Outline

• Why is modelling & simulation important?
• The Luleå mixed lubrication model
  – Surface Topography
  – Computing Flow factors
  – Component simulation
• Current activities
• Future work
Motivation

Understanding

Testing new ideas

Optimisation

Ranking

\[ \nabla \cdot \left( \frac{\rho h^3}{12\eta} \nabla p \right) = \nabla \cdot \left( \frac{1}{2} \mathbf{u} \rho h \right) + \frac{\partial}{\partial t} (\rho h) \]

\[ \eta ? \]

\[ \eta_1, \eta_2, \eta_3 \ldots \]
Motivation

“A complement to:

Experiments

Full-scale

Component

Model

“cheap”
Motivation

Few commercially available packages

- AVL
- Excite
- Piston&Rings
- Ricardo Suite
- COMSOL
- Multiphysics
- Lubrication Shell
- MIT Consortium
The Luleå Mixed Lubrication Model

Developed by: The division of Machine Elements at LTU

Flow Factor computations
- Flow between asperities
- Asperity deformation

Component Simulation
- Utilizing the Flow Factors
- All regimes considered
- Coarse grid = fast
- Pressure
- Load
- Friction
- Leakage

Topography representation

6 PhDs
5 Lics
60+ publications
40+ Tribology
20+ Mathematics
A two scale approach

**Local scale;** describing the Surface Topography

**Global scale;** describing Geometry
- Incorporating the effects of roughness through homogenization
1. Representative roughness
   – # of realizations / measurements
   – Resampling, interpolation
   – Filtering, mirroring

2. Flow factors
   – Contact mechanics
     • Material model - Linear Elastic Perfectly Plastic
     • # Loads (=> separations)
   – Local problems
     • Core of the homogenization
     • # Separations

3. Component simulation
   – Interpolate ff’s onto global domain and solve for homogenized pressure
Artificial surfaces measured with AFM and VSI
Anomalies created from measurement technique observed
Effect on tribological parameters investigated...

<table>
<thead>
<tr>
<th></th>
<th>$S_a$ (μm)</th>
<th>$S_k$ (μm)</th>
<th>$S_{pk}$ (μm)</th>
<th>$S_{vk}$ (μm)</th>
</tr>
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<tbody>
<tr>
<td>AFM</td>
<td>39.0</td>
<td>10.9</td>
<td>45.1</td>
<td>101.0</td>
</tr>
<tr>
<td>VSI</td>
<td>91.6</td>
<td>64.3</td>
<td>220.0</td>
<td>521.0</td>
</tr>
</tbody>
</table>

Large differences in roughness parameters for artificial surfaces
Far smaller differences for 'real' surfaces
However, care must be taken with 'extreme' surfaces, i.e. laser textured

Paper by Andrew Spencer et al. - Trib. Int. Vol. 57
• Mirroring => Perfect periodicity
Topography representation

ORIGINAL IMAGE

MIRRORED IMAGE

Mirrored about the x axis

Mirrored about the y axis
Topography representation

- Resampling
• Revamped!
• Was – Matlab 2007 + COMSOL Multiphysics 3.5a
• Is – MATLAB code only!

• Mini-courses / tutorial sessions on the usage of the code will be given.

(http://www.python.org/ code under construction)
Flow factor computations

Contact mechanics
- BEM model

Local problems
- Homogenization

How to achieve a physically acceptable result?
- Representative contact mechanics model
- Clearance measure defining direct contact
- Full film computation over the non-contact area only
Why don’t we do as Patir & Cheng?

