Pressure Calculation from Experimentally Evaluated Lubricant Thickness within EHL Contacts

M. Vrbka, M. Vaverka, R. Poliščuk, I. Křupka, M. Hartl
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**Introduction – dents in machine parts**

- **Dents on the rubbing surfaces**
  - defects generated by debris or wear particles passing through the contact
  - abrasive wear or surface initiated fatigue
  - surface features as a modification of the surface topography
  - beneficial tribological performances (reduced friction and wear e.g. mechanical seals, piston rings)

Experimental methods of contact pressure evaluation

**Lubricated contact:**

- **spectroscopic techniques**
  - Raman microspectrometry – e.g. Coulon et al.
  - Infrared spectroscopy – e.g. LaPlant et al.

- **direct measurement using sensors** – e.g. Höhn et al.

- **inverse calculation from measured film thickness**
  - elasticity theory + multilevel method – e.g. Larsson et al.
  - FFT-based techniques – e.g. Molimard et al.

Larsson, P.O. et al.: Pressure fluctuations as grease soaps pass through an EHL contact.


Experimental methods of contact pressure evaluation

Non-lubricated contact:

- **silica layer deformation measurement** – Cann and Spikes
- **ultrasound imaging** – e.g. Pau et al.
- **measurement based on reflectivity change of surface** – e.g. Diaconescu et al.
- **pressure-sensitive films** – e.g. Fujifilm

Cann, P.M., Spikes, H.A., Measurement of pressure distribution in EHL-Development of Method and application to dry static contacts.

Pau, M., Aymerich, F., Ginesu, F., Distribution of contact pressure in wheel-rail contact area.
Aim of work

The aim of our work is to calculate pressure distribution within EHL point contact from experimentally evaluated film thickness, which is obtained very accurately for variety of operating conditions (e.g. for non zero slide-to-roll ratio, dented surfaces).

distribution of lubricant **film thickness** from experiment (dented contact)

distribution of **pressure**
Experimental apparatus

- SXGA digital camera
- Microscope
- Rotary encoder
- Servomotor
- 25.4 mm steel ball
- Cr coated glass disc
- Xenon flash lamp 2.9 μs pulse
Experimental conditions

Paraffinic Base Oil SR600 at 25°C
Dynamic viscosity: 0.221 Pa⋅s
Pressure-viscosity coefficient: 23 GPa⁻¹

Glass Disc:  \( E = 81 \) GPa, \( \nu = 0.207 \)

Steel Ball: Diameter: 25.4 mm
RMS roughness: ~ 4 nm
\( E = 207 \) GPa, \( \nu = 0.3 \)

Load: 28 N (\( \rho_{\text{Hertz}} = 0.505 \) GPa)

mean surface velocity \( u = 0.027 \) m/s

\[
\Sigma = \frac{2(u_D - u_B)}{(u_D + u_B)}
\]

\( \Sigma = 0 \) - pure rolling conditions
\( \Sigma < 0 \) - disc moves slower than ball
\( \Sigma > 0 \) - disc moves faster than ball
The lip of raised metal is removed by polishing to avoid surface damage under thin film lubrication conditions.
Experimental results – film thickness (pure rolling conditions $\Sigma = 0$)
Components of lubricant film thickness

- Contact pressure is related to the elastic deformation
- Elastic deformation can be derived from film thickness

\[ u_{sum}(x, y) = h(x, y) - g_1(x, y) + h_0 \]
Inverse calculation of pressure from film thickness

The pressure can be calculated from elastic deformations using inverse elasticity theory:

\[
 u(x, y) = \frac{2}{\pi E_r} \int_{-a}^{a} \int_{-a}^{a} \frac{p(x_1, y_1) dx_1 dy_1}{\sqrt{(x-x_1)^2 + (y-y_1)^2}}
\]

Evaluation of pressure is an inverse problem:

\[
P_s = K_{r,s}^{-1} U_r
\]

- \(U_r\)……vector of deformations
- \(P_s\)……vector of pressures
- \(K_{r,s}^{-1}\)……inverse of two-dimensional compliance matrix with dimension \(n^2\)

\(h_0\) can be determined by the force balance condition
**Replacement of inverse compliance matrix by convolution**

Influence coefficients of matrix $K^{-1}$ repeat for each pressure pixel with a constant scheme.

The large inverse matrix $K^{-1}$ (dim. $n^2$) could be replaced by floating convolution window $C$ (dim. $n$), generated from characteristic profile (row) of already precalculated inverse matrix $K^{-1}$ - inversion is made only once.

$P = K^{-1} \cdot U$

$Lubricant film thickness from experiment$

$Elastic deformations U$

$Inversion of compliance matrix K$

$Contact pressure$

$Lubricant film thickness from experiment$

$Elastic deformations U$

$Floating convolution window C$

$Contact pressure$

$Significant acceleration of calculation speed$

**Convolution Matrix Radial Profile**

- Central profile
- Detail of the central area

Index of coefficient, domain 64x64 pixels

$P_{[x,y]} = C \cdot U_{[C]}$
Generalization of the compliance convolution matrix

Variation of reduced elasticity modulus \((E_r)\) causes:

\[
C_{New Er} = \frac{E_{rNew}}{E_{rOld}} C_{Old Er}
\]

Variation of distance between pixels \((d)\) causes:

\[
C_{New d} = \frac{d_{Old}}{d_{New}} C_{Old Er}
\]

⇒ A single convolution matrix could be applied for analysis of any deformation data with any combination of \(E_r\) and \(d\) without requirement of matrix re-inversion.
Contact pressure – smooth contact (pure rolling conditions \( \Sigma = 0 \))
Contact pressure – dented contact (non zero slide-to-roll ratio)

\[ \sum = 0.55 \]
Depth
230 nm

\[ \sum = 0.45 \]
Depth
360 nm
Contact pressure – dented contact (non zero slide-to-roll ratio)

$\Sigma = 0.55$
Depth
230 nm

$\Sigma = 0.45$
Depth
360 nm
Contact pressure – dented contact (non zero slide-to-roll ratio)

$\Sigma = -0.5$
Depth
360 nm

$\Sigma = 0.45$
Depth
360 nm
Effect of disturbances in input data on calculated pressure

Dashed and dotted line: deformation obtained directly from measurement in nanometers with one decimal place (Ångstrom resolution)

Dashed line: deformation in nanometers rounded to integer

Solid line: deformation after smoothening using low-pass filter (5x5)
Conclusions and future prospects

- We are able to calculate contact pressure from experimentally evaluated lubricant thin film thickness in contact of both smooth and dented surfaces. The numerical technique is based on inverse elasticity theory.

- Resource- and time-consuming inversion of compliance matrix was replaced by convolution algorithm that leads to significant improvement of calculation speed – it is not necessary to use multilevel methods and any boundary conditions for contact pressure.

- The presented technique is now applied to studying textures of dents and their effect on lubricant film thickness and distribution of contact pressure. At present, the investigation is extended to experimental research of surface fatigue of machine parts with dented surfaces.