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# Hydrodynamic Bearings for Space Mechanisms Considering Surface Roughness and Elastic Deformation

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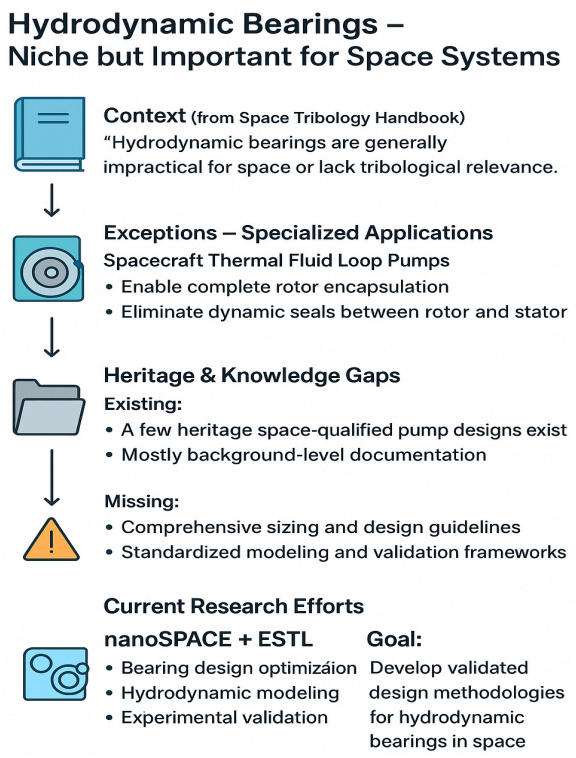
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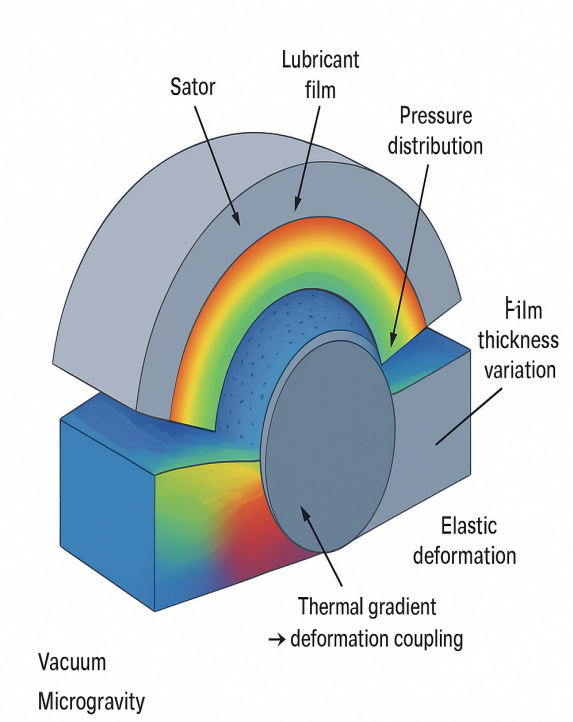
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**ABSTRACT**

The Space Tribology Handbook makes only a brief mention of hydrodynamic bearings, stating that "hydrodynamic bearings are not considered, as such bearings are generally either impractical for space applications or do not involve tribological behavior." While this assessment holds true for most space mechanisms, certain specialized applications do employ hydrodynamic bearings. One notable example is pumps used in spacecraft thermal fluid loops, where such bearings enable complete rotor encapsulation and eliminate the need for dynamic seals between the rotor and stator. Some heritage designs of space-qualified pumps exist and are discussed as background in this paper. However, the existing literature lacks comprehensive guidelines for the sizing and design of mechanisms incorporating hydrodynamic bearings. The work conducted by nano SPACE and ESTL aims to address this gap through dedicated activities in bearing design, modeling, and experimental validation. In space mechanisms, hydrodynamic bearings are vital for ensuring precise, low-friction, and long-life rotational motion under microgravity and vacuum conditions. This study investigates the influence of surface roughness and structural deformation (elastic or thermoelastic) on the performance characteristics of hydrodynamic bearings operating in space environments. The analysis incorporates the modified Reynolds equation, accounting for roughness parameters, film thickness variations, and bearing elastic compliance. Results indicate that micro-level roughness significantly alters pressure distribution and load capacity, while elastic deformation plays a key role in maintaining film stability under varying thermal and dynamic loads. The findings are crucial for designing reliable, lightweight, and durable bearings for satellites, gyroscopes, reaction wheels, and robotic joints.

