RELIABILITY OF HYDRODYNAMIC BEARINGS IN TRANSMISSION SYSTEMS

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Where is Poitiers?

Poitiers 88,000 residents

+ surroundings 134,000

More than 30,000 students

POITIERS, **THE UNIVERSITY** AND **THE CITY**

The University of Poitiers was founded in 1431, making it one of the oldest universities in Europe, with:

- 30,000 students
- 3,000 staff and personnel
    - -1,600 teachers and researchers
    - -1,400 administrative and technical staff

In the 16th century, Poitiers University shines on the cultural life of the city. At that time, it is cited as the second university in France after Paris ; 4000 students attend the university, some of which become famous: Joachim du Bellay, Guez de Balzac, Rabelais, Descartes, Francis Bacon..

POITIERS, **THE UNIVERSITY** AND **THE CITY**

Poitiers is a city of art and history

Remains of Gallo-Roman publics baths and arenas

Middle-age Cathedral : Notre Dame La Grande

2000 years of history

Pprime institute

Pprime Institute

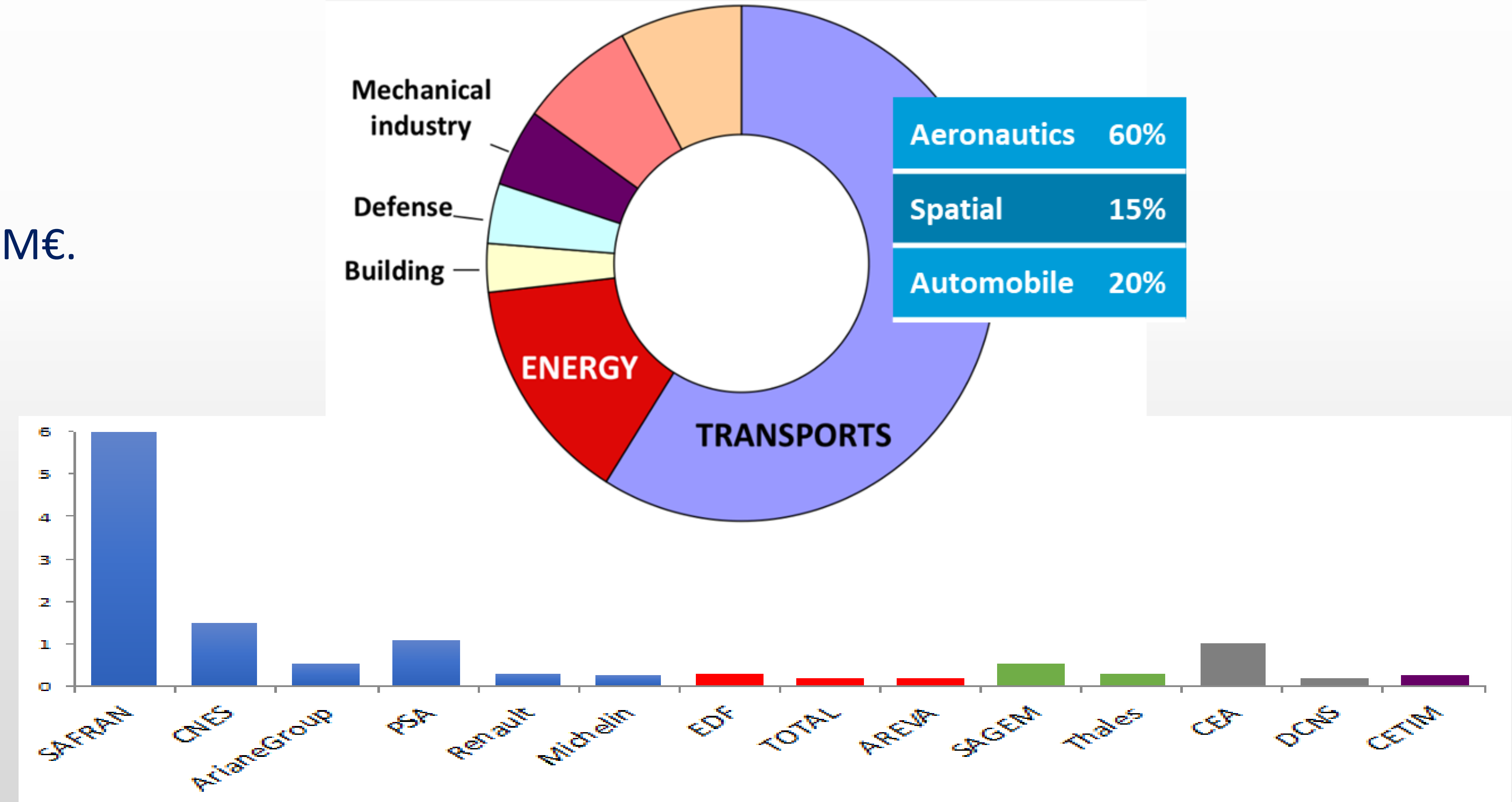
- 3 research departments:
  - Physics and Mechanics of Materials
  - Fluids, Thermal and Combustion Sciences
  - Mechanical Engineering and Complex Systems

■ **Key facts:**

- *172 university researchers and lecturers*
- *102 technical staff*
- *15 emeritus researchers*
- *165 PhD students*
- *43 interns*

Pprime institute

- Permanent academic, administrative and technical staff salaries : 20 M€.
- State Support: 1 M€.
- Industrial contracts: 5 M€.
- Grants: 3,5 M€.



Outline

1. Introduction

- *Lubrication regimes.*
- *Hydrodynamic lubrication: the oil wedge effect.*
- *Journal bearings technology: terminology, type of bearings.*
- *Applications and illustrations.*

2. Lubricants

3. Lubrication

- *Reynolds equation.*
- *Thermal effects in hydrodynamic bearings.*
- *Deformation effects.*

Outline

4. Hydrodynamic bearings – Static behavior :

Lift-off force, friction and flow rate.

Sizing criteria.

Materials and coatings.

5. Failure modes

In transmissions

In hydrodynamic bearings

6. Reliability

Design of experience

Sensitivity analysis

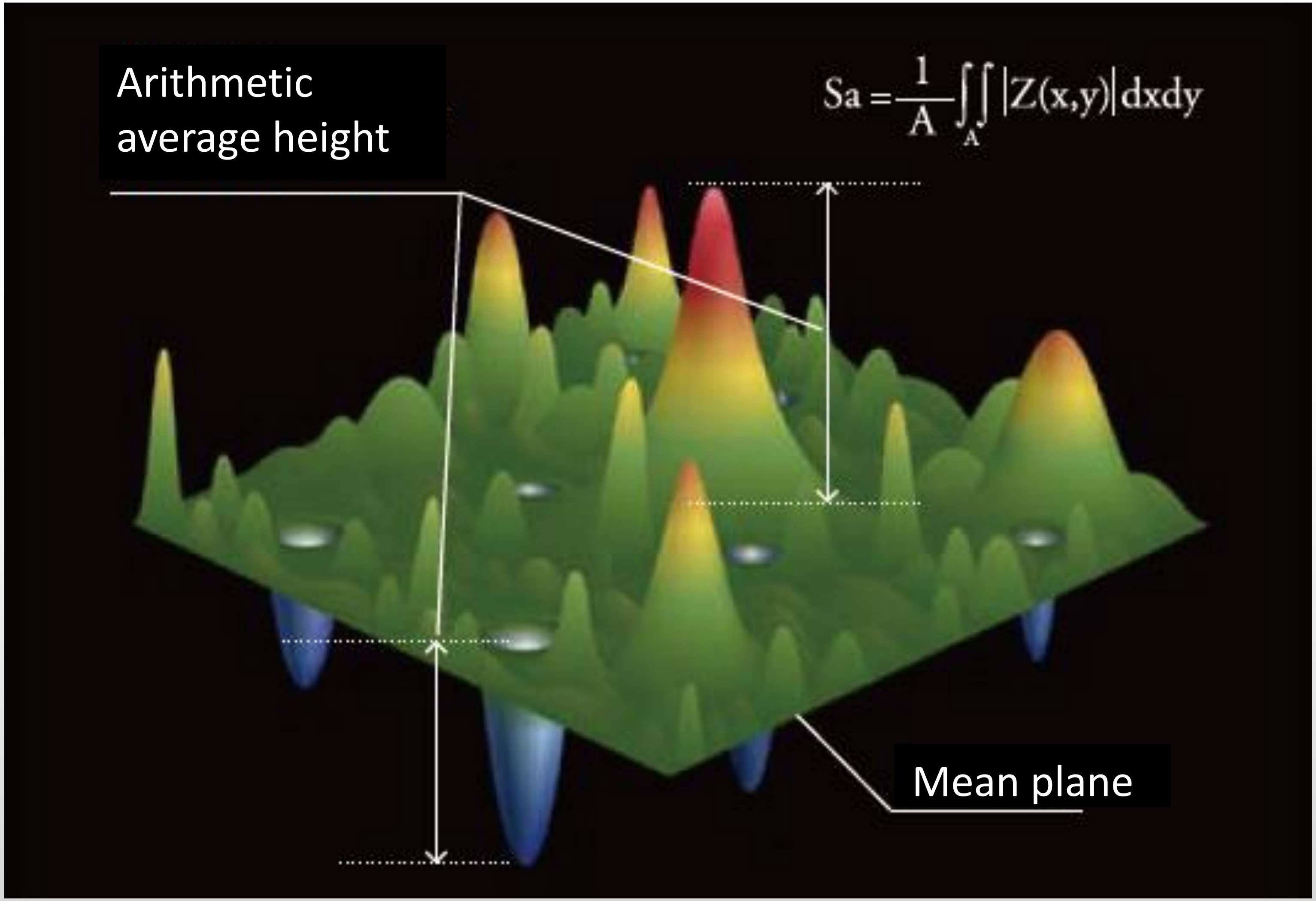
Reliability evaluation on a journal bearing

1. INTRODUCTION

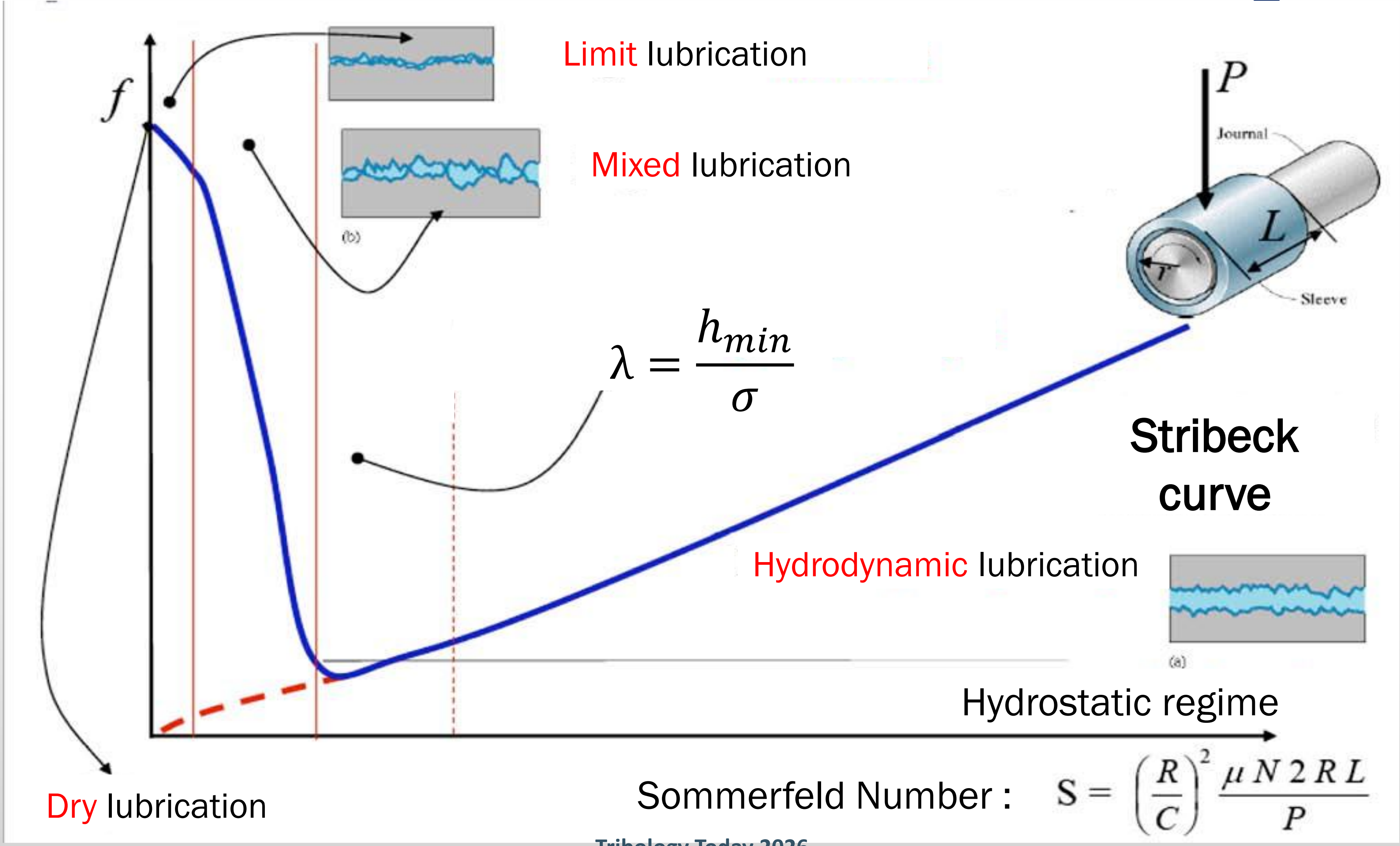
Introduction

- The behavior, service life, and performance of guiding elements representing hydrodynamic bearings and thrust bearings depend on numerous parameters:
  - *geometric parameters (dimensions and shape),*
  - *kinematic and dynamic parameters (rotational speed and applied load),*
  - *lubricant characteristics (lubricant viscosity and density).*
- *Thus, the study of these devices is based not only on lubrication theory, but also on a set of conditions related to the environment of the mechanisms. The minimum thickness of the lubricating film must always be significantly greater than the sum of the surface roughness heights.*
- *The power dissipated by shear in the lubricating fluid (especially under severe operating conditions) causes the temperature of the mechanism to rise. This increase in temperature leads to a decrease in the viscosity of the lubricant (significant reduction in load capacity) and elastic deformation of the surfaces in contact.*

1. Introduction : Properties of surfaces



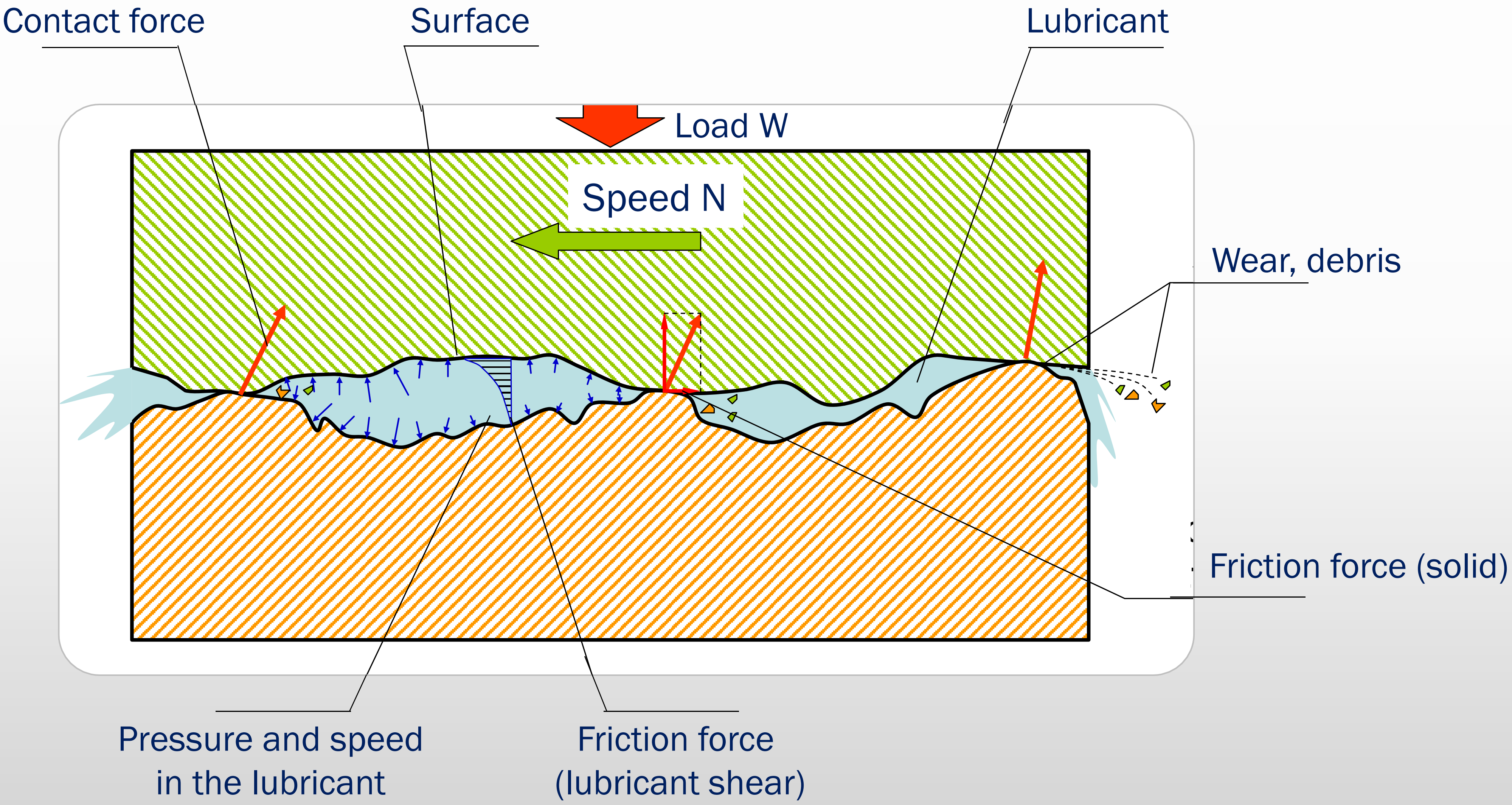
1. Introduction : different lubrication regimes



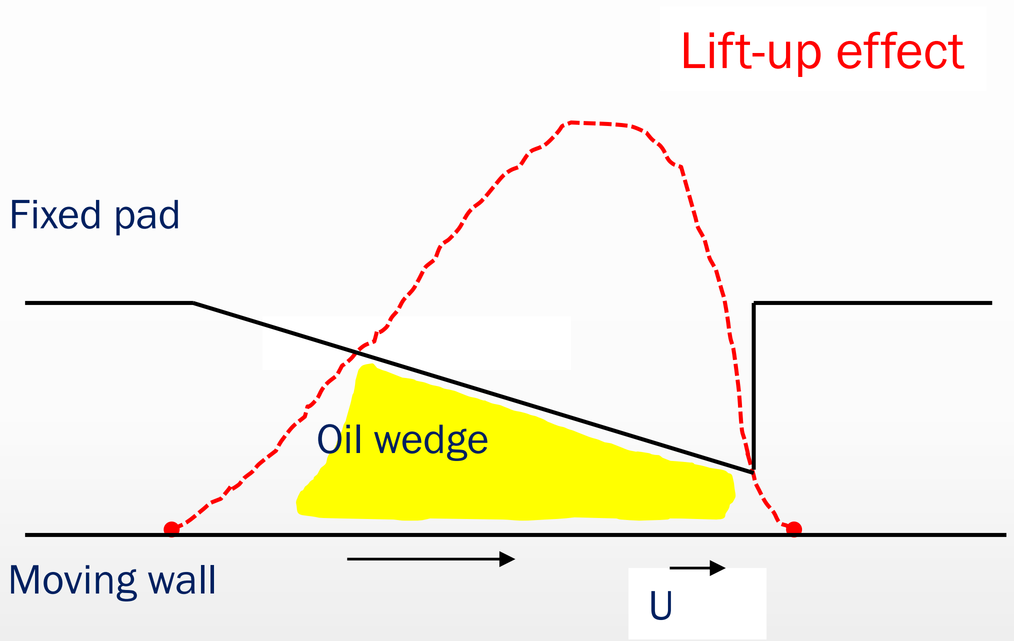
$$\lambda = \frac{h_{min}}{\sigma}$$

Sommerfeld Number : $S = \left(\frac{R}{C}\right)^2 \frac{\mu N 2 R L}{P}$

1. Introduction : different lubrication regimes



1. Introduction : the oil wedge



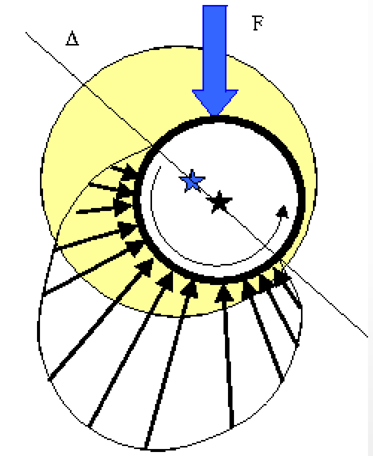
- *Oil accumulation under a fixed pad.*
- *Separation of the surfaces by creating a pressure field*
- *Hydrodynamic bearings use this phenomenon*

1. Introduction : terminology

Bearings : rotating machines guiding devices

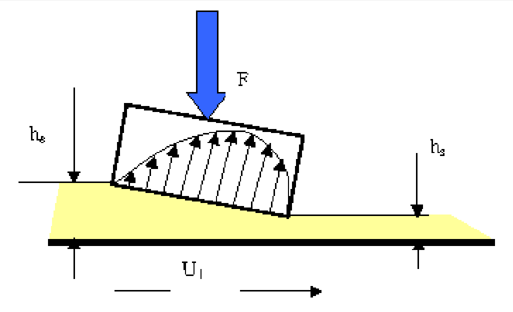
➡ JOURNAL BEARINGS (RADIAL LOADING)

- Shaft = rotating part
- Housing = fixed part



➡ THRUST BEARINGS (AXIAL LOADING)

– Flat surface rotating with the shaft (runner) facing fixed surface with fixed geometry or tilting pads.



1. Introduction : terminology

➡ **EVOLUTION OF TECHNOLOGIES AND SPECIFICATIONS**

– Problems of design.

