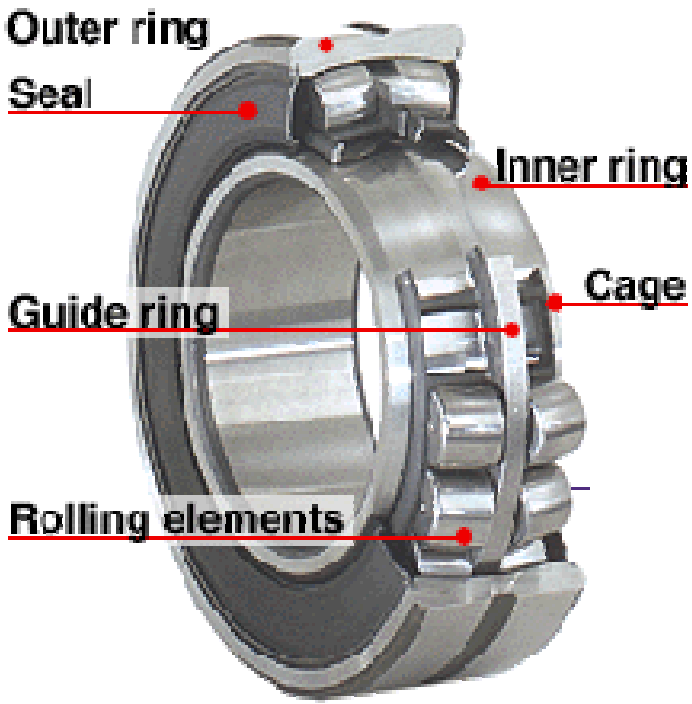
UNIVERSITY OF TWENTE.

THIN LAYER FLOW

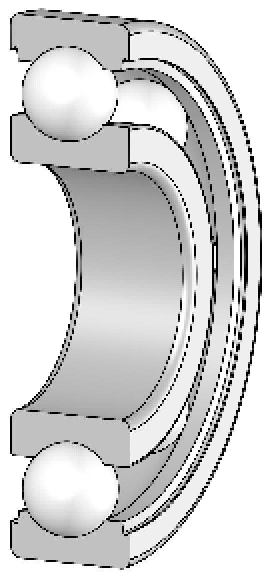
IN ROLLING ELEMENT BEARINGS

C.H. (KEES) VENNER

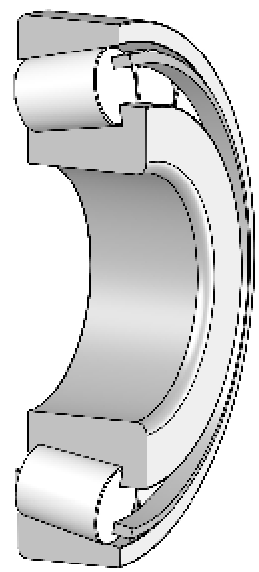
ROLLING ELEMENT BEARINGS



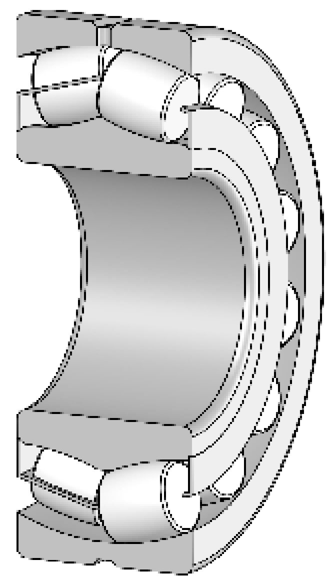
TYPES



Ball bearing

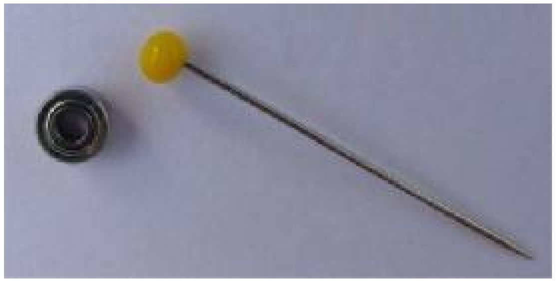


Taper roller bearing



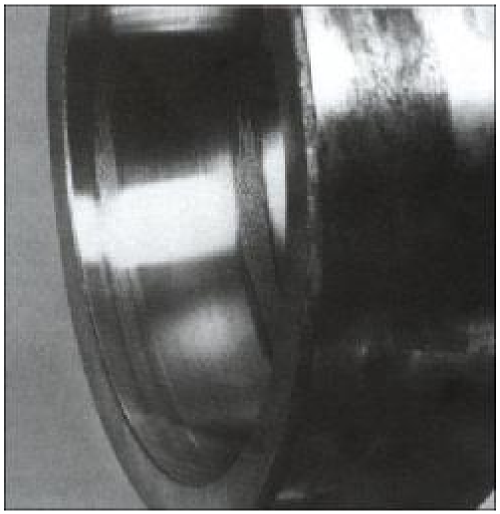
Spherical roller bearing

SIZES

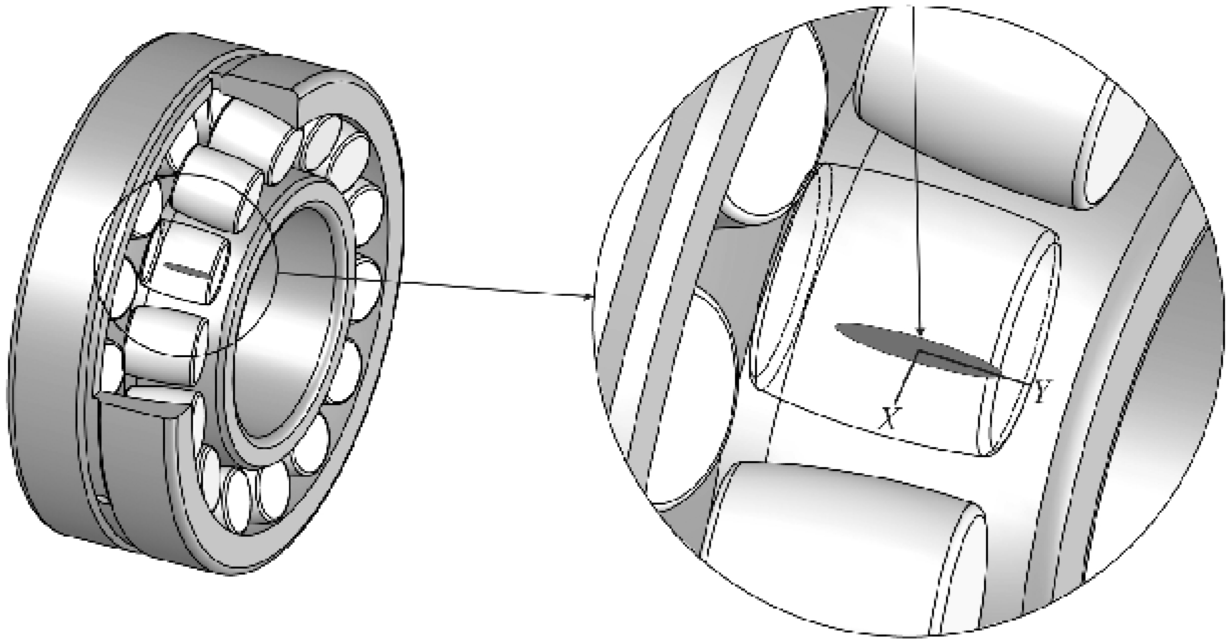


ROLLING CONTACTS

WEAR



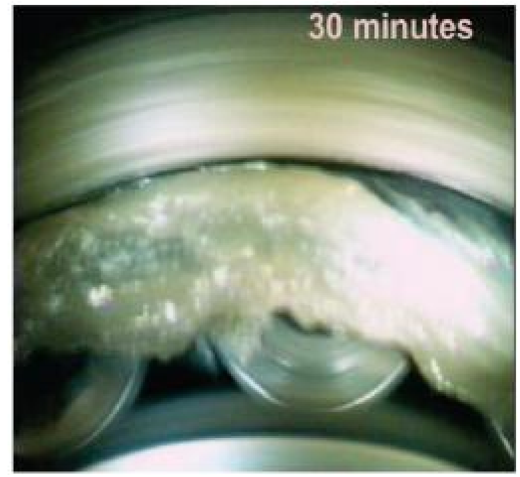
Contact: roller - raceway



Extreme pressures **à** 1-3 GPa

LUBRICATION

Grease or oil



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

> 80% grease lubricated

OBJECTIVE

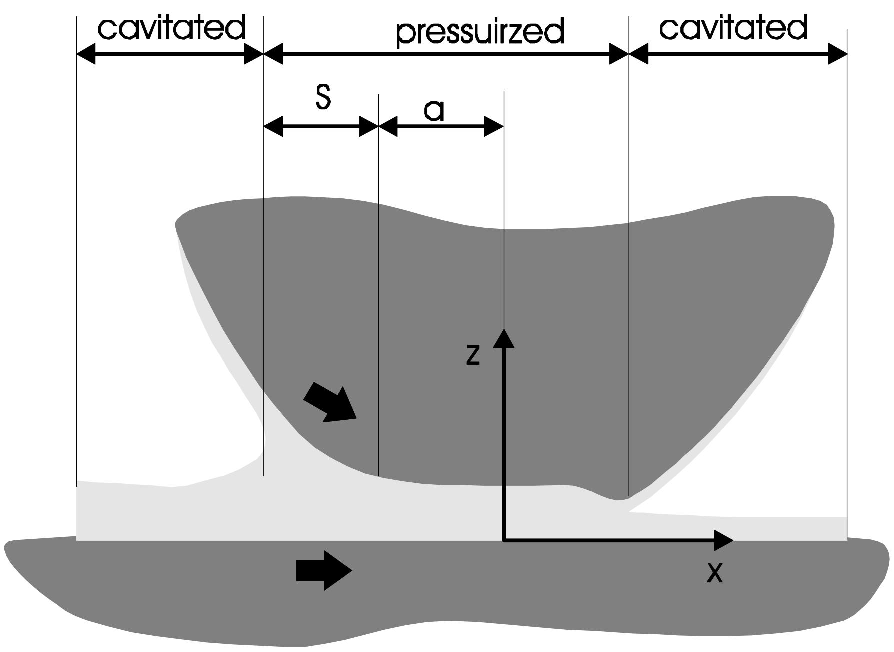
- Accurate prediction of

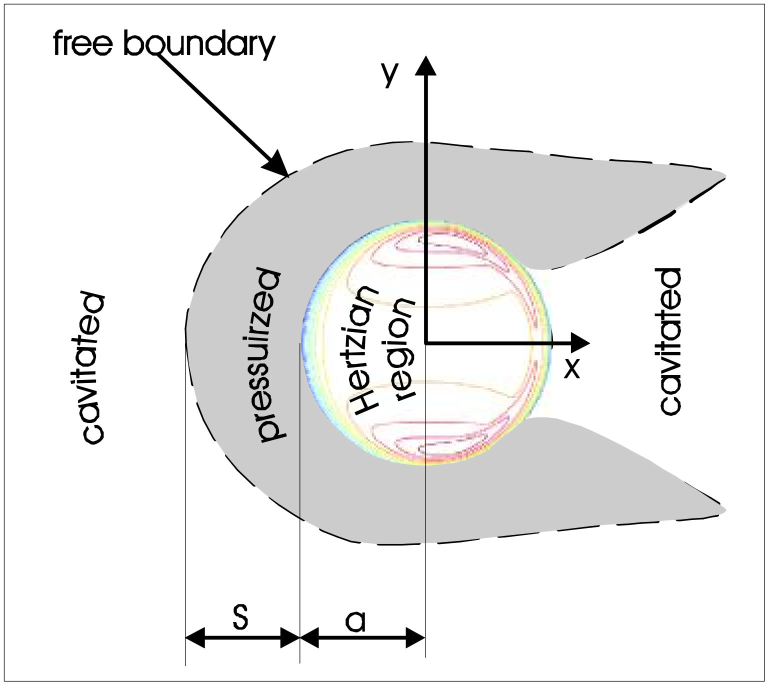
  Service life= min(fatigue life, grease life)

- 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 ?

MODELING (Single Contact): EHL

Experimental





SINGLE CONTACT MODELING (EHL)

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

$$\frac{\partial}{\partial X}\left(e\,\frac{\partial P}{\partial X}\right)+\frac{\partial}{\partial Y}\left(e\,\frac{\partial P}{\partial Y}\right)-\Lambda(T)\frac{\partial\left(q\,\overline{r}\,H\right)}{\partial X}-\frac{\partial\left(q\,\overline{r}\,H\right)}{\partial T}=0$$

\+ viscosity en density pressure law

Gap height h: undeformed shape+elastic deformation

$$H(X,Y,T)=-\Delta(T)+\frac{X^2}{2}+\frac{Y^2}{2}+\frac{2}{p^2}\iint_S\frac{P(X',Y',T)\,dX'\,dY'}{\sqrt{(X-X')^2+(Y-Y')^2}}$$

Equation of Motion

$$\frac{1}{\Omega^2}\frac{d^2\Delta}{dT^2}+\frac{3}{2p}\iint_S P(X,Y,T)\,dX\,dY+\overline{K}\cdot\Delta=1+\overline{K}\Delta_\infty$$

MULTISCALE/MULTILEVEL COMPUTATIONAL METHODS

Conceptual approach:

§ Identify **problematic** components responsible for computational slowness (slow convergence, multi-summations).