**Subject Classification:** Primary Classification Space Tribology, Hydrodynamic Lubrication, Aerospace Mechanical Systems, Secondary Classification, Elastohydrodynamic and Thermoelastohydrodynamic Lubrication, Surface Roughness Modeling, Spacecraft Thermal Control Systems, Precision Rotating Machinery, Satellite and Attitude Control Mechanisms **PACS (Physics and Astronomy Classification Scheme):** 46.55.+d – Tribology and mechanical contacts, 47.15.G– – Lubrication flows, 68.35.Af – Surface roughness, **ASJC (Scopus):** 2210 – Mechanical Engineering, 1909 – Aerospace Engineering, 2205 – Materials Engineering.




## Introductions:

Hydrodynamic bearings are widely used in terrestrial machinery due to their ability to provide low-friction, wear-free operation and high load-carrying capacity through the formation of a self-sustained lubricant film. In contrast, their application in space mechanisms has traditionally been limited, primarily because of the challenges posed by vacuum environments, microgravity, stringent mass and volume constraints, and the long operational lifetimes required of spacecraft components. Consequently, classical space tribology references, including the Space Tribology Handbook, largely exclude hydrodynamic bearings, considering them either impractical for space use or outside the scope of conventional tribological behavior. Despite this general perception, hydrodynamic bearings play a critical role in certain specialized space applications. Notably, they are employed in spacecraft thermal control systems, particularly in pumps circulating heat-transfer fluids, where hydrodynamic bearing configurations enable full encapsulation of the rotor. This design eliminates the need

for dynamic seals between the rotor and stator, significantly reducing leakage risks, contamination, and wear—key concerns in long-duration missions. Several heritage designs of space-qualified pumps have demonstrated the feasibility and reliability of hydrodynamic bearings under space-relevant conditions, underscoring the need for a more systematic understanding of their design and performance. Unlike rolling-element bearings, whose space qualification and design methodologies are well established, hydrodynamic bearings for space mechanisms lack comprehensive sizing rules, performance prediction frameworks, and validated design guidelines. Existing studies are largely adapted from terrestrial lubrication theory and often neglect factors that become particularly significant in space environments, such as ultra-smooth or engineered surface finishes, extreme thermal gradients, and the elastic or thermoelastic deformation of lightweight bearing structures. These factors can critically influence lubricant film formation, pressure distribution, load capacity, and overall bearing stability. Surface roughness, even at micro- and nano-scales, can substantially alter hydrodynamic lubrication behavior by modifying flow characteristics and local pressure generation within the lubricant film. In space-qualified mechanisms, where precision manufacturing and advanced surface treatments are common, the interaction between roughness-induced flow effects and thin lubricant films becomes especially pronounced. Similarly, elastic and thermoelastic deformation of bearing surfaces—driven by mechanical loads and temperature variations—can change the effective film thickness and geometry, thereby affecting the robustness of hydrodynamic lubrication under varying operational conditions. Motivated by these challenges, the present study investigates hydrodynamic bearings for space mechanisms with particular emphasis on the coupled effects of surface roughness and elastic deformation. Using a modified Reynolds equation that incorporates roughness parameters, film thickness variations, and bearing compliance, the analysis aims to provide deeper insight into pressure distribution, load-carrying capacity, and film stability under space-relevant operating conditions. The findings contribute toward establishing a more reliable theoretical and practical foundation for the design of lightweight, durable, and high-precision hydrodynamic bearings suitable for satellites, gyroscopes, reaction wheels, robotic joints, and spacecraft thermal management systems. Tribology plays a pivotal role in the reliable operation of mechanical systems, governing friction, wear, and lubrication across a wide range of engineering applications. Classical investigations by Stribeck (1902) and Archard (1956) laid the foundational understanding of friction regimes and wear mechanisms, establishing the well-known Stribeck curve and wear laws that continue to underpin modern lubrication theory. These early insights were later formalized and expanded through comprehensive treatments of hydrodynamic and elastohydrodynamic lubrication, notably in the works of Dowson and Higginson (1977), Cameron (1981), and Hamrock et al. (2004), which provide the theoretical basis for fluid-film bearing design. Hydrodynamic and fluid-film bearings are widely employed in high-speed and high-load machinery due to their ability to support loads through pressure generated within a lubricant film. Design methodologies for journal and thrust bearings have evolved through extensive analytical and experimental studies, as summarized by Allaire and Flack (1981), Childs (1993), Rowe (2012), and

