THIN LAYER FLOW
IN ROLLING ELEMENT BEARINGS

C.H. (KEES) VENNER
ROLLING ELEMENT BEARINGS

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
TYPES

- Ball bearing
- Taper roller bearing
- Spherical roller bearing
SIZES

UNIVERSITY OF TWENTE.
ROLLING CONTACTS

WEAR

Contact: roller - raceway

Extreme pressures $\geq 1-3$ GPa

UNIVERSITY OF TWENTE.
LUBRICATION

Grease or oil

† Protect surfaces by separation (thickener layer/oil layer)
† Reduce friction (just a little lubricant !!!!)
† Protection against contamination

> 80% grease lubricated

UNIVERSITY OF TWENTE.
OBJECTIVE

- Accurate prediction of
  Service life = \min(\text{fatigue life, grease life})

- Prediction of subsurface stresses and film thickness in relation to:
  - OLD: Nominal operating conditions and lubricant properties
  - NEW: Variations in time due to force, speed, start-stop, roughness moving through contact

- Lubricant availability (local amount, local properties)

- Active re-lubrication?

- Grease composition: Thickener rich protective layers?

UNIVERSITY OF TWENTE.
MODELING (Single Contact): EHL

Experimental

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
SINGLE CONTACT MODELING (EHL)

Flow: Navier Stokes, Narrow Gap (lubrication) assumption:

\[
\frac{\partial}{\partial X} \left( \varepsilon \frac{\partial p}{\partial X} \right) + \frac{\partial}{\partial Y} \left( \varepsilon \frac{\partial p}{\partial Y} \right) - \Lambda(T) \frac{\partial (\theta \rho H)}{\partial X} - \frac{\partial (\theta \rho H)}{\partial T} = 0
\]

Gap height \( h \): undeformed shape + elastic deformation

\[
H(X,Y,T) = -\Delta(T) + \frac{X^2}{2} + \frac{Y^2}{2} + \frac{2}{\pi^2} \int \int_s \frac{P(X',Y',T) dX' dY'}{\sqrt{(X - X')^2 + (Y - Y')^2}}
\]

Equation of Motion

\[
\frac{1}{\Omega^2} \frac{d^2 \Delta}{dT^2} + \frac{3}{2\pi} \int \int_s P(X,Y,T) dXdY + \overline{K} \cdot \Delta = 1 + \overline{K} \Delta_{\infty}
\]

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
Conceptual approach:

- Identify **problematic** components responsible for computational slowness (slow convergence, multi-summations).
- Design **accurate** representation for **efficient** solution (computation).

**Appearances:**

- Standard: **Geometric** Multigrid
- Advanced: General Systems: **AMG**
- Advanced: Physics, Chemistry, Particles, etc.

**Result:**

- O(N) solver: realistic conditions, many unknowns (points*timesteps) on small computers
RESULTS SINGLE CONTACT EHL

- Pressure
- Fractional film content
- Film
- Footprint

UNIVERSITY OF TWENTE.
Faculty CTW/Engineering Fluid Dynamics
SINGLE CONTACT VALIDATION

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
STEADY STATE

Standard mineral oil (shell TT9)
STEADY STATE

U = 0.05 m/s

U = 1.28 m/s

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
TIME VARYING: LOAD


UNIVERSITY OF TWENTE.
Faculty CTW/Engineering Fluid Dynamics
TIME VARYING “ROUGHNESS”

measured

computed

h=280 nm

Venner, C.H., Kaneta, M., and Lubrecht, A.A.,

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
STARVED CONTACTS: EXPERIMENTAL
STARVED CONTACTS
Direct relation between inlet layer and film thickness in the contact.

Accurate prediction when oil layer thickness correctly modeled.

APPLICATION TO REAL BEARINGS?

Complications:

§ Repeated overrolling in very short time
§ Billions of overrollings in life-time !!!! (even MG doesn’t help enough)
§ Lubricant migration (grease bleeding, cage, centrifugal forces etc.)
  determines inlet layer of oil on surface to each the contact
§ ……

Solution: Thin Layer flow model for layer flow, linked to direct relation
  between layer and film from starved contact.
THIN LAYER FLOW MODEL: INTRO

- To develop a model that predicts change supply layer thickness.
- Use model to predict long term film thickness decay.