§ Design **accurate** representation for **efficient** solution (computation)

§ **Appearances:**

Standard: **Geometric** Multigrid

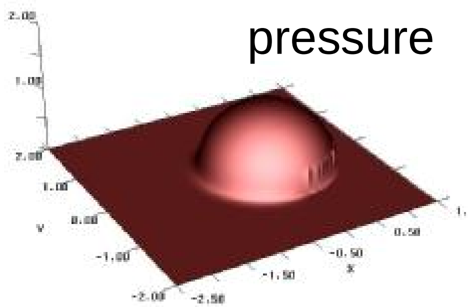
Advanced: General Systems: **AMG**

Advanced: Physics, Chemistry, Particles, etc.

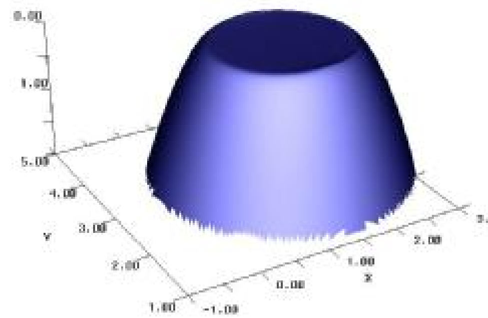
§ **Result:**

O(N) solver: realistic conditions, many unknowns (points*timesteps) on small computers

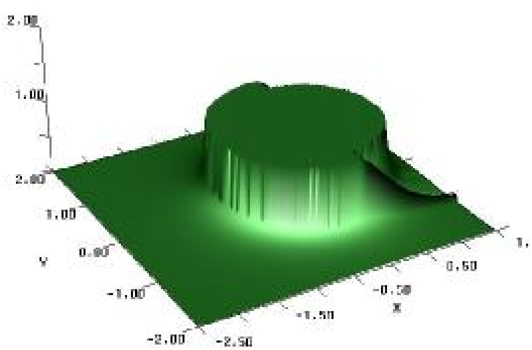
RESULTS SINGLE CONTACT EHL



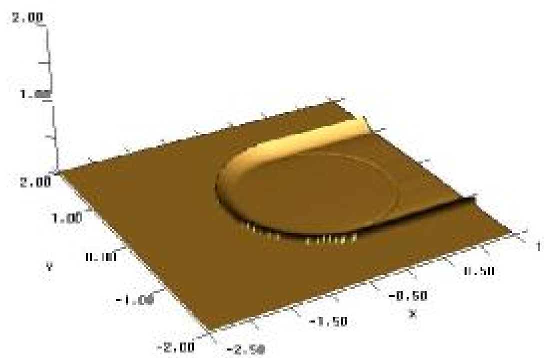
pressure



film

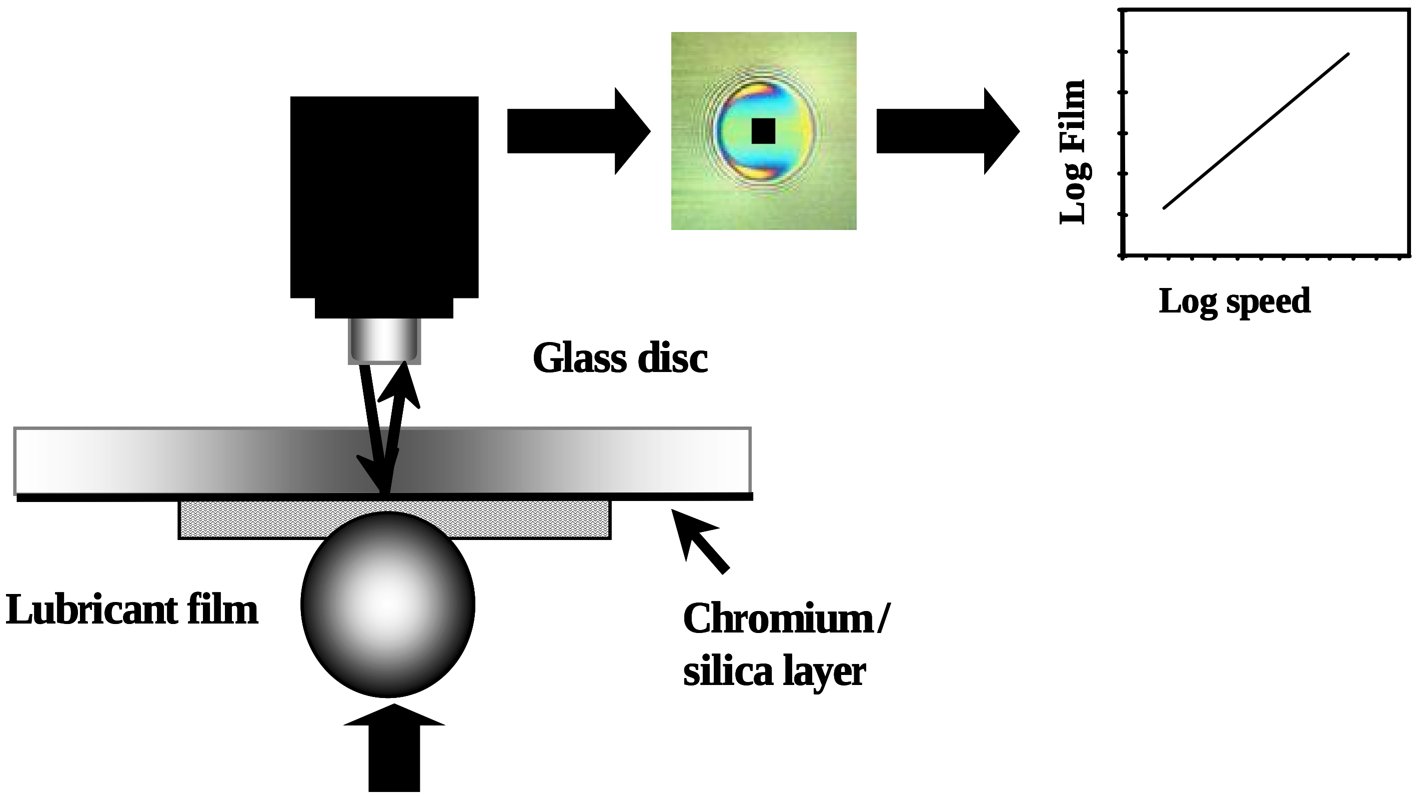


Fractional film content



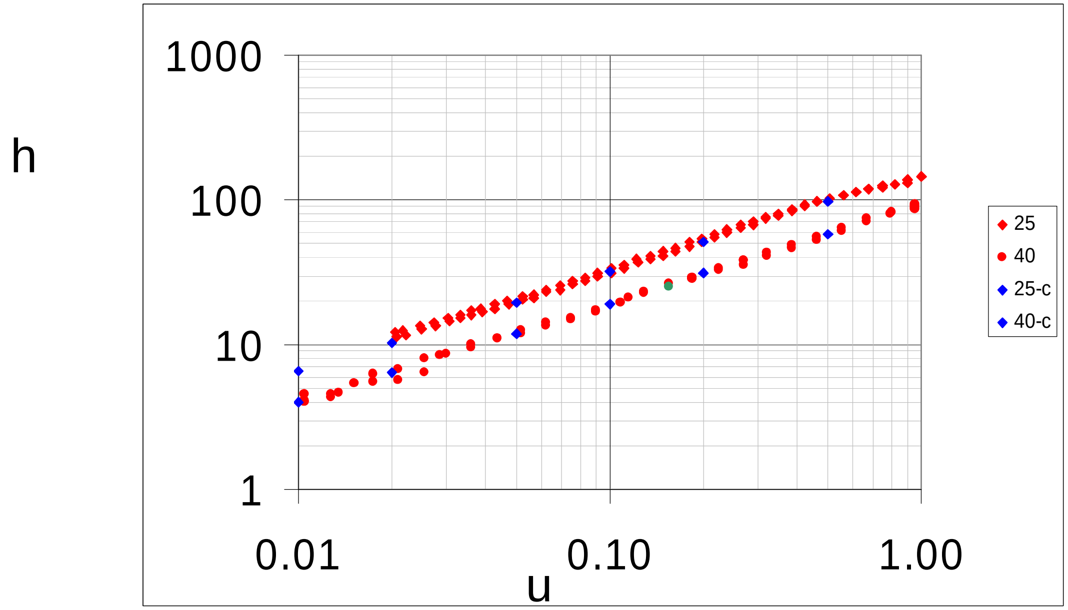
footprint

SINGLE CONTACT VALIDATION

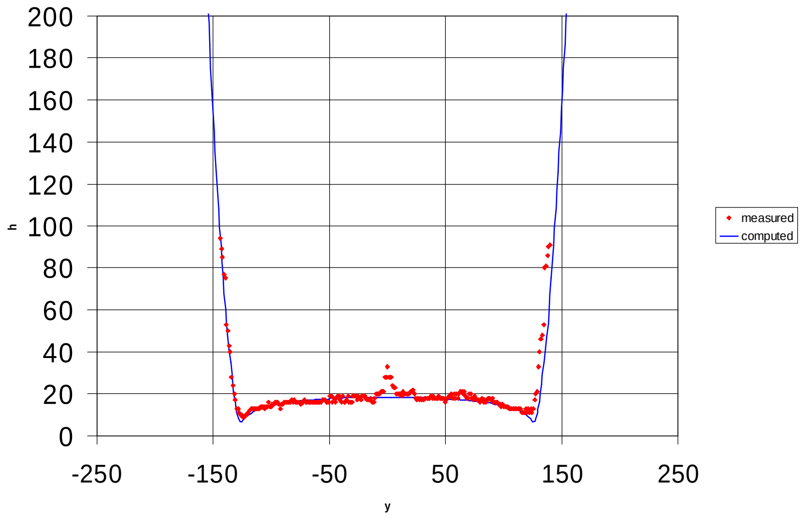


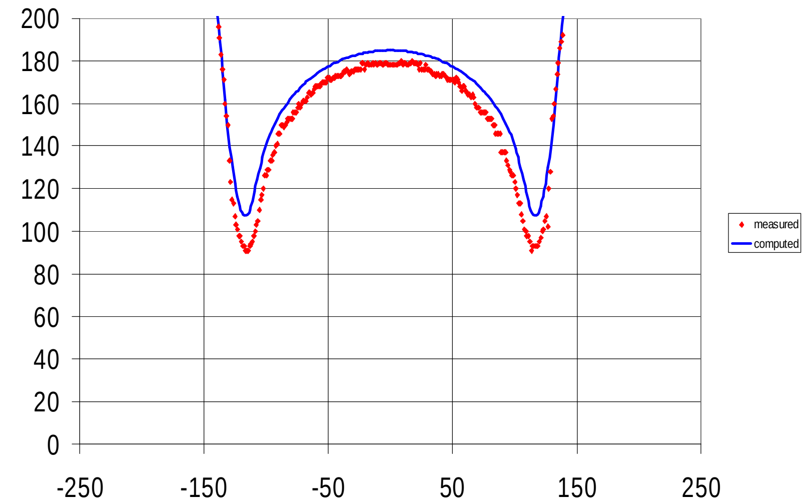
STEADY STATE

Standard mineral oil (shell TT9)

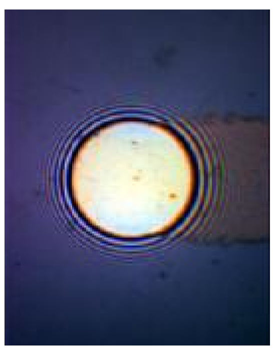


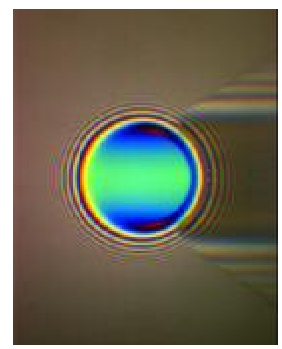
STEADY STATE





U=0.05 m/s



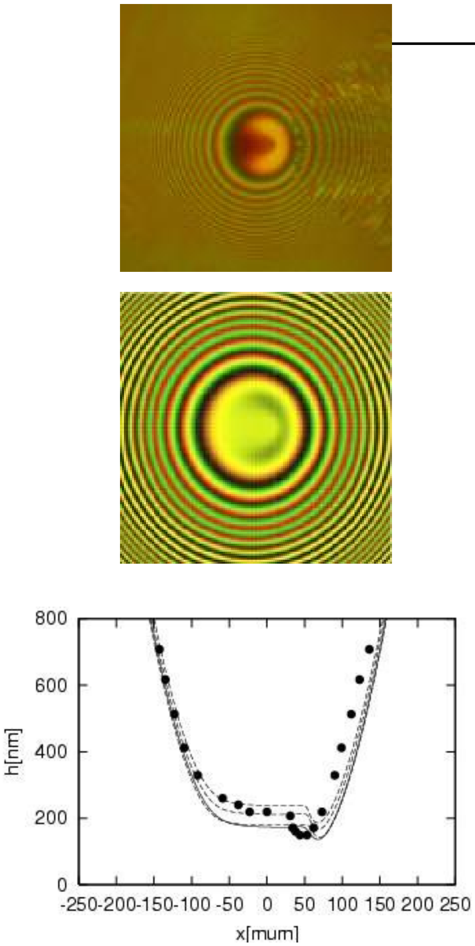


U=1.28 m/s

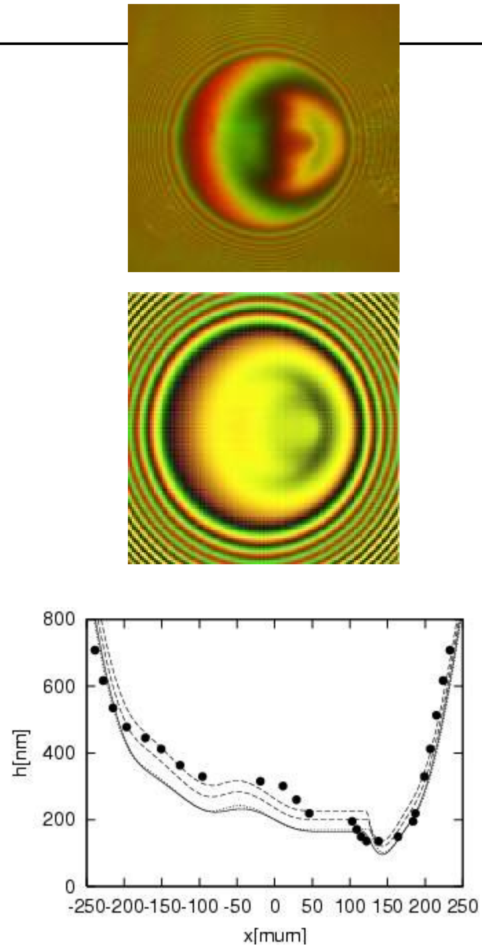
TIME VARYING: LOAD

Experimental results: Sakamoto, M., Nishikawa, H., Kaneta, M., Proc. 30th Leeds –Lyon Symposium On Tribology, p391-399 (2004)