– Sharp choice criteria.

➡ **BEARINGS**

– Rotating device guidance

– Ensure load capacity under normal or unattended operating conditions

➡ **GOOD UNDERSTANDING OF THE GUIDING DEVICE**

– Analysis of the physical phenomena which occur at the interface between two pieces in relative motion to avoid wear, warmup or seizure problems

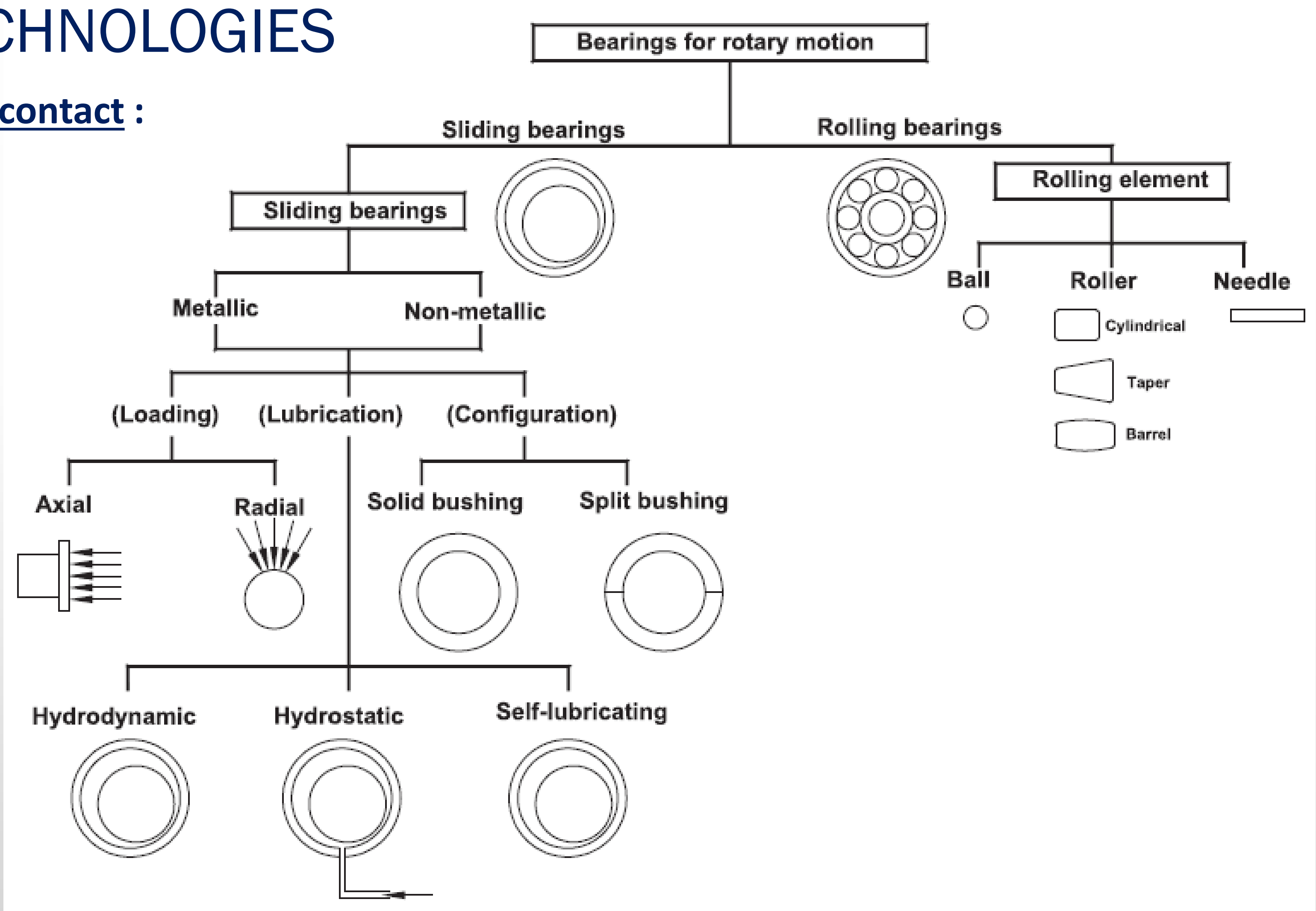
SOLUTIONS

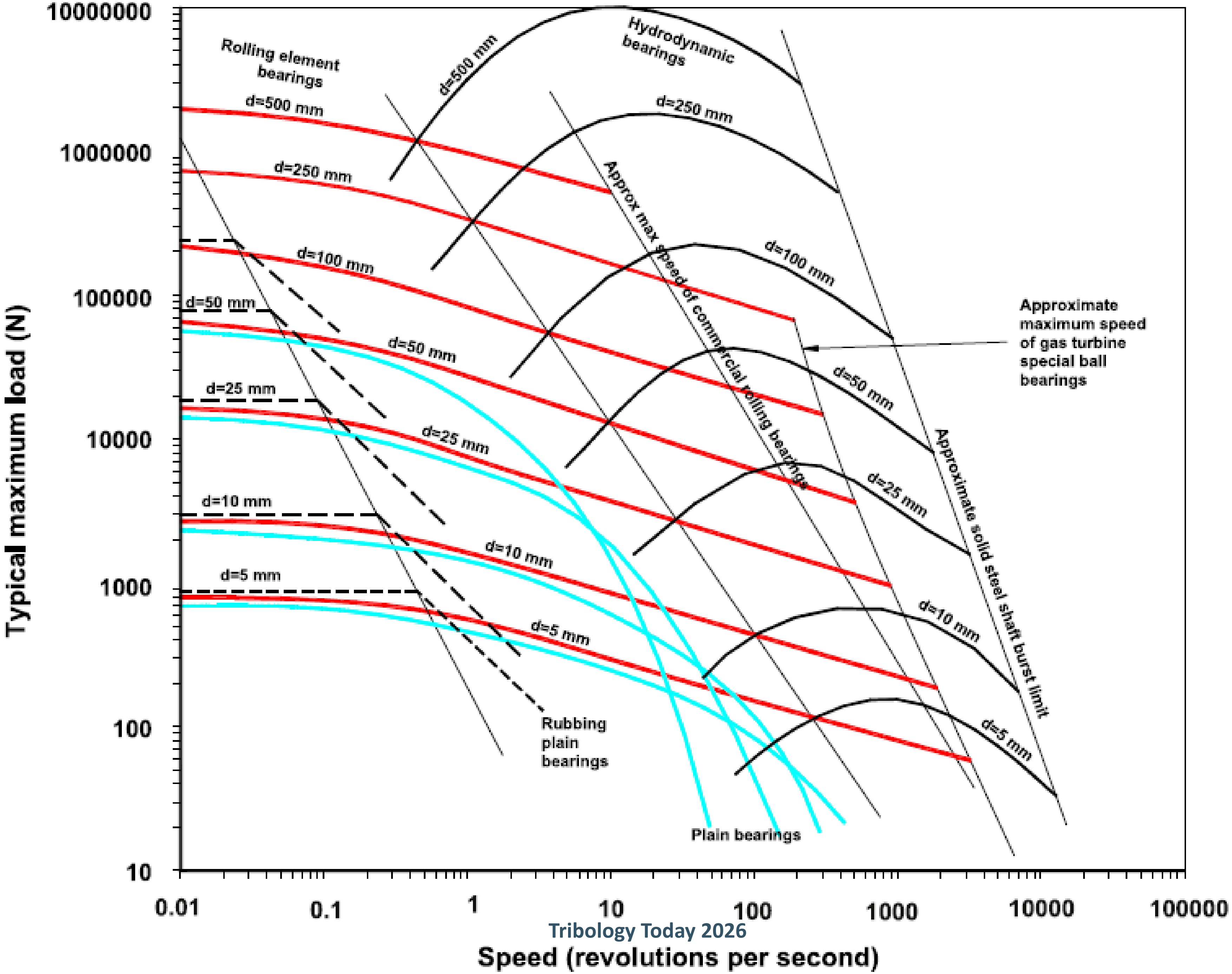
- Use of materials allowing required speeds and loads,
- Add a third part with a low friction coefficient,
- Fluid to ensure the cooling of the contact,
- Use of rolling elements

1. Introduction : terminology :

SEVERAL TYPES OF TECHNOLOGIES

- **guiding with <u>no sliding at the contact</u> :**
  - Rolling element bearings
- **guiding with <u>sliding contact</u>** :
  - Dry bearings
  - Porous bearings
- **guiding <u>without contact</u> :**
  - Magnetic bearings
  - Fluid film bearings




Typical maximum load (N)
10000000
1000000
100000
10000
1000
100
10
Speed (revolutions per second)
0.01
0.1
1
10
100
1000
10000
100000
Rolling element bearings
d=500 mm
d=250 mm
d=100 mm
d=50 mm
d=25 mm
d=10 mm
d=5 mm
Hydrodynamic bearings
d=500 mm
d=250 mm
d=100 mm
d=50 mm
d=25 mm
d=10 mm
d=5 mm
d=50 mm
d=25 mm
d=10 mm
d=5 mm
Approx max speed of commercial rolling bearings
Approximate maximum speed of gas turbine special ball bearings
Approximate solid steel shaft burst limit
Rubbing plain bearings
Plain bearings

1. Introduction : applications and illustrations.

ROLLING ELEMENT BEARINGS

⇨ **PRESENTATION**

- Guiding and centering function of the shaft in the bearing bushing
- Commonly used because of many advantages:
  - ease of implementation,
  - autonomous operation,
  - low dissipated power,
  - diversity for almost all industrial applications.

⇨ **CONDITIONS**

- Wide range of applications since they can withstand high specific loads and high rotational speeds.

1. Introduction : applications and illustrations.

HYDROSTATIC BEARINGS

⇨ **DISADVANTAGES**

– Cost (manufacturing and maintainance)

– Space requirement

⇨ **PRESENTATION**

- Pressurized injection of the fluid through the bearing by cells where the pressure is constant
- Balancing the load applied to the bearing by the presence of a lubricating film between the shaft and the bearing bush
- Moderate speed, heavy load

rotating shaft ⇨ hybrid bearing.

⇨ **ADVANTAGES**

- No wear
- No stress concentration
- Improved dynamic behavior

1. Introduction : applications and illustrations.

HYDRODYNAMIC BEARINGS

PRESENTATION

– Shaft rotating in a housing with a lubricating film separating the surfaces

CONDITIONS

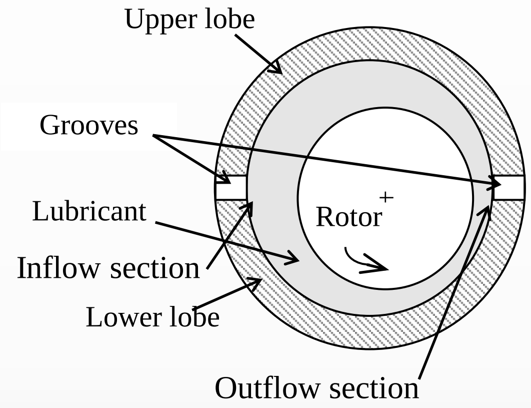
– Creation of an oil wedge inside the film

– Pressure film generation thanks to fluid shear and squeeze

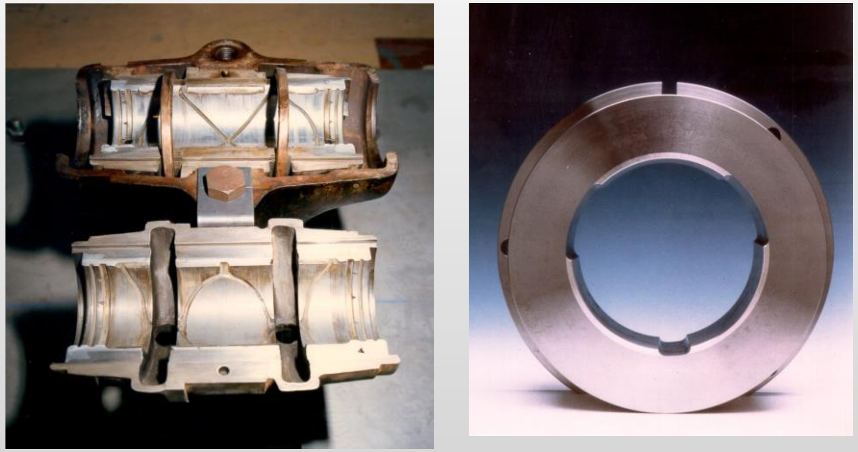
SEVERAL GEOMETRIES

– Fixed geometry (plain, lemon, n lobes, CJGB, ...)

– Tilting-pad

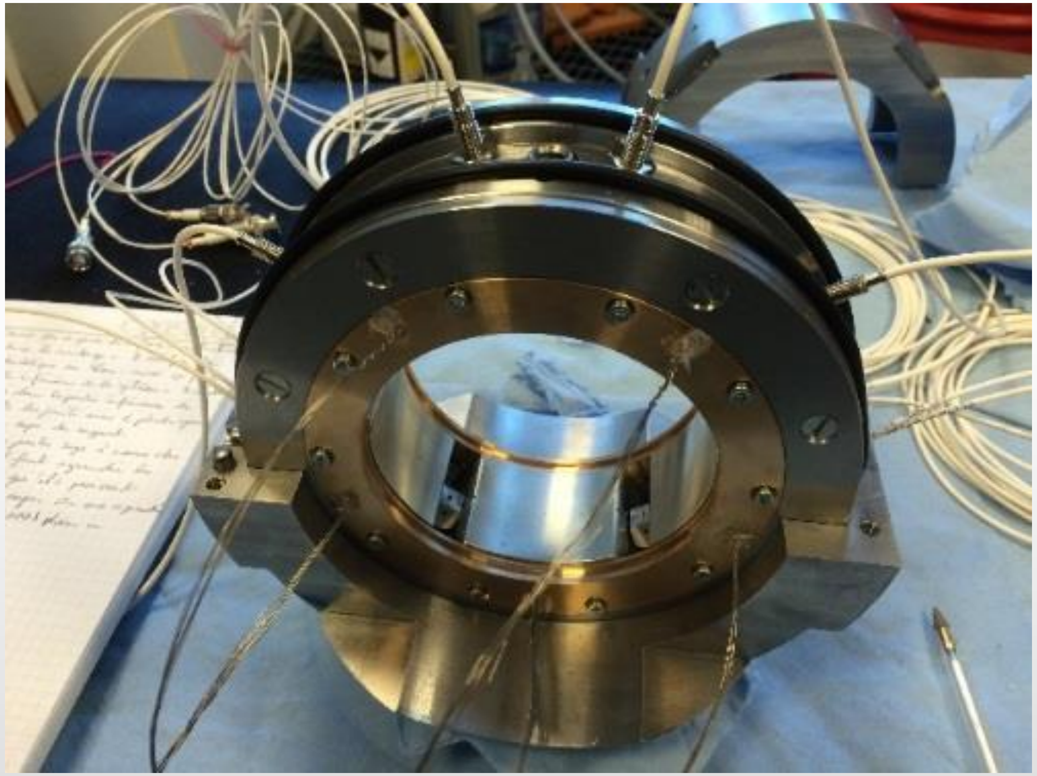


Schematic bearing view



1. Introduction : applications and illustrations.

HYDRODYNAMIC BEARINGS



Tilting-pad Journal Bearing

CONDITIONS

- High rotational speed
- Heavy Loads

CHOICE OF THE TYPE OF BEARING

From operating conditions, find a compromise between :

- Support the load with a reasonable film thickness
- Do not generate instabilities
- Evacuate the heat due to shear in order to avoid hotspots

1. Introduction : applications and illustrations.

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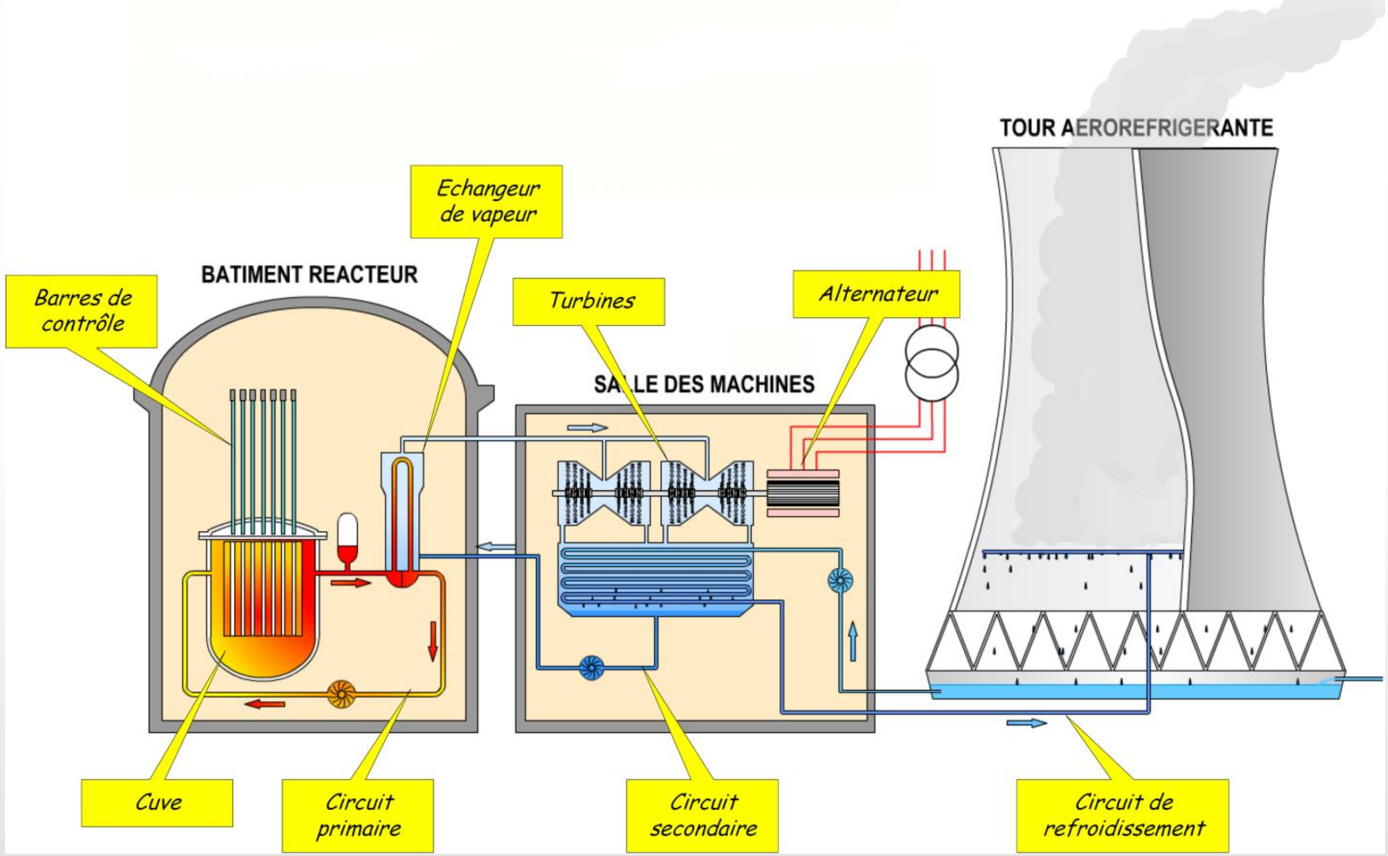
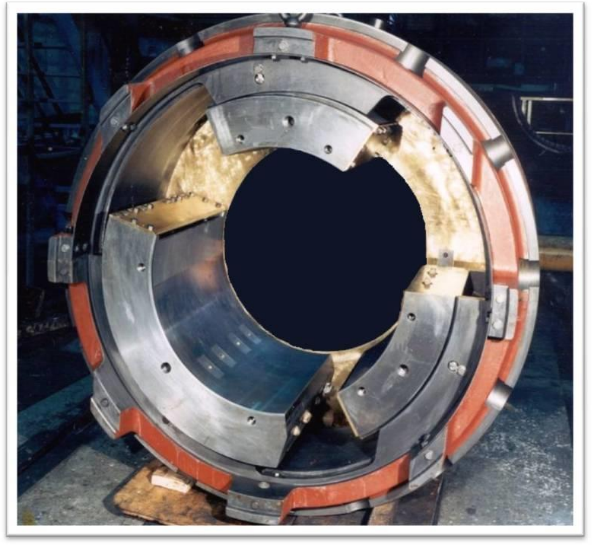
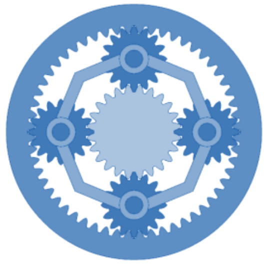
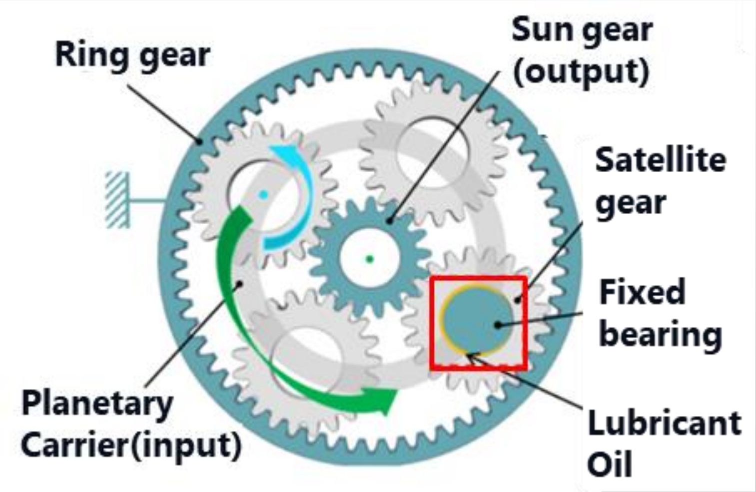
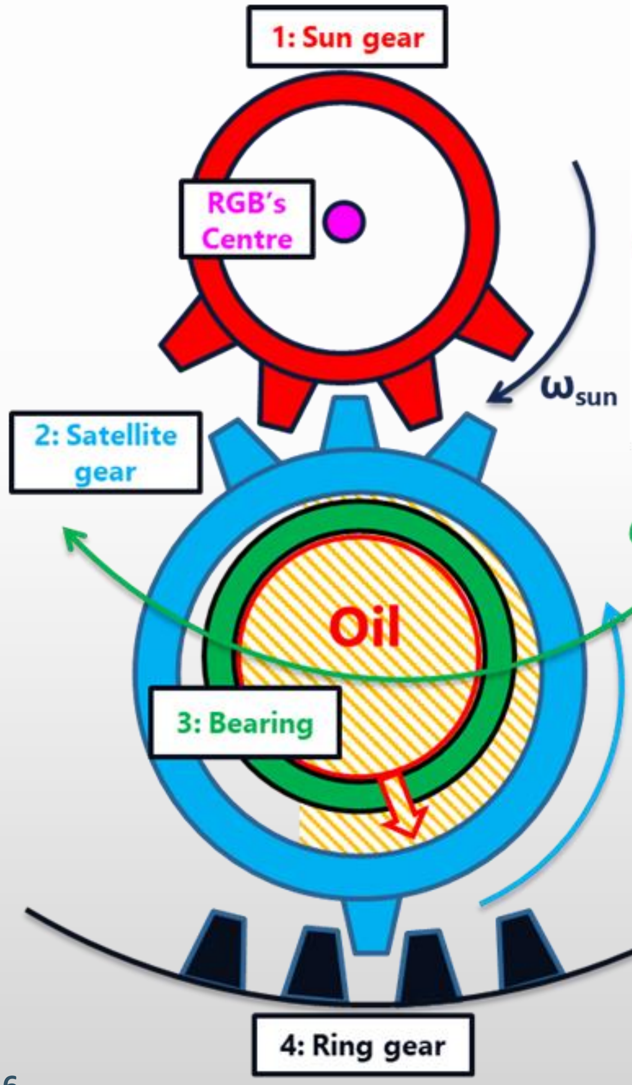


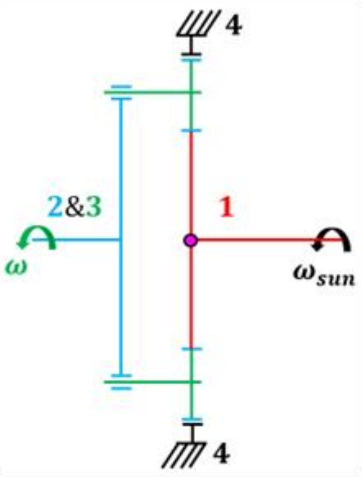


1. Introduction : applications and illustrations.









2. LUBRICANTS

Mandatory for a lubricated bearing!