Stachowiak and Batchelor (2014). These works highlight the importance of bearing geometry, lubricant rheology, thermal effects, and dynamic stability. Furthermore, the influence of surface roughness and mixed lubrication regimes has been systematically addressed through the average flow models developed by Patir and Cheng (1978, 1979) and the conceptual framework of mixed lubrication articulated by Spikes (1997). In aerospace and space applications, tribological challenges are significantly amplified by extreme environmental conditions, including vacuum, microgravity, wide temperature variations, and stringent reliability requirements. Early space missions revealed the limitations of conventional lubrication approaches, as documented in NASA Apollo experience reports (Samonski & Tucker, 1972) and subsequent assessments of spacecraft lubrication and wear issues (Spalvins, 1986; Fusaro & Khonsari, 1991; McMurtry, 1993). These challenges prompted the development of specialized design guidelines and standards, encapsulated in the NASA Space Tribology Handbook (NASA Glenn Research Center, 2007), the ESA Space Mechanisms Handbook (ESA-ESTEC, 2011), and ECSS standards for space mechanisms (ESA-ESTEC, 2019). Although rolling-element bearings and solid or boundary lubrication have traditionally dominated space mechanisms, fluid-film and gas-lubricated bearings have attracted renewed interest for specific aerospace applications, such as turbomachinery, reaction wheels, and life-support systems. Advances in gas foil bearings (Heshmat, 1994), thermoelastohydrodynamic analysis (San Andrés & Childs, 1997), and aerospace-specific bearing designs (Kingsbury, 1999; Johnson et al., 2019) demonstrate the feasibility of fluid-film concepts under carefully controlled conditions. Lessons learned from on-orbit failures, such as the ISS ammonia pump incident (Bruckner & Manco, 2014), further emphasize the critical role of lubrication reliability in space systems. Recent decades have seen significant progress in enhancing bearing performance through hybrid and smart lubrication concepts. Hydromagnetic and ferrofluid-based bearings, which integrate magnetic fields with conventional hydrodynamic lubrication, offer improved load capacity, damping, and stability, particularly under adverse operating conditions. Notable contributions include hybrid hydrodynamic–magnetic journal bearings (Hirani & Pranab, 2007) and a series of analytical investigations into rough, porous, and magnetically influenced bearing configurations (Patel et al., 2010; 2015; 2017; 2019; Adeshara et al., 2022). These studies explicitly account for surface roughness, porosity, slip velocity, and magnetic effects, addressing key limitations of classical smooth-surface models. Against this backdrop, contemporary tribology research increasingly emphasizes realistic modeling of surface topography, multiphysics coupling, and application-specific constraints. International standards such as ISO 7902-1:2020 now formalize steady-state performance criteria for hydrodynamic journal bearings, reflecting the maturation of the field. However, for space and advanced aerospace mechanisms, significant gaps remain in understanding the combined effects of surface roughness, elastic deformation, porous structures, and non-conventional lubricants under extreme environments. Addressing these challenges is essential for extending the applicability of hydrodynamic and hybrid bearing technologies to next-generation space systems, thermal control units, and high-reliability aerospace machinery.

