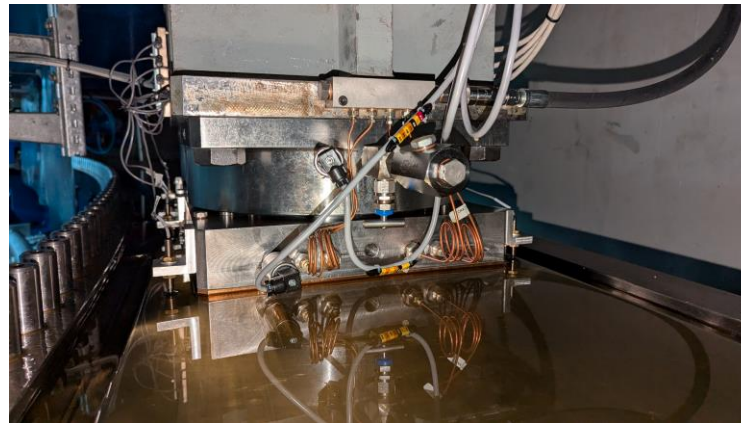
- Current method on VLT
- Only for static condition
- Operator dependent



Measurement on outer ring (VLT)

INDUCTIVE SENSORS

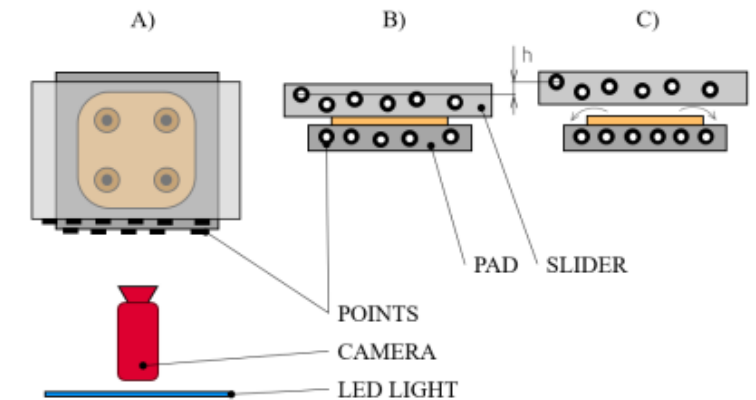
- Online diagnostics
- Precise position of sensor
- Proposed upgrade for VLT



Measurement on outer ring (VLT)

OPTICAL POINT TRACKING

- Static camera
- Detection of points deviations
- Tested on 2PAD



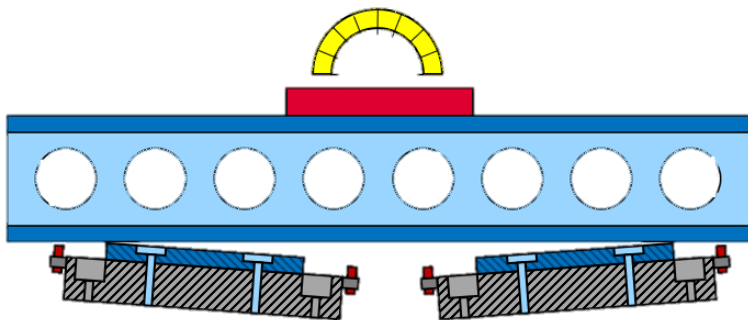
OPT setup

MATERIAL AND METHODS

ALIGNMENT METHODS – 2PAD

CONVENTIONAL GAUGES

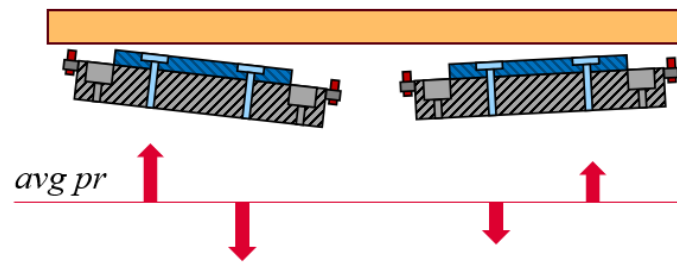
- Operator dependent
- Large deviations



Measurement with straight edge and spirit level

PRESSURE METHOD

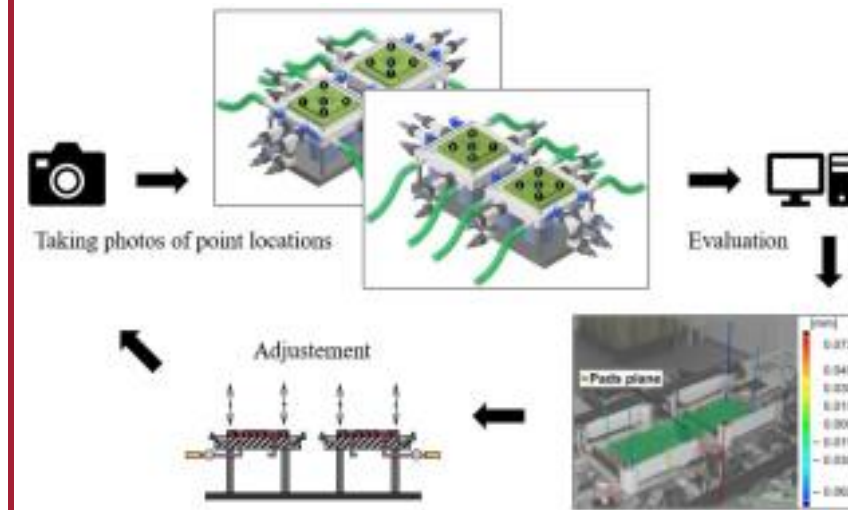
- In-situ potential
- Equal pressure in recesses