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
THIN LAYER FLOW IN BEARINGS

Contact pressure effect

Centrifugal effect

Lubricant film thickness distribution

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
COMBINING LAYERS: EQUIPARTITION

The concept

Object 2

Object 1

Contact area

h = h_1

h_2 = h_2

h_1 - h_2

Measurement setup

Measurements have been carried out by H. de Ruig and R. Meeuwenoord at SKF ERC

Measurement Results

Slit thickness:

5 µm

10 µm

20 µm

40 µm

Measurements have been carried out by H. de Ruig and R. Meeuwenoord at SKF ERC

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
CONTACT PRESSURE: BEARING

Mass conservation

$$\frac{\partial h_\infty}{\partial t} = - \frac{1}{\rho_0 l_t} \frac{\partial q_y}{\partial y}$$

Mass flow in EHL contacts

$$\hat{q}_y(y,t) = \sum_{k=1}^{n_c} \hat{q}_{y,k}$$

$$\hat{q}_{y,k}(y,t) = \frac{1}{2\pi} \int_0^{2\pi} \int_{a^-}^{a^+} \left( -\frac{\rho h^3}{12\eta} \frac{\partial p}{\partial y} \right)_k dx dy$$

$$\eta = \eta(p) \quad p = p(x,y,\psi,t)$$

$$\rho = \rho(p) \quad h = h(x,y,\psi,t)$$
**CONNECTION TO “INSIDE CONTACT”**

\[ h_{\text{oil}} \to 0 \quad \lim_{h_{\text{oil}} \to 0} \frac{2 h_{\text{oil}}}{\bar{\rho}} \]

**Layer thickness**

Layer thickness

\[ h_{\text{oil}} \to 0 \quad \lim_{h_{\text{oil}} \to 0} \frac{2 h_{\text{oil}}}{\bar{\rho}} \]

**Pressure**

Pressure

\[ h_{\text{oil}} \to 0 \quad \lim_{h_{\text{oil}} \to 0} p = p_h \sqrt{1 - \left( \frac{x}{a} \right)^2 - \left( \frac{y}{b} \right)^2} \]
**SINGLE CONTACT: VALIDATION**

**Circular contact**

- $F = 20 \text{ N}, p_h = 0.5 \text{ GPa}, \eta_0 \approx 0.8 \text{ Pa.s}$

**Elliptical contact**

- $F = 30 \text{ N}, p_h = 0.33 \text{ GPa}, \eta_0 \approx 0.85 \text{ Pa.s}$


**UNIVERSITY OF TWENTE.**

Faculty CTW/Engineering Fluid Dynamics
SINGLE CONTACT: VALIDATION

Starved Elasto-Hydrodynamic Lubrication

Central film thickness vs. Time [seconds]

UNIVERSITY OF TWENTE. Faculty CTW/Engineering Fluid Dynamics
SINGLE CONTACT: VALIDATION

(a) Initial oil layer distribution
(b) $t = 0$ sec. $h = 147$ nm
(c) $t = 123$ sec. $h = 67$ nm
(d) $t = 744$ sec. $h = 27$ nm

Graph showing film thickness $h$ over time $t$.

UNIVERSITY OF TWENTE.  
Faculty CTW/Engineering Fluid Dynamics
CONTACT PRESSURE: BEARING

UNIVERSITY OF TWENTE.
CONTACT PRESSURE: BEARING

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
VARYING BEARING LOAD

$F_i = 2.5 \text{ kN}, \Omega = 3000 \text{ rpm}$

$F_i = 10 \text{ kN}, \Omega = 3000 \text{ rpm}$
VARYING BEARING SPEED

Faculty CTW/Engineering Fluid Dynamics

UNIVERSITY OF TWENTE.
FILM THICKNESS DECAY

\[ F_r = 10 \text{ kN}, \Omega_r = 3000 \text{ rpm} \]