--- Incorrect modelling of the so called micro-bearing problems

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Paper by Almqvist et al. – ASME Journal of Tribology, Vol. 133
We want to:

- Include inter-asperity coupling
- Have a deterministic representation of the surface

Or as Greenwood & Tripp?
CM theory of B.N.J. Persson

![CM theory of B.N.J. Persson](image)

Contact pressure (-) vs. Average interfacial separation (Å)

- **MD**
- **Theory**
- **BEM**
- **GFMD**

Current Activities

- Cavitation  VR
- Asperity collision  SSF
- Wear modelling  VR, SSF, Sauer-Danfoss
- Piston ring - Cylinder liner lubrication  SSF, Scania
Cavitation

- Universal equation (Non-linear)
  - Elrod – “Incompressible HL”
  - Vijayaraghavan Compressible

- Linear Complementarity Problem
  - Dini - Incompressible
  - Almqvist & Wall - Compressible

\[ A(\theta)\theta = b, \]
\[ g(\theta) = \begin{cases} 
1, & \theta \geq 1 \\
0, & \theta < 1 
\end{cases} \]
\[ Ap + B(1 - \theta) = b, \]
\[ p(1 - \theta) = 0 \]
• Friction contribution to deformation included
• FFT accelerated solution procedure

Frictionless

\[ N \]

Friction included

\[ F_f = \mu N \]

PhD Student - Joel Furustig
After the first component scale simulation, new flow factors can be computed and then incorporated to compensate for possible plastic deformations.
Mesh convergence studies & Optimisation of geometries have been conducted to verify the accuracy of the model.

Thermoelasto-plastic, time dependent simulations in LS DYNA

Interference:

\[ \delta \]
Asperity collision study

Thermo-elasto-plastic, time dependent simulations in LS DYNA

Interference  Friction  Velocity

Stress  Plastic strain  Temperature
Stress grows from zero to the maximum value, then decreases to the residual stress after collision.

The distorted stress profile is due to the existence of friction.

Maximum stress is observed near the surface and large plastic deformation are observed.
• Maximum plastic strain is found close to the surface
• Wear model could be established -> plastic strain is larger than a critical value means seizure.
• Maximum temperature is found at the smaller (top) asperity
• Max temp rise $\approx 40^\circ$
Modelling PRCL lubrication

Optimizing Surface Texture for Combustion Engine Cylinder Liners

Andrew Spencer

PhD Student - Andrew Spencer
How to incorporate honing grooves?

\[ \text{Pressure (Pa)} \]

- Smooth
- Homogenized
- Deterministic

\[ x/L \]

PhD Student - Andrew Spencer
Current Activities

- Cavitation
- Asperity collision
- Wear modelling
- Piston ring - Cylinder liner lubrication
- Power losses in hydraulic motors
- Lubrication of cam – roller systems

Energimyndigheten, Scania, Volvo
VR, Hägglunds Drives
Scania, Bosch, HD
Computational server usage

**TS1 average usage by day**

- **CPU**
- **Memory**

**TS1 CPU usage by hour**
- 00:00 - 08:00
- 08:00 - 16:00
- 16:00 - 24:00

**TS1 Memory usage by hour**
- 00:00 - 08:00
- 08:00 - 16:00
- 16:00 - 24:00

**TS2 average usage by day**

- **CPU**
- **Memory**

**TS2 CPU usage by hour**
- 00:00 - 08:00
- 08:00 - 16:00
- 16:00 - 24:00

**TS2 Memory usage by hour**
- 00:00 - 08:00
- 08:00 - 16:00
- 16:00 - 24:00
Reducing engine friction

- Out of roundness
- Ring twist & dynamics
- Floating liner test rig

Volvo Powertrain AB
Energy agency
Scania

- Effect of laser texture
More than 50% reduction of power losses

PhD Student - Patrik Isaksson

Bosch Rexroth (Hägglunds drives AB)

Simulated and measured friction for bearing B
Hägglunds drives AB (Bosch Rexroth), Sweden
Robert Bosch GmbH, Germany
Scania AB, Sweden

Aim
A fast and reliable tool for prediction of slippage in cam - roller contacts
Application of LMLM

Are the scales separable? Reaction forces?

Conformal contact
Non-conformal contact

Global

Local
The dynamic behaviour can be predicted if the physics can represented by a mathematical model:

\[ \sum F_x = m \ddot{x} \]
• Inter-asperity cavitation
• Micro-EHL
• Non-Newtonian Rheology
Thank you for your attention!

Questions?