Adjustment of recess pressure

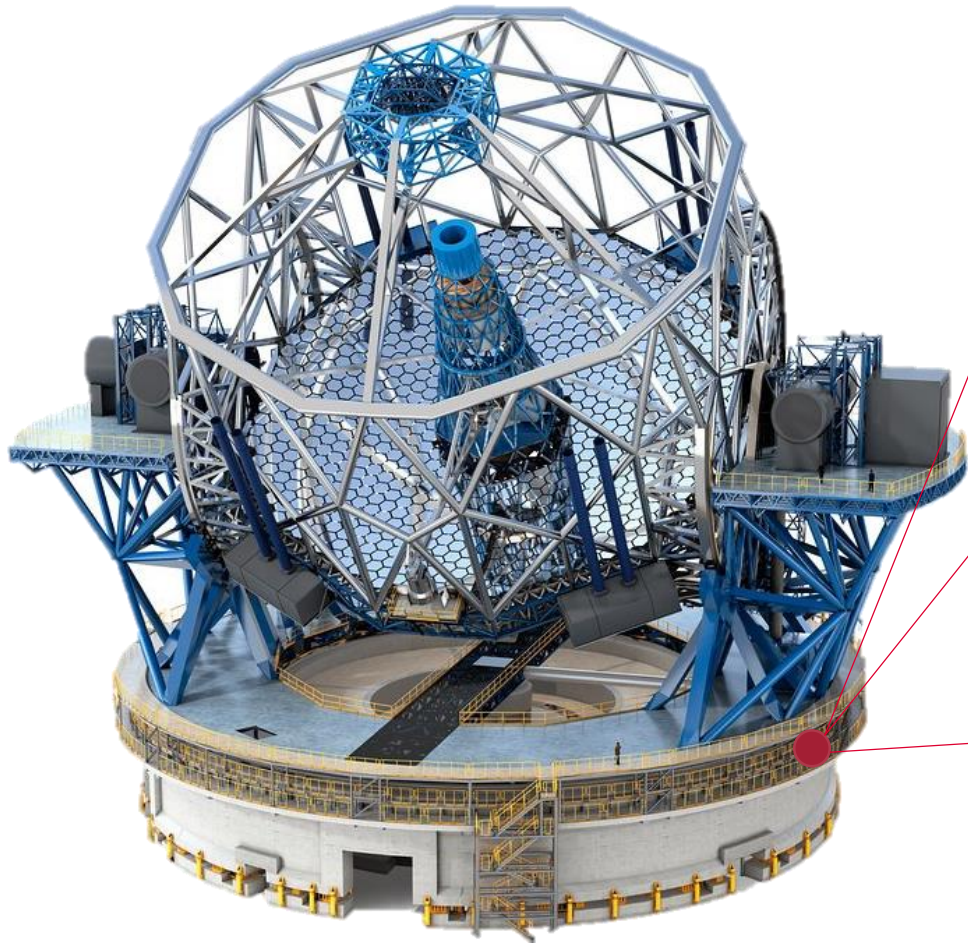
OPTICAL COORDINATE MEASUREMENT

- Position of points in 3D space
- Reference plane fitting

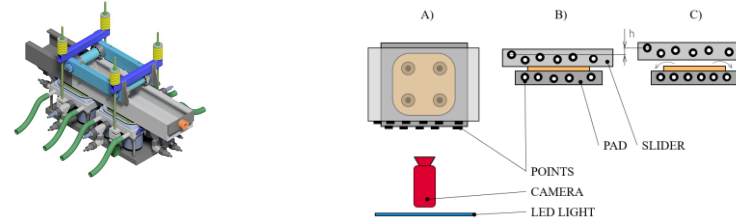


Work flow of OCM method

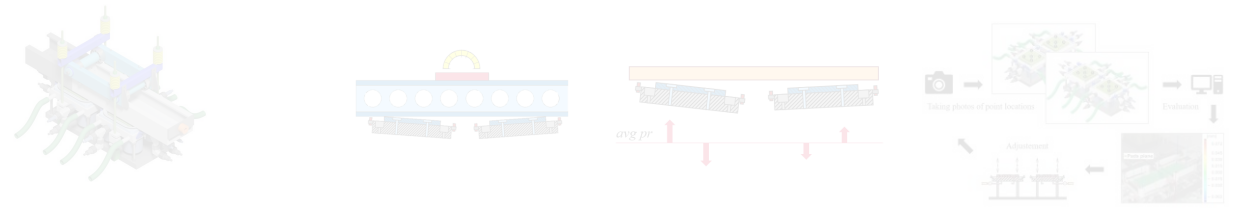
THESIS LAYOUT



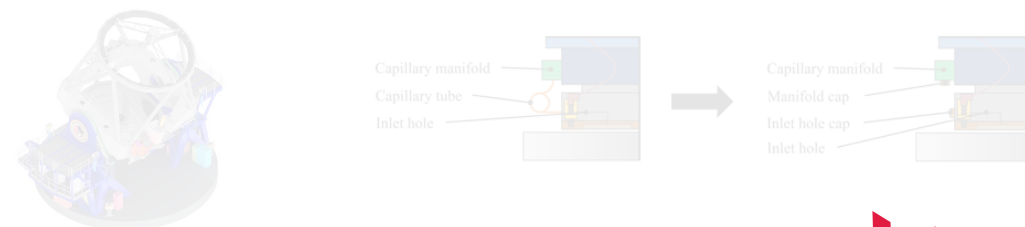
FILM THICKNESS MEASUREMENT



ALIGNMENT



SAFETY PROCEDURE

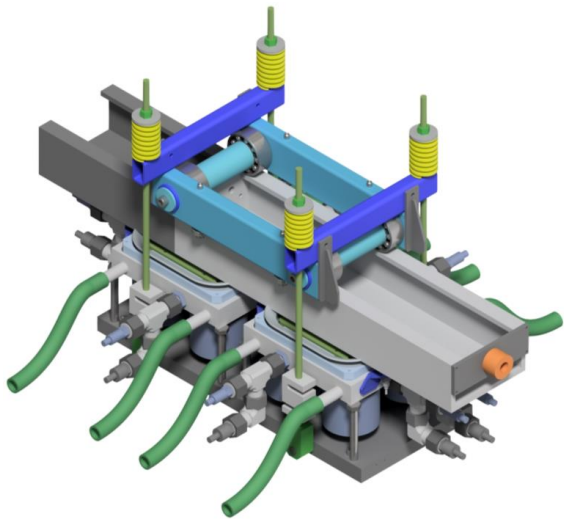


RESULTS

FILM THICKNESS MEASUREMENT

OPTICAL POINT TRACKING

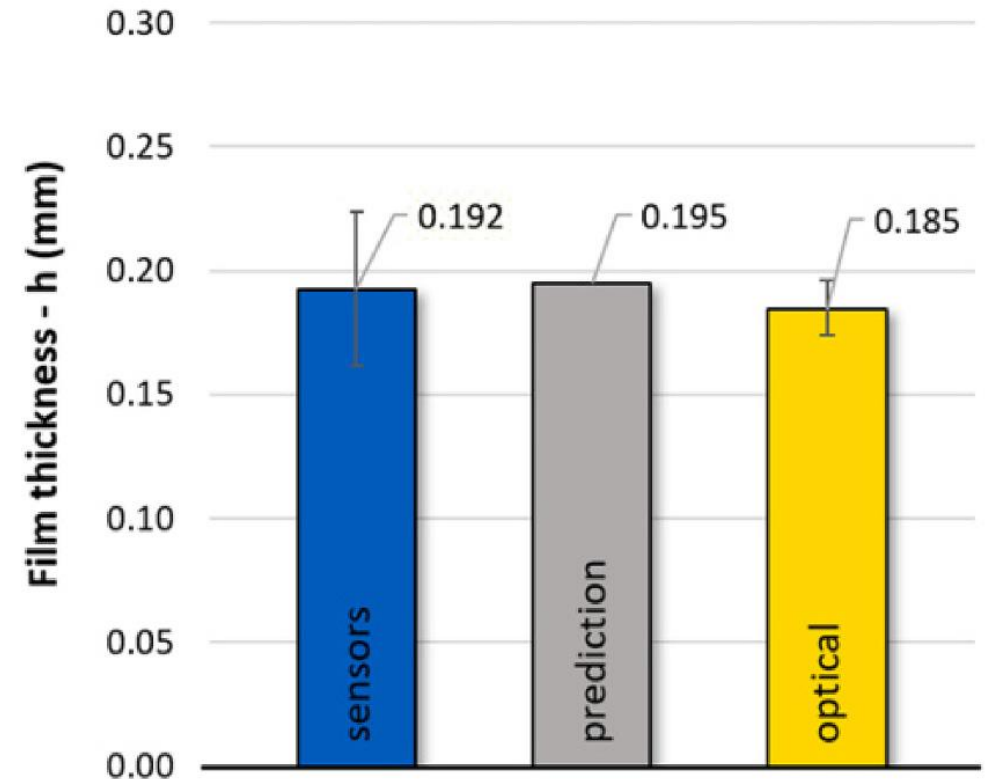
- New method of film thickness measurement
- Lower measured film deviation than sensors



Load: **16 kN**
Pressure: **5 bar**
Flow: **4 l/min**



Michalec, M.; Hurník, J.; Foltýn, J.; Svoboda, P. Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method. Proc. Inst. Mech. Eng. Part J.-J. Eng. Tribol. (2023).