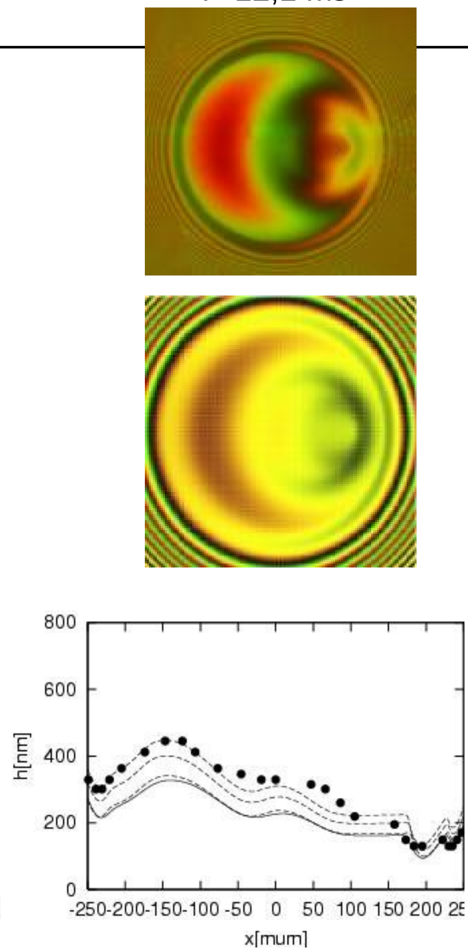
T=0 ms



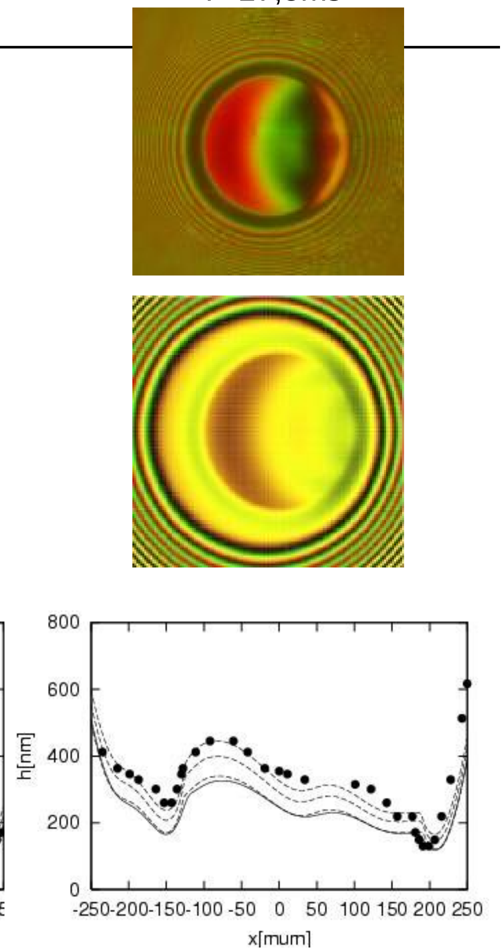
T=8 ms



T=12,1 ms



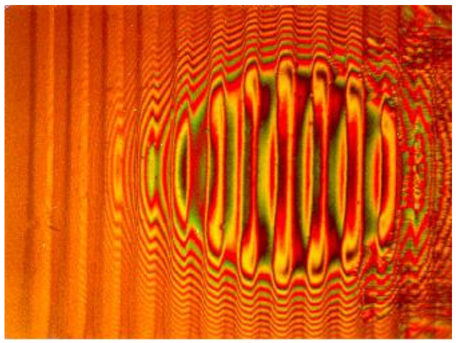
T=17,5ms

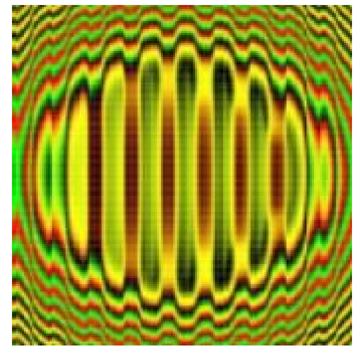


TIME VARYING “ROUGHNESS”

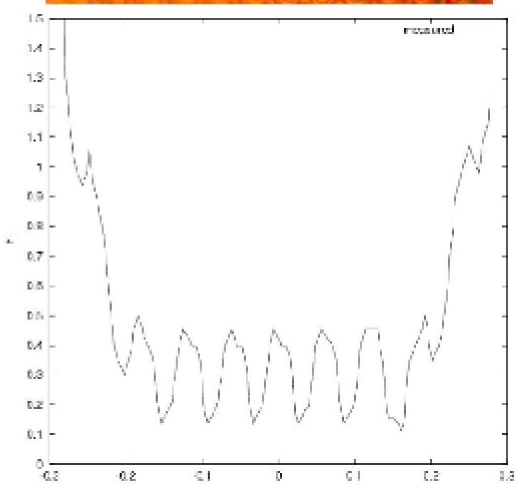
measured

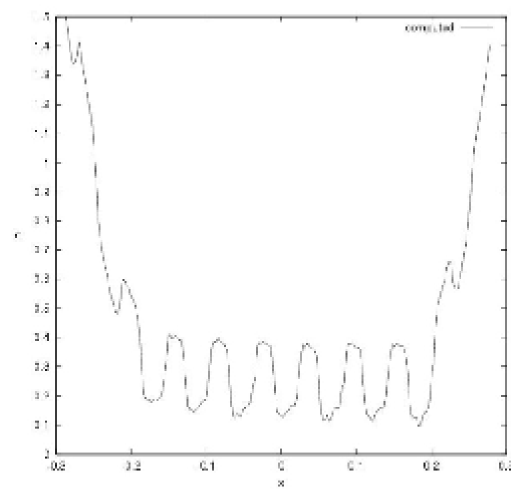
computed





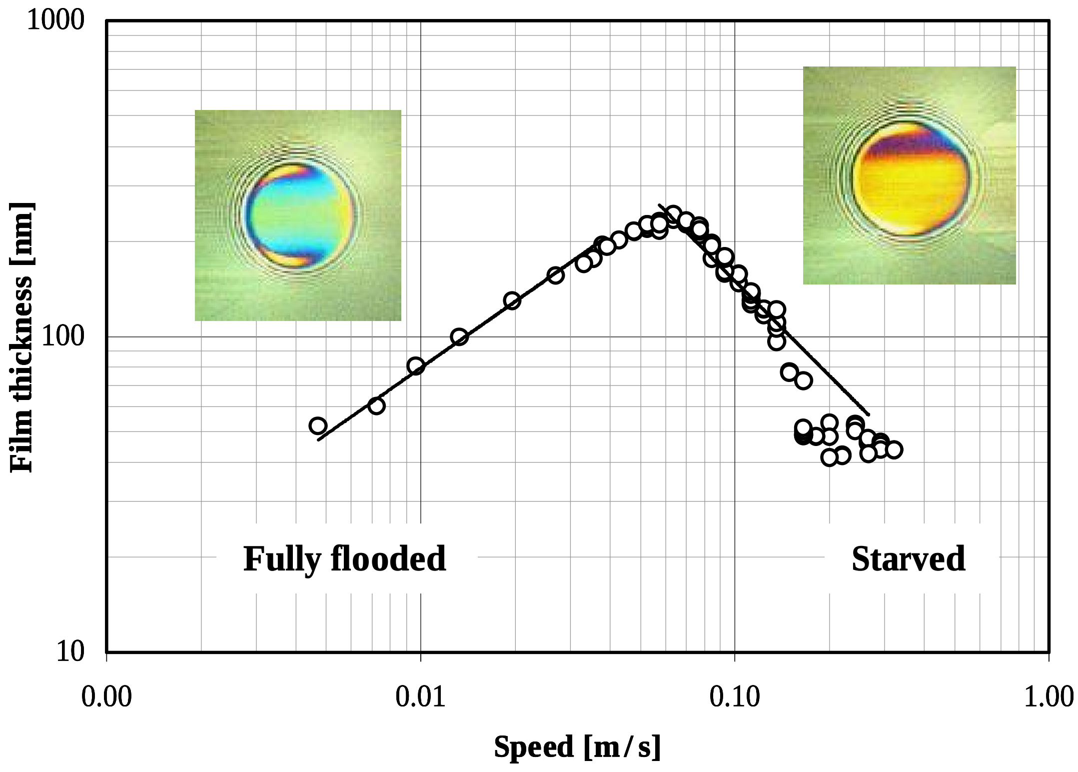
h=280 nm



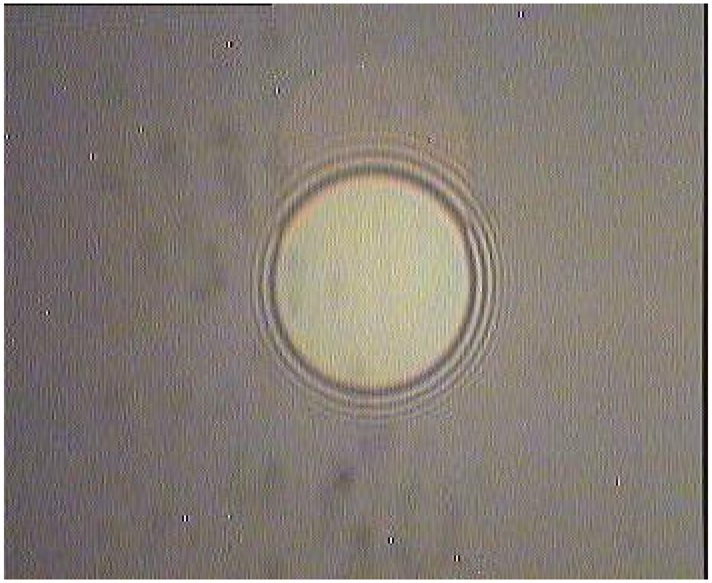


Venner, C.H., Kaneta, M., and Lubrecht, A.A.,
Proceedings 26th Leeds Lyon Symposium on Tribology, p25-36 (2000)

STARVED CONTACTS: EXPERIMENTAL



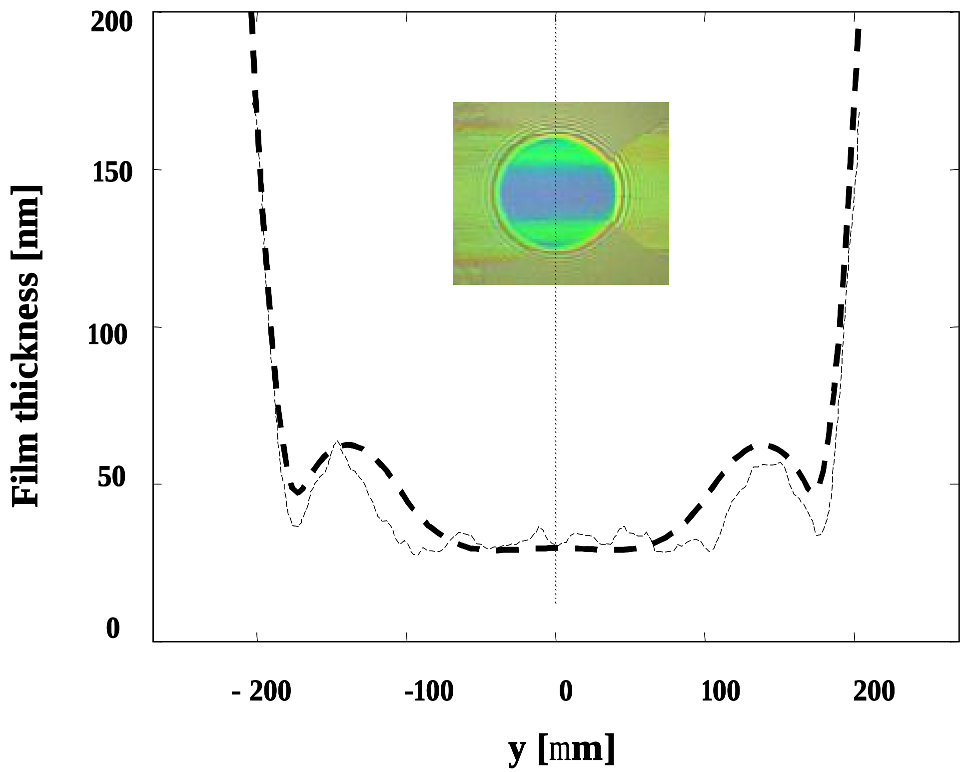
STARVED CONTACTS



STARVED CONTACTS

Direct relation between inlet layer and film thickness in the contact.

Accurate prediction when oil layer thickness correctly modeled.