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>Speed [rpm]</th>
<th>At [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>750</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>1500</td>
<td>3.8</td>
</tr>
<tr>
<td>10</td>
<td>3000</td>
<td>5.8</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
<td>5.7</td>
</tr>
<tr>
<td>2.5</td>
<td>3000</td>
<td>5.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load [kN]</th>
<th>Speed [rpm]</th>
<th>At [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>750</td>
<td>0.048</td>
</tr>
<tr>
<td>10</td>
<td>1500</td>
<td>0.072</td>
</tr>
<tr>
<td>10</td>
<td>3000</td>
<td>0.109</td>
</tr>
<tr>
<td>5</td>
<td>3000</td>
<td>0.105</td>
</tr>
<tr>
<td>2.5</td>
<td>3000</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Spherical Roller Bearing

Deep groove Ball Bearing

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
CONCLUSION

Film decay model for bearings developed based on:

- Thin layer flow model
- Starved EHL

Model is developed to predict change of supply layer

- Centrifugal effects
- Contact pressure effects

Single Contact Model is validated experimentally

Bearing Model is worst case, further validation needed and addition of sources
Challenges and Future Role of Physics+Chemistry

Optimization of Lubricant availability and composition

- Nano-scale protective layers (grease composition)
- Activate local relubrication (meniscus/contact line control/momentary lubricant supply)
- Mixed lubrication modeling
- Transition to zero film physically correctly
- Multiscale Islands
Acknowledgement

Many collaborators
1. Brandt (Weizmann Institute of Science, Israel)
2. Lubrecht (INSA-Lyon), Greenwood (Cambridge, UK), Hooke (Birmingham, UK), Cann (Imperial College), Bair (Georgia Tech, USA)
3. PhD Students: Ysbrand Wijnant, Benoit Jacod, Daniel van Odyck, Gheorghe Popovici, Marco van Zoelen
4. STW, SKF ERC

Thank you for your kind attention
THIN LAYER FLOW

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Navier-Stokes equation (incompressible flow, constant viscosity):

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = f_x - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = f_y - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]

\[
\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = f_z - \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
THIN LAYER FLOW

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 1: \[ \varepsilon = \frac{H}{L} \quad W = \varepsilon U \]

\[ \varepsilon^2 \text{Re} \left( \frac{\partial \bar{u}}{\partial \tilde{t}} + \bar{u} \frac{\partial \bar{u}}{\partial \tilde{x}} + \bar{v} \frac{\partial \bar{u}}{\partial \tilde{y}} + \bar{w} \frac{\partial \bar{u}}{\partial \tilde{z}} \right) = \bar{f}_x - \frac{\partial \bar{p}}{\partial \tilde{x}} + \varepsilon^2 \frac{\partial^2 \bar{u}}{\partial \tilde{x}^2} + \varepsilon^2 \frac{\partial^2 \bar{u}}{\partial \tilde{y}^2} + \frac{\partial^2 \bar{u}}{\partial \tilde{z}^2} \]

\[ \varepsilon^2 \text{Re} \left( \frac{\partial \bar{v}}{\partial \tilde{t}} + \bar{u} \frac{\partial \bar{v}}{\partial \tilde{x}} + \bar{v} \frac{\partial \bar{v}}{\partial \tilde{y}} + \bar{w} \frac{\partial \bar{v}}{\partial \tilde{z}} \right) = \bar{f}_y - \frac{\partial \bar{p}}{\partial \tilde{y}} + \varepsilon^2 \frac{\partial^2 \bar{v}}{\partial \tilde{x}^2} + \varepsilon^2 \frac{\partial^2 \bar{v}}{\partial \tilde{y}^2} + \frac{\partial^2 \bar{v}}{\partial \tilde{z}^2} \]

\[ \varepsilon^4 \text{Re} \left( \frac{\partial \bar{w}}{\partial \tilde{t}} + \bar{u} \frac{\partial \bar{w}}{\partial \tilde{x}} + \bar{v} \frac{\partial \bar{w}}{\partial \tilde{y}} + \bar{w} \frac{\partial \bar{w}}{\partial \tilde{z}} \right) = \bar{f}_z - \frac{\partial \bar{p}}{\partial \tilde{z}} + \varepsilon^4 \frac{\partial^2 \bar{w}}{\partial \tilde{x}^2} + \varepsilon^4 \frac{\partial^2 \bar{w}}{\partial \tilde{y}^2} + \varepsilon^2 \frac{\partial^2 \bar{w}}{\partial \tilde{z}^2} \]
THIN LAYER FLOW