CONCLUSION

SCIENTIFIC QUESTION 1

HYPOTHESIS 1

VERIFIED

Optical methods can reliably support assessment of minimum film thickness

Measurement deviation: 3.6%

Measurement resolution: up to 0.001 mm

SCIENTIFIC QUESTION 1

HYPOTHESIS 2

VERIFIED

Optical alignment methods thus represent an effective preventive measure against local film thinning

Alignment precision: ± 0.01 mm

Improvement vs mechanical method: 6× reduction in deviation

SCIENTIFIC QUESTION 2

HYPOTHESIS 3

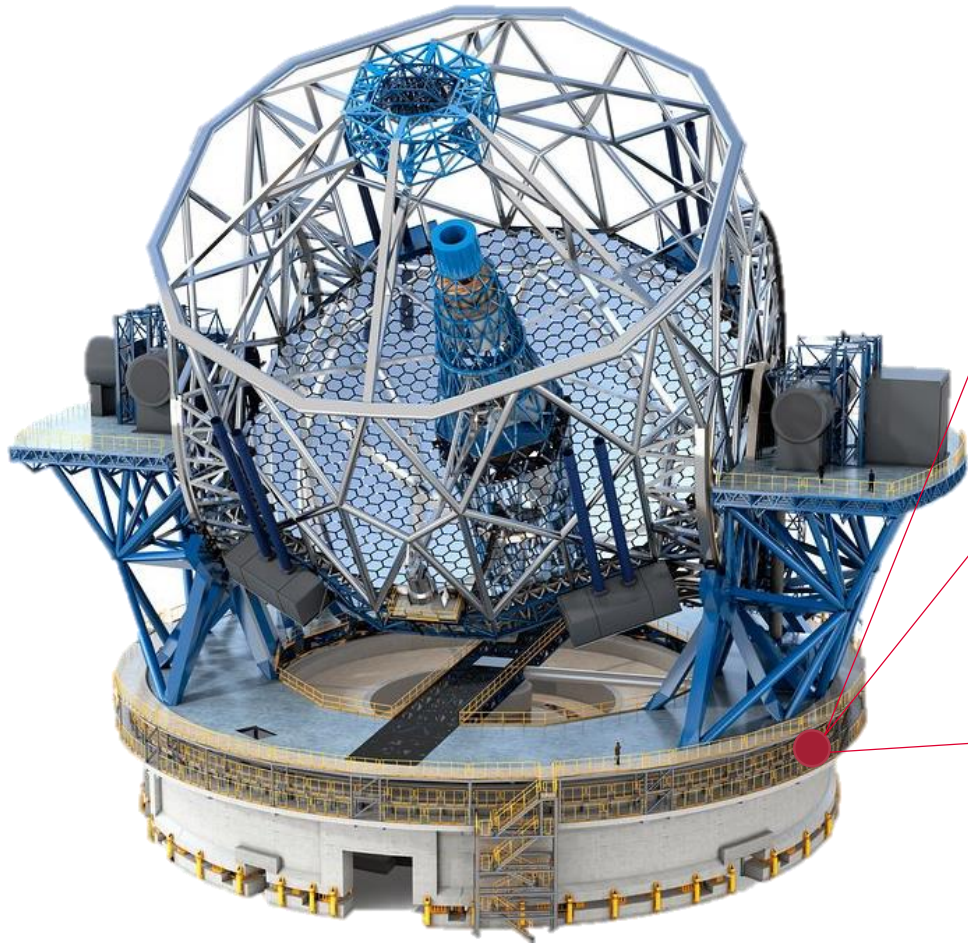
VERIFIED

Ideal assumptions of restrictors do not adequately account for realistic fault scenarios.
Continuous film thickness monitoring can provide early identification of critical states.

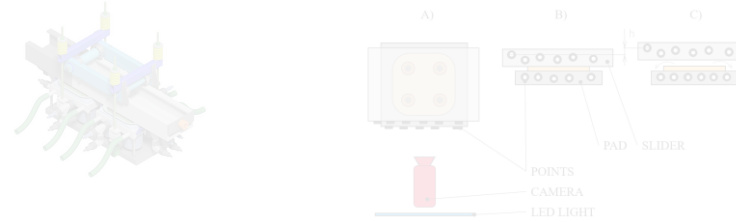
Film thickness drop due blockage: >20 μm