2. Lubricants

- Different types of lubricants

  - *Gaseous: air, neon, nitrogen, hydrogen, oxygen…*

    (high speed applications, reduce friction)

  - *Liquids: water, oil, liquid metal…*

    (lubrication et calories evacuation with the need of a cooling system)

  - *Plastics: greases, pastes…*

    (no cooling necessary, low speed applications)

  - *Solids: MoS2, PTFE, graphite…*

    (extreme operating conditons, high temperatures, extreme vacuum, high pressures, harsh environments)

2. Liquid lubricants

- Specific heat & density (imposed flow)

  ↳ calories evacuation

- From all physical properties of a lubricant, viscosity is the most important in lubrication

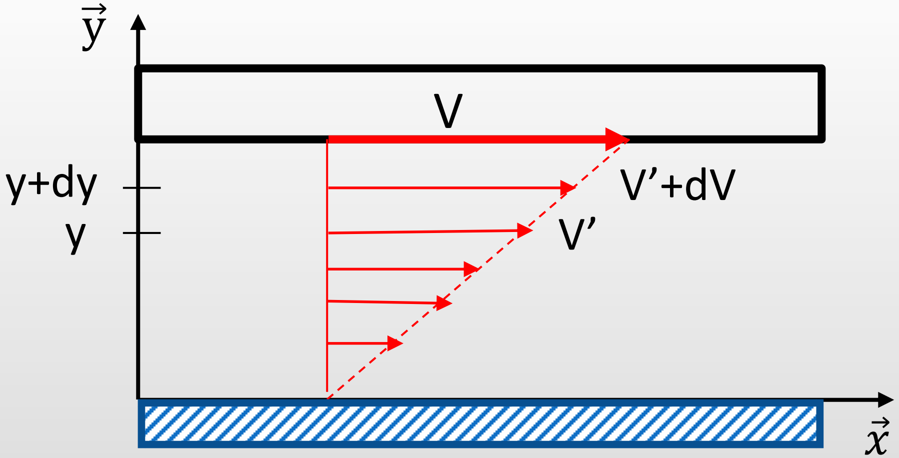
- The viscosity determines:
  - *Friction losses,*
  - *Load carrying capacity,*
  - *Film Thickness.*

2. Lubricants

- The viscosity of a liquid is its property resulting from the resistance of its molecules to a force tending to displace it by sliding within it.

From NF-T-60-100 (1959)

- The resistive force can be calculated using Newton's formula for laminar fluid flow between a moving plate and a fixed plate:



The tangential stress is called shear stress (τ). It can be written as :

$$\tau = \mu \frac{dv}{dy}$$

2. Lubricants

- Viscosity definition

$$\boxed{\tau = \mu \frac{dv}{dy}}$$

- μ is the **dynamic viscosity**, expressed in Pa.s or Pl:

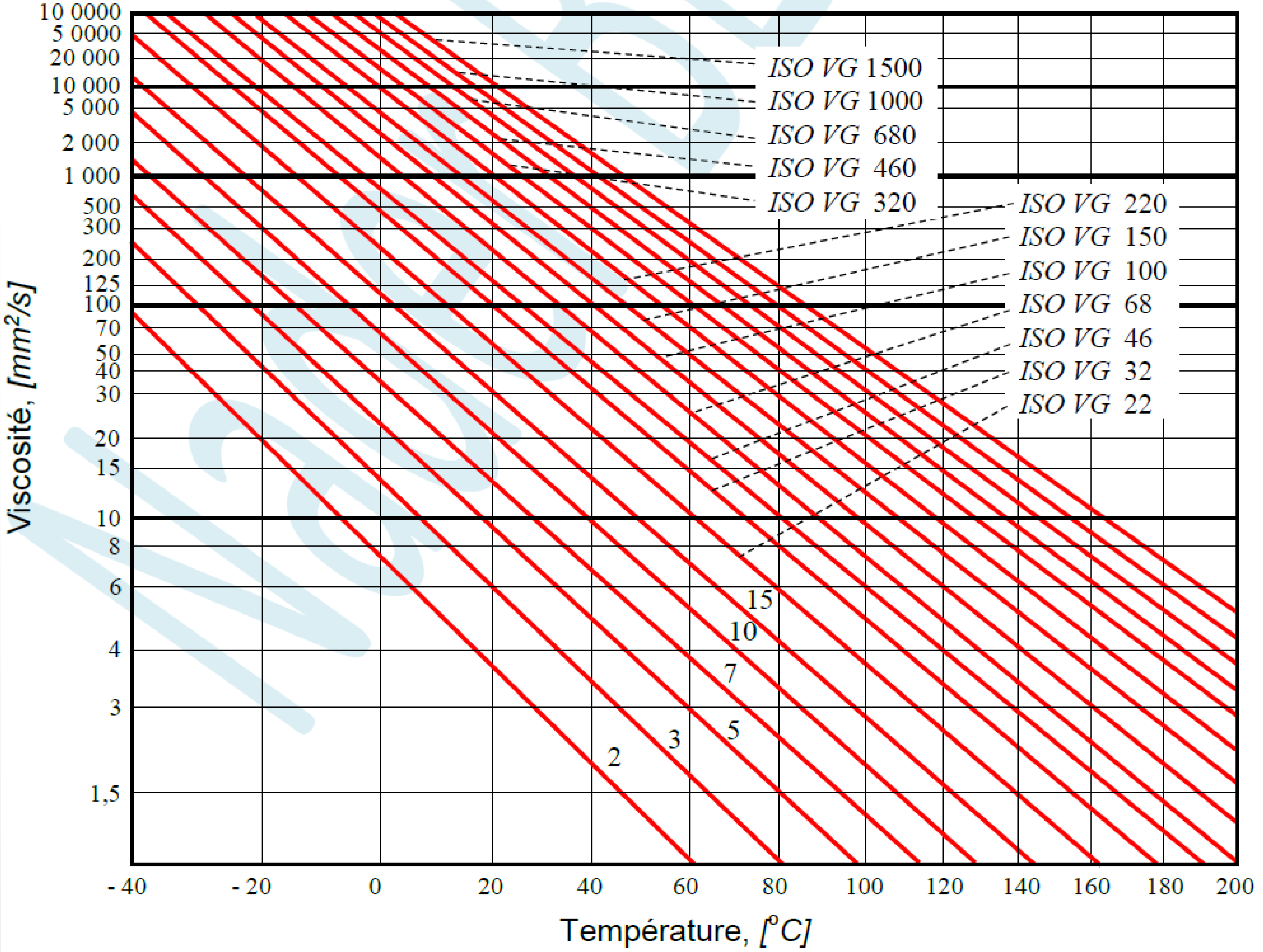
Poiseuille	1 Pl = 1 Pa.s
Poise	1 Po = 10^{-1} Pa.s
CentiPoise	1cPo = 10^{-3} Pa.s = 1 mPa.s

- **Kinematic viscosity ν** is expressed in m²/s, more often in mm²/s : $\boxed{\nu = \frac{\mu}{\rho}}$

Stokes	1 St = 1 cm²/s = 10^{-4} m²/s
CentiStokes	1 cSt = 10^{-6} m²/s

2. Lubricants

Generally speaking, lubricants have a viscosity which strongly depends on temperature.



2. Lubricants

Different relations describing the viscosity variation as a function of temperature exist:

- Inverse polynomial relationship : $\mu = \mu_0 e^{-\left(\frac{a+bT+cT^2}{T}\right)}$

where μ_0 is the viscosity at a given temperature, T is the absolute temperature and a, b and c are constants related to the oil's properties.;

- McCoull & Walther relationship:

$$log(log(\gamma+a))=-mlog(T)+n$$

where γ is the kinematic viscosity of the lubricant, T is the absolute temperature and a, m and n are constants related to the oil's properties;

2. Lubricants

- <u>Exponential relationship :</u> $\mu = \mu_0 e^{-\beta(T-T_0)}$

where μ_0 is the dynamic viscosity at a reference temperature T_0 and $\boldsymbol{\beta}$ the thermoviscosity coefficient related to the oil's properties;

$\beta = 0{,}034\ K^{-1}$ for an ISO VG 32 oil, with $40°C < T < 100°C$

$\mu_0 = 0{,}028\ Pa.s$ at $T_0 = 40°C$

2. Lubricants

The viscosity of most oils increases with pressure. This effect, known as piezoviscosity, is very important in the case of elastohydrodynamic contacts (bearings, cams, gears, etc.).

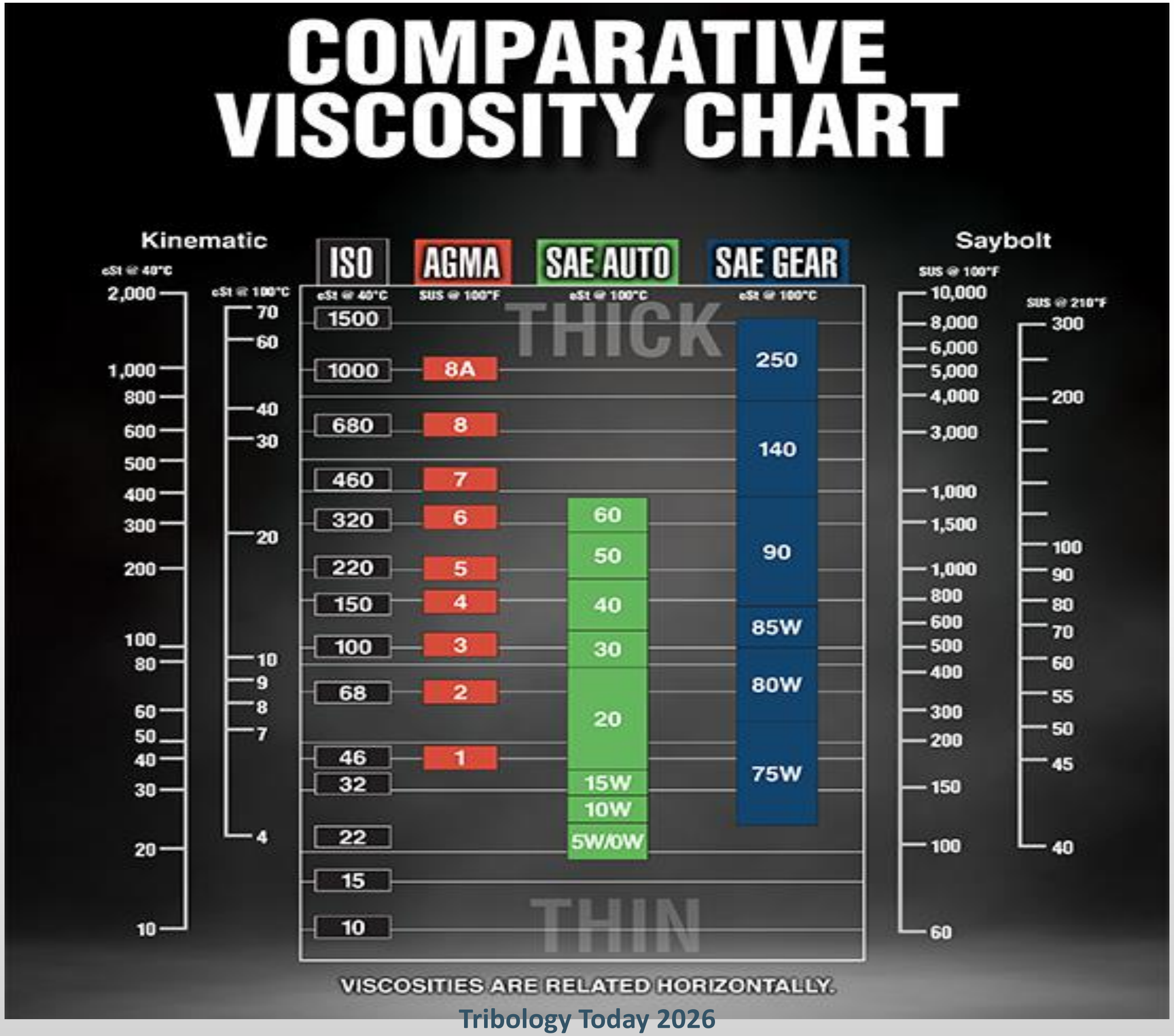
To characterize this effect, the Barus relationship can be used (1893):

$$\boldsymbol{\mu = \mu_0 e^{\alpha p}}$$

where $\boldsymbol{\mu_0}$ is the dynamic viscosity of the reference lubricant and $\boldsymbol{\alpha}$ the piezoviscosity coefficient related to the oil's properties;

$$\mathbf{5}.10^{-9} \leq \boldsymbol{\alpha} \leq \mathbf{40}.10^{-9} \text{ Pa.s}$$

2. Lubricants : classifications



3. REYNOLDS EQUATION

The lubricaton theory base

3.1 Reynolds Equation

➡ Presence of a viscous oil film between two surfaces

✚ A pressure field builds-up inside the fluid

➡ Maintain of the lubricating film
Balance of the applied load

Hydrodynamic Lubrication ➡ Pressure is generated by the converging gap and the relative movement of the surfaces

Hydrostatic Lubrication ➡ Pressure is generated by an external device

3.1 Reynolds Equation

Fluid squeeze and shear in the convergent

➡ Pressure build-up inside the contact

Objective : calculate the pressure field

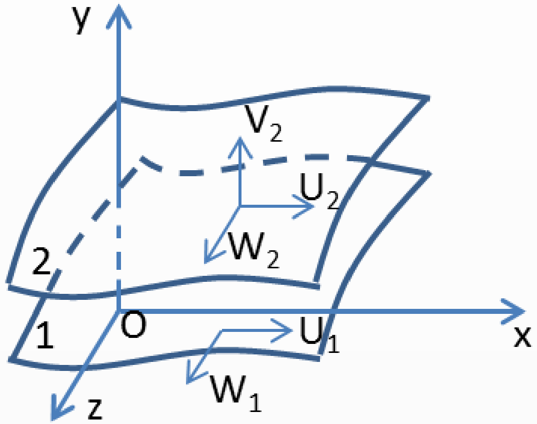
➡ Navier et Stokes Equation

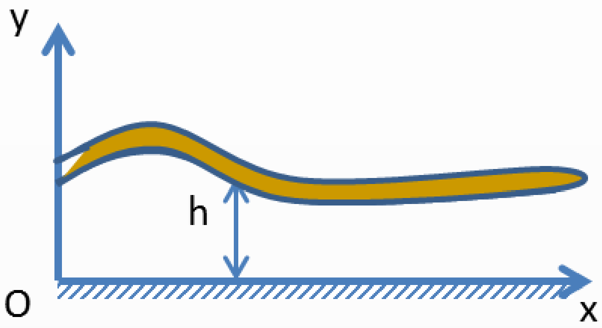
✚ Assumptions:

- *Continuous medium*
- *Newtonian fluid*
- ***The film thickness is very small compared to the other dimensions***
- *External mass forces are neglected*
- *Inertia is negligible*
- *No slip between fluid and walls*
- *Fluid viscosity does not vary along the film thickness*
- *Constant density*

Non-newtionien (Experimentboy)

3.1 Reynolds Equation





$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial z}\right)$$
$$= 6\,(U_1-U_2)\frac{\partial h}{\partial x}+6\,(W_1-W_2)\frac{\partial h}{\partial z}+6h\frac{\partial}{\partial x}[(U_1+U_2)]+6h\frac{\partial}{\partial z}[(W_1+W_2)]+12V_2$$

with

- p : pressure
- h : film thickness
- μ : dynamic viscosity
- U_i, V_i, W_i : surface velocities along directions x, y, z

3.2 Thermal effects

➡ Fluid shearing ➡ heat generation

⬇

variation of viscosity with temperature :

Exponential law : $\mu = \mu_0 e^{-\beta(T-T_0)}$

Mac Coull & Walther law : $log(log(\gamma+a))=-mlog(T)+n$

Inverse polynomial law : $\mu = \mu_0 e^{-\left(\frac{a+bT+cT^2}{T}\right)}$

⬇

Variation of the pressure field and of the performance of the bearing

3.2 Thermal effects

- **THD approach**

➡ Temperature determination in both the lubricant and the solids

- Energy equation for the film :

$$\underbrace{\rho\frac{\partial T}{t}+\rho u\frac{\partial T}{\partial x}+\rho v\frac{\partial T}{\partial y}+\rho w\frac{\partial T}{\partial z}}_{convection}=\underbrace{\kappa\frac{\partial^2 T}{\partial y^2}}_{conduction}+\underbrace{\mu\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]}_{viscous\ dissipation}$$

with

- *T : temperature within the fluid at any point,*
- *u, v, w : velocity components,*
- *ρ : density of the lubricant,*
- *κ : thermal conductivity of the lubricant,*
- *μ : dynamic viscosity of the lubricant*

- Heat equations
  - *In the housing*

$$\rho_c\frac{\partial T}{\partial t}+\kappa_c\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{r\partial\theta^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right]=0$$

  - *In the shaft*

$$\rho_a\frac{\partial T}{\partial t}+\kappa_a\left[\frac{\partial^2 T}{\partial x^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right]=0$$

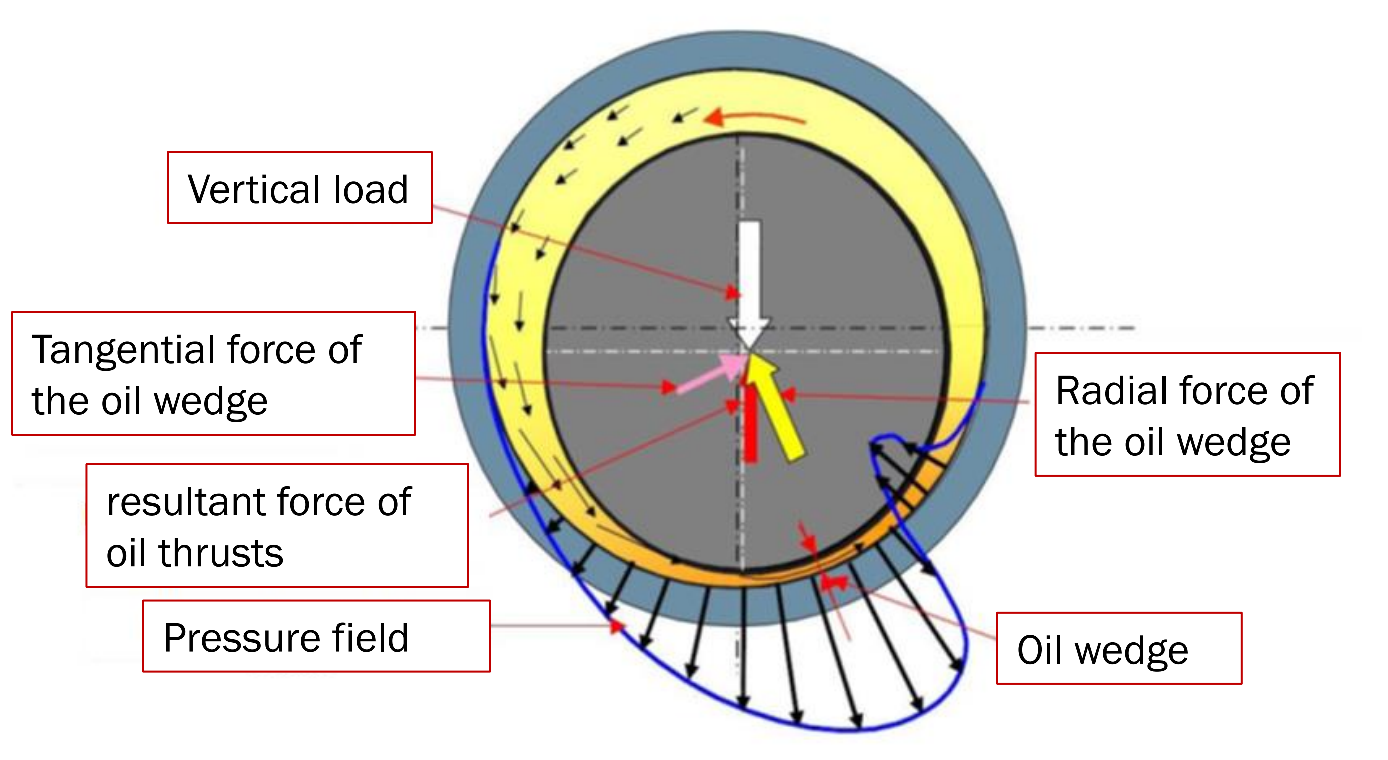
3.3 Deformation effects

- **Mechanical deformations**
  - Due to extreme fluid pressures or contact pressure
  - Solid parts of the bearing, housing and/or shaft can deform
  - The geometry of the bearing is modified
- **Thermal deformations**
  - Due to high fluid temperatures inside the bearing
  - Solid parts of the bearing, housing and/or shaft can deform
  - The geometry of the bearing is modified
- **Numerical calculations**
  - Calculations have to be performed using in-house FE codes or commercial ones
  - The film thickness is modified and introduced in the calculations of the bearing.