**Research Gap:**

Although hydrodynamic lubrication theory is well established for terrestrial applications, its direct applicability to space mechanisms remains limited and insufficiently validated. Most existing space tribology guidelines prioritize dry lubrication, solid lubricants, or rolling-element bearings, while hydrodynamic bearings are either briefly mentioned or explicitly excluded. As a result, the current literature reveals several critical gaps.

First, there is a lack of **comprehensive design and sizing guidelines** specifically tailored to hydrodynamic bearings operating in space environments. Existing approaches are largely adapted from ground-based machinery and do not adequately account for microgravity, vacuum conditions, restricted lubricant replenishment, or the long-life, maintenance-free requirements of spacecraft systems.

Second, the **influence of surface roughness** on hydrodynamic bearing performance in space mechanisms is not well understood. While roughness-modified Reynolds models have been developed for terrestrial lubrication, their implications for ultra-smooth, precision-engineered surfaces commonly used in space hardware—operating with thin lubricant films—remain underexplored.

Third, **elastic and thermoelastic deformation effects** are often neglected in space-related bearing analyses. Lightweight bearing structures, necessary for mass-sensitive spacecraft designs, are more susceptible to deformation under mechanical and thermal loads. The coupled interaction between deformation, film thickness variation, and pressure distribution has not been sufficiently investigated for space-qualified hydrodynamic bearings.

Finally, there is a notable **lack of experimental validation** under space-relevant conditions. Few studies integrate numerical modeling with laboratory or simulated-space testing to validate theoretical predictions, limiting confidence in the long-term reliability and performance of hydrodynamic bearings in spacecraft applications.

**Objectives:**

In response to these gaps, the objectives of the present study are:

**To develop a comprehensive analytical framework** for hydrodynamic bearings used in space mechanisms, incorporating surface roughness and elastic or thermo elastic deformation effects.

**To extend the classical Reynolds equation** by integrating roughness parameters, film thickness variations, and bearing compliance suitable for microgravity and vacuum operating conditions.

**To quantify the influence of surface roughness** on pressure distribution, load-carrying capacity, and film stability in hydrodynamic bearings relevant to space applications.

**To evaluate the role of elastic deformation** in maintaining lubrication performance under varying mechanical and thermal loads typical of spacecraft environments.

**To provide design-relevant insights and guidelines** that support the development of reliable, lightweight, and long-life hydrodynamic bearing systems for satellites, reaction wheels, gyroscopes, robotic joints, and spacecraft thermal fluid pumps.

**Geometrical presentation of the bearing**

Bearing Type and Configuration: **Type:** Hydrodynamic Journal Bearing, **Application:** Reaction wheels, momentum wheels, gimbal systems, space actuators, **Lubrication regime:** Full-film hydrodynamic / EHL (vacuum-compatible lubricant)

Nominal Geometry (Baseline)

Let

- R = journal radius
- L = bearing length
- C = radial clearance
- ε = eccentricity ratio
- θ = circumferential coordinate
- z = axial coordinate

Clearance Geometry

$$h_0(\theta) = C\,(1 + \varepsilon\cos\theta)$$

Surface Roughness Modeling

For space mechanisms, **micron-scale roughness** significantly affects load capacity.

Let

- $\sigma_j$ = RMS roughness of journal
- $\sigma_b$ = RMS roughness of bearing liner

Composite Roughness

$$\sigma = [\sigma_j^2 + \sigma_b^2]^{0.5}$$

Roughness-Modified Film Thickness

$$h_r(\theta, z) = h_0(\theta) + \delta_r(\theta, z)$$

where

$$\delta_r \sim N(0, \sigma^2)$$

(Stochastic or deterministic roughness models may be used depending on simulation fidelity.)