Operational dynamic fluctuation: up to 40 μm

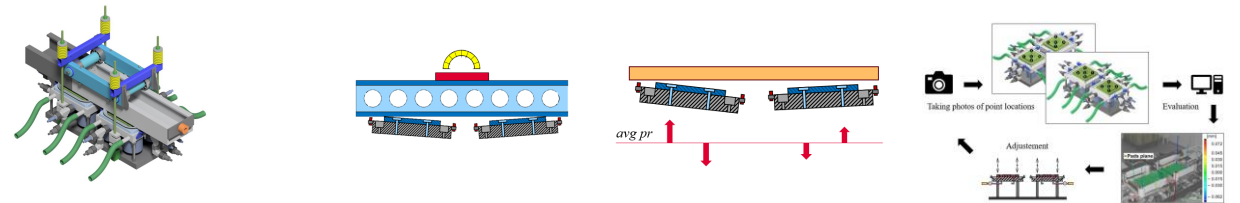
THESIS LAYOUT



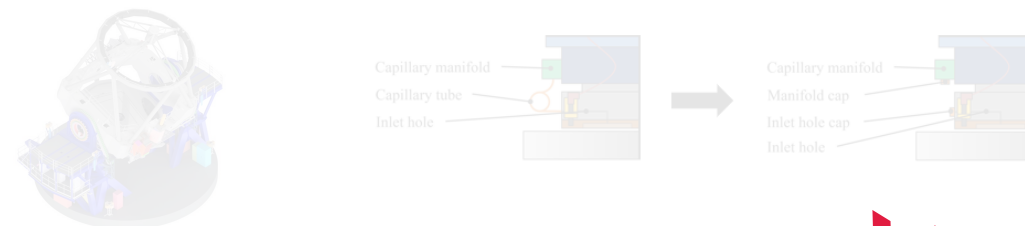
FILM THICKNESS MEASUREMENT



ALIGNMENT



SAFETY PROCEDURE

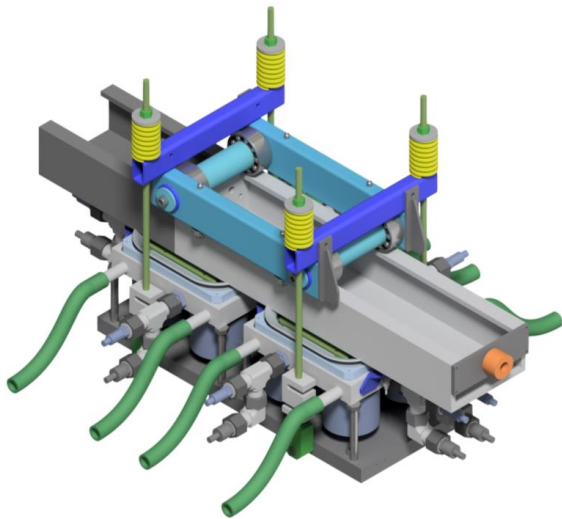


RESULTS

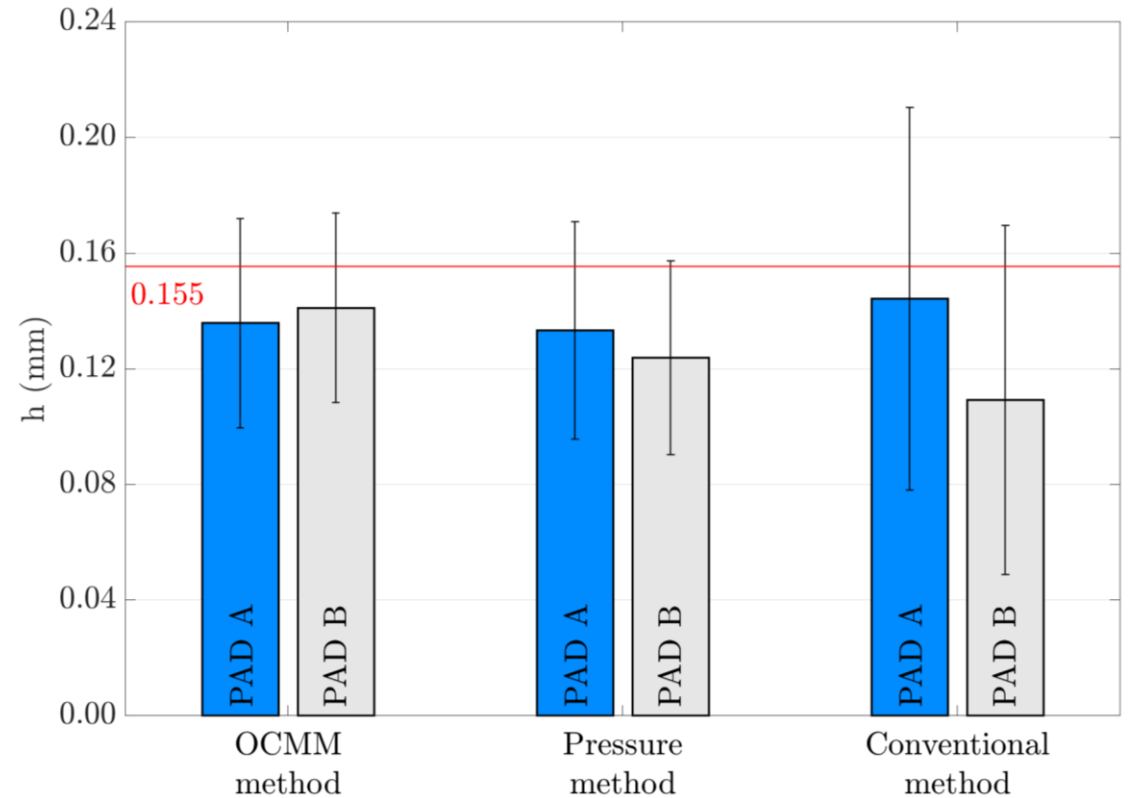
ALIGNMENT

THICKNESS MEASUREMENT

- Comparison with prediction
- Combined influence of measurement errors



Load: **19,6 kN**
Pressure: **7 bar**
Flow: **6 l/min**

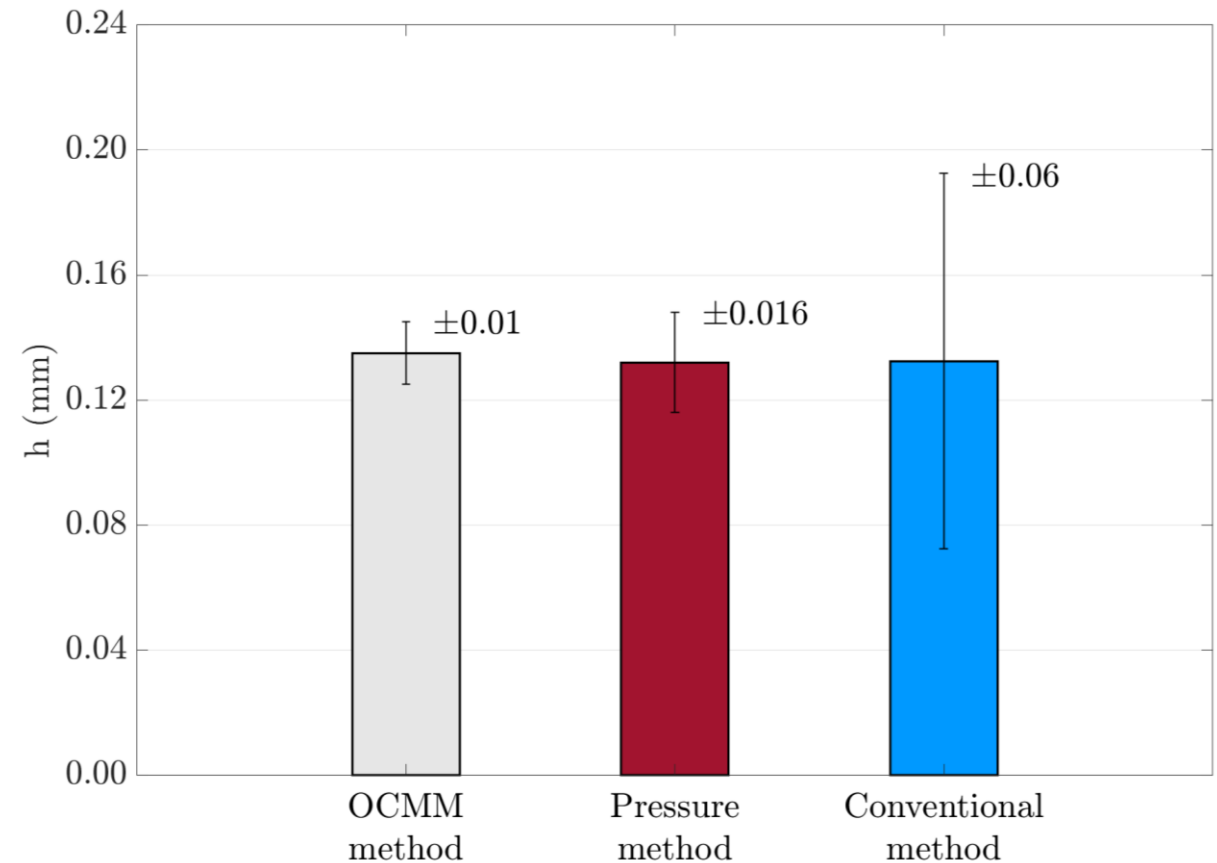


RESULTS

ALIGNMENT

OPTICAL COORDINATE MEASUREMENT

- Most uniform film
 - Thickness variation of ± 0.01 mm
- Repeatable



Alignment methods comparison



Foltýn, J.; et.al: Pad Alignment Methods and Their Impact on Large Hydrostatic Bearing Precision. Machines. (2024).