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 2: $\varepsilon = \frac{H}{L}$ $W = \varepsilon U$

$$\varepsilon^2 \text{Re} \left( \frac{\partial \bar{u}}{\partial t} + \bar{u} \frac{\partial \bar{u}}{\partial x} + \bar{v} \frac{\partial \bar{u}}{\partial y} + \bar{w} \frac{\partial \bar{u}}{\partial z} \right) = \bar{f}_x - \frac{\partial \bar{p}}{\partial x} + \varepsilon^2 \frac{\partial^2 \bar{u}}{\partial x^2} + \varepsilon^2 \frac{\partial^2 \bar{u}}{\partial y^2} + \frac{\partial^2 \bar{u}}{\partial z^2}$$

$$\varepsilon^2 \text{Re} \left( \frac{\partial \bar{v}}{\partial t} + \bar{u} \frac{\partial \bar{v}}{\partial x} + \bar{v} \frac{\partial \bar{v}}{\partial y} + \bar{w} \frac{\partial \bar{v}}{\partial z} \right) = \bar{f}_y - \frac{\partial \bar{p}}{\partial y} + \varepsilon^2 \frac{\partial^2 \bar{v}}{\partial x^2} + \varepsilon^2 \frac{\partial^2 \bar{v}}{\partial y^2} + \frac{\partial^2 \bar{v}}{\partial z^2}$$

$$\varepsilon^4 \text{Re} \left( \frac{\partial \bar{w}}{\partial t} + \bar{u} \frac{\partial \bar{w}}{\partial x} + \bar{v} \frac{\partial \bar{w}}{\partial y} + \bar{w} \frac{\partial \bar{w}}{\partial z} \right) = \bar{f}_z - \frac{\partial \bar{p}}{\partial z} + \varepsilon^4 \frac{\partial^2 \bar{w}}{\partial x^2} + \varepsilon^4 \frac{\partial^2 \bar{w}}{\partial y^2} + \varepsilon^2 \frac{\partial^2 \bar{w}}{\partial z^2}$$

UNIVERSITY OF TWENTE. Faculty CTW/Engineering Fluid Dynamics
THIN LAYER FLOW

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 2:

\[
0 = f_x - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial z^2} \right)
\]
\[
0 = f_y - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial z^2} \right)
\]
\[
0 = f_z - \frac{\partial p}{\partial z}
\]
**THIN LAYER FLOW**

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

**Step 2:**

\[
0 = f_x - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial z^2} \right)
\]

\[
0 = f_y - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial z^2} \right)
\]

\[
0 = f_z - \frac{\partial p}{\partial z}
\]
THIN LAYER FLOW

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 3:

\[ p = f_z (z - h) - \tau_c \kappa + p_0 \]

\[ \langle u \rangle = \frac{1}{h} \int_0^h u \, dz = \frac{h^2}{3\mu} \left[ f_x + \frac{3}{8} h \frac{\partial f_z}{\partial x} + f_z \frac{\partial h}{\partial x} + \tau_s \left( \frac{\partial^3 h}{\partial x^3} + \frac{\partial^3 h}{\partial y^2 \partial x} \right) \right] \]

\[ \langle v \rangle = \frac{1}{h} \int_0^h v \, dz = \frac{h^2}{3\mu} \left[ f_y + \frac{3}{8} h \frac{\partial f_z}{\partial y} + f_z \frac{\partial h}{\partial y} + \tau_s \left( \frac{\partial^3 h}{\partial x^2 \partial y} + \frac{\partial^3 h}{\partial y^3} \right) \right] \]
THIN LAYER APPROXIMATION