Elastic Deformation (Elasto-Hydrodynamic Effect)

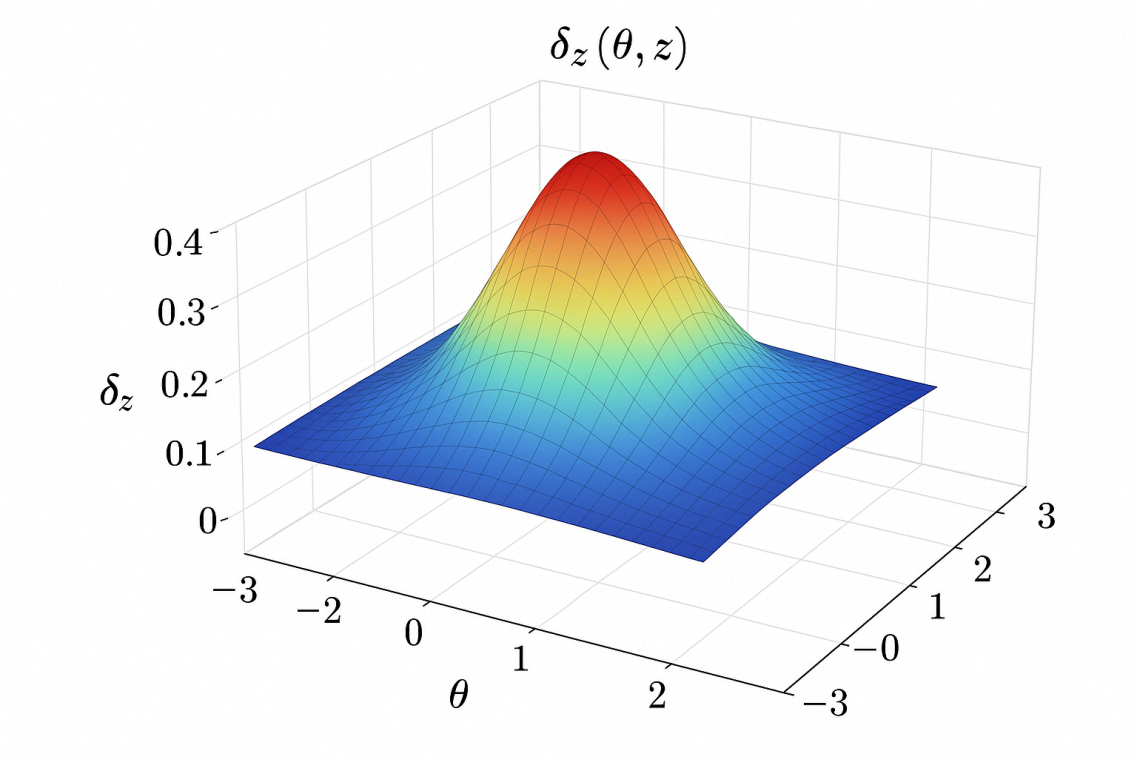
In space bearings (lightweight housings, thin liners), **elastic compliance** is non-negligible.