CONCLUSION

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SCIENTIFIC QUESTION 2

HYPOTHESIS 3

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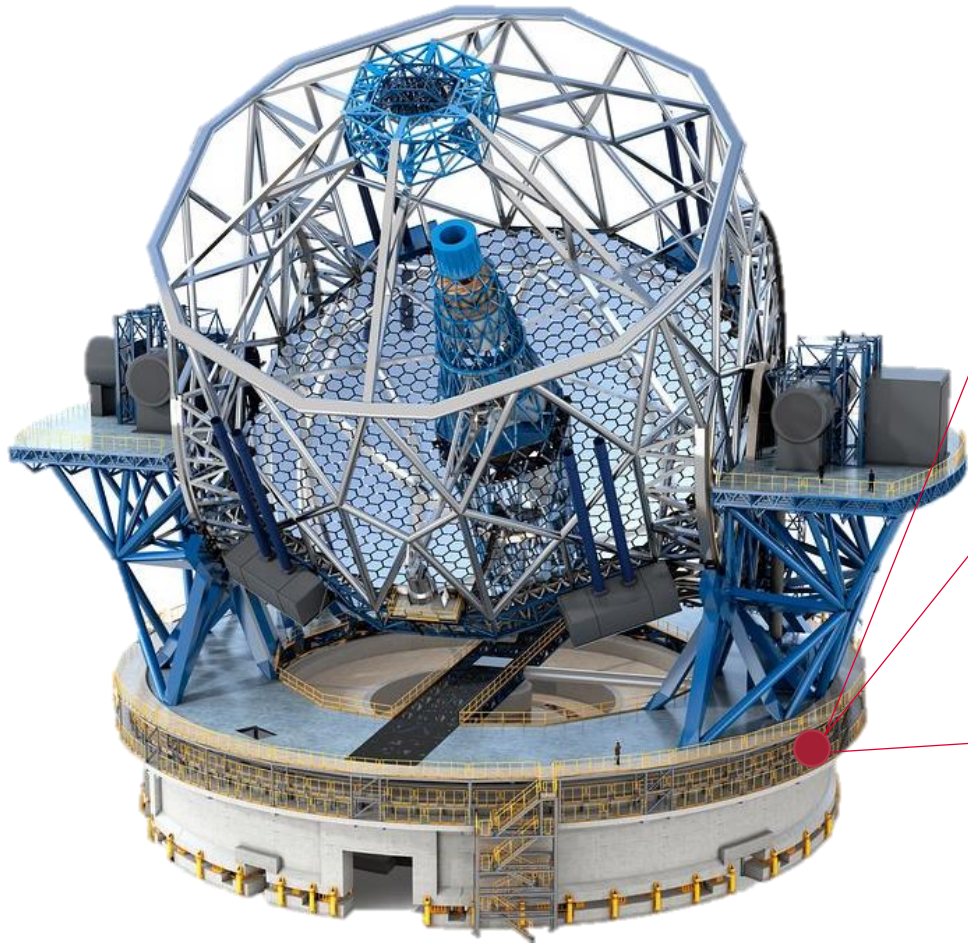
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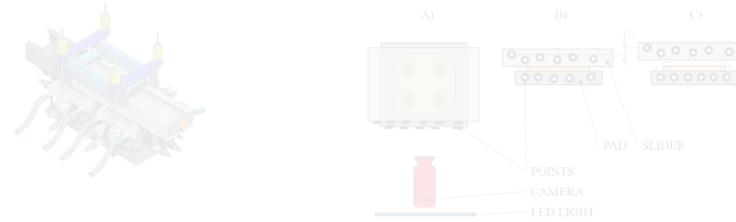
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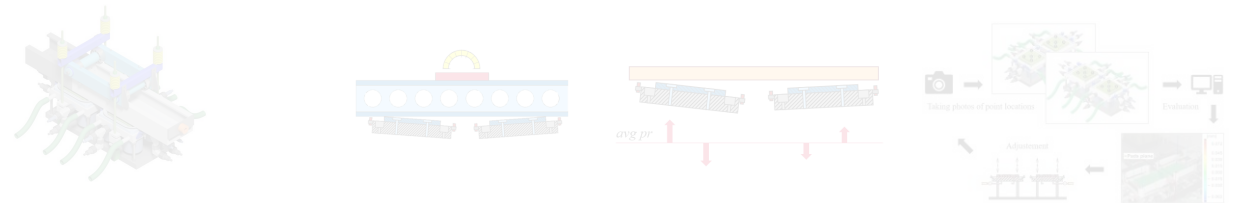
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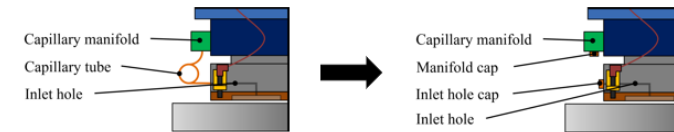
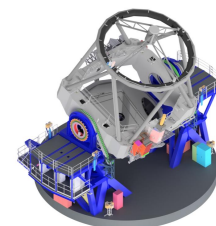
FILM THICKNESS MEASUREMENT