4. HYDRODYANMIC BEARING

Static behavior

4.1 Hydrodynamic Bearings - Static behavior



- Hydrodynamic lubrication of journal bearings:
- 4 main parameters
  - *Position,*
  - *Pressure,*
  - *Friction,*
  - *Temperature (solids, fluid)*

4.2 Sizing criteria

FIELD OF USE - PHYSICAL AND TECHNICAL CRITERIA

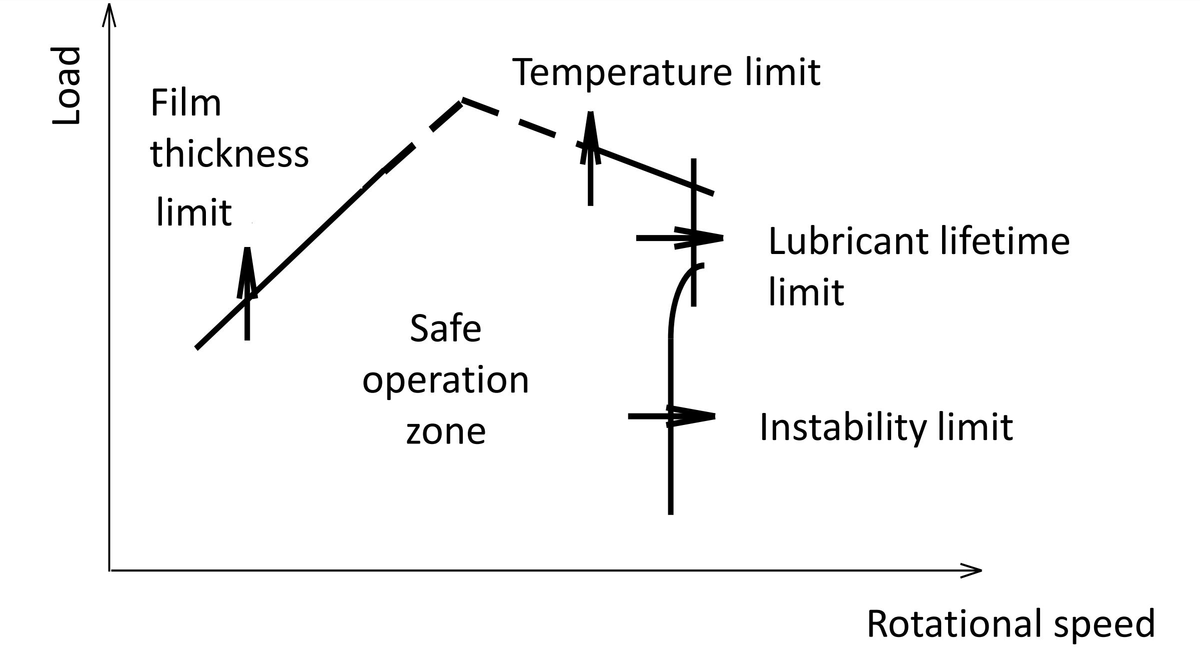
- *Rotational speed*
- *Type of load*
- *Component dimensions*
- *Material and lubricant characteristics*
- *Operating conditions.*

The choice of bearing is generally determined by:

- *Rotational speed*
- *Load*
- *Shaft diameter*

4.2 Sizing criteria

- **Operating limits of hydrodynamic bearings**



Operating limits

- Risk of contact
- Risk of babbitt melting
- Risk of oxydation of the lubricant
- Risk of instability

Sizing criteria

- Lubricant lifetime
- Babbitt lifetime
- Minimum film thickness
- Contact geometry

4.3 Materials and coatings

- The use of different materials and coatings influences the behavior of the bearing
  - *Temperature (film thickness, load capacity…)*
  - *Ability to support harsh conditions (pollution, starvation…)*
  - *Wear performance*
- It depends on the type of use of the bearing:
  - *Marine applications*
    - Water lubricated: steel shaft with bronze sleeve and polymer bushing
    - Oil lubricated: steel shaft with either babbitt or bronze bushing
  - *ICE*
    - Steel shafts with bronze bearings (turbocharger), babbitted bearings (cranckshaft, con-rods) with eventually coatings, DLC coating (camshaft)
  - *Turbomachinery*
    - Shaft: Steel (hardened, nitrided…) and coated steel (MoS_2, DLC…)
    - Housing : babbitted (large bearings), bronze, coated steel or bronze, polymers, etc.

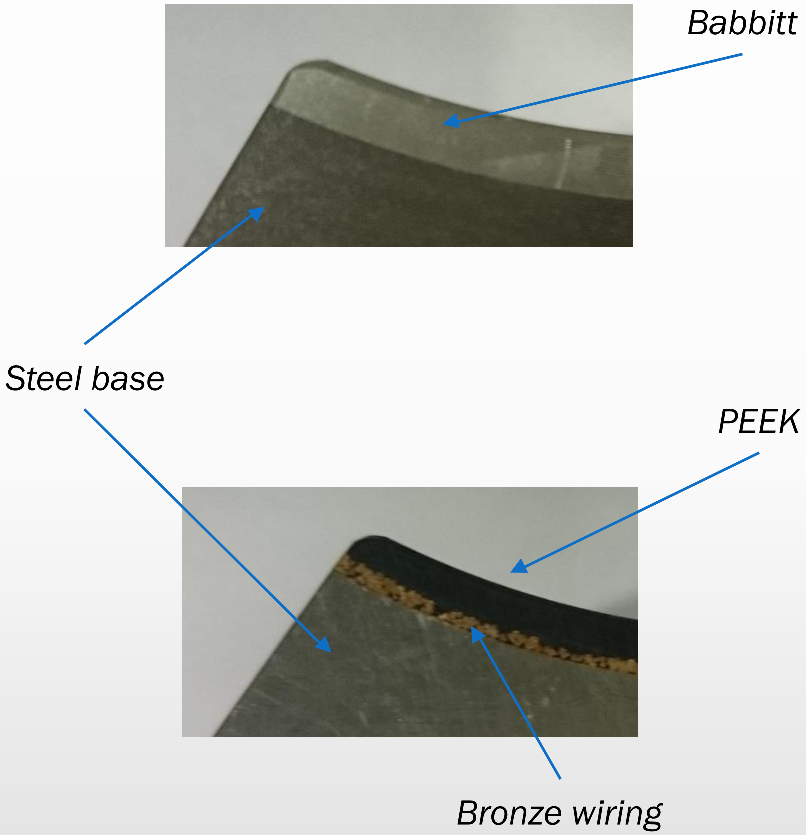
4.3 Materials and coatings

Material Type	Base Composition	Key Properties	Typical Applications
Babbitt Alloys	Tin, copper, antimony	Excellent conformability and embeddability; low friction	Light to medium load machinery
Bronze Alloys	Copper, tin, zinc	High strength, good fatigue resistance	Medium to heavy-duty applications
Aluminum Alloys	Aluminum, silicon, copper	High thermal conductivity, lightweight	Automotive engines, compressors
Copper Alloys	Copper	Strong load capacity, fair compatibility	Diesel engines, turbines
Polymer Composites	PTFE, PEEK, or reinforced resins	Self-lubricating, corrosion-resistant	Dry or marginal lubrication systems
Ceramic Materials	Silicon nitride, alumina	Excellent heat resistance, low wear	High-speed or precision equipment

4.3 Materials and coatings

Property / Material	Babbitt	Bronze	Aluminum	Copper	Polymer	Ceramic
Load Capacity	Medium	High	Medium	Very High	Medium	Very High
Friction Coefficient	Low	Moderate	Low	Moderate	Very Low	Very Low
Thermal Conductivity	High	High	Very High	High	Moderate	Low
Corrosion Resistance	Moderate	Good	Excellent	Moderate	Excellent	Excellent
Maintenance Requirement	High	Medium	Medium	Medium	Very Low	Low
Typical Applications	Pumps, light machinery	Industrial equipment	Automotive engines	Power systems	Dry-running systems	High-speed precision devices

4.3 Materials and coatings

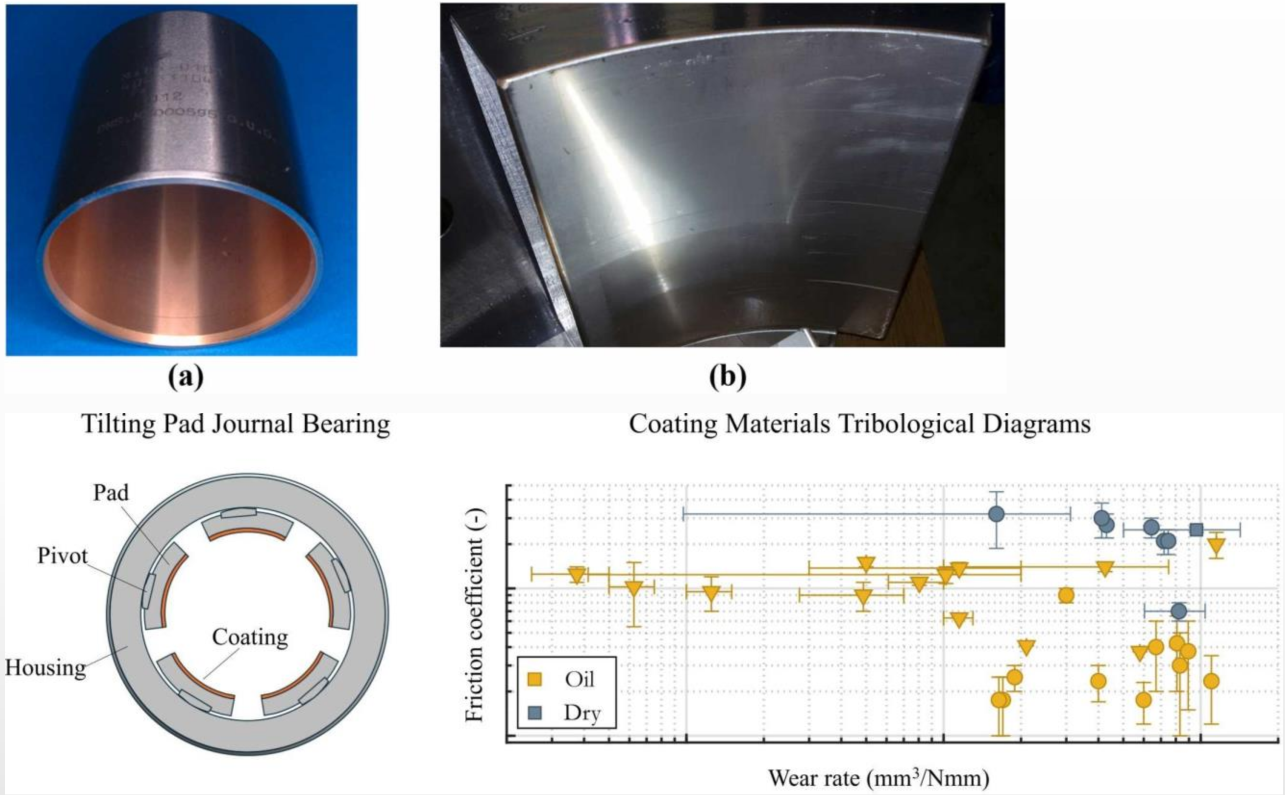


Babbitt

Steel base

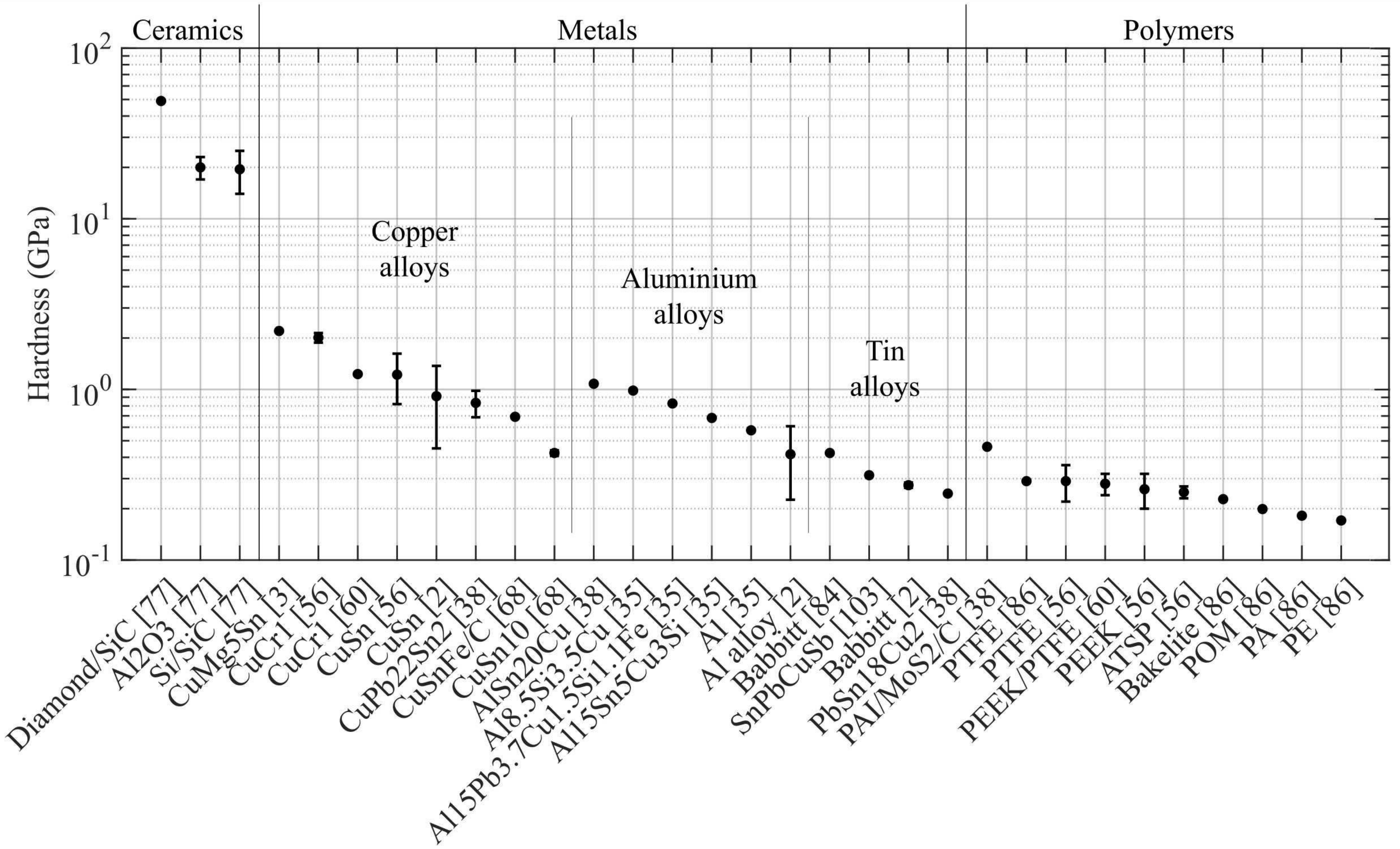
PEEK

Bronze wiring



A. Betti, A. Riva, P. Forte, S. Chatterton, E. Ciulli,
Coating materials for journal bearings,
Tribology International,
Volume 219,
2026,

4.3 Materials and coatings



4.3 Materials and coatings

- **DLC**

  Diamond-Like Carbon. A coating that offers unmatched properties: low friction, high hardness, and high corrosion resistance. When wear protection and good sliding are required, DLC and other carbon-based coatings are the perfect solution.
    - prevent wear due to their excellent tribological properties
    - resistant to abrasive and adhesive wear (suitable for use in applications that experience extreme contact pressure) both in rolling and sliding contact.
    - Insensitive to temperature
    - often used to prevent wear on razor blades and metal cutting tools
    - used in bearings, cams, cam followers, and shafts in the automobile industry. The coatings reduce wear during the 'break-in' period, where drive train components may be starved for lubrication.
- **PTFE**

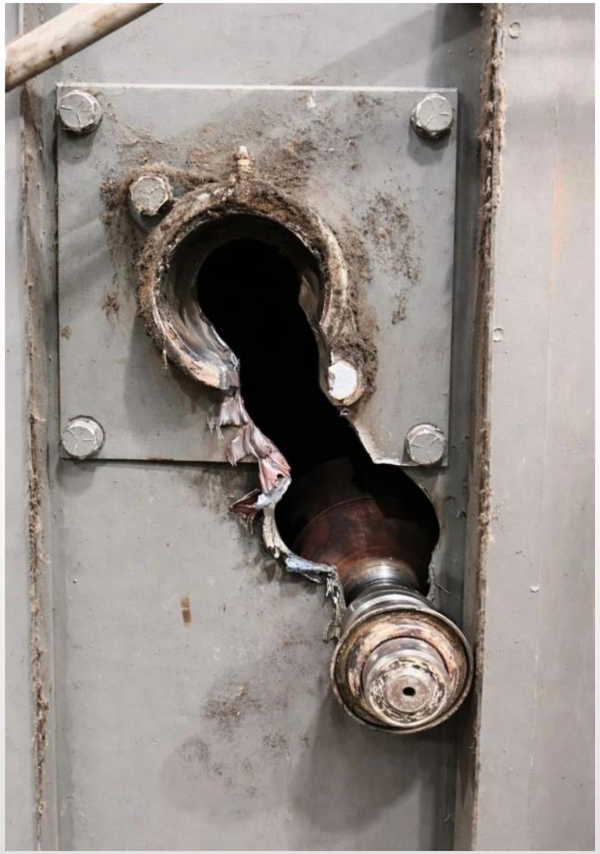
  PolyTetraFluoroEthylene. Soft polymeric material with good friction properties depending on its composition. Sensible to temperature, operating temperatures quite low.
- **PEEK**

  PolyEtherEtherKetone. Medium hard polymeric material with good friction properties depending on its composition. High operating temperatures, up to 180°C.

4.4 Summary

- What is important to know about a **hydrodynamic bearing**?
  - *Its dimensions*
    - Length, Diameter
    - Radial clearance
  - *The operating conditions*
    - Load (static or dynamic)
    - Speed

- What is important about the **lubricant**?
  - *Viscosity*
  - *Density*
  - *Specific heat*
  - *How viscosity can vary with temperature and/or pressure*



5. FAILURE MODES

5.1 What defines a failure?

In general, **failure** refers to the state or condition of not meeting a desired or intended objective, or the inability of a system, component, or process to perform its required function.

It can apply to:

- **Business/Project:** The inability to achieve goals, such as financial loss, project abandonment, or bankruptcy.
- **Personal:** A lack of success in achieving a personal goal or expectation.
- **Technical/Engineering:** A loss of function or breakdown of a machine, structure, or system (e.g., engine failure, structural failure).

5.1 What defines a failure mode?

In mechanical engineering, a **failure mode** is the way in which a product, component, assembly, process, or organization fails or deviates from specifications.

Failure Mode and Effects Analysis (FMEA)

2 aspects:

- Qualitative:
  - ➢ List potential failures of the system,
  - ➢ Search and identify their causes,
  - ➢ Find the effects on clients, users, internal and/or external environment.
- Quantitative:
  - ➢ Estimation of the risk associated to the failure.
  - ➢ Identify and hierachisation the potential failures
  - ➢ Decision which diminish the impact of the failure and/or suppress its causes

5.2 Failure modes in transmissions

1. **Normal Wear:**
   - Gear Wear: Progressive loss of material on gear teeth due to friction and cyclic loads.
   - Bearing Wear: Degradation of surfaces, balls, rollers, or cages in bearings, leading to mechanical gaps and vibrations.
   - Belt and Chain Wear: Elongation, cracking, or loss of tension, reducing transmission efficiency.
2. **Material Fatigue:**
   - Cracking and Fracture: Microcracks develop under repeated loads, potentially leading to sudden failure (e.g., shafts, gear teeth).
   - Pitting: Formation of small craters on gear or bearing surfaces due to repeated contact stress.
3. **Mechanical Overload:**
   - Shear or Excessive Torsion: Breakage of shafts or keys under excessive torque.
   - Plastic Deformation: Permanent deformation of components (e.g., crushed gear teeth).
4. **Lubrication Failures:**
   - Insufficient Lubrication: Increased friction, overheating, and accelerated wear.
   - Lubricant Contamination: Presence of abrasive particles (dust, metal) or water, degrading surfaces and reducing lubrication effectiveness.
   - Incorrect Lubricant: Using lubricants with unsuitable viscosity or additives for operating conditions.

5.2 Failure modes in transmissions

5. **Corrosion:**
   - Oxidation: Rust on metal components, especially in humid or chemically aggressive environments.
   - Contact Corrosion: Degradation of contacting surfaces (e.g., fretting corrosion).
6. **Misalignment and Mechanical clearance:**
   - Poor Alignment: Premature wear of gears, bearings, or joints due to misaligned shafts or components.
   - Excessive clearance: Noise, vibrations, and loss of precision in transmission.
7. **Thermal Failures:**
   - Overheating: Expansion of materials, loss of mechanical properties, or even localized melting (e.g., gear seizing).
8. **Design or Assembly Errors:**
   - Unsuitable Materials: Use of materials that are too fragile or not resistant to operating conditions.
   - Incorrect Assembly: Over-tightening or under-tightening, improper adjustment of clearances, or assembly errors.
9. **Vibrations et resonance**
   - Vibration Fatigue: Failure or damage to components due to prolonged vibrations or resonance phenomena.