Chevalier, F. Lubrecht, A.A., Cann, P., Dalmaz, G., and Colin, F. Proceedings 22nd Leeds Lyon Symposium on Tribology, p 126-133, (1998)

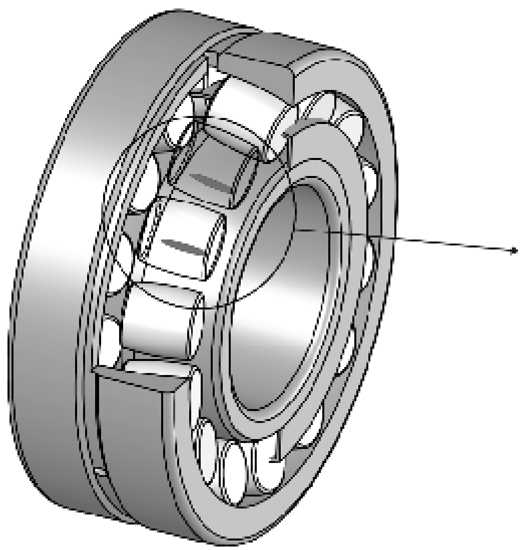
APPLICATION TO REAL BEARINGS ?

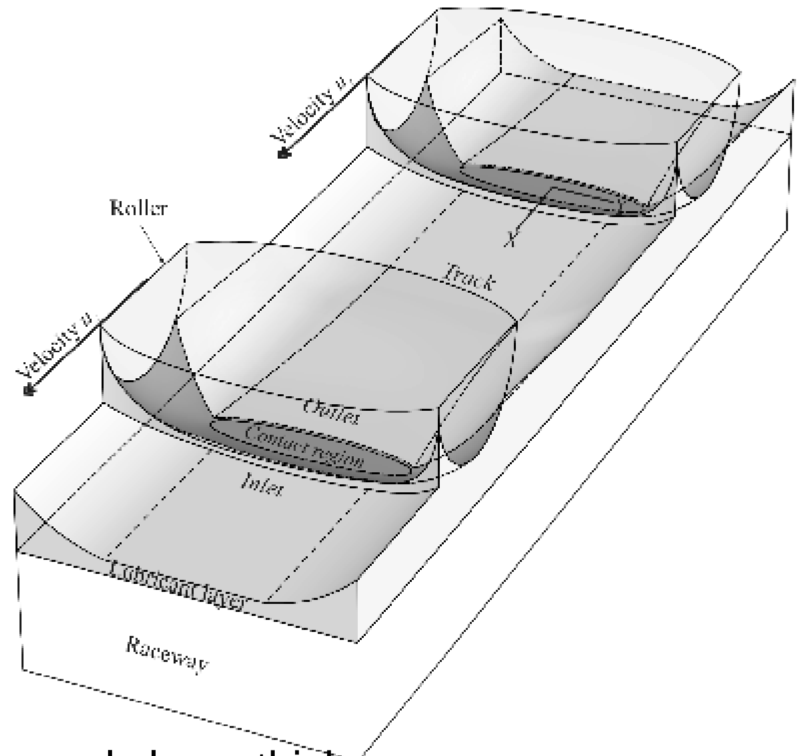
Complications:

- 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

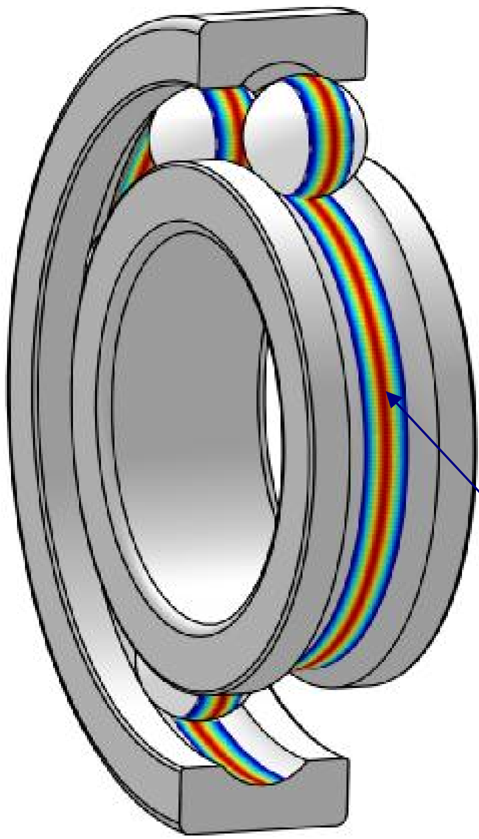




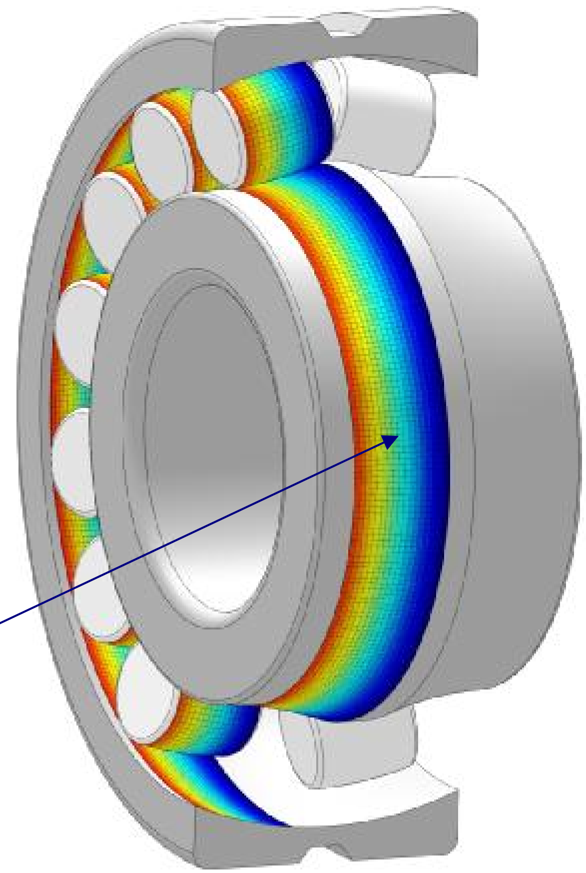
- To develop a model that predicts change supply layer thickness.
- Use model to predict long term film thickness decay.

THIN LAYER FLOW IN BEARINGS

Contact pressure effect



Centrifugal effect

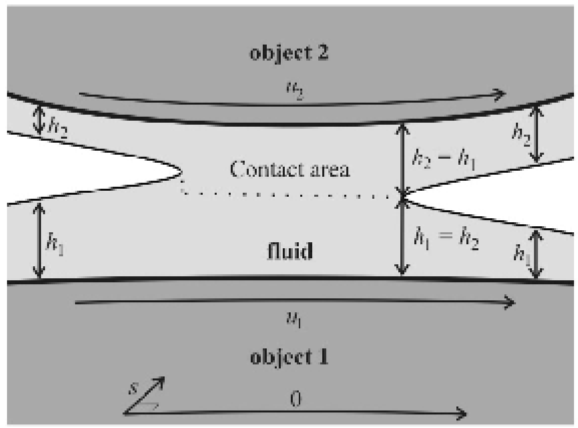


Lubricant film

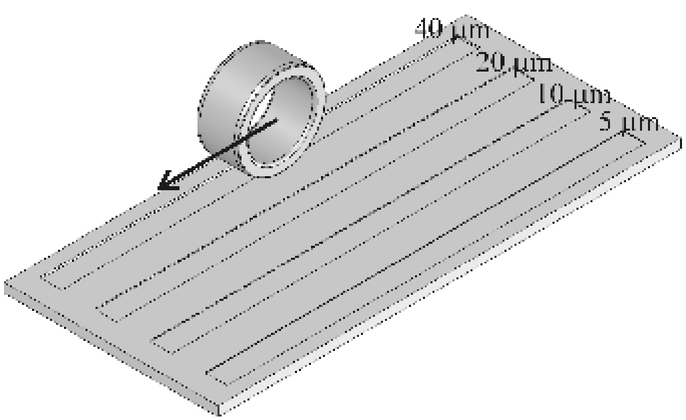
thickness distribution

COMBINING LAYERS: EQUIPARTION

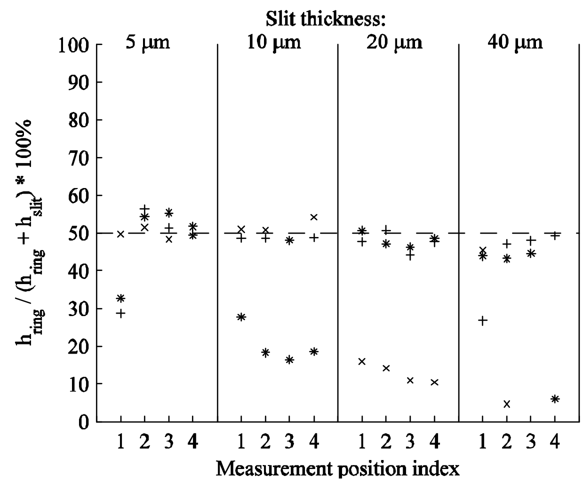
The concept



Measurement setup



Measurement Results



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

CONTACT PRESSURE: BEARING

Mass conservation

$$\frac{\partial \tilde{h}_\infty}{\partial t} = -\frac{1}{r_0 l_t}\frac{\partial \hat{q}_y}{\partial y}$$

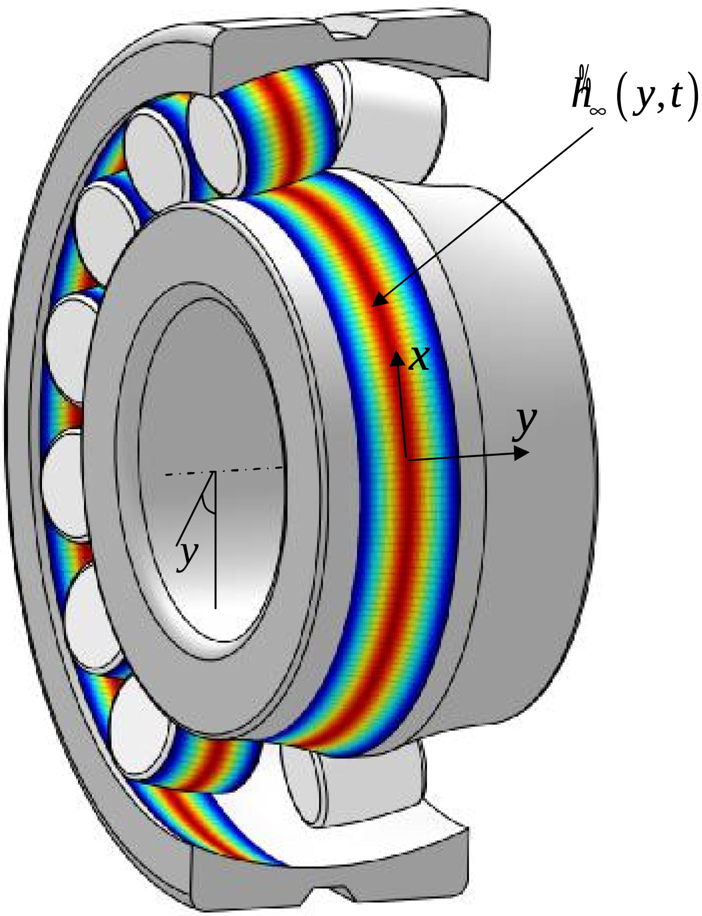
Mass flow in EHL contacts

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

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

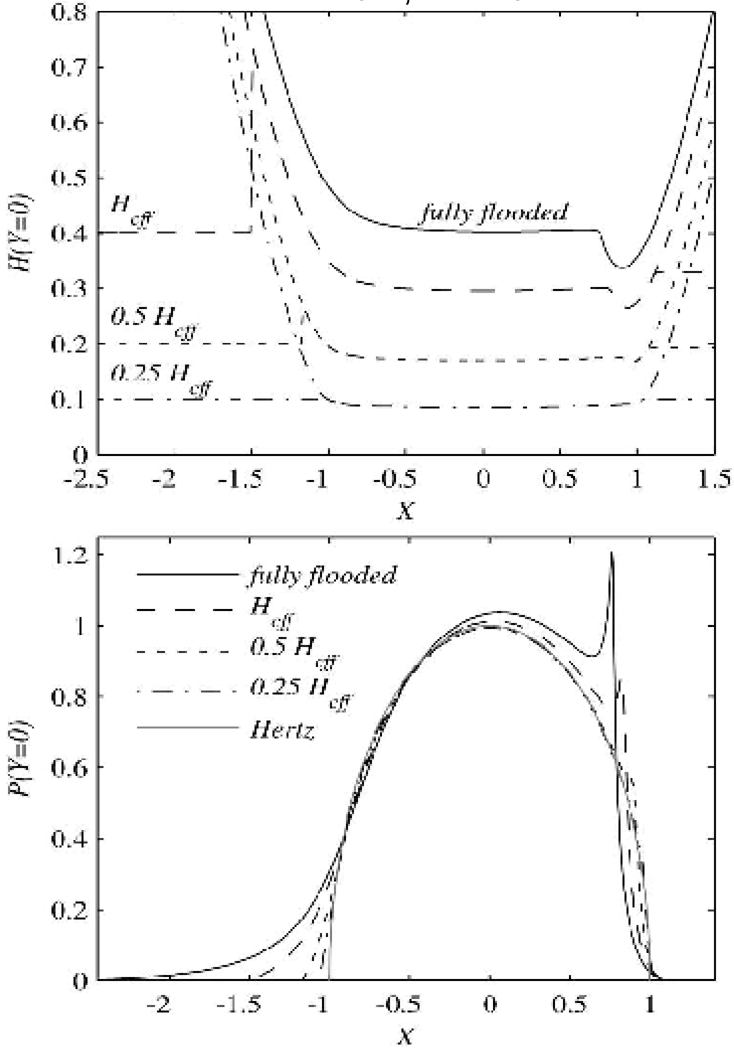
$h = h\left(p\right)$ $\quad\quad$ $p = p\left(x,y,y,t\right)$