ALIGNMENT



SAFETY PROCEDURE

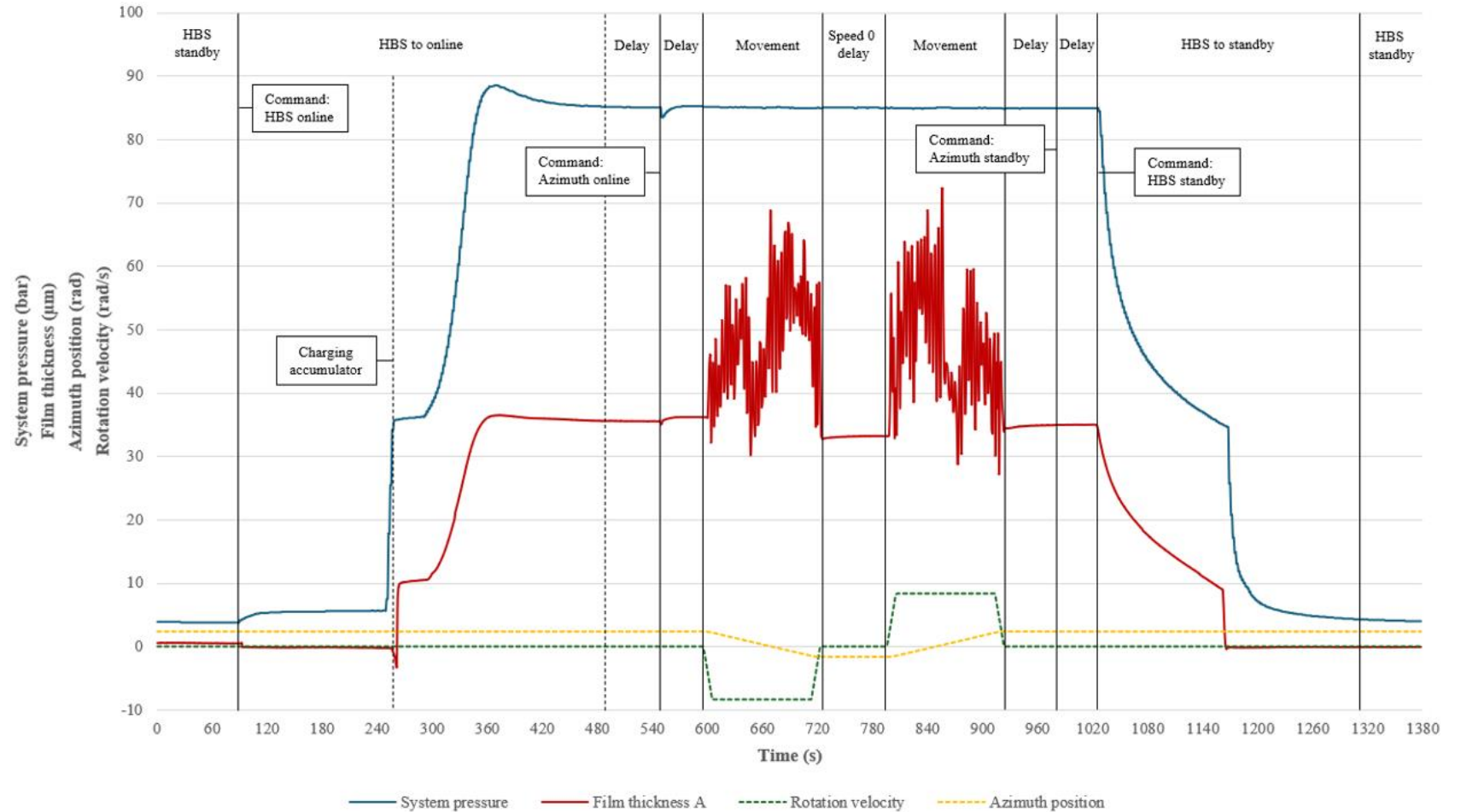
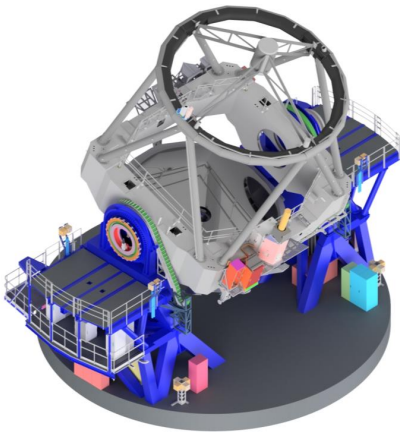


RESULTS

SAFETY PROCEDURE

THICKNESS MEASUREMENT

- New method proposed
- Operational fluctuation $40 \mu\text{m}$
- Connected with alignment
- Movement of 230 deg

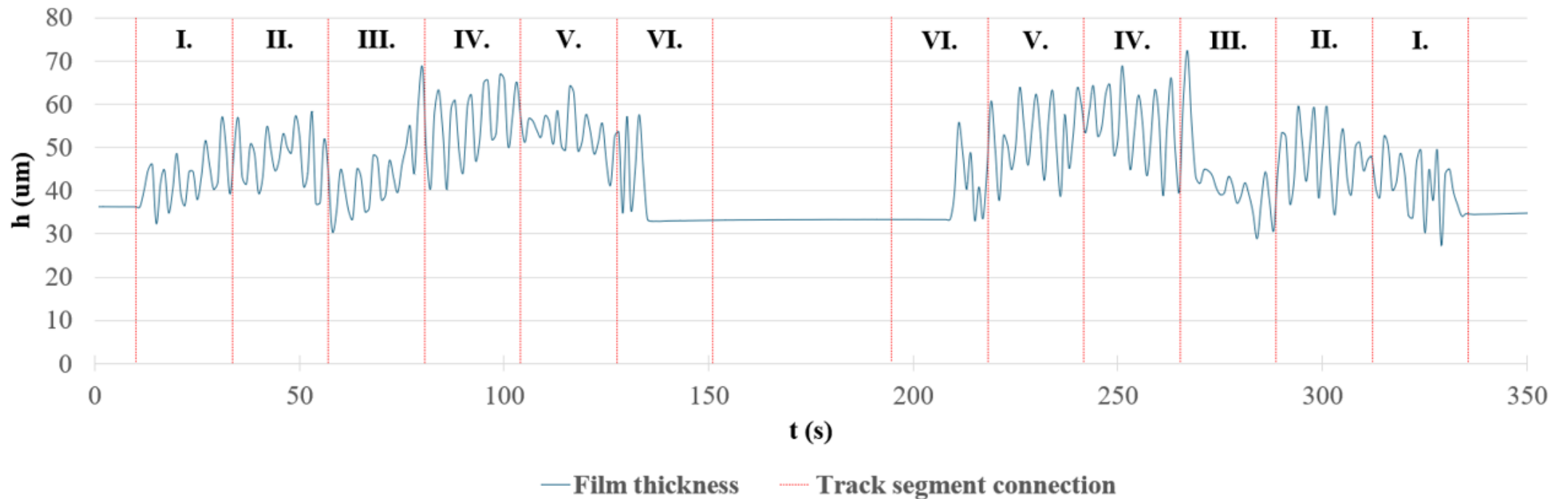
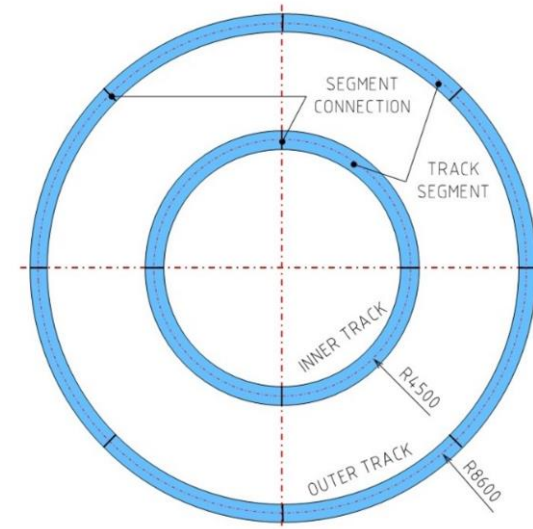