5.2 Failure modes in transmissions

How to Prevent These Failures?

- Preventive Maintenance: Regular inspection of component condition, proper lubrication, and replacement of worn parts.
- Monitoring Operating Conditions: Measuring vibrations, temperature, and noise to detect anomalies.
- Adherence to Specifications: Using recommended materials, lubricants, and assembly procedures.

5.2 Failure modes in transmissions

1. **Environmental factors**
   - Extreme Temperatures: Operating outside the designed temperature range, affecting material properties and lubricants.
   - Humidity and Chemicals: Exposure to corrosive or abrasive environments.
   - Dust and Debris: Ingress of particulate matter, accelerating wear and contamination.

2. **Human factors**
   - Improper Operation: Overloading, sudden starts/stops, or misuse of the equipment.
   - Neglect: Skipping maintenance, ignoring warning signs, or failing to replace worn parts.
   - Poor Training: Operators or maintenance personnel lacking knowledge of proper procedures.

Preventive Measures:

- Design: Use robust materials, proper sizing, and consider environmental conditions.
- Maintenance: Regular inspections, lubrication, alignment checks, and timely replacement of worn parts.
- Monitoring: Implement sensors for temperature, vibration, and load to detect early signs of failure.
- Training: Ensure operators and maintenance staff are trained in best practices.

5.3 Failure modes in hydrodynamic bearings

- There are four main failure modes for journal bearings
  - *Seizing*
  - *Wear*
  - *Burn (extreme heating of the surface)*
  - *Corrosion*

- **Seizing**

Seizing is a failure phenomenon where direct contact between moving surfaces causes material transfer from one to the other.

This failure mode occurs when the lubricating film is not yet generated (boundary/mixed lubrication), disrupted, or destroyed, often due to overload, insufficient speed, or overheating during start-up/shutdown or under-feeding phases.

5.3 Failure modes in hydrodynamic bearings

- **Wear**

Wear is a process of progressive degradation of the surfaces in contact, resulting from the loss of material due to mechanical and tribological interactions.

Unlike seizure, which is a rapid and often catastrophic event, wear occurs slowly, over a long period of time, due to repeated stress and phenomena such as abrasion, adhesion, or erosion.

- **Burning**

Burning surfaces (shafts and/or bearings) is a type of thermal failure caused by excessive overheating of bearing surfaces.

This overheating is generally caused by the system's inability to dissipate the heat generated by friction or by a failure of the lubricant (mainly the coking of the lubricating oil). Burning can result in thermal alteration of the bearing materials and irreversible effects on its mechanical and tribological properties, which can impact the reliability of the bearing at the end of its service life.

- **Corrosion**

Corrosion is a chemical degradation phenomenon that occurs when the bearing material reacts with aggressive substances present in the environment or lubricant.

Unlike other mechanical failure modes such as wear or seizure, corrosion results from electrochemical reactions that gradually degrade the bearing surface, affecting its hydrodynamic properties and its ability to support high loads and speeds.

5.3 Failure modes in hydrodynamic bearings

- Causes of failure are :
  - *Cavitation:* Formation and implosion of vapor bubbles in the lubricant, caused by pressure variations. This creates micro-jets that damage the bearing surface, leading to erosion and degradation of the material.
  - *Particle ingestion:* The presence of solid contaminants in the lubricant such as metal debris or dust, acts as an abrasive, causing wear on the bearing surfaces during normal operation. This manifests itself in the form of scratches of varying depths (sometimes critical) and in different positions on the surface of the shaft or the inner face of the bearing.
  - *Coating defect:* Problems related to the quality or adhesion of the protective coating on the bearing. This can lead to delamination under critical local pressure, premature wear, or exposure of the base material (substrate) to wear and corrosion.
  - *Oil coking:* Thermal degradation of the lubricating oil, forming carbonized deposits(called cokes). These semi-solid deposits can thermally degrade bearing surfaces by creating areas of burning or even seizure.

5.3 Failure modes in hydrodynamic bearings

- Causes of failure are :
  - *Poor design*: Defects in bearing design (e.g., inadequate tolerances, inappropriate choice of materials, or poor dimensioning that does not meet application specifications). This can cause poor load distribution or an inability to maintain an effective lubricating film.
  - *External environment*: The influence of the surrounding environment, such as wind, humidity, dust, or external human factors (such as frequent assembly errors in the industry), can alter the performance of the bearing and cause it to fail.
  - *Starvation*: Insufficient lubricant supply, caused by poor circulation, channel obstruction, or insufficient pressure, can occur particularly in aircraft, especially during certain specific phases of flight, such as wind milling or during a voluntary or involuntary supply system shutdown. These situations result in the bearing operating with reduced lubrication or even without oil (degraded operation), at flow rates insufficient to form a complete fluid film at high rotational speeds. This leads to a breakdown of the lubricating film, resulting in direct contact between the metal surfaces.
  - *Production*: Manufacturing defects, such as geometric imperfections, inappropriate surface roughness, or inadequate heat treatment, do not necessarily meet the specifications established upstream and assumed to be perfect during the design phase.

5.4 Summary

Once the **Failure Mode and Effects Analysis (FMEA)** is finished, we have all parameters to start the evaluation of the transmission reliability based on :

- A good knowledge of the eventual failures,

- A hierarchization of the failure modes as a function of their risks

-> The **sensitivity analysis** is thus a preliminary step in uncertainty quantification. It helps reduce the stochastic dimensionality of the problem by selecting only the most relevant parameters for the reliability analysis.

These parameters can be used to be implemented in a calculation module of a numerical code to evaluate the reliability of the considered device.

6. RELIABILITY

6.1 Reliability

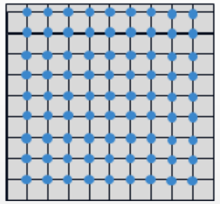
- Definition: **reliability** refers to the ability of a component, system, or product to perform its intended function without failure for a specified period, under stated operating conditions. It is a measure of dependability and is critical in ensuring safety, performance, and customer satisfaction.
  - *Probability of Success: reliability is often expressed as the probability that a system will operate without failure for a given time under specific conditions. For example, a reliability of 99.9% over 10,000 hours means the system is expected to fail only 0.1% of the time within that period.*
  - *Failure Rate: the frequency at which failures occur, often measured as failures per unit time (e.g., failures per million hours).*
  - *Mean Time Between Failures (MTBF): a metric used to quantify reliability, representing the average time between failures for repairable systems.*
  - *Mean Time To Failure (MTTF): similar to MTBF, but used for non-repairable systems, indicating the average time until the first failure.*

6.1 Reliability

- Once we have chosen which parameters we want to consider in our reliability evaluation by the sensitivity analysis (mechanical properties, oil properties, geometry…)

1. Perform calculations (it could be experimental tests) and evaluate the criteria.
2. **Design of experience** = choose points in predefined parameters space: several methods

Regular grid

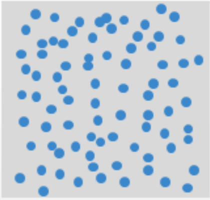


1

Random (Monte Carlo)

2

Sobol (Quasi Monte Carlo)



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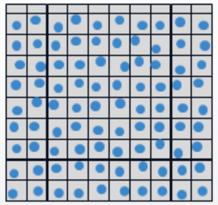
Latin Hypercube Sampling



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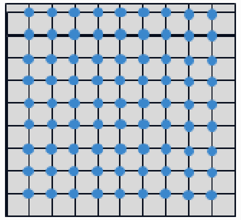
Methode	Uniformity	Convergence	Complexity	Recommanded dimensions	**Weak divergence** better spatial coverage) -> suitable for estimating Sobol indices
Grid	++	+++ (if small dimensions)	++	+ Weak	+
Random (Monte Carlo)	+	+ $\mathcal{O}\left(\frac{1}{\sqrt{N}}\right)$	++	+++ High	++
Sobol (Quasi Monte Carlo)	+++	+++ $\mathcal{O}\left(\frac{\log^d N}{\sqrt{N}}\right)$	+++	+++ High	++++
LHS	+++ (marg.)	++	+++	++ Average	+++

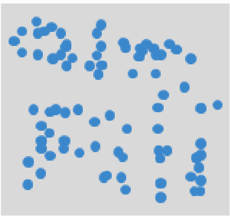
6.1 Reliability

Regular grid



1

Random (Monte Carlo)



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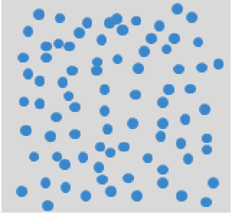
Sobol (Quasi Monte Carlo)



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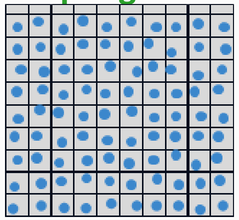
Latin Hypercube Sampling



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6.1 Reliability

- Once we have chosen which parameters we want to consider in our reliability evaluation (mechanical properties, oil properties, geometry…) by the sensitivity analysis

1. Perform calculations (it could be experimental tests) and evaluate the criteria.

2. **Design of experience** = choose points in predefined parameters space

Each point will then be evaluated to determine the corresponding value of the outcomes of interest (using a numerical simulator, an experimental protocol, observation of a production process, etc.). **Objective**: explore the behavior of outputs of interest using a limited number of evaluations.

3. Propagate the uncertainties in the model

4. Evaluate the reliability in terms of the chosen parameters

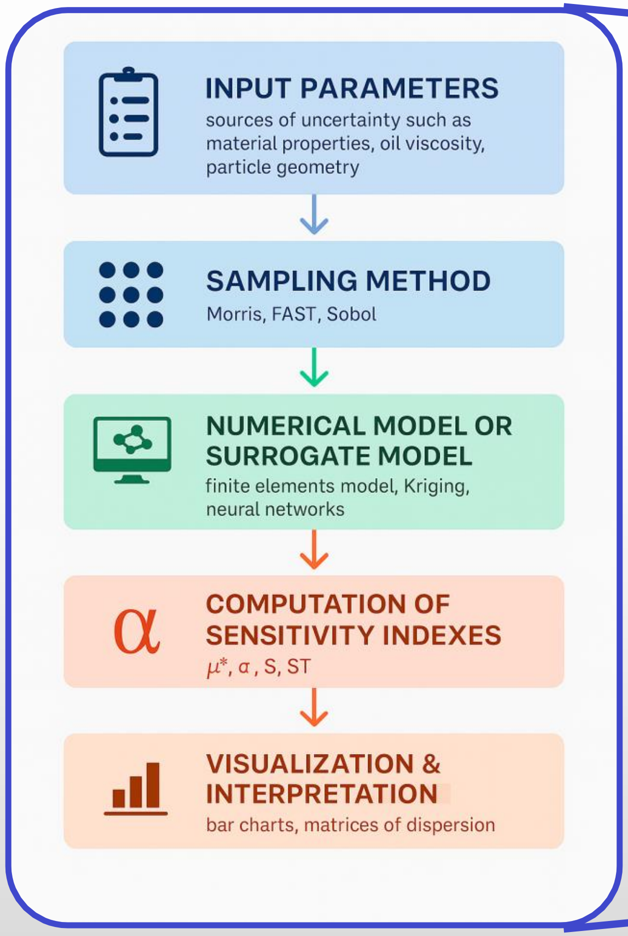
6.2 Sensitivity analysis

- How do perturbations in the model inputs lead to disturbances in the response?
- 3 methods:
  - Screening methods: Quantitative analysis of the impact of input variables on response variability => ranking of input variables based on their influence on response variability
  - Local SA: Examines how small disturbances around a nominal input value affect the output value (OAT (One Factor At A Time) gradient approach)

$$S_i = \frac{\partial y}{\partial x_i}(x_1^0, \ldots, x_p^0)$$

  - Global SA: The variability of the model output within its range of variation + information on the correlation between the input variables (MC sampling)

6.2 Sensitivity analysis



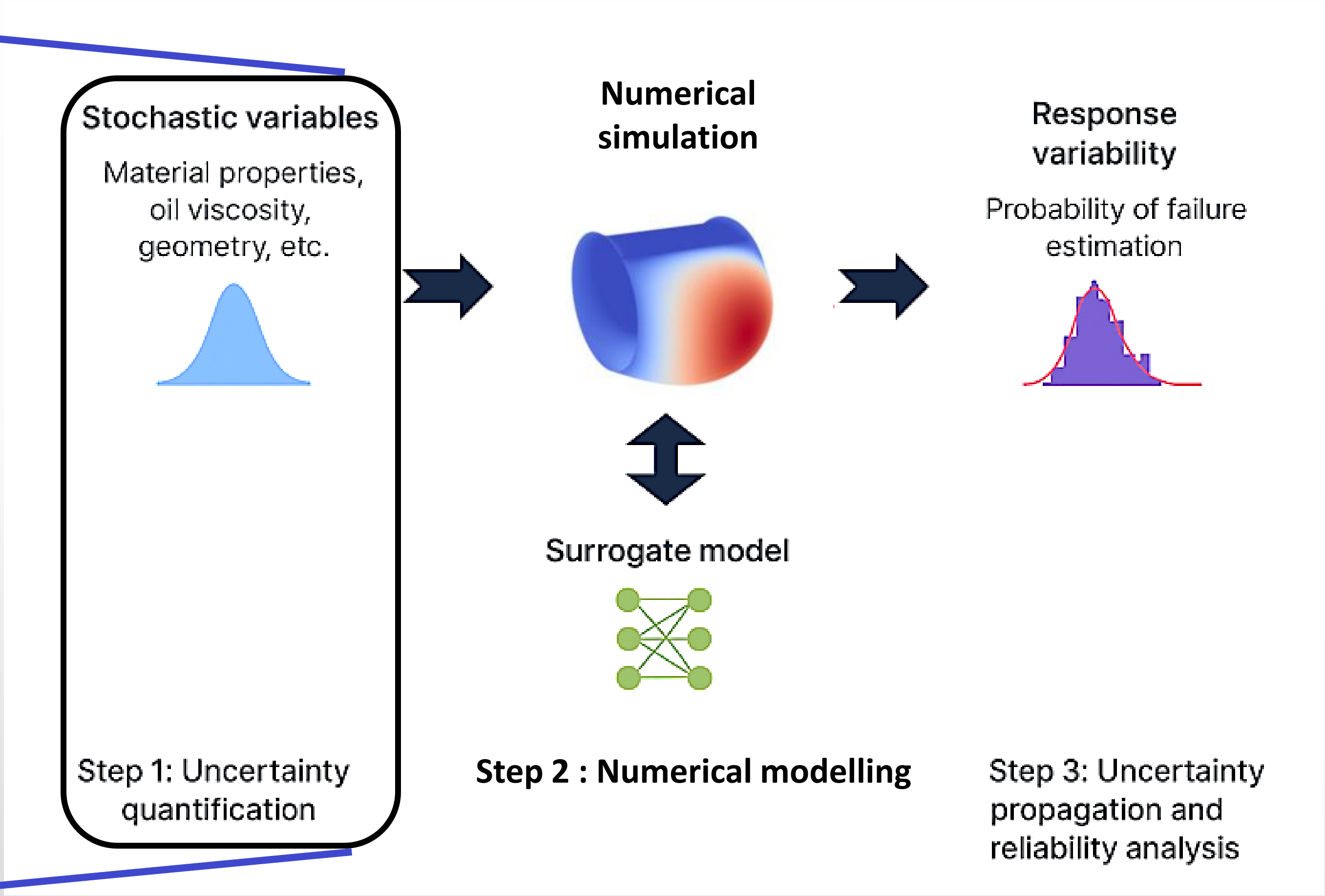
INPUT PARAMETERS
sources of uncertainty such as material properties, oil viscosity, particle geometry

SAMPLING METHOD
Morris, FAST, Sobol

NUMERICAL MODEL OR SURROGATE MODEL
finite elements model, Kriging, neural networks

COMPUTATION OF SENSITIVITY INDEXES
μ^*, α , S, ST

VISUALIZATION & INTERPRETATION
bar charts, matrices of dispersion



Stochastic variables

Material properties, oil viscosity, geometry, etc.

Step 1: Uncertainty quantification

Numerical simulation

Surrogate model

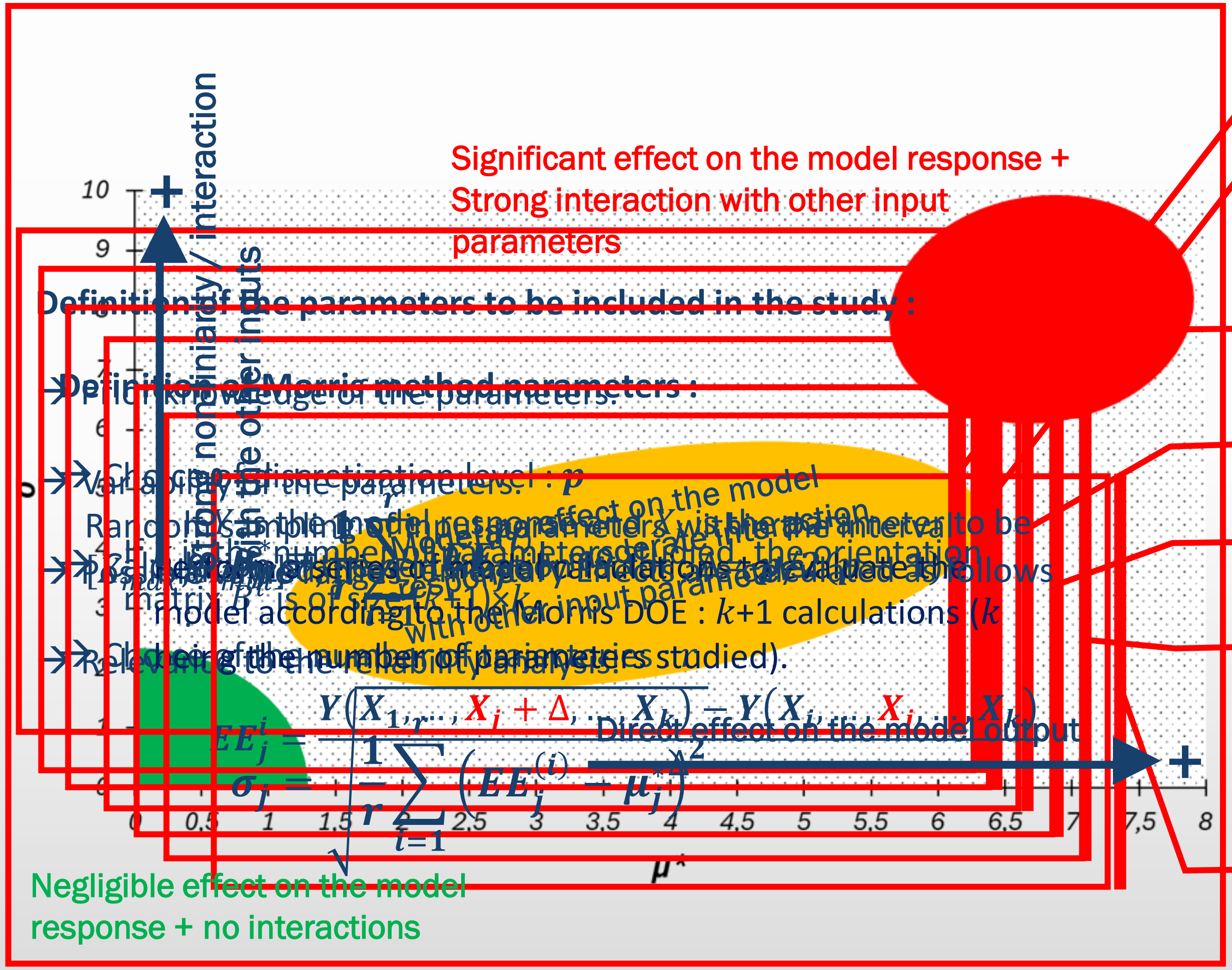
Step 2 : Numerical modelling

Response variability

Probability of failure estimation

Step 3: Uncertainty propagation and reliability analysis

6.2 Sensitivity analysis



Significant effect on the model response + Strong interaction with other input parameters

Definition of the parameters to be included in the study :

- Prior knowledge of the parameters.
- Variability of the parameters.
- Relevance to the reliability analysis.