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \rightarrow 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 4:

\[
\begin{align*}
\frac{1}{3\mu} \frac{\partial}{\partial x} \left( h^3 \left[ f_x + \frac{3}{8} h \frac{\partial f_z}{\partial x} + f_z \frac{\partial h}{\partial x} + \tau_s \left( \frac{\partial^3 h}{\partial x^3} + \frac{\partial^3 h}{\partial y^2 \partial x} \right) \right] \right) + \ldots \\
\frac{1}{3\mu} \frac{\partial}{\partial y} \left( h^3 \left[ f_y + \frac{3}{8} h \frac{\partial f_z}{\partial y} + f_z \frac{\partial h}{\partial y} + \tau_s \left( \frac{\partial^3 h}{\partial x^2 \partial y} + \frac{\partial^3 h}{\partial y^3} \right) \right] \right) + \frac{\partial h}{\partial t} = 0
\end{align*}
\]


UNIVERSITY OF TWENTE.
THIN LAYER APPROXIMATION

1. Scale the N-S equations
2. Take the limit as taking the limit of as $\varepsilon \to 0$
3. Derive equation velocities
4. Insert the velocities into continuity equation.

Step 4:

\[
\frac{1}{3\mu} \frac{\partial}{\partial x} \left( h^3 \left[ f_x + \frac{3}{8} h \frac{\partial f_z}{\partial x} + f_z \frac{\partial h}{\partial x} + \tau_s \left( \frac{\partial^3 h}{\partial x^3} + \frac{\partial^3 h}{\partial y^2 \partial x} \right) \right] \right) + \ldots
\]

\[
\frac{1}{3\mu} \frac{\partial}{\partial y} \left( h^3 \left[ f_y + \frac{3}{8} h \frac{\partial f_z}{\partial y} + f_z \frac{\partial h}{\partial y} + \tau_s \left( \frac{\partial^3 h}{\partial x^2 \partial y} + \frac{\partial^3 h}{\partial y^3} \right) \right] \right) + \frac{\partial h}{\partial t} = 0
\]

CENTRIFUGAL EFFECTS RACEWAY

Example

UNIVERSITY OF TWENTE.

Faculty CTW/Engineering Fluid Dynamics
CENTRIFUGAL EFFECTS RACEWAY

Example
**CENTRIFUGAL EFFECT RACEWAY: VALIDATION**

Flow equation
\[
\frac{1}{r} \frac{\partial}{\partial s} \left( \frac{h^3}{3n_0} \frac{r f_s}{s} \right) + \frac{\partial h}{\partial t} = 0
\]

Body force equation
\[
f_s = \rho \Omega^2 r \frac{dr}{ds}
\]

---


UNIVERSITY OF TWENTE.
SIMPLIFICATION

2D \not\equiv 1D:

- Equipartition
- Contact pressure smoothening
- Surface tension

\[
\frac{1}{3\mu} \frac{\partial}{\partial y} \left( h^3 f_x \right) + \frac{\partial h}{\partial t} = 0
\]

- Hyperbolic equation, easily solved by method of characteristics

UNIVERSITY OF TWENTE.
CENTRIFUGAL EFFECT ROLLER

Flow equation

\[ \frac{1}{r} \frac{\partial}{\partial s} \left( \frac{h^3}{3 \eta_0} r f_s \right) + \frac{\partial h}{\partial r} = 0 \]

Body force equation

Raceways:

\[ f_{s, rw} = \rho \Omega_{rw}^2 r \frac{dr}{ds} \]

Rollers:

\[ f_{s, rol} = \rho \Omega_{ca}^2 \left( \sin^2(\gamma) z_{rol} + \sin(\gamma) R_{rol} \right) \frac{dz_{rol}}{ds} \]

\[ + \left( \left( \frac{1}{2} \cos^2(\gamma) \right) \Omega_{ca}^2 + 2 \Omega_{ca} \Omega_{rol} \cos(\gamma) + \Omega_{rol}^2 \right) \rho r_{rol} \frac{dr_{rol}}{ds} \]
CENTRIFUGAL EFFECT: BEARING

• Time steps:

\[ t/\tau = \frac{\eta}{H^2 \rho \Omega^2} = 0, 0.3, 1, 3, 10, 50 \]