Modeling, Improving, and Scaling of Lubricating Interfaces in Axial Piston Machines

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Swashplate type axial piston machine applications

- High operating pressure
- Variable displacement
- High power density
- High efficiency

Axial piston pumps and motors

0.5cc - 1000cc
Swashplate type axial piston machine

Introduction
Modeling
Innovation
Scaling
Outlook and Conclusions

Cylinder block/Valve plate interface

Piston / Cylinder interface

Slipper / Swashplate interface

Videos from Schenk, A.
Challenge of lubricating interfaces design

Introduction
Modeling
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Scaling
Outlook and Conclusions

Complicated interactive physical phenomena
- Piston micro motion
- Slipper micro motion
- Block micro motion

Challenge of lubricating interfaces design

Complicated interactive physical phenomena
- Piston micro motion
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Interactive physical phenomena

Challenge of lubricating interfaces design

- Fluid film behavior
- Elastic deformation
- Heat transfer
- Micro motion

Videos from Zecchi, M.
Challenge of lubricating interfaces design

Lubricating interfaces are difficult to design, due to the interactive physical phenomena including:

- Macro and micro motion
- Fluid hydrostatic and hydrodynamic effects
- Viscous shear and energy dissipation
- Heat transfer
- Elastic deformation
- Surface texture and Surface shaping
Swashplate type axial piston machine

**Efficiency**
- Up to 50% contribution to FP system power loss

**Robustness**
- Main contributor to pump and motor failure

**Designing cost**
- More than 80% design effort on Lubricating interfaces
Research Topics

Introduction  Modeling  Innovation  Scaling  Outlook and Conclusions

Modeling
- Essential insight of lubricating interface behavior

Improving
- Efficient and Robust design
- Designing process

Scaling
- Is lubricating interface scalable
  - No, why not
  - Yes, How

Efficiency

Robustness

Designing cost
Axial piston machine modeling approach

**Fluid-Structure and Thermal Interaction**

- **Solid Body Thermal Deformation**
- **Solid Body Heat Transfer**

**Fluid-Structure Interaction**

**Elastic Deformation**

**FVM Fluid model**

**Modeling**

**Fluid model: Pressure**

\[ \sum_i \Gamma_i (\nabla p)_i A_i = \int_{V} S dV \]

**Reynolds Equation**

**Fluid model: Temperature**

\[ \rho c_p V \cdot \nabla T - \nabla \cdot (\lambda \nabla T) = \mu \Phi_D \]

**Energy Equation**
Axial piston machine modeling approach

**Introduction**
- Modeling
- Innovation
- Scaling
- Outlook and Conclusions

**Modeling**

**Pressure solver overhaul**
- Validated load carrying capability prediction.
- Robust and accurate scheme for low film thickness and contact region.

Shang, L. (2018 dissertation)

**Temperature solver overhaul**
- Convection
- Conduction
- Energy dissipation
- Compression
- Expansion
- Temperature changing rate


**Integrated heat transfer model**
- Robust scheme allows for extreme operating temperature
- Converge with less iteration

Experimental validation

EHD test pump
Bushings surface temperature distribution measurement during operation

Experimental validation

EHD test pump

Bushing surface temperature distribution measurement during operation

- Temperature at 2.5mm from DC
- Temperature at 26.15mm from DC

准确的流体行为预测（accurate fluid behavior prediction）

Measurement
Before temperature overhaul
After temperature overhaul

Shang, L (2018 dissertation)
From modeling to innovation

**Modeling**

- **Pump lifetime study**

- **Pump design optimization**

**Innovation**

- **Micro shaping concept**

- **Virtual prototyping**

**Insight of lubricating interface behavior**

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Introduction  
Modeling  
Innovation  
Scaling  
Outlook and Conclusions

Scaling

- Lubricating interfaces are **difficult to design**
- Wide range of demanded size

> 2000 times in size

1. Are lubricating interfaces linearly scalable?
2. Is there an effective scaling rule?
Scalability of elastic deformation

Linear scaling rule:

\[ \lambda = \left( \frac{V}{V_0} \right)^{\frac{1}{3}} \]

\[ h = \lambda \cdot h_0 \quad l = \lambda \cdot l_0 \]

\[ p = p_0 \quad T = T_0 \]

Elastic deformation due to thermal and pressure load

\[ \Delta h_2 = \lambda \cdot \Delta h_1 \]

Hydrostatic/hydrodynamic pressure distribution

\[ \lambda = 1 \]

\[ \lambda = 2 \]

Not scalable
Scalability of fluid domain heat transfer

**Linear scaling rule:**

\[
\lambda = \left( \frac{V}{V_0} \right)^{\frac{1}{3}}
\]

\[h = \lambda \cdot h_0 \quad l = \lambda \cdot l_0\]

\[p = p_0 \quad T = T_0\]

**Fluid domain temperature**

- Not scalable
- \(\lambda = 1\)
- \(\lambda = 2\)

**Solid domain heat transfer**

- Not scalable
- \(\lambda = 1\)
- \(\lambda = 2\)
Are lubricating interfaces linearly scalable?
- No
- Only because that hydrostatic/hydrodynamic pressure distribution, and fluid/solid domain temperature distribution are not scalable.

Is there an effective scaling rule?
- Yes
- Scaling guide has been proposed based on the findings from the scaling study.
- More effective scaling rules are proposed for three lubricating interfaces.

Where are we on axial piston machines modeling?

Power loss distribution:
Simulation vs measurement

52 cc unit, 50°C, 50%, 2000 rpm, 170 bar

Outlook

- Micro-scale tribological characterization
  - Measurement-driven simulation
  - Novel test rig for small contact patch measurement

75% accurate on power loss prediction
Outlook

- Micro-scale tribological characterization
  - Measurement-driven simulation
  - Novel test rig for small contact patch measurement

- Computational efficiency optimization
  - Contribution-based computational power allocation
  - AI-aided simulation
Conclusion

- Lubricating interfaces in axial piston machines are difficult to design
- Modeling tool helps to understand the essential insight of lubricating interface behavior
- Innovative design and innovative design process are made possible by the modeling tool
- Lubricating interface are not linear scalable due to thermal and hydrostatic/dynamic effects only
- Outlook of the model development is discussed
Thank you!