$r = r\left(p\right)$ $\quad\quad$ $h = h\left(x,y,y,t\right)$



CONNECTION TO "INSIDE CONTACT"

M=20.1, L = 10.4



Layer thickness

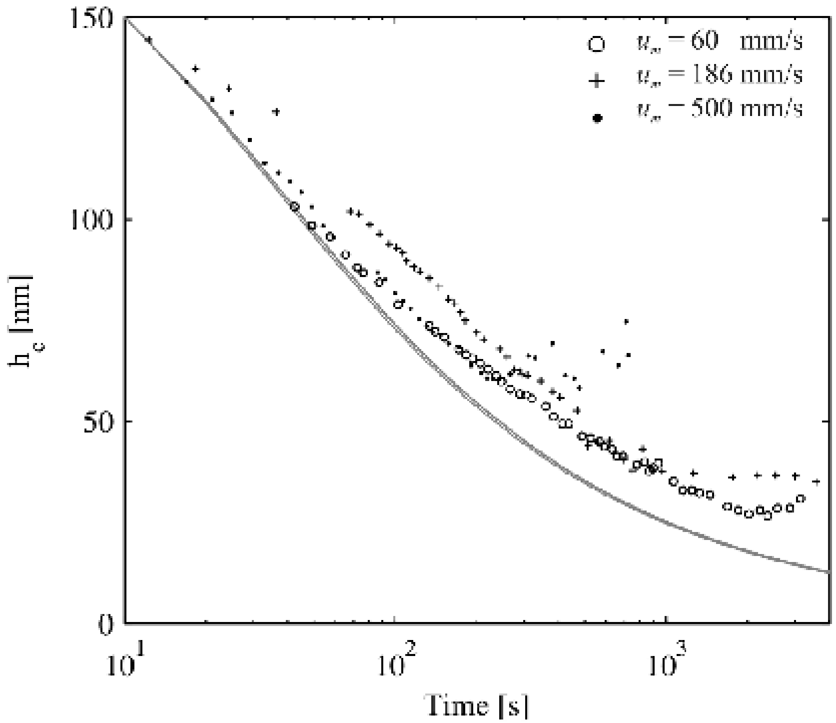
$$\lim_{h_{oil}\to 0} h = \frac{2\bar{h}_\infty}{\bar{r}}$$

Pressure

$$\lim_{h_{oil}\to 0} p = p_h\sqrt{1-\left(\frac{x}{a}\right)^2-\left(\frac{y}{b}\right)^2}$$

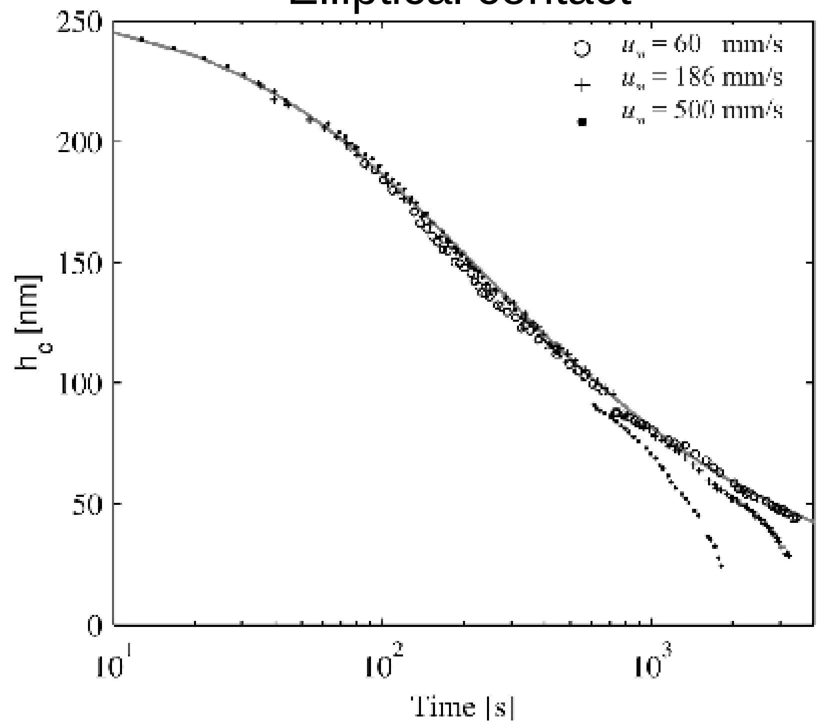
SINGLE CONTACT: VALIDATION

Circular contact



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

Elliptical contact

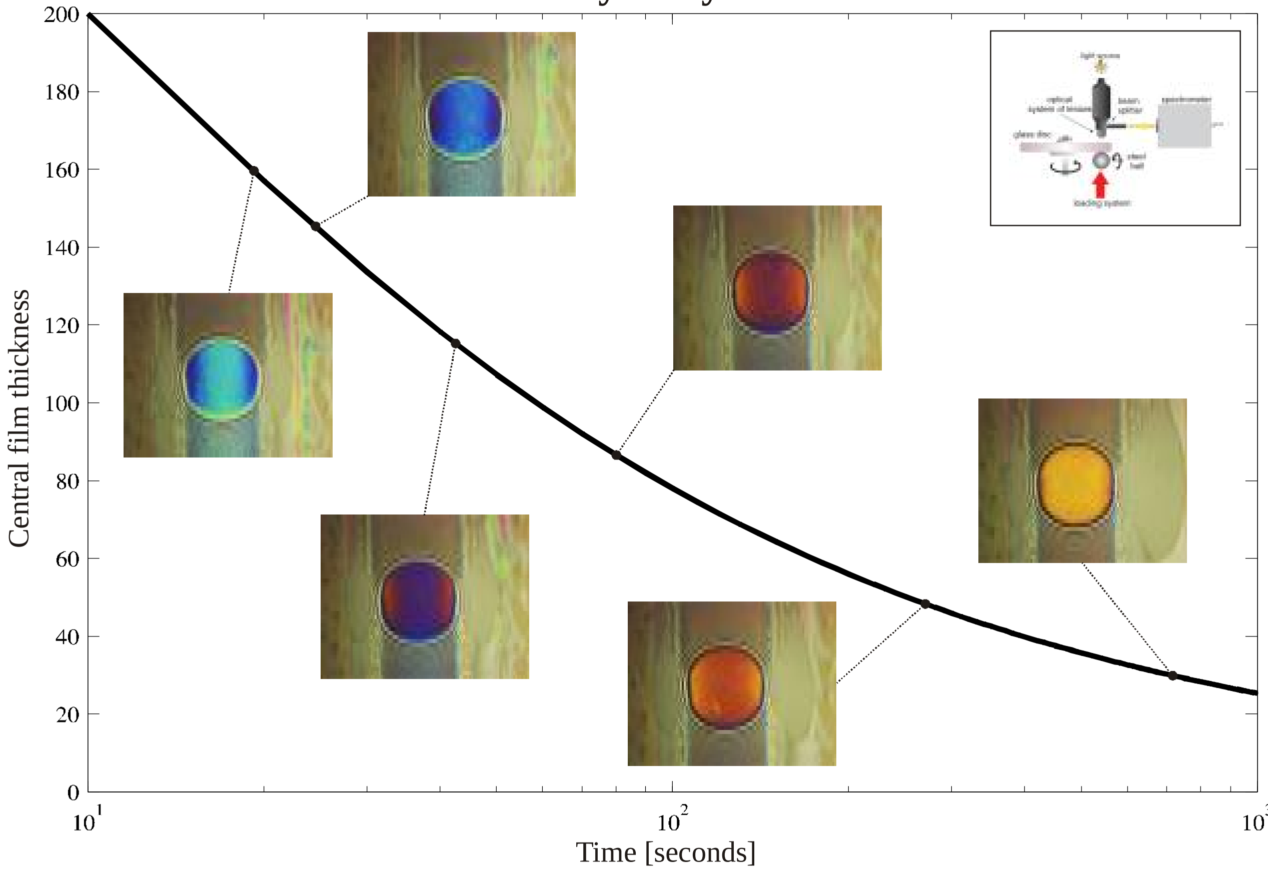


F = 30 N, p_h = 0.33 GPa, $\eta_0 \approx$ 0.85 Pa.s

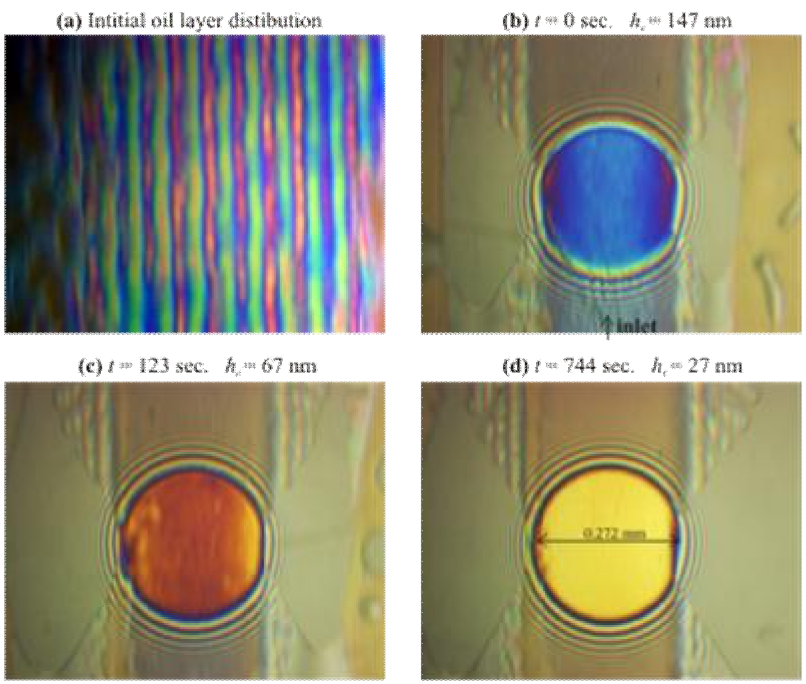
van Zoelen, M. T.; Venner, C. H. & Lugt, P. M. “Prediction of Film Thickness Decay in Starved EHL Contacts using a Thin Layer Flow Model,” *Journal of Engineering Tribology, ImechE*, **2009**, *223*, In Press.