Definition of Morris method parameters :

- Choice of discretization level : p
- Choice of the number of trajectories r

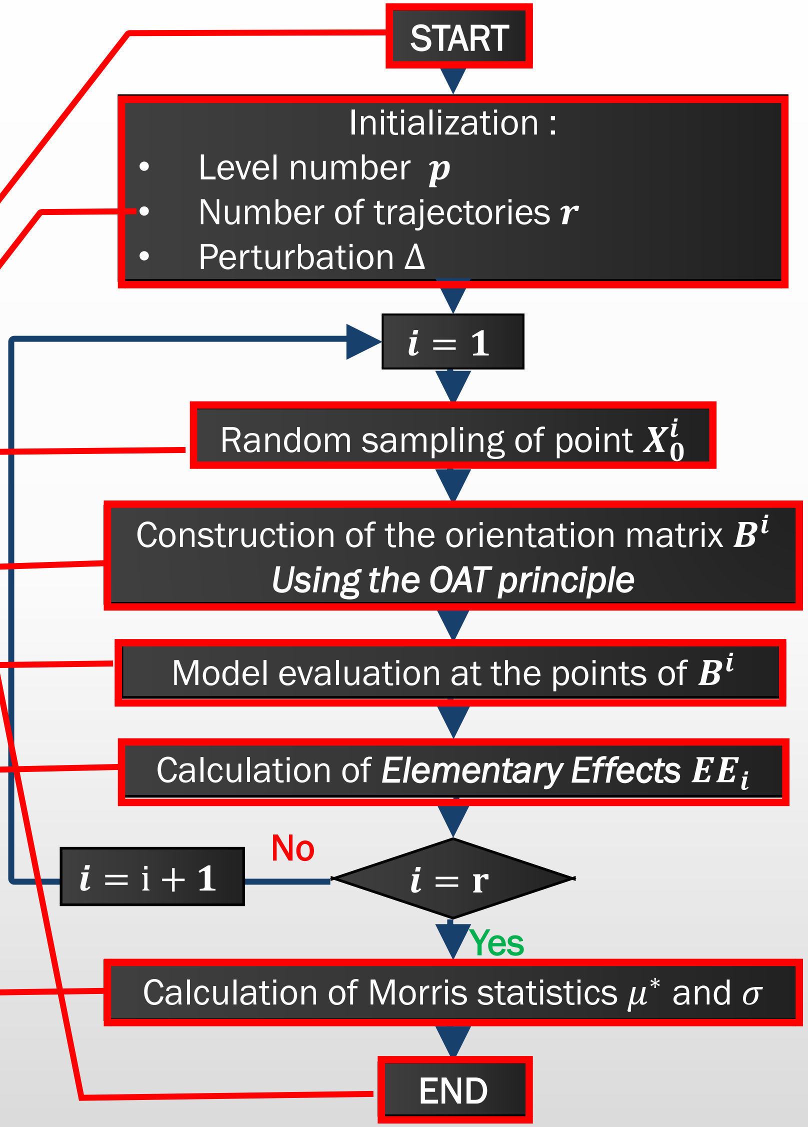
Random sampling of input parameters within the interval

model according to the Morris DOE : k+1 calculations (k the number of parameters studied).

$$EE_j^i = \frac{Y(X_1,\ldots,X_j+\Delta,\ldots,X_k) - Y(X_1,\ldots,X_j,\ldots,X_k)}{\Delta}$$

$$\sigma_j = \sqrt{\frac{1}{r}\sum_{i=1}^{r}\left(EE_j^{(i)} - \mu_j^*\right)^2}$$

Negligible effect on the model response + no interactions



START

Initialization :
- Level number p
- Number of trajectories r
- Perturbation Δ

$i = 1$

Random sampling of point X_0^i

Construction of the orientation matrix B^i *Using the OAT principle*

Model evaluation at the points of B^i

Calculation of *Elementary Effects* EE_i

$i = r$

No

$i = i + 1$

Yes

Calculation of Morris statistics μ^* and σ

END

6.3 Example on a journal bearing

Possible failure modes of a hydrodynamic bearing

Wear during life phases without hydrodynamic film.
- Engine start/stop.
- Oil interruption during operation.

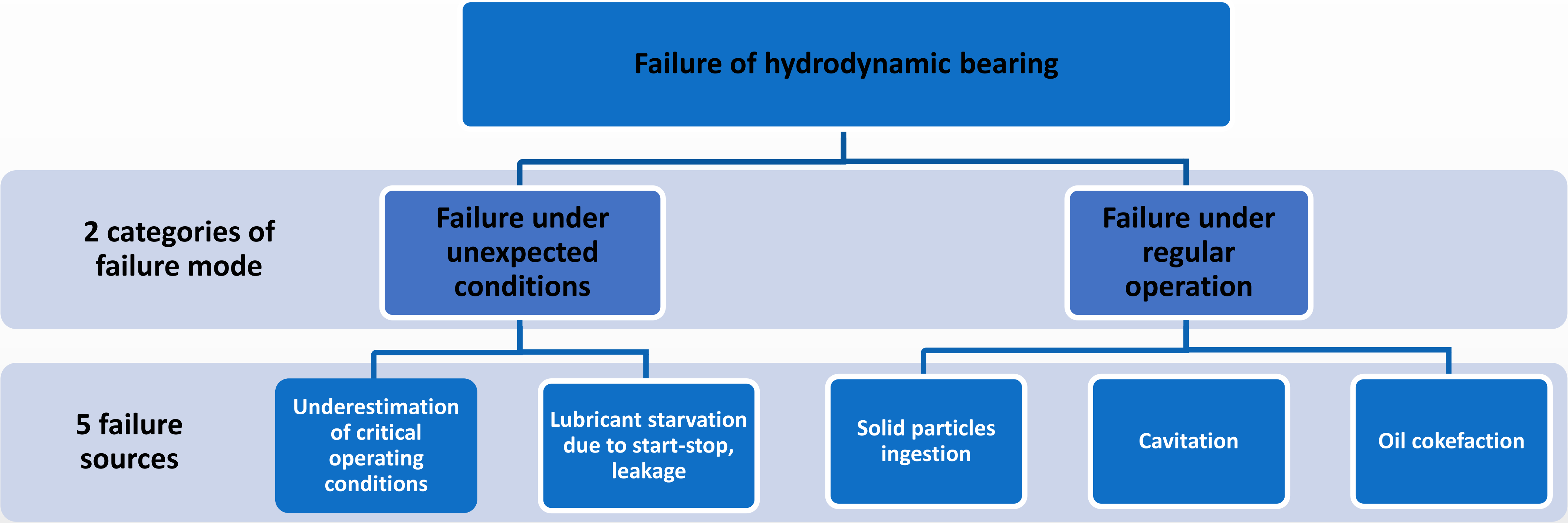
Cavitation wear.

Damage due to particles in the oil.

Coating delamination due to quality defects.

Oil coking due to exceeding the limit temperature.

6.3 Example on a journal bearing



Failure of hydrodynamic bearing

2 categories of failure mode

Failure under unexpected conditions

Failure under regular operation

5 failure sources

Underestimation of critical operating conditions

Lubricant starvation due to start-stop, leakage

Solid particles ingestion

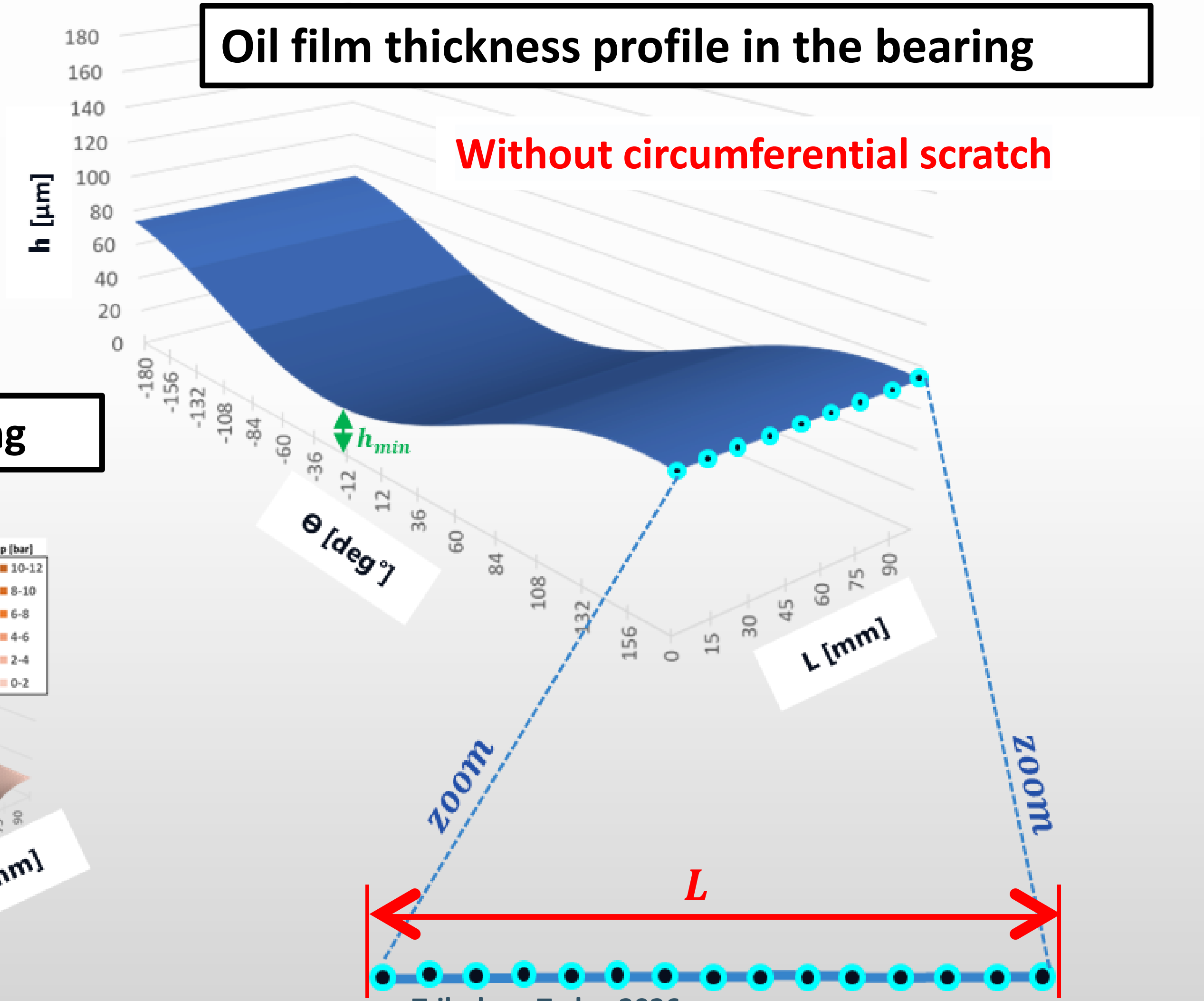
Cavitation

Oil cokefaction

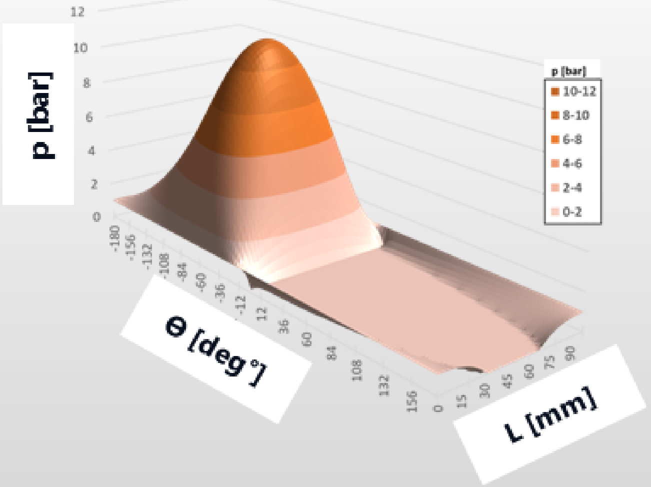
Operating parameters	Geometry	Materials	Lubrication	Defects
• Load • Speed • Feeding pressure and temperature • Minimum film thickness	• Diameter • Length • Clearance	• Young modulus • Surface finish (Sa, Spk, Sq, etc.) • Coatings	•Oil Cp • dynamic viscosity at X°C •Density	•Scratch depth •Scratch position •Number of defects •Geometry of the defects

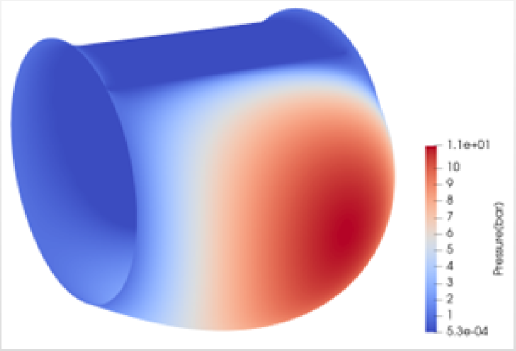
6.3 Example on a journal bearing

Oil film thickness profile in the bearing



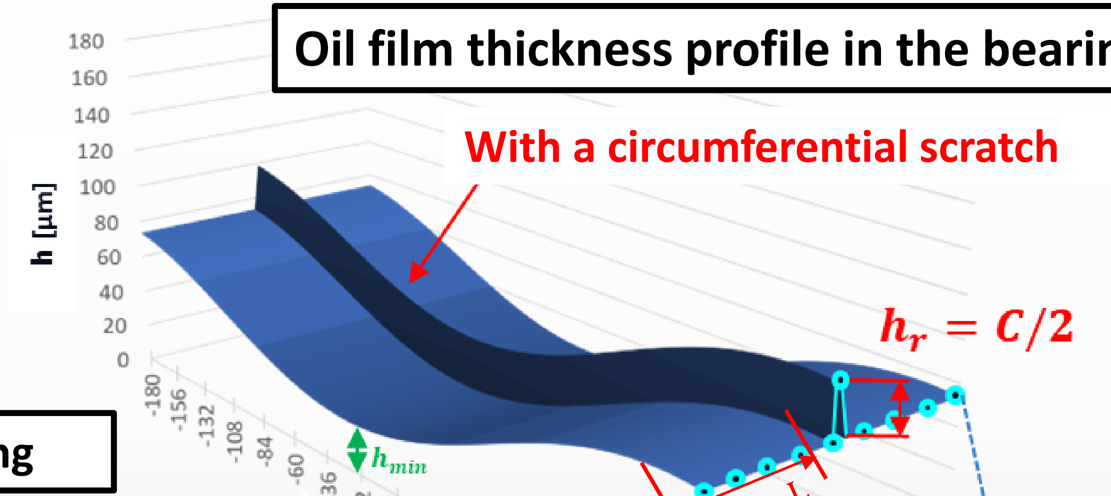
Pressure field in the bearing

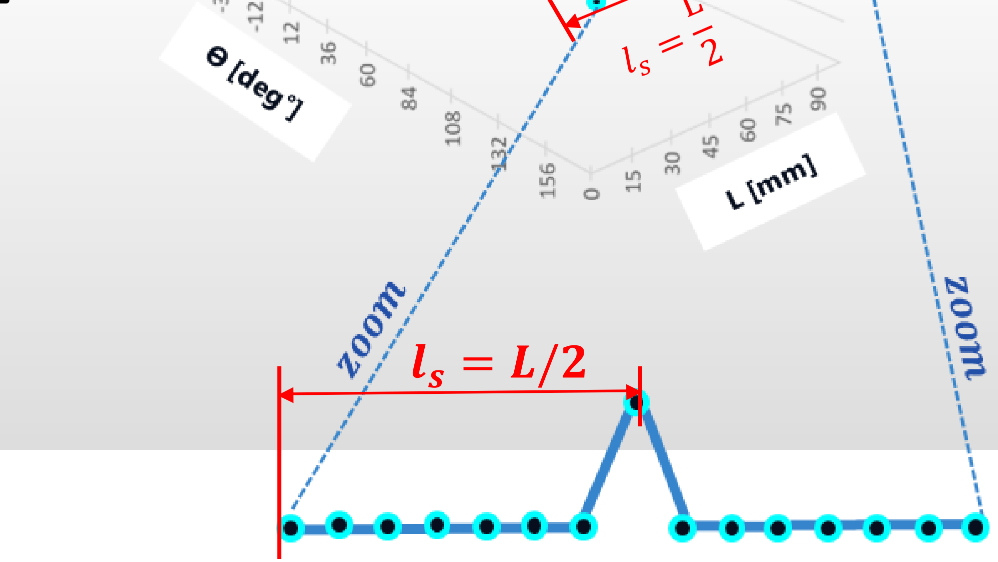




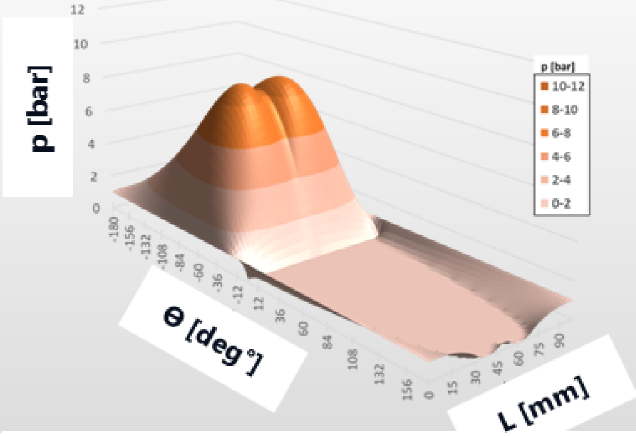
6.3 Example on a journal bearing

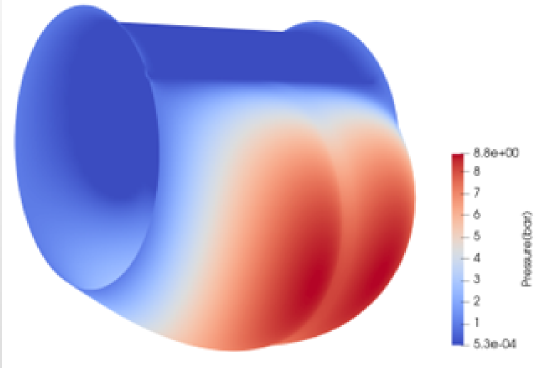
Oil film thickness profile in the bearing