RESULTS

SAFETY PROCEDURE

TRACK INFLUENCE

- Symmetrical behavior
- Segment connections changes the trend
- Solution - alignment

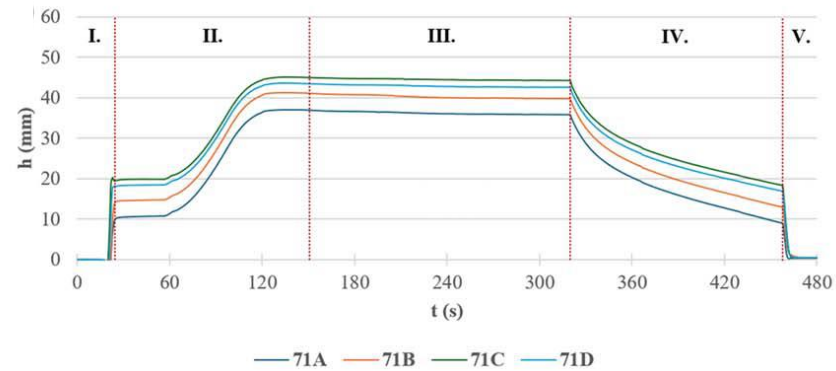
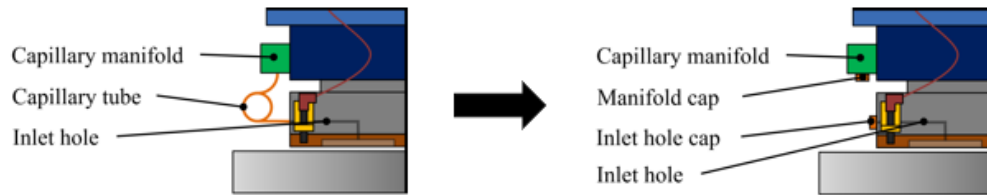
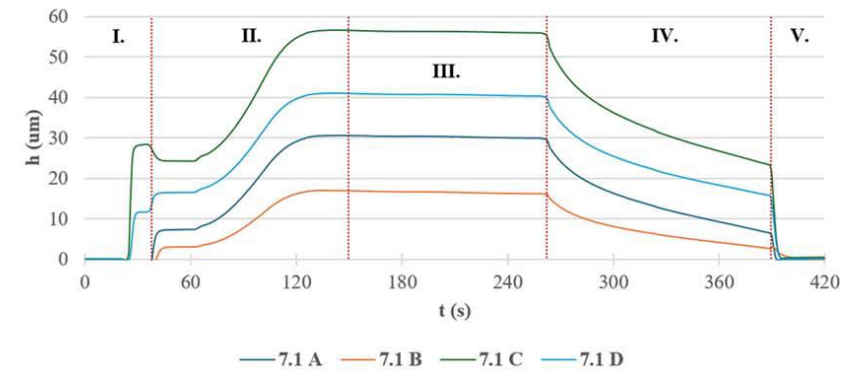
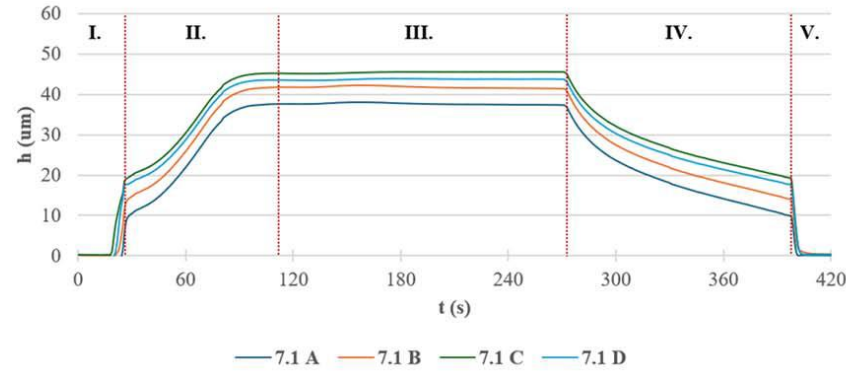


RESULTS

SAFETY PROCEDURE

CAPILLARY BLOCKAGE

- Artificial blockage - cap
- Azimuth static
- Film thickness drop $>20 \mu\text{m}$



ASME

TRANSACTIONS OF THE ASME
JOURNAL OF TRIBOLOGY



Foltýn, J.; et.al.: "Failure prevention procedure of the Very Large Telescope hydrostatic bearing pads based on lubricating film thickness measurement." ASME. J. Tribol. (2025).

CONCLUSION

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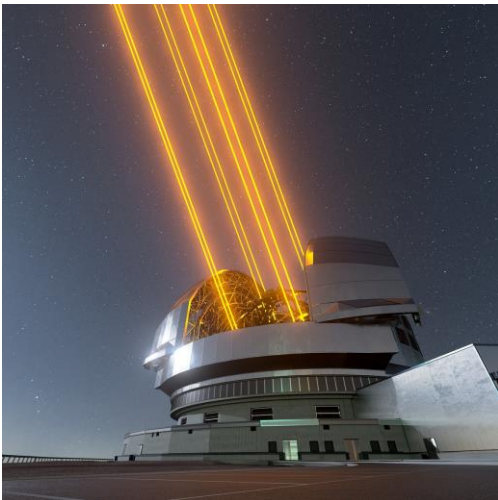
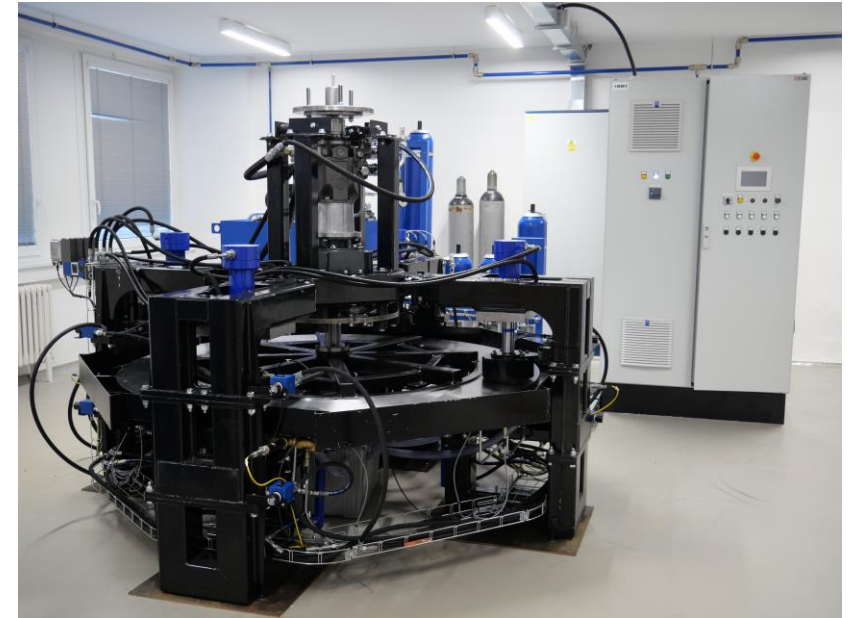
Operational dynamic fluctuation: up to 40 μm