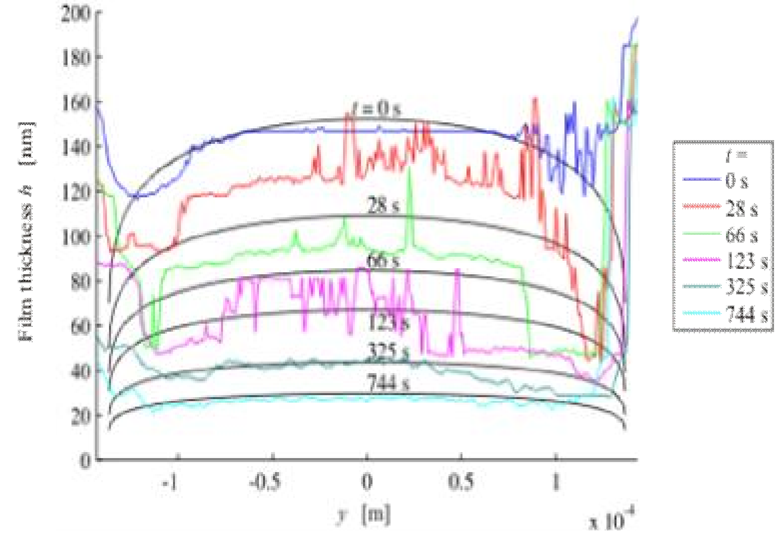
SINGLE CONTACT: VALIDATION

Starved Elasto-Hydrodynamic Lubrication

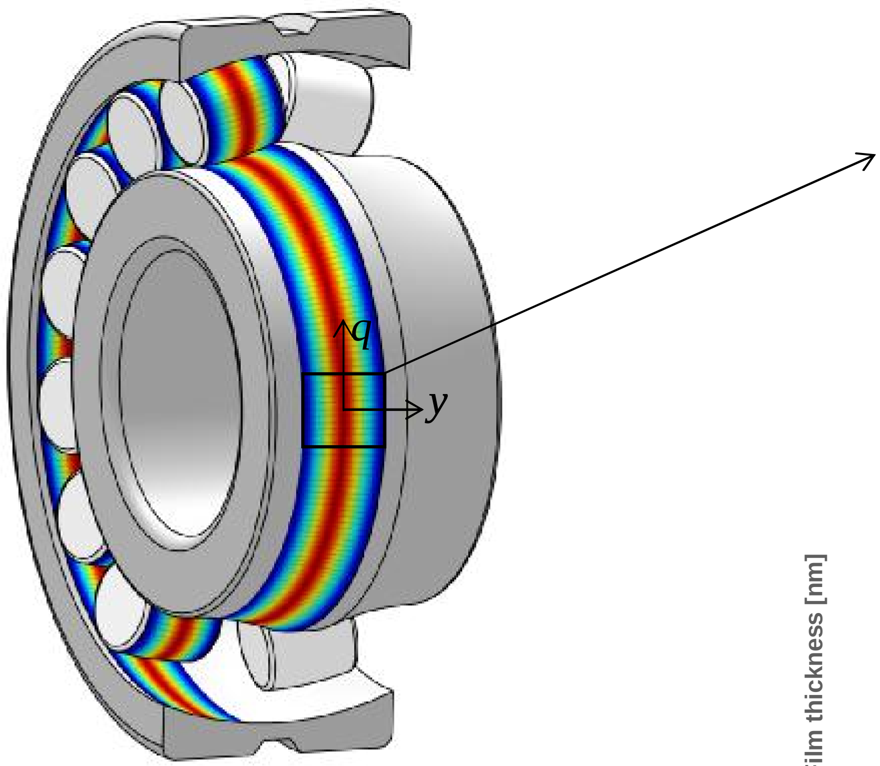


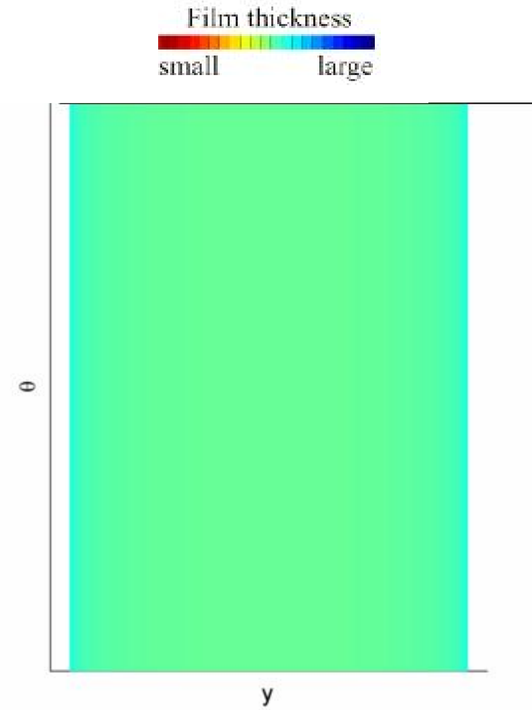
SINGLE CONTACT: VALIDATION

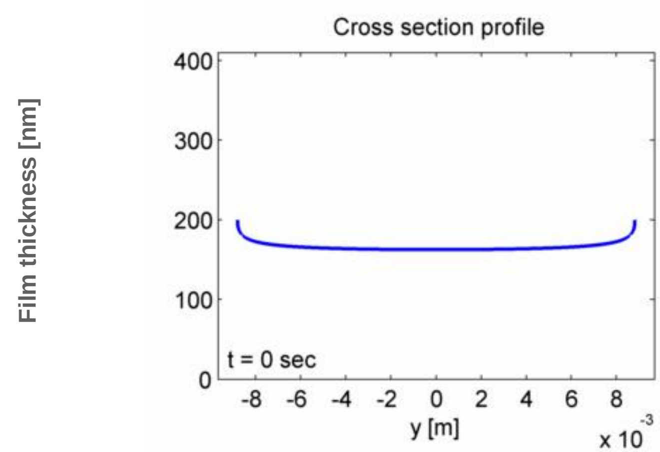




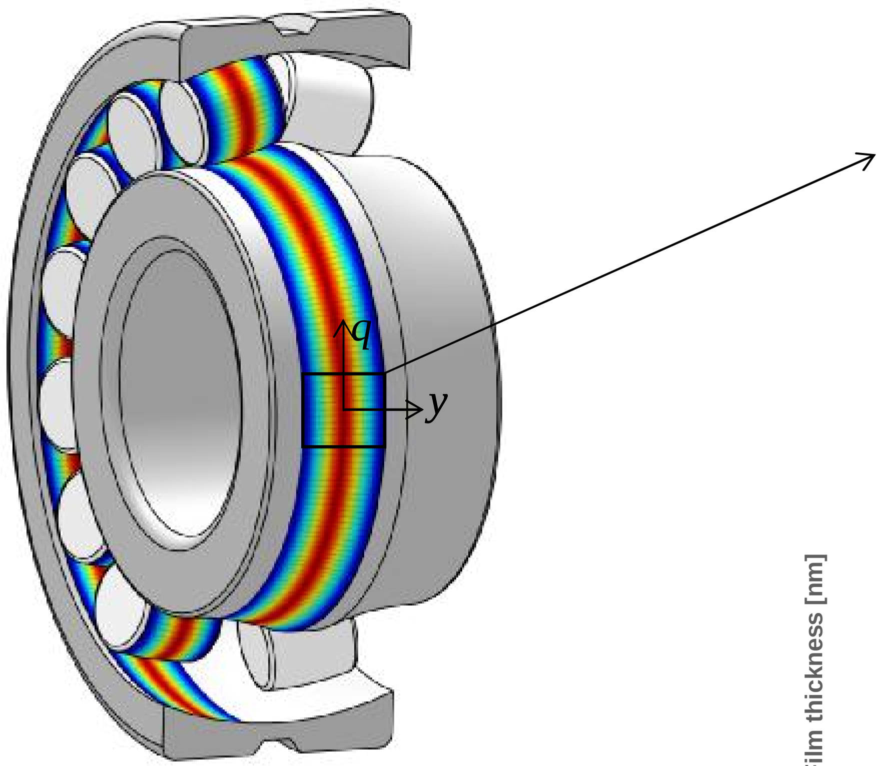
CONTACT PRESSURE: BEARING

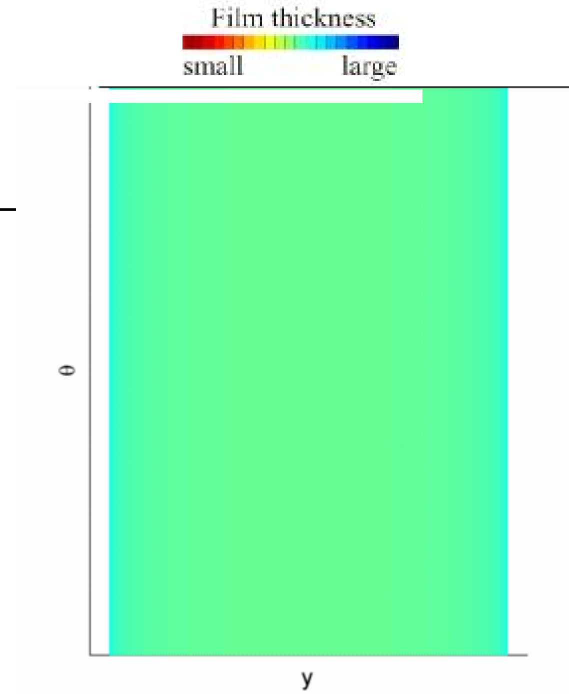


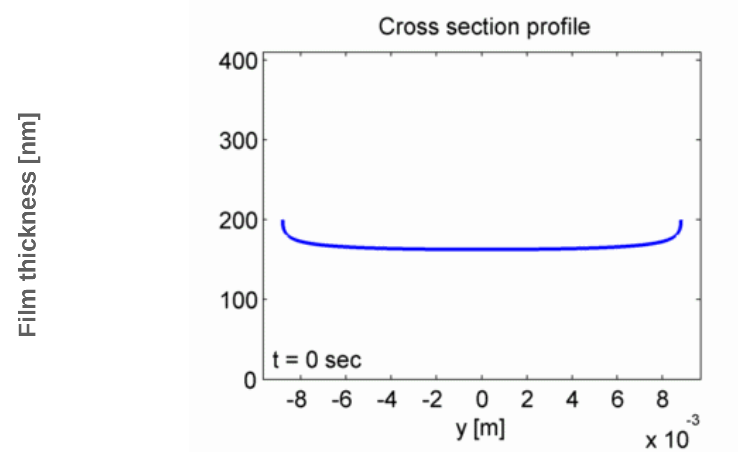




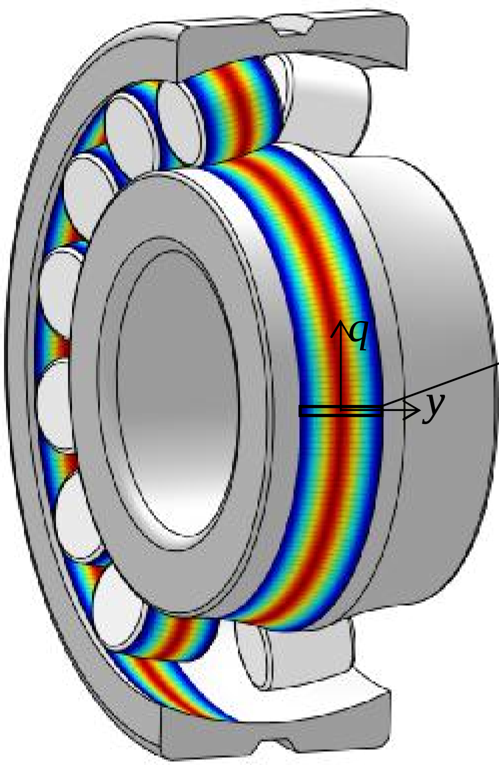
CONTACT PRESSURE: BEARING

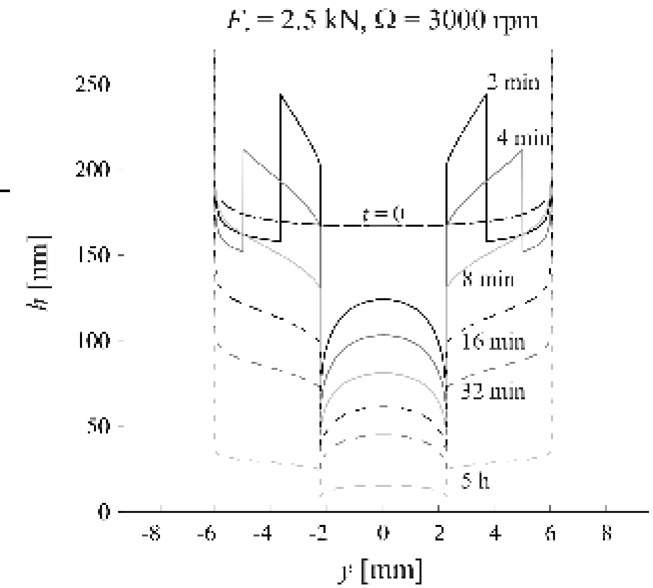


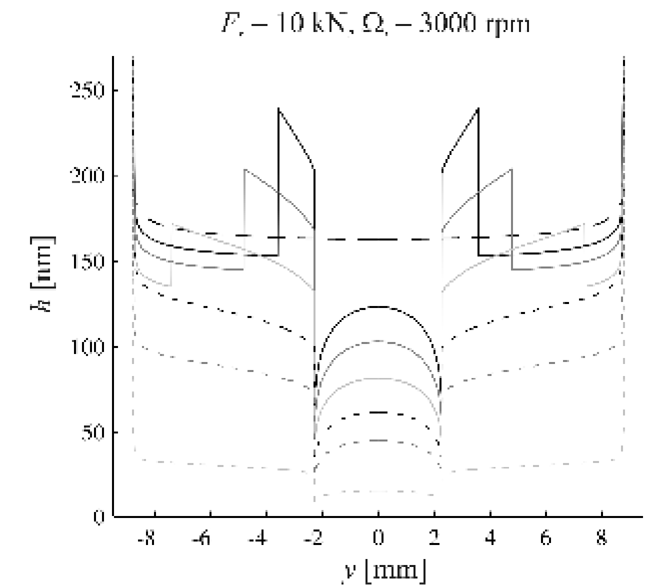




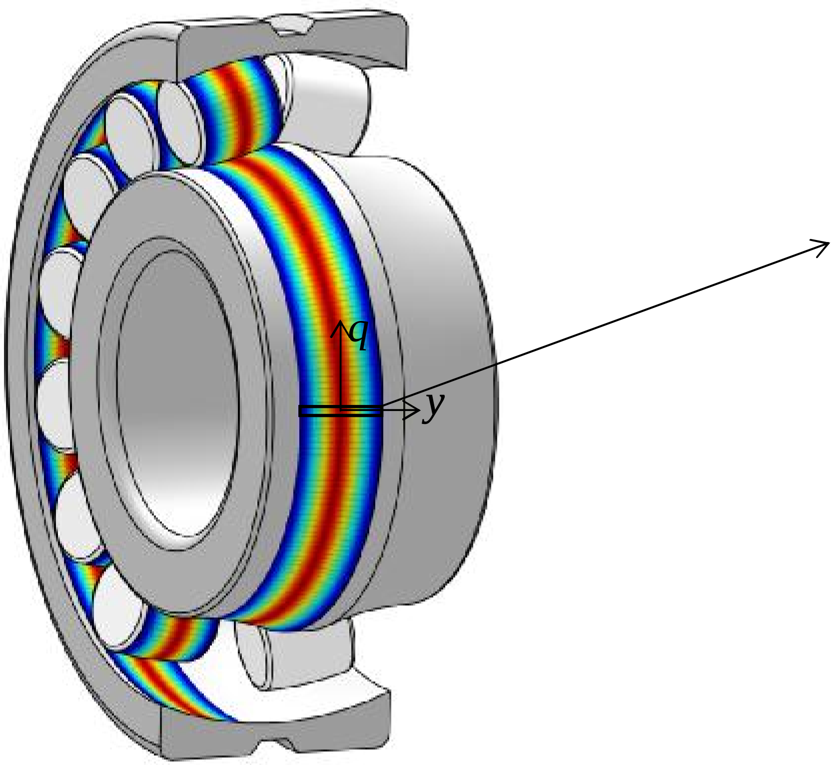
VARYING BEARING LOAD

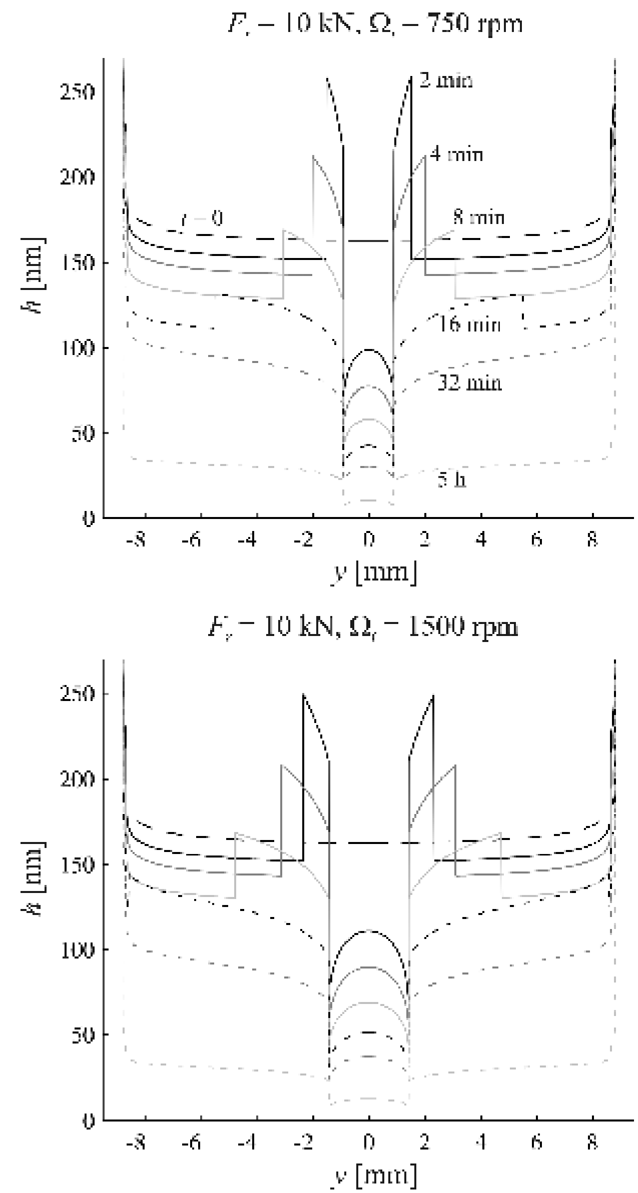




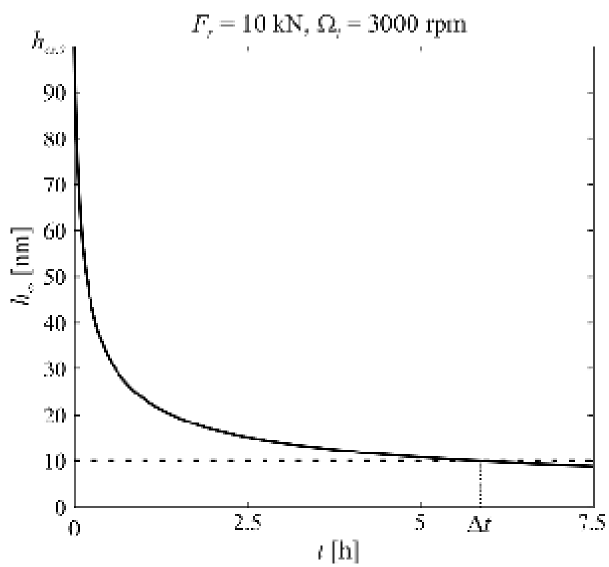


VARYING BEARING SPEED

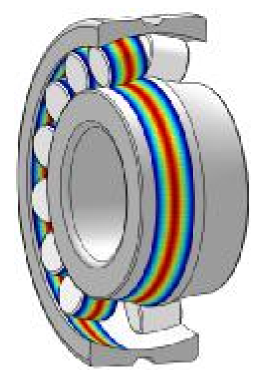




FILM THICKNESS DECAY

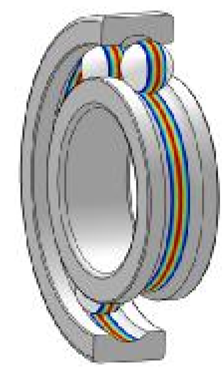


Spherical Roller Bearing



Load [kN]	Speed [rpm]	Δt [h]
10	*750*	**2.5**
10	*1500*	**3.8**
10	*3000*	**5.8**
5	*3000*	**5.7**
2.5	*3000*	**5.6**

Deep groove Ball Bearing



Load [kN]	Speed [rpm]	Δt [h]
10	*750*	**0.048**
10	*1500*	**0.072**
10	*3000*	**0.109**
5	*3000*	**0.105**
2.5	*3000*	**0.100**

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

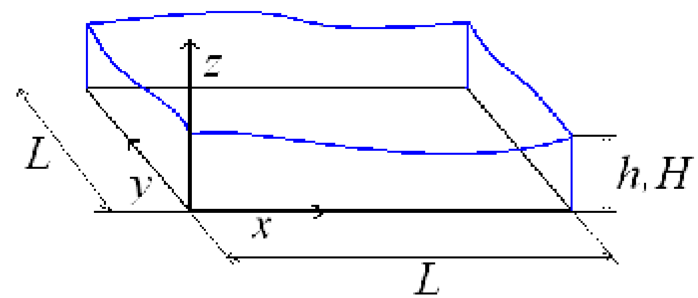
Many collaborators

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):

$$r\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)= f_x-\frac{\partial p}{\partial x}+m\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$r\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)= f_y-\frac{\partial p}{\partial y}+m\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$r\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)= f_z-\frac{\partial p}{\partial z}+m\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

THIN LAYER FLOW

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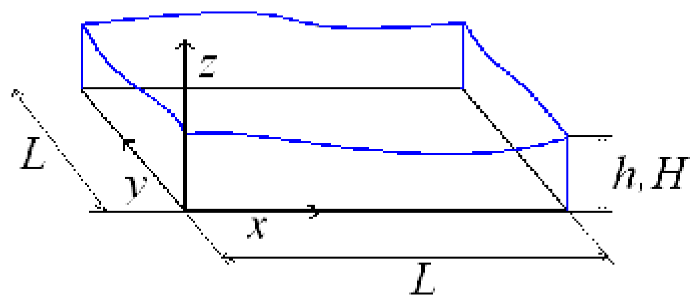

Step 1: $e = \dfrac{H}{L}$ $\qquad W = eU$

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

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

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

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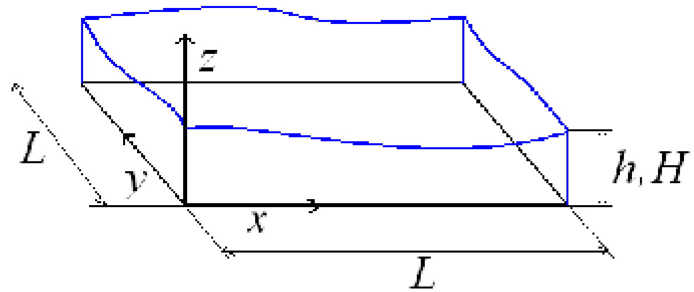

Step 2: $e = \frac{H}{L} \quad W = eU$