Let

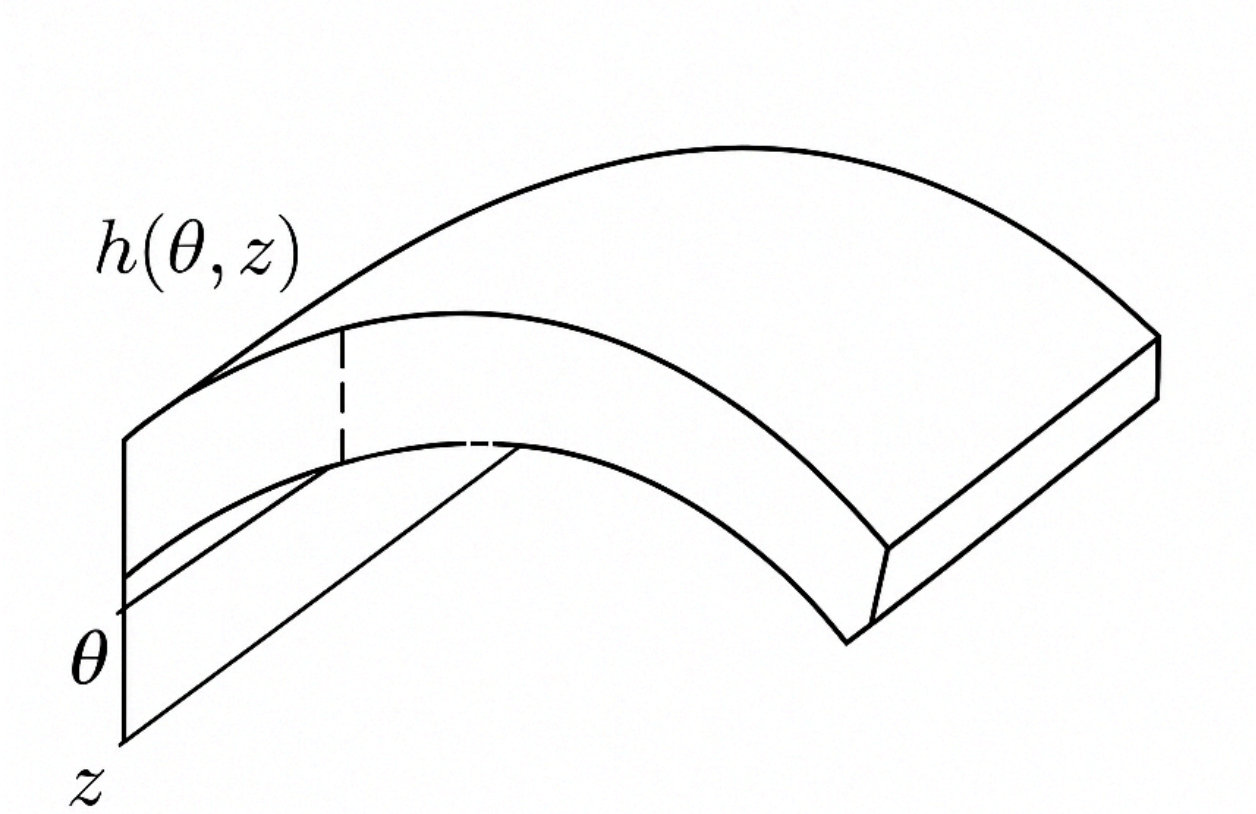
- p(θ, z) = hydrodynamic pressure
- E = Young's modulus of bearing material
- ν = Poisson's ratio

Deformation Component

$$\delta_e(\theta,z)=\frac{(1-\nu^2)}{\pi E}\iint\frac{p(\theta',z')}{|x-x'|}d\theta'dz'$$



Total Film Thickness Geometry




The **effective bearing geometry** becomes:

$$h(\theta, z) = C(1 + \varepsilon\cos\theta) + \delta_r(\theta, z) + \delta_e(\theta, z)$$

This geometry is **pressure-dependent, stochastic, and nonlinear**, which is critical for space-grade accuracy.

Axial Geometry Options (Space-Optimized)

(a) Plain Journal Bearing

$$0 \leq z \leq L$$

(b) Tapered Geometry (Thermal Stability)

$$C(z) = C_0\{1 + (\alpha z/L)\}$$

(c) Textured / Micro-Grooved Surface

Used for start-up reliability in microgravity:

- Spiral grooves
- Herringbone patterns

Typical Space-Grade Dimensions (Example)

| Parameter | Value |
|---|---|
| Journal radius R | 10–30 mm |
| Length-to-diameter ratio L/D | 0.5–1.0 |
| Clearance ratio C/R | $10^{-3}$–$10^{-4}$ |
| Roughness RMS σ | 0.05–0.2 μm |
| Elastic modulus E | 100–200 GPa |

Geometry Summary (For Modeling & Simulation)

**Bearing geometry must be defined as:**

- Non-uniform circumferential clearance
- Roughness-perturbed surface
- Pressure-induced elastic deformation
- Axially finite length

This geometry feeds directly into