CONCLUSION

FILM THICKNESS MEASUREMENT



PAD ALIGNMENT



SAFETY PROCEDURE

The measurement of film thickness is used as a safety criterion for the **VLT**, with future application to an **Extremely Large Telescope**

LIST OF PUBLICATIONS

Foltýn, J.; Flores, E.; Tapia, M.; Álvarez, N.; Michalec, M.; and Svoboda, P. "Failure prevention procedure of the Very Large Telescope hydrostatic bearing pads based on lubricating film thickness measurement." *ASME. J. Tribol.* (2025). <https://doi.org/10.1115/1.4068788> [IF 3.0]



Foltýn, J.; Hurník, J.; Michalec, M.; Svoboda, P.; Křupka, I.; and Hartl, M. Pad Alignment Methods and Their Impact on Large Hydrostatic Bearing Precision. *Machines.* (2024). <https://doi.org/10.3390/machines12080549> [IF 2.5]

Michalec, M.; Hurník, J.; Foltýn, J.; Svoboda, P. Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method. *Proc. Inst. Mech. Eng. Part J.-J. Eng. Tribol.* (2023). <https://doi.org/10.1177/13506501221108138> [IF 1.8]

Foltýn, J., Maccioni, L., Michalec, M., Concli, F., Svoboda, P. Uncertainty analysis of hydrostatic bearing working conditions with experimental, CFD, and analytical approach. *Forsch Ingenieurwes* 89, 67 (2025). <https://doi.org/10.1007/s10010-025-00836-9> [IF 1.2]



Foltýn, J., Maccioni, L., Michalec, M., Concli, F., Svoboda, P. (2024). The Influence of Measurement Uncertainties and Input Parameters on Hydrostatic Bearing Performance: Analytical, Experimental, and Numerical Comparison. In: *ISIEA 2024. Lecture Notes in Networks and Systems*, vol 1124. Springer, Cham. https://doi.org/10.1007/978-3-031-70462-8_2



Michalec, M., Foltýn, J., Svoboda, P., Křupka, I., Hartl, M. Performance and stability comparison of hydrostatic bearing pad geometry optimization approaches. *Forsch Ingenieurwes* 89, 65 (2025). <https://doi.org/10.1007/s10010-025-00837-8> [IF 1.2]

Michalec, M., Daněk, L., Foltýn, J., Svoboda, P., Gachot, C., Hartl, M. and Křupka, I. (2025), Comparative Wear and Friction Analysis of Sliding Surface Materials for Hydrostatic Bearing under Oil Supply Failure Conditions. *Adv. Eng. Mater.* 2401733. <https://doi.org/10.1002/adem.202401733>

Michalec, M., Foltýn, J., Svoboda, P., Křupka, I., Hartl, M. (2024). Experimental Comparison of Hydrostatic Bearing Pad Geometry Optimization Approaches Under Static Conditions. In: *ISIEA 2024. Lecture Notes in Networks and Systems*, vol 1124. Springer, Cham. https://doi.org/10.1007/978-3-031-70462-8_1

Michalec, M.; Foltýn, J.; Dryml, T.; Snopek, L.; Javorský, D.; Čupr, M.; Svoboda, P. Assembly Error Tolerance Estimation for Large-Scale Hydrostatic Bearing Segmented Sliders under Static and Low-Speed Conditions. *Machines*, (2023), vol. 11, no. 11, <https://doi.org/10.3390/machines11111025>

Michalec, M., Polnický, V., Foltýn, J., Svoboda, P., Šperka, P., Hurník, J.: The prediction of large-scale hydrostatic bearing pad misalignment error and its compensation using compliant support. *Precis. Eng.* 75, 67–79 (2022). <https://doi.org/10.1016/j.precisioneng.2022.01.011>



OTHER RESULTS

APPLIED RESEARCH OUTCOMES

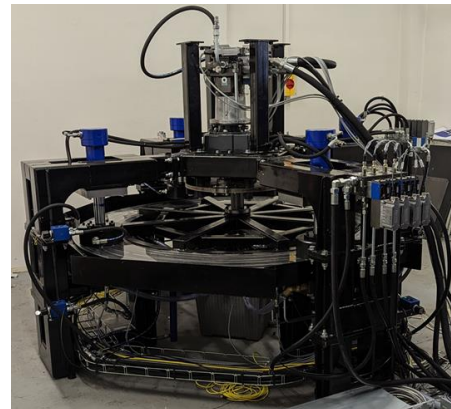
SVOBODA, P.; POLNICKÝ, V.; MICHALEC, M.; FOLTÝN, J.; MARTINEK, J.; ROBENEK, V.; DRHA, V.: **Device for testing operating conditions of hydrostatic support.**, 37631, 2024, *utility model*

FOLTÝN, J.; MICHALEC, M.; POLNICKÝ, V.; SVOBODA, P.; MARTINEK, J.; ROBENEK, V.; DRHA, V.: **Experimental device 4PAD; hydrostatic rotary table with mechatronic systems based on adaptive control loops.**, 2023, *functional sample*

FOLTÝN, J.; POLNICKÝ, V.; MICHALEC, M.; SVOBODA, P.; MARTINEK, J.; ROBENEK, V.: **Experimental device 3PAD; hydrostatic bearing with feedback control of the lubricant film thickness**, 2023, *functional sample*



3PAD



4PAD

CONFERENCE

ITC FUKUOKA 2023 (Poster)

MOTIVATION
Hydrostatic bearing pad alignment directly affects its precision and performance, and therefore is essential for a proper and precise function. The aim was to investigate which alignment method provides the highest precision for large-scale hydrostatic bearings.

INTRODUCTION
In case of large-scale bearings exceeding tens of metres, it is not possible for some of its parts to be created in a single piece or to secure desirable machining precision. Moreover, they are difficult to transport and assemble.

MATERIAL & METHODS
The experimental hydrostatic bearing device consisted of two pads (Fig. 2), a load frame and a hydraulic unit. The pad geometry was designed with four circular recesses. The load can be applied up to 5 t. The hydraulic unit was able to supply a flow rate of up to 10 l/min at a pressure of 100 bar.

EXPERIMENTAL CONDITIONS

- Load 2 t/pad
- Total flow: 6 l/min
- Hydraulic oil: ISO VG 46
- Pressure gauges ±0.5% bar
- Proximity sensors ±0.01 mm
- Repeated 4 times

RESULTS & DISCUSSION
The lubricating film thickness achieved the highest average values and the best prediction agreement with OCMM method (Fig. 5). The bearing operated in an optimal mode, which led to better performance and precision of the bearing. At the same time, the smallest thickness variations occurred over the pad area (Fig. 6). The method is characterized by high alignment accuracy and can be used for a wide range of hydrostatic bearing sizes. In addition, no sensors on the bearing are required for alignment.

THANK YOU FOR YOUR ATTENTION

Jan Foltýn, Ing.

Jan.Foltyn@vut.cz



**INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN**

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