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

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

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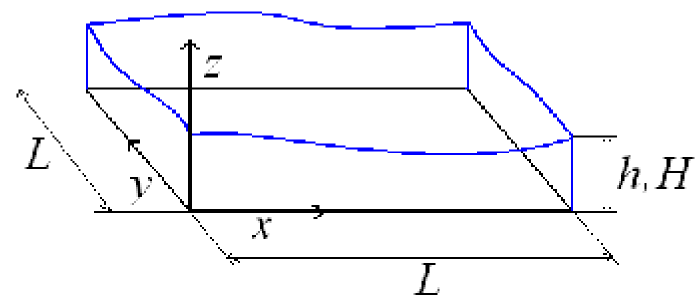

Step 2:

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

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

$$0 = f_z - \frac{\partial p}{\partial z}$$

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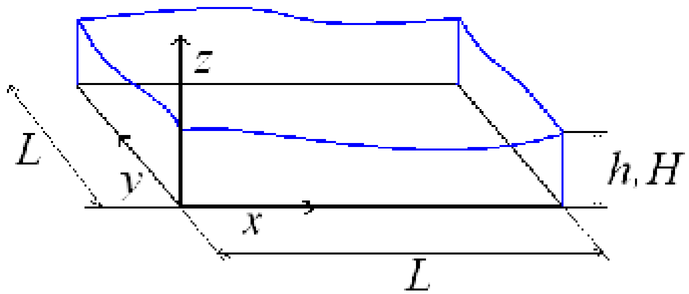

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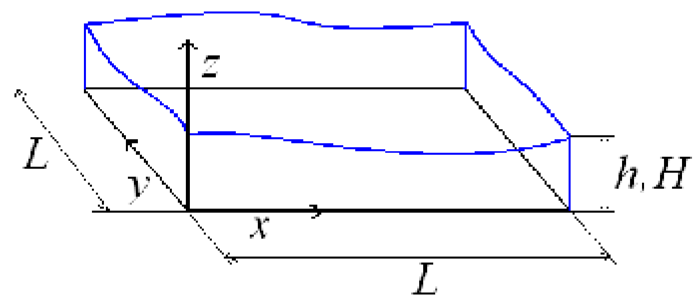

Step 3:

$$p = f_z\left(z - h\right) - t_c k + p_0$$

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

$$\langle v \rangle = \frac{1}{h}\int_0^h v\,dz = \frac{h^2}{3m}\left[f_y + \tfrac{3}{8} h \frac{\partial f_z}{\partial y} + f_z \frac{\partial h}{\partial y} + t_s \left(\frac{\partial^3 h}{\partial x^2 \partial y} + \frac{\partial^3 h}{\partial y^3} \right) \right]$$

THIN LAYER APPROXIMATION

1. Scale the N-S equations
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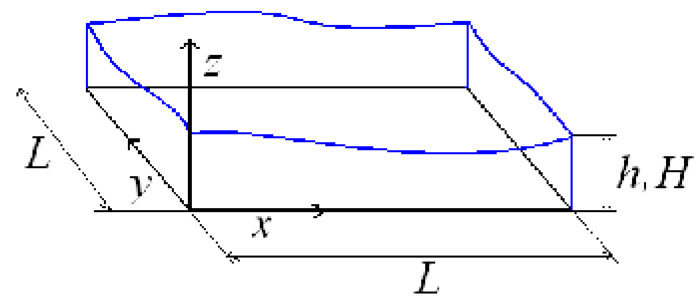

Step 4:

$$\frac{1}{3m}\frac{\partial}{\partial x}\left(h^{3}\left[f_{x}+\tfrac{3}{8}h\frac{\partial f_{z}}{\partial x}+f_{z}\frac{\partial h}{\partial x}+t_{s}\left(\frac{\partial^{3}h}{\partial x^{3}}+\frac{\partial^{3}h}{\partial y^{2}\partial x}\right)\right]\right)+\ldots$$

$$\frac{1}{3m}\frac{\partial}{\partial y}\left(h^{3}\left[f_{y}+\tfrac{3}{8}h\frac{\partial f_{z}}{\partial y}+f_{z}\frac{\partial h}{\partial y}+t_{s}\left(\frac{\partial^{3}h}{\partial x^{2}\partial y}+\frac{\partial^{3}h}{\partial y^{3}}\right)\right]\right)+\frac{\partial h}{\partial t}=0$$

van Zoelen, M. T.; Venner, C. H. & Lugt, P. M. "*Free Surface Thin Layer Flow on Bearing Raceways,*" *Journal of Tribology, ASME,* **2008**, *130*, 021802

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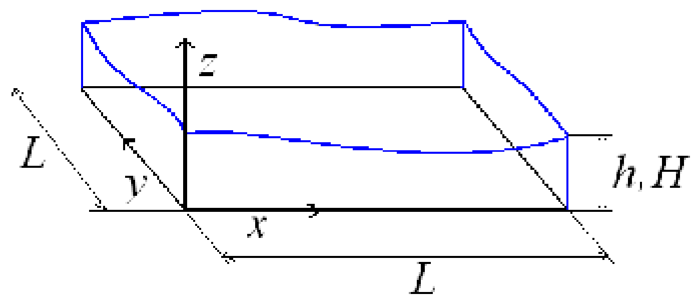


Step 4:

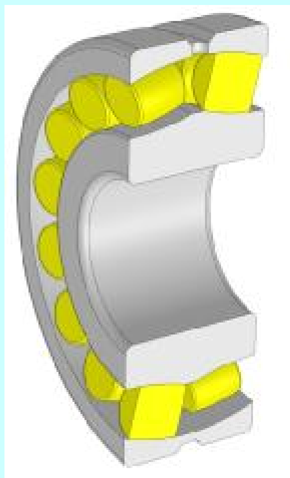
$$\frac{1}{3m}\frac{\partial}{\partial x}\left(h^3\left[f_x + \tfrac{3}{8}h\frac{\partial f_z}{\partial x} + f_z\frac{\partial h}{\partial x} + t_s\left(\frac{\partial^3 h}{\partial x^3} + \frac{\partial^3 h}{\partial y^2 \partial x}\right)\right]\right) + \ldots$$