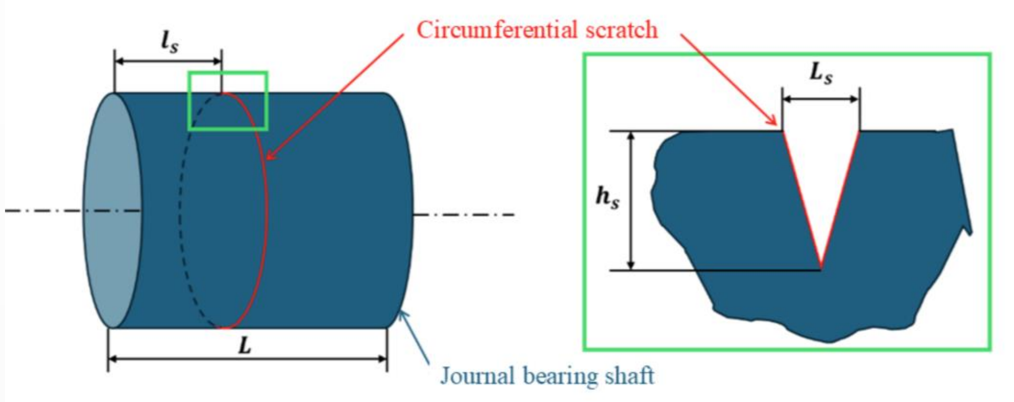


Pressure field in the bearing

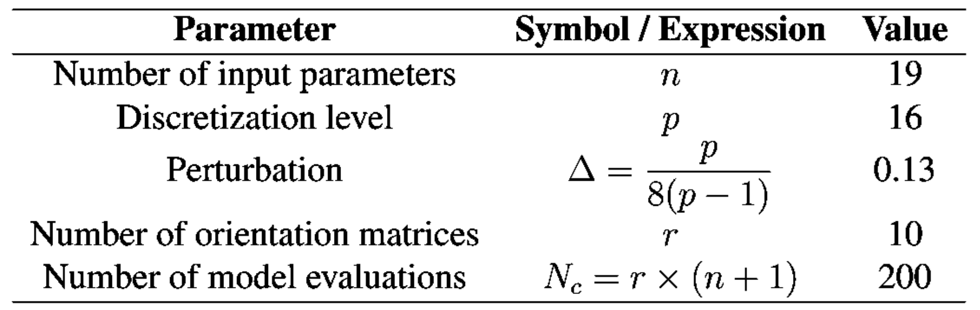




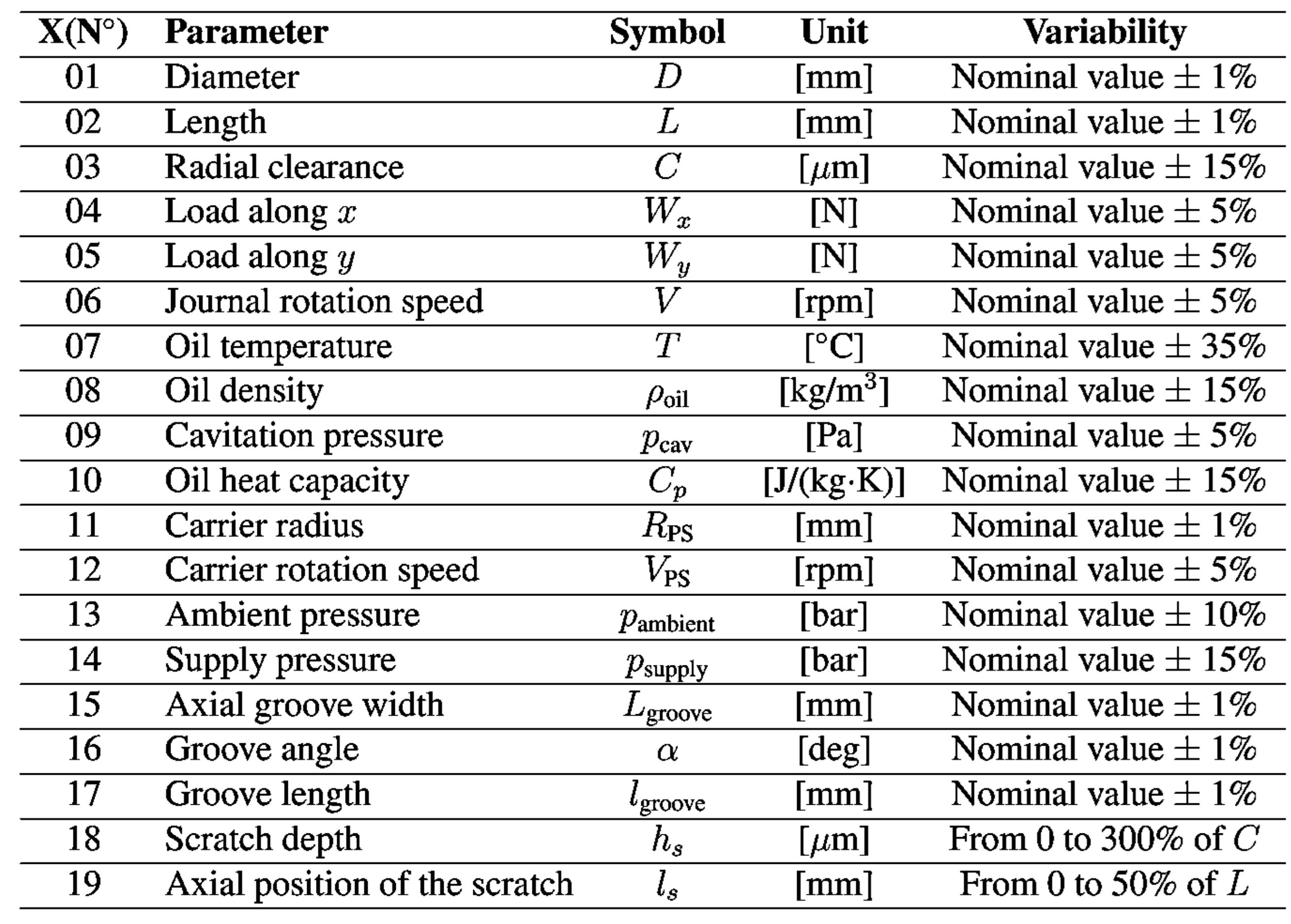
6.3 Example on a journal bearing



Parameters of the Morris method



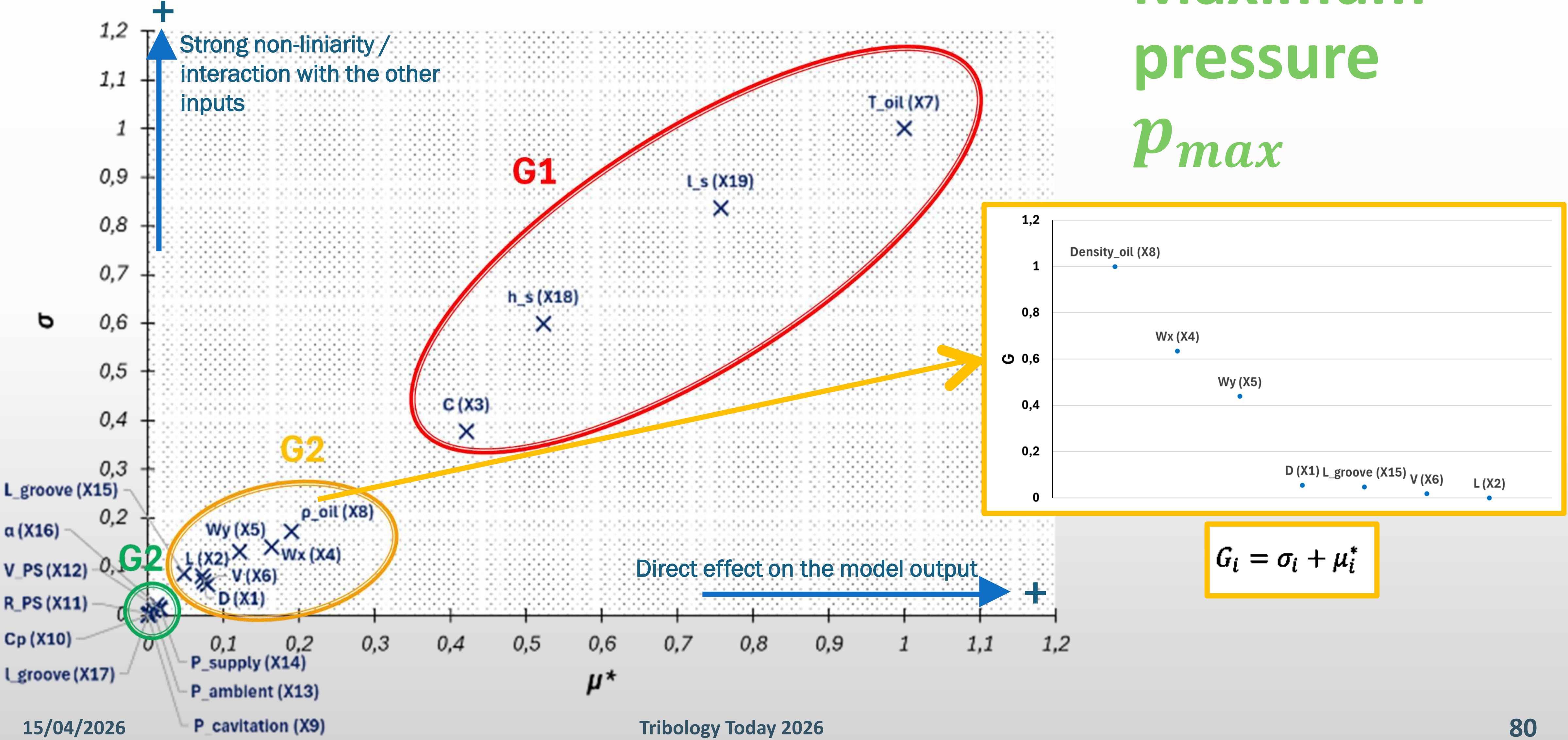
Parameter	Symbol / Expression	Value
Number of input parameters	n	19
Discretization level	p	16
Perturbation	$\Delta = \dfrac{p}{8(p-1)}$	0.13
Number of orientation matrices	r	10
Number of model evaluations	$N_c = r \times (n+1)$	200



X(N°)	Parameter	Symbol	Unit	Variability
01	Diameter	D	[mm]	Nominal value ± 1%
02	Length	L	[mm]	Nominal value ± 1%
03	Radial clearance	C	[μm]	Nominal value ± 15%
04	Load along x	W_x	[N]	Nominal value ± 5%
05	Load along y	W_y	[N]	Nominal value ± 5%
06	Journal rotation speed	V	[rpm]	Nominal value ± 5%
07	Oil temperature	T	[°C]	Nominal value ± 35%
08	Oil density	ρ_{oil}	[kg/m^3]	Nominal value ± 15%
09	Cavitation pressure	p_{cav}	[Pa]	Nominal value ± 5%
10	Oil heat capacity	C_p	[J/(kg·K)]	Nominal value ± 15%
11	Carrier radius	R_{PS}	[mm]	Nominal value ± 1%
12	Carrier rotation speed	V_{PS}	[rpm]	Nominal value ± 5%
13	Ambient pressure	p_{ambient}	[bar]	Nominal value ± 10%
14	Supply pressure	p_{supply}	[bar]	Nominal value ± 15%
15	Axial groove width	L_{groove}	[mm]	Nominal value ± 1%
16	Groove angle	α	[deg]	Nominal value ± 1%
17	Groove length	l_{groove}	[mm]	Nominal value ± 1%
18	Scratch depth	h_s	[μm]	From 0 to 300% of C
19	Axial position of the scratch	l_s	[mm]	From 0 to 50% of L

6.3 Example on a journal bearing

Maximum pressure p_{max}

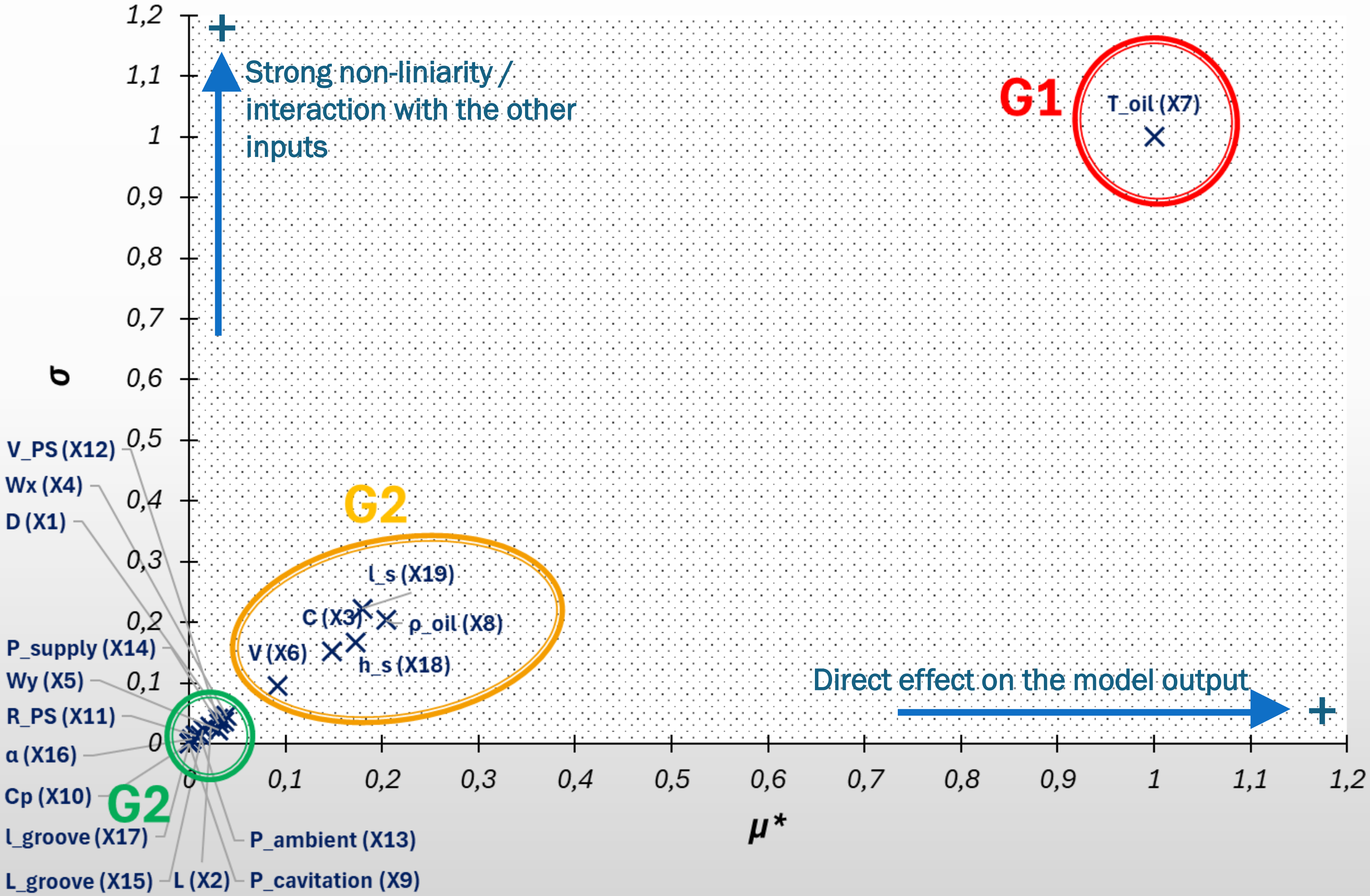


Strong non-liniarity / interaction with the other inputs

Direct effect on the model output

$$G_i = \sigma_i + \mu_i^*$$

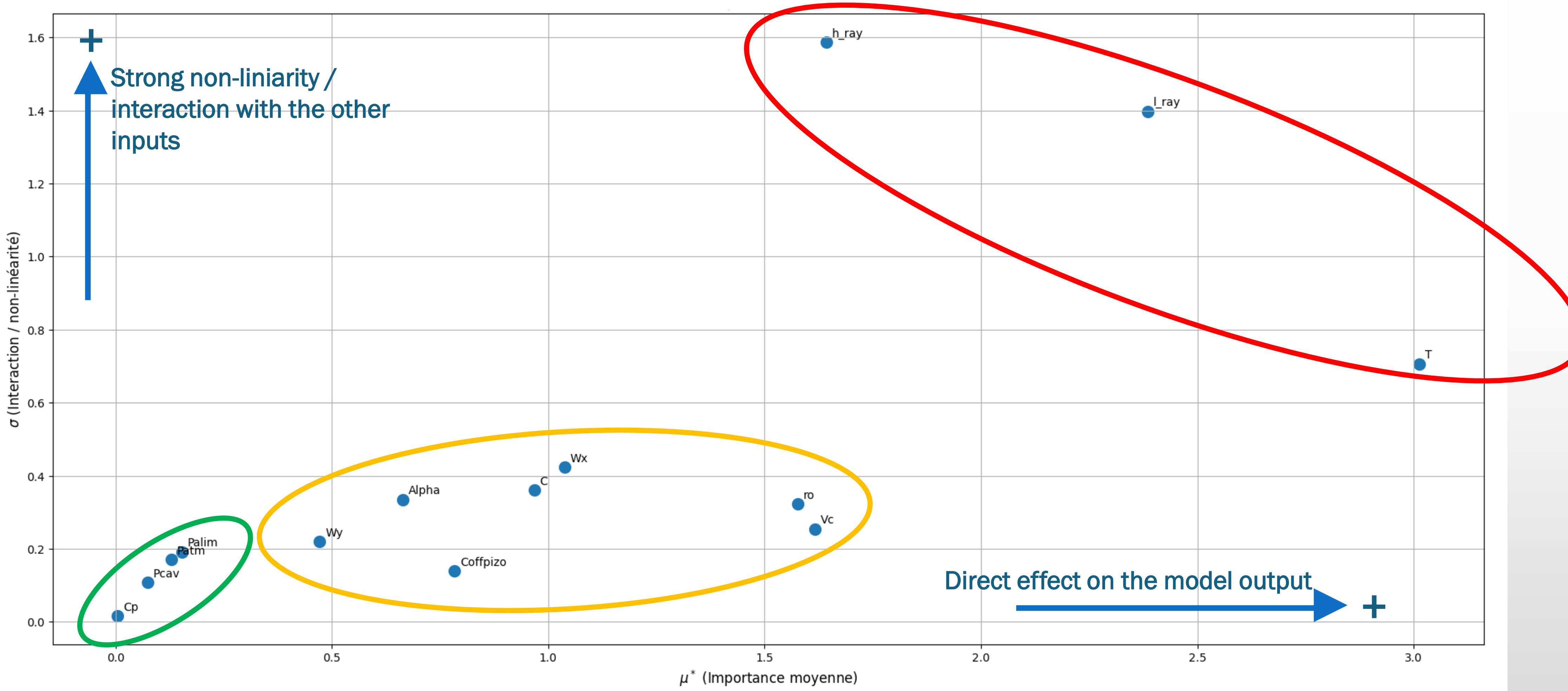
6.3 Example on a journal bearing



Minimum film thickness

h_{min}

6.3 Example 2 on a journal bearing



Strong non-liniarity / interaction with the other inputs

Direct effect on the model output

6.3 Example 2 on a journal bearing

FAST method (Fourier Amplitude Sensitivity Test)

→ explore the effect of each **parameter** on the model's output **by varying** all parameters simultaneously according to a sinusoidal function, each with its own natural frequency.

$$x_i(s) = \frac{1}{2}\left[\sin(\omega_i s) + 1\right] \cdot (x_{i,\max} - x_{i,\min}) + x_{i,\min}$$

- Where ***s*** is an exploration parameter
- $\boldsymbol{\omega_i}$ is a unique frequency attached to each parameter
- The model $f(x_1(s), \dots, x_k(s))$ is then evaluated for a series of ***s***.

→ Calculate the influence of each parameter based on its natural frequency by applying a Fourier analysis to the output.

$$N_{\text{total}} = N \times k$$

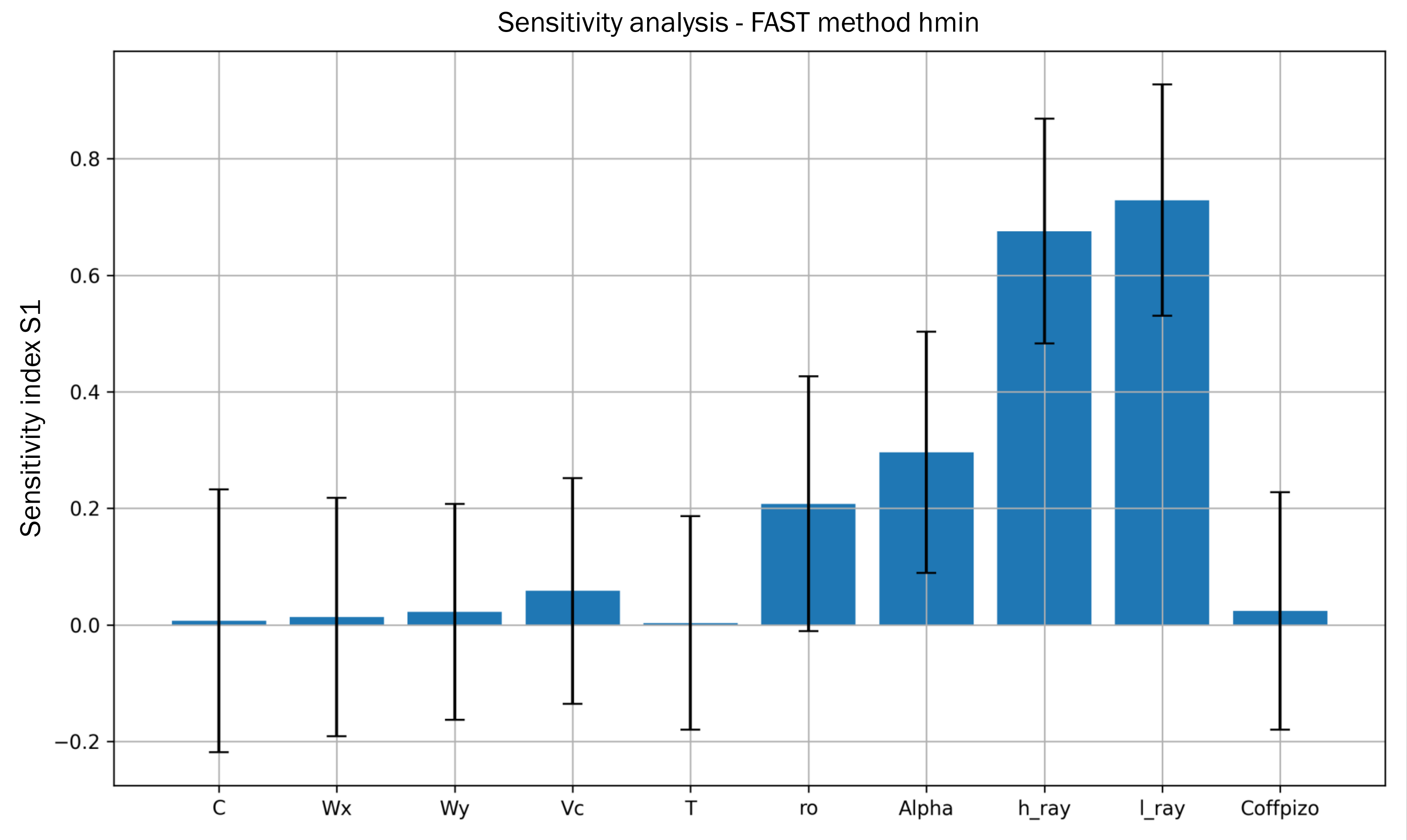
- Where ***N*** is the number pf parameter samples
- ***k*** is the number of parameters
- ***M*** is the number of harmonics (typically 4)

$$N > 4M^2 = 4 \times 4^2 = 64$$

$$S_1^{(i)} = \frac{D_i}{D}$$

- D_i contribution to the variance due to x_i
- D total variance of the model

6.3 Example 2 on a journal bearing



6.4 Reliability evaluation (MC)

■ Monte Carlo method

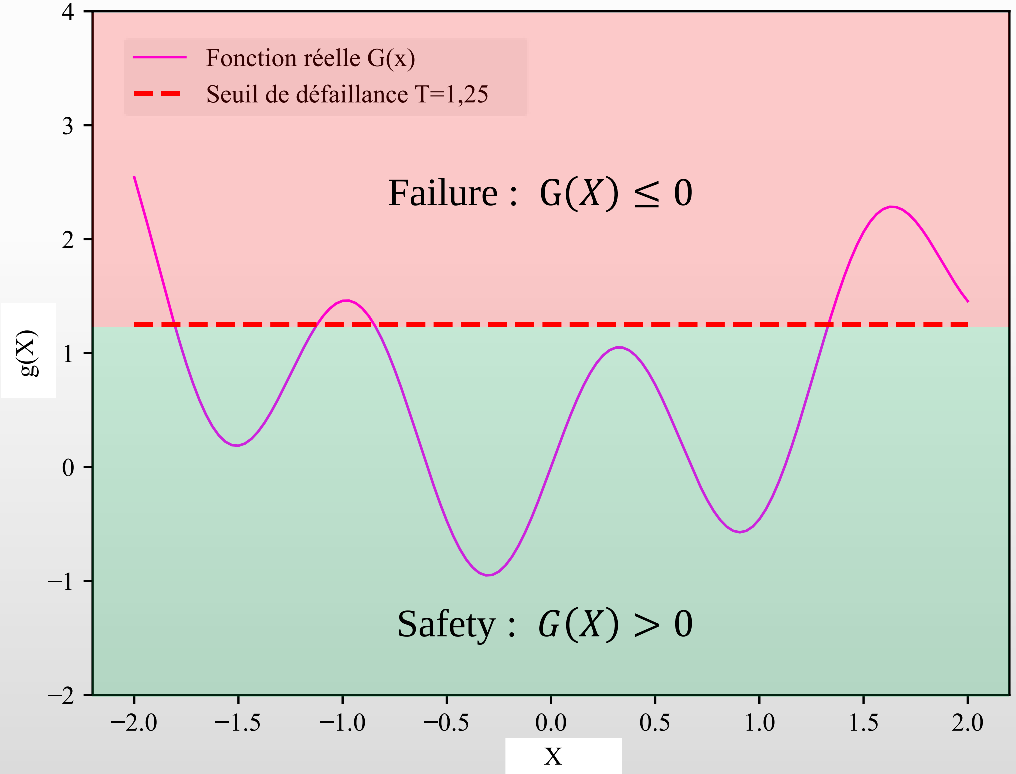
- Failure probability

$$P_f = \int \dots \int_{G(\mathbf{x})\leq 0} f_X(\mathbf{x})d\mathbf{x}$$

- Monte-Carlo Simulation (MCS):

$$P_f = \int \int_{G(\mathbf{x})\leq 0} f_X(\mathbf{x})d\mathbf{x} \approx \mathbb{E}[\mathbb{1}(X)]\,;\ \mathbb{1}(X) = \begin{cases} 1 & if\ G(\boldsymbol{X}) \leq 0 \\ 0 & if\ G(\boldsymbol{X}) > 0 \end{cases}$$

- **1D Model :** $g(X) = 0{,}5X^2 + \sin(5X)$
- **Random variable :** $X \sim \mathcal{N}(0{,}0.4)$
- **Limit state function :** $\mathrm{G}(X) = T - g(X)$



6.4 Reliability evaluation (MC)

- Failure probability

$$P_f = \int \dots \int_{G(\mathbf{x})\leq 0} f_X(\mathbf{x})d\mathbf{x}$$

- Monte-Carlo Simulation (MCS):

$$P_f = \int \int_{G(\mathbf{x})\leq 0} f_X(\mathbf{x})d\mathbf{x} \approx \mathbb{E}[\mathbb{I}(X)]\,;\ \mathbb{I}(X) = \begin{cases} 1 & if\ G(\boldsymbol{X}) \leq 0 \\ 0 & if\ G(\boldsymbol{X}) > 0 \end{cases}$$

