Metal-to-metal seals
Leakage through loading and unloading

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Metal-to-metal seals

An example of application: the oil recovery industry
Metal-to-metal seals

Other shapes and applications

- O-rings
- Gaskets
- Built in the larger system

- Nuclear applications
- Ultra-high vacuum vessels
- Petroleum recovery
- ...

Whenever other seals cannot be used (due to temperature, pressure, geometry, ...)

\[ p_{in} > p_{out} \]

Used in critical applications  There is a strong need to understand their behavior
Metal-to-metal seals

Typical topography of a metal to metal seal

- Out-of-flatness
- Crowning radius
- Waviness
- Roughness
Metal-to-metal seals

Typical topography of a metal to metal seal

~0.5 mm

~ 2.5 mm
Metal-to-metal seals

Typical topography of a metal to metal seal
Flow through metal-to-metal seals

Input topography

Percolating fluid

Pressure gradient
Why is it interesting to study the unloading of seals

Unloading will occur during operation

The applied load can be reduced during operation

- Increase on internal pressure
- Stress relaxation
- Vibrations in the system
- Failures elsewhere

It is important to understand how our seal will behave
Why is it interesting to study the unloading of seals

Effect of plastic deformation
Why is it interesting to study the unloading of seals

Effect of plastic deformation

Apply a load

In-contact surfaces
Why is it interesting to study the unloading of seals

Effect of plastic deformation

Release the load

Plastically deformed surfaces

Flow

Much smaller gap \(\rightarrow\) Good for sealing
Why is it interesting to study the unloading of seals

Overestimation of the required load

Say you have defined a maximum acceptable leakage e.g. $10^{-2}$

Considering the loading curve only would exaggerate the required load
Why is it interesting to study the unloading of seals

Overestimation of the required load

Say you have defined a maximum acceptable leakage e.g. $10^{-2}$

Considering the loading curve only would exaggerate the required load

Extra load required is around 3 times larger
Why is it interesting to study the unloading of seals

The unloading curve is more beneficial for sealing.

It can be reached by preloading the seal at a load higher than what is required.

Design tool?

The unloading curve is more beneficial for sealing.

It can be reached by preloading the seal at a load higher than what is required.
An approach to simulate metal-to-metal seals

Input
- Surface topography
- Seal geometry
- Surface and fluid properties

Contact mechanics
- Infinite half space assumption (Thick walls)
- Elastic-perfectly plastic material

Fluid mechanics
- Reynolds equation
  - Thin film approximation
  - Laminar flow
  - Incompressible fluid
  - Newtonian, iso-viscous fluid

Output
- Leakage

Well described in literature
Leakage during loading and unloading

The graph shows the relationship between permeability and the ratio $W/E^*$ for both loading and unloading processes. The permeability is plotted on a logarithmic scale, and $W/E^*$ is also on a logarithmic scale. The graph indicates a decrease in permeability as $W/E^*$ increases, with distinct curves for loading and unloading.
Leakage during loading and unloading

- Loading: Rapid increase in leakage
- Unloading: Slow increase in leakage
- No leakage
Leakage during loading and unloading

- **Loading**
  - **Rapid increase in leakage**
  - **Slow increase in leakage**
  - **No leakage**

- **Unloading**
  - **Safe during unloading**
Why does the safe operating region exists?

The flattening of sinusoidal waves – The Westergaard solution

- Pressure required to close the gap completely
- Gap: $\Delta$
- Wavelength: $\lambda$
- Pressure: $p^*$
Why does the flat region exist?

The flattening of sinusoidal waves – The Westergaard solution

\[ h = \Delta \left( 1 - \cos \left( \frac{2\pi x}{\lambda} \right) \right) \]

Pressure required to close the gap completely

\[ p = \bar{p} + p^* \cos \left( \frac{2\pi x}{\lambda} \right) \]

\[ p^* = \frac{\pi E^* \Delta}{\lambda} \]
Why does the flat region exists?

The flattening of sinusoidal waves – The Westergaard solution

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Why does the flat region exists?
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The flattening of sinusoidal waves – The Westergaard solution

\[ p^* = \frac{\pi E^* \Delta}{\lambda} \]

Why does the flat region exists?

Low pressure
Elastic deformation

High pressure
Plastic deformation
Why does the flat region exists?

Behaviour of the seal
Why does the flat region exists?

Behaviour of the seal

- Isolated contact islands
- Plastic deformation of high frequency components
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Behaviour of the seal

- Small frequency components are still flattened
- The contact reduced by shrinking of the clusters and loosing contact at isolated spots
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- Small frequency components start to recover
- Large regions loose contact
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- Large regions lose contact
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Behaviour of the seal

- The areas where the pressure was high are now smooth
Can we predict the extent of the safe zone?

\[
\frac{W}{E^*} (-)
\]

- Loading
- Unloading

\[W_{sz}\] Safe during unloading

- Slow increase in leakage
Can we predict the extent of the safe zone?

1. Represent the surface as a sum of sinusoidal waves
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1. Represent the surface as a sum of sinusoidal waves
2. Identify which waves can seal without deforming plastically
3. Identify the load \( W_{sz}^{sin} \) at which the recovery of elastic deformation makes each of those waves stop sealing
4. The load at which the safe zone ends is defined as \( W_{sz} = \max\{W_{sz}^{sin}\} \)
Can we predict the extent of the safe zone?

![Graph showing permeability vs. loading/unloading]

- Predicted value
- Slow increase in leakage
- Safe during unloading

$W_{sz}$
Conclusions

• The first unloading presents a much lower leakage than the first loading
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• During unloading, load can be reduced significantly before leakage increases significantly → safe zone

• The safe zone can be explained by a combination of elastic and plastic deformation of different wavelengths

• We can use the previous explanation to estimate the extend of the safe zone
Future/ongoing work

• Validate the model against experimental results

• Deepen the study of the unloading
  – In which conditions is the safe zone enhanced?
  – (Not always present but observed in measured surfaces)

• Refine the predictive model

• Extend the study to cover the full size of a seal
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