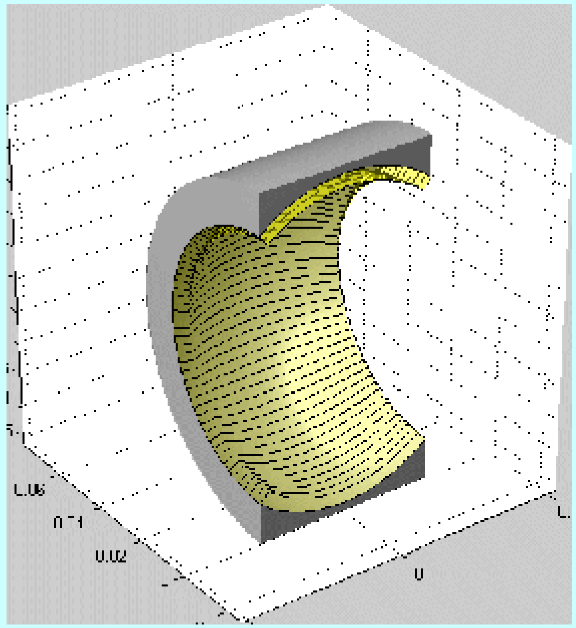
$$\frac{1}{3m}\frac{\partial}{\partial y}\left(h^3\left[f_y + \tfrac{3}{8}h\frac{\partial f_z}{\partial y} + f_z\frac{\partial h}{\partial y} + t_s\left(\frac{\partial^3 h}{\partial x^2 \partial y} + \frac{\partial^3 h}{\partial y^3}\right)\right]\right) + \frac{\partial h}{\partial t} = 0$$

van Zoelen, M. T.; Venner, C. H. & Lugt, P. M. "*Free Surface Thin Layer Flow on Bearing Raceways,*" *Journal of Tribology, ASME,* **2008**, *130*, 021802

CENTRIFUGAL EFFECTS RACEWAY

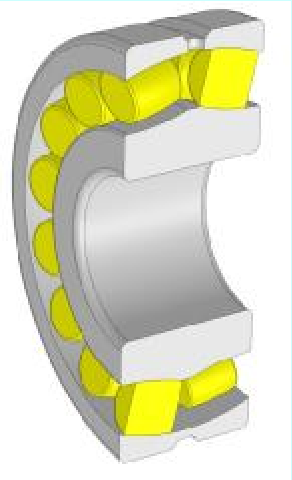
Example

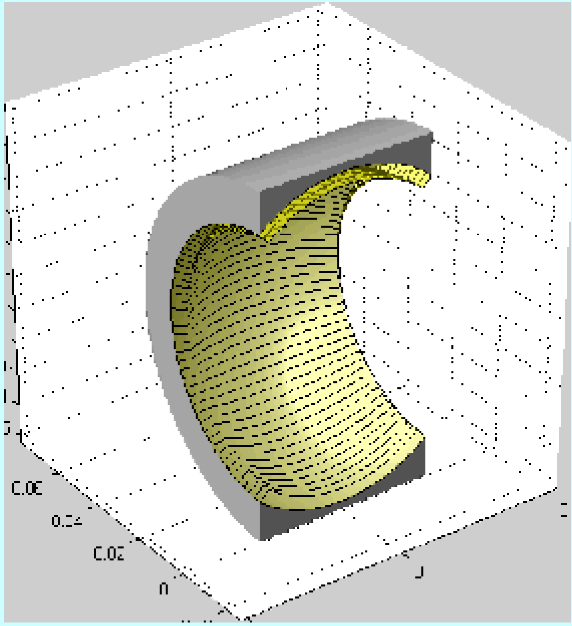




CENTRIFUGAL EFFECTS RACEWAY

Example





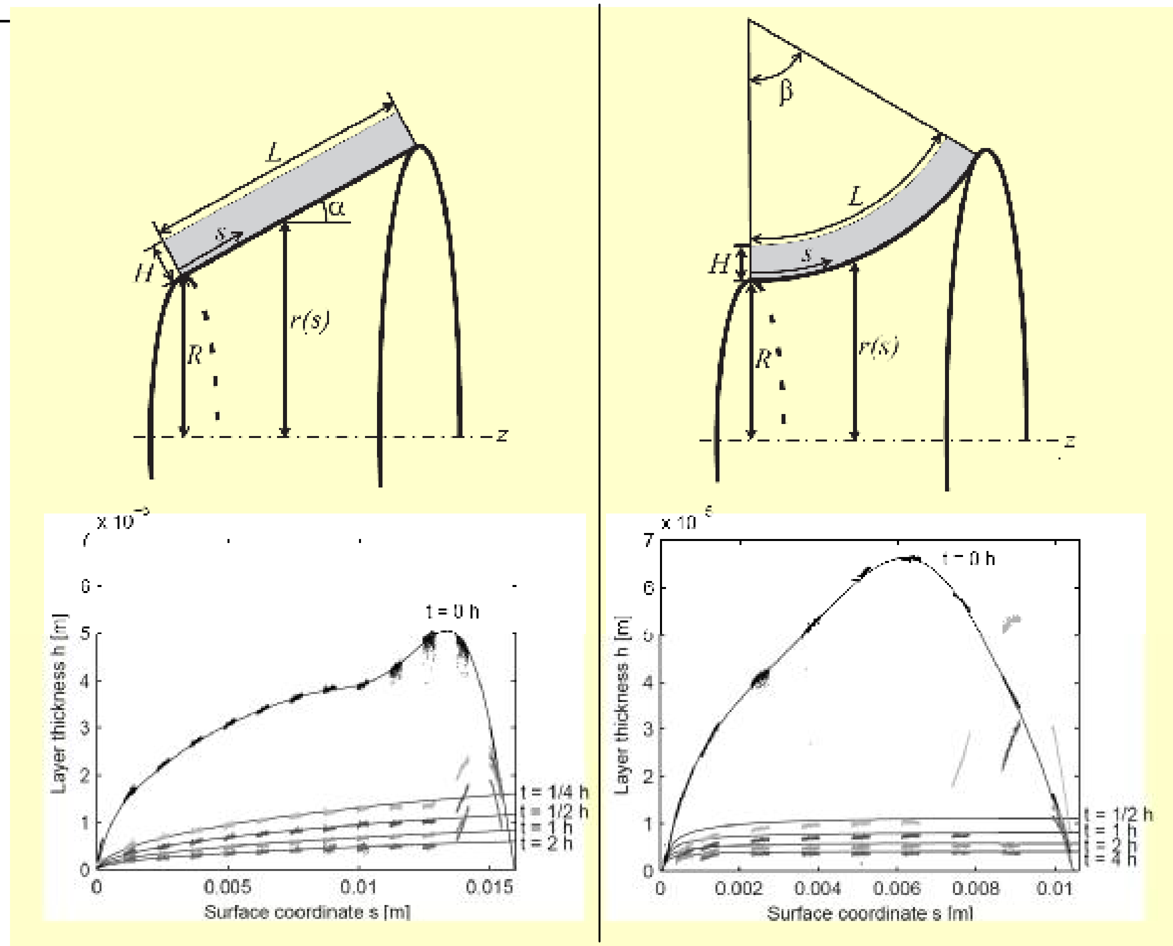
CENTRIFUGAL EFFECT RACEWAY: VALIDATION

Flow equation

$$\frac{1}{r}\frac{\partial}{\partial s}\left(\frac{h^3}{3h_0} r\ f_s\right)+\frac{\partial h}{\partial t}=0$$

Body force equation

$$f_s = r\Omega^2 r\frac{dr}{ds}$$



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SIMPLIFICATION

<u>2D à 1D:</u>

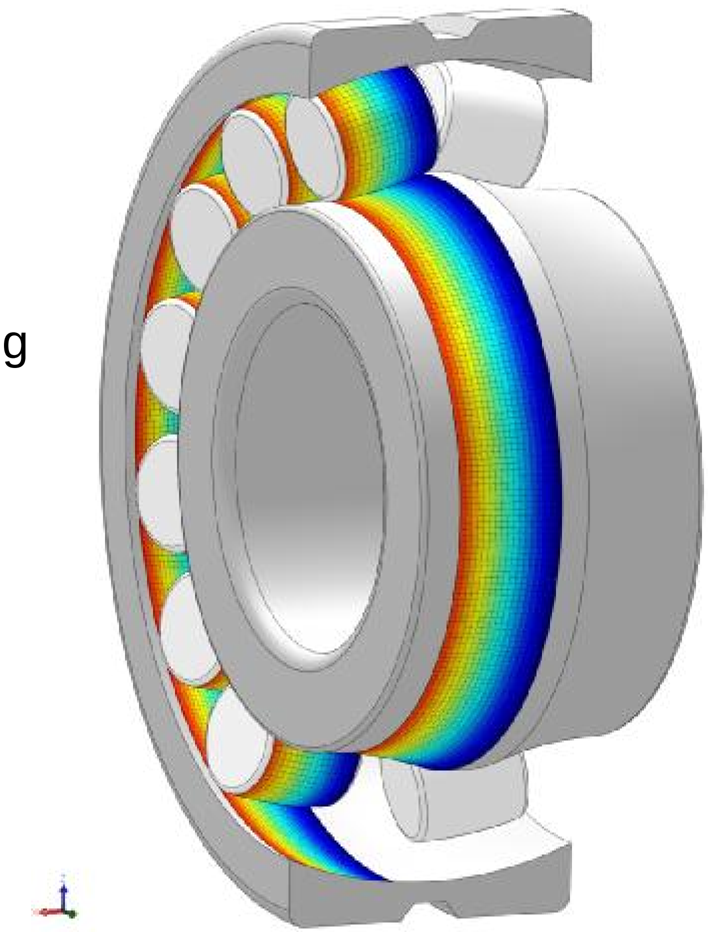
§ Equipartition

§ Contact pressure smoothening

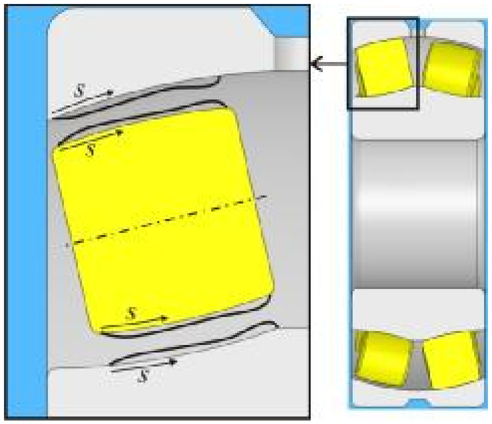
§ Surface tension

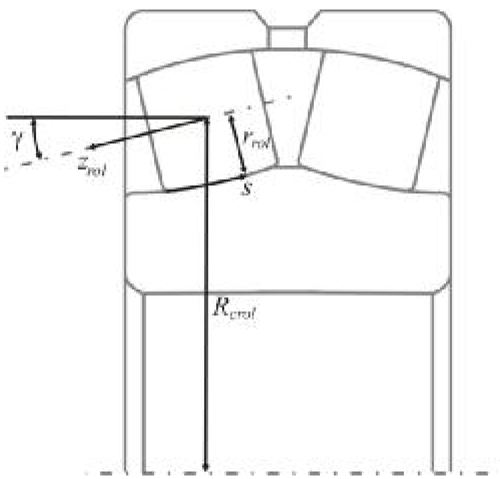
$$\frac{1}{3m}\frac{\partial}{\partial y}\left(h^3 f_x\right)+\frac{\partial h}{\partial t}=0$$

§ Hyperbolic equation, easily solved by method of characteristics



CENTRIFUGAL EFFECT ROLLER





Flow equation

$$\frac{1}{r}\frac{\partial}{\partial s}\left(\frac{h^3}{3h_0} r\ f_s\right)+\frac{\partial h}{\partial t}=0$$

Body force equation

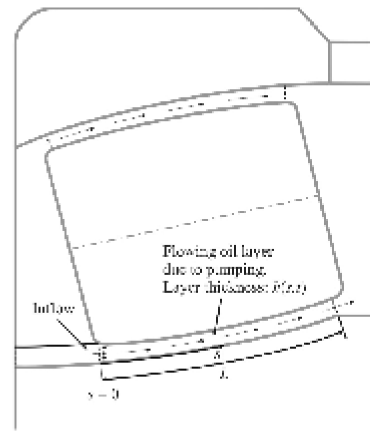
Raceways:

$$f_{s,rw} = r\Omega_{rw}{}^2 r\frac{dr}{ds}$$

Rollers:

$$f_{s,rol} = r\ \Omega_{ca}{}^2\left(\sin^2(g)\, z_{rol}+\sin(g)\, R_{crol}\right)\frac{dz_{rol}}{ds}$$
$$+\left(\left(\tfrac{1}{2}\cos^2(g)+\tfrac{1}{2}\right)\Omega_{ca}{}^2+2\Omega_{ca}\Omega_{rol}\cos(g)+\Omega_{rol}{}^2\right) r\, r_{rol}\frac{dr_{rol}}{ds}$$

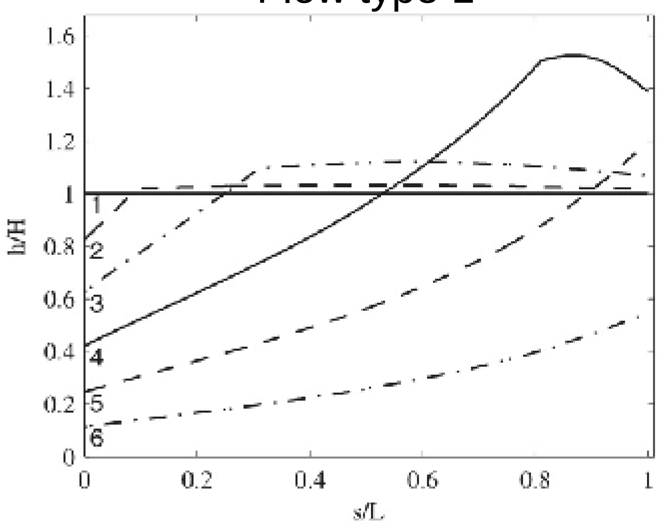
CENTRIFUGAL EFFECT: BEARING



- Time steps:

$$t/t = \frac{h}{H^2 r \Omega^2} = 0,\ 0.3,\ 1,\ 3,\ 10,\ 50$$

Flow type 1



Flow type 2