- Practically, N_{MC} observations from X are randomly sampled according to the joint density function $f_X(\mathbf{x})$. The probability P_f can be estimated as:

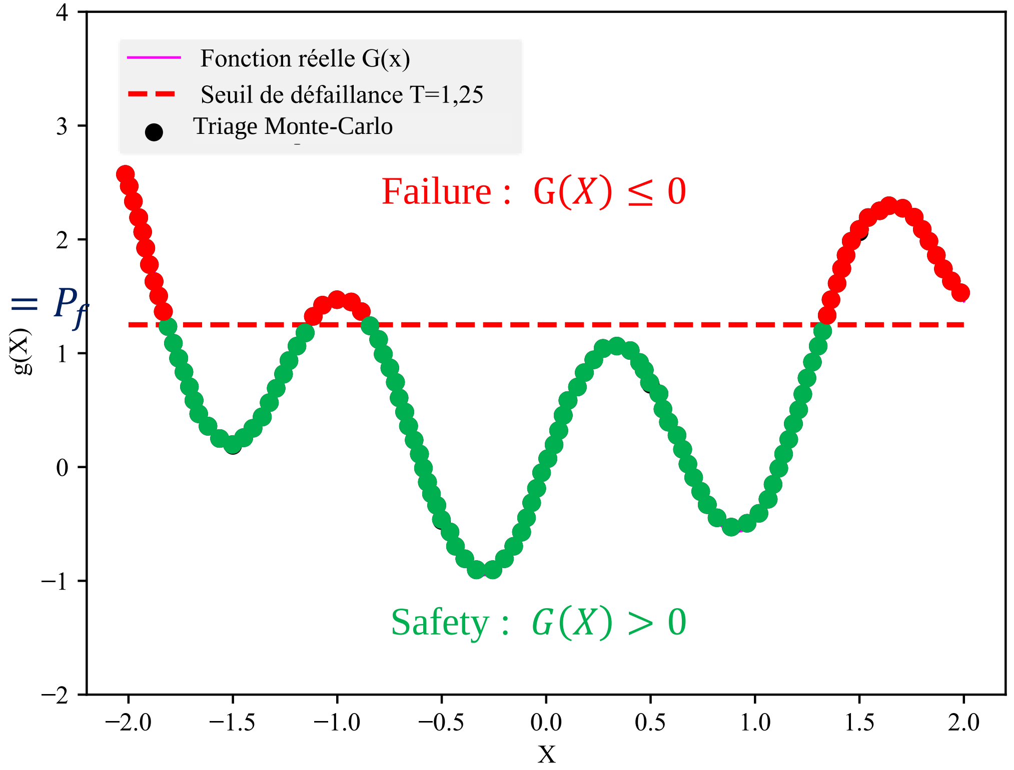
Unbiased estimator: $\mathbb{E}[\hat{P}_f] = P_f$

$$\hat{P}_f \approx P_f = \frac{1}{N_{MC}} \sum_{i=1}^{N_{MC}} \mathbb{I}(X_i)$$

Unbiased estimator: $\mathbb{E}[\hat{P}_f] = P_f$

- Failure probability variation coefficient $CoV(\hat{P}_f) = \sqrt{\frac{1-\hat{P}_f}{N_{MC}\hat{P}_f}}$
- → Practically, the goal is to have $CoV(\hat{P}_f) \leq 5\%$

- **1D Model :** $g(X) = 0{,}5X^2 + \sin(5X)$
- **Random variable :** $X \sim \mathcal{N}(0{,}0.4)$
- **Limit state function :** $\mathrm{G}(X) = T - g(X)$



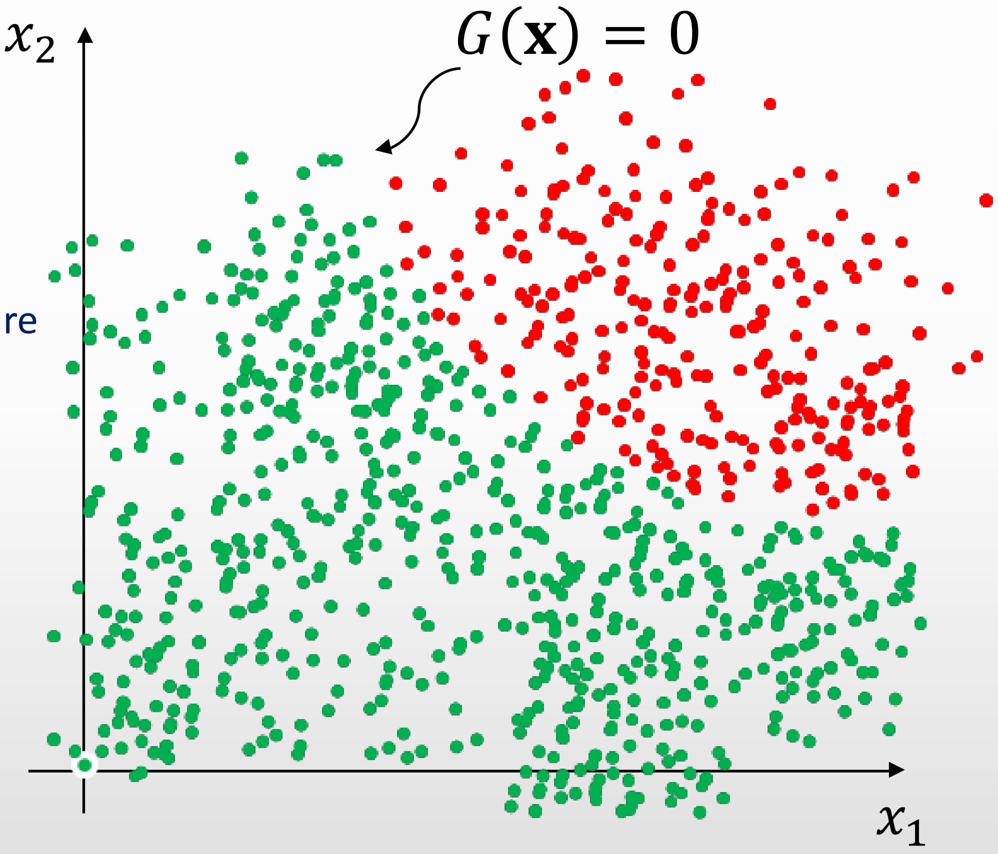
6.4 Reliability evaluation (MC)

2D Monte-Carlo Simulations (MCS) :

1) Generate a large number of random samples.
2) Evaluate the performance function for each sample.
3) Count the number of sampled configurations that fall within the failure region.
4) Probability of failure $\simeq \dfrac{\textit{Number of failing configurations}}{\text{Total number of samples}}$

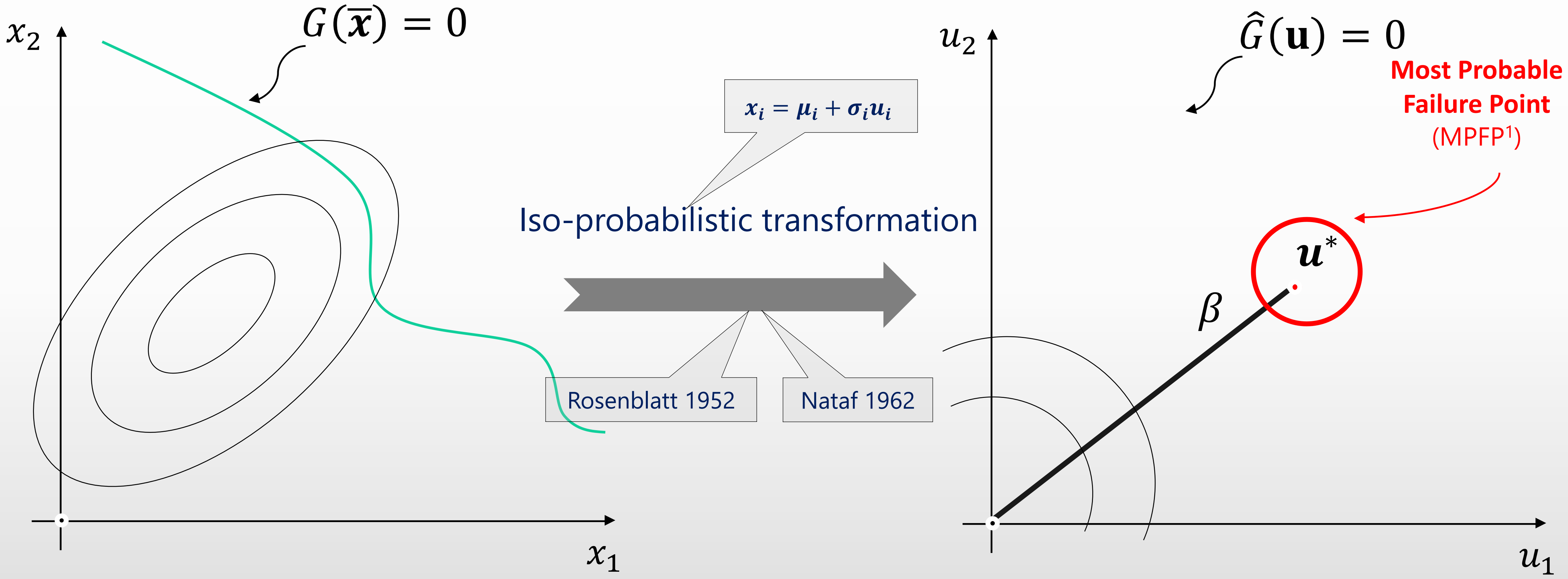
$$P_f \simeq \frac{1}{N}\sum_{k=0}^{N} \mathbb{I}\left[G\left(\mathbf{x}^{(\boldsymbol{k})}\right) \leq 0\right] \quad ; \; \mathbb{I}(X) = \begin{cases} 1 & if\ G(\boldsymbol{X}) \leq 0 \\ 0 & if\ G(\boldsymbol{X}) > 0 \end{cases}$$

$$P_f \underset{N \to \infty}{\to} P_f^{(theoretical)}\text{郎}$$



For $P_f \simeq 10^{-\mathrm{n}}$, it has to be realized between $10^{\mathrm{n}+2}$ and $10^{\mathrm{n}+3}$ Monte-Carlo simulations

6.4 Reliability evaluation (FORM/SORM)



$\boldsymbol{x_i = \mu_i + \sigma_i u_i}$

Iso-probabilistic transformation

Rosenblatt 1952

Nataf 1962

Most Probable Failure Point

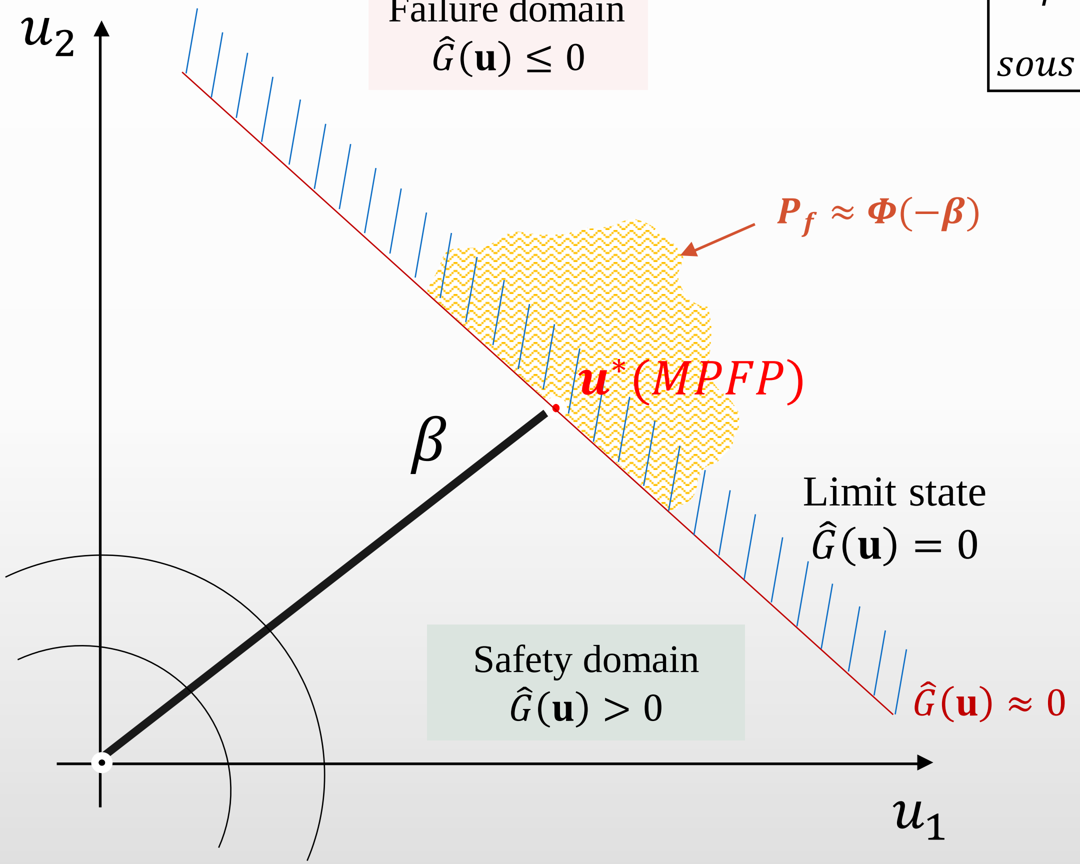
(MPFP[1])

Physical space: a space of random variables in their physical units, along with their actual distributions and dependencies (means, variances, correlations).

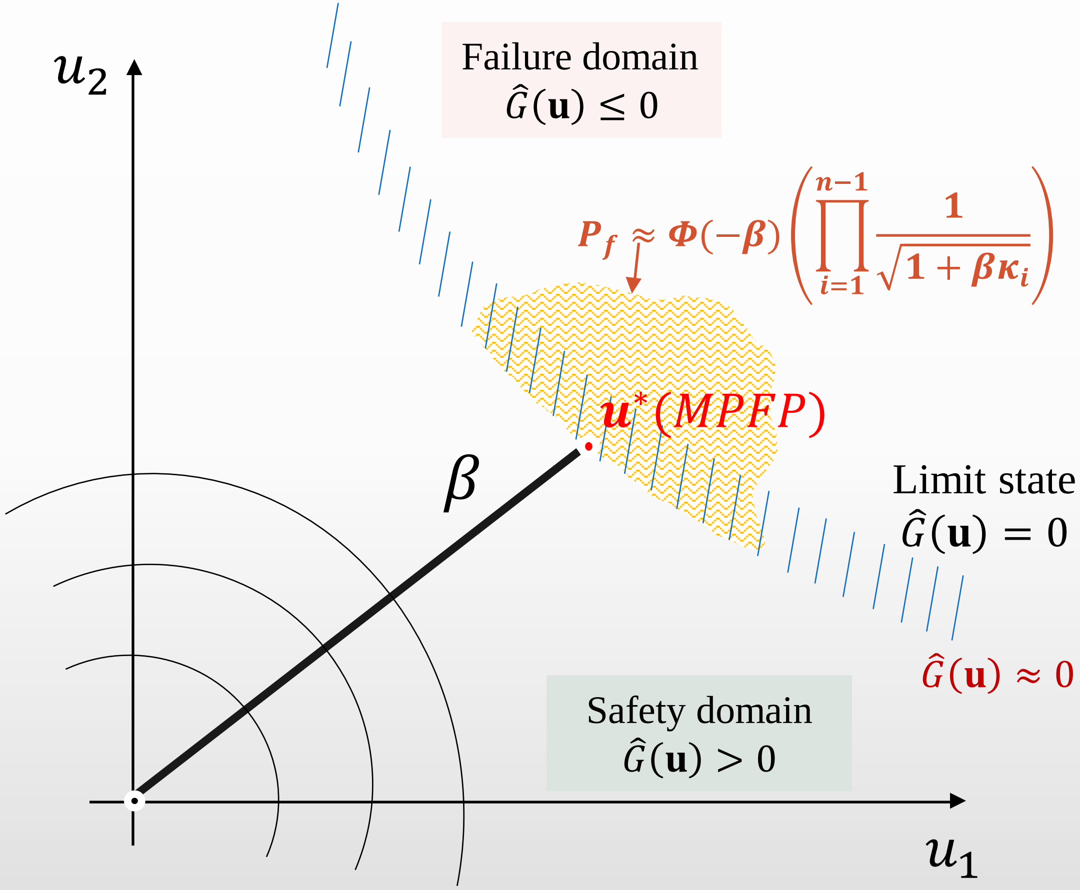
Normed space: a space of independent Gaussian variables with mean zero and unit standard deviation.

6.4 Reliability evaluation (FORM/SORM)

$$\beta = \min_{\mathbf{u}} \|\mathbf{u}\| \quad sous: \ \hat{G}(\mathbf{u}) \leq 0$$



FORM



SORM

6.4 Reliability evaluation journal bearing

Variable aléatoire	**Loi marginale**	**Moyenne μ**	**Ecart type σ**
Diamètre **D**	Normal	100	10
Longueur **L**	Normal	500	50
Jeu radial **C**	Log-Normal	40	4
Vitesse de rotation $\mathbf{V_a}$	Normal	1500	150

Limit state function:

$$G(\mathbf{x},\mathbf{d}) = W_{critical} - W(\mathbf{x},\mathbf{d})$$

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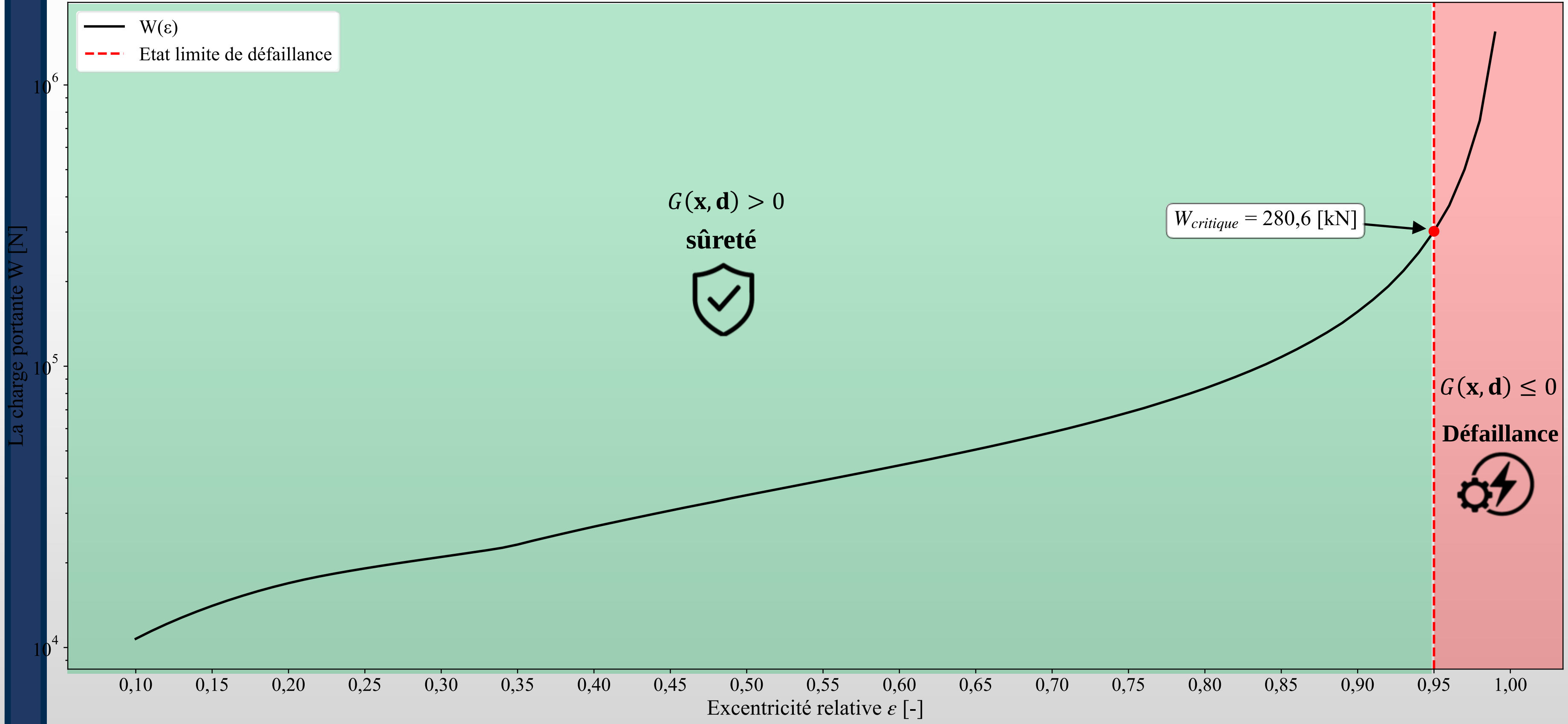
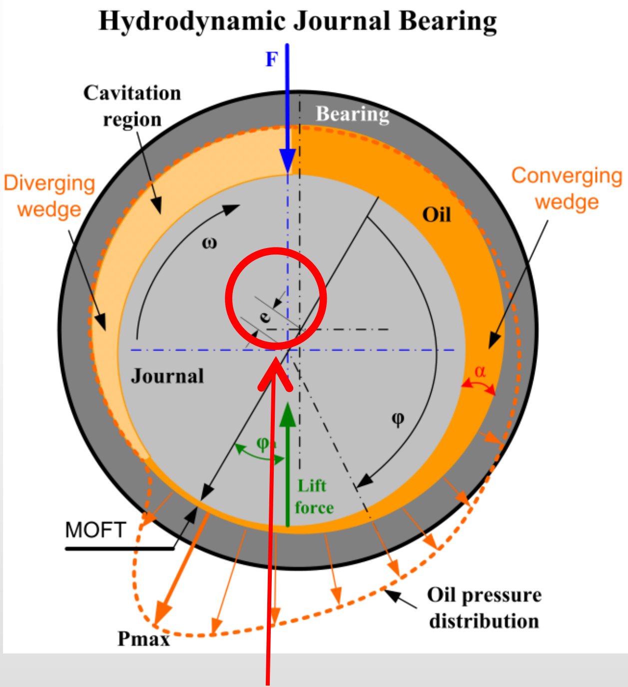
Calculation at imposed position with mean values of random variables





$$\varepsilon = e/C$$

QUESTIONS?

Thanks a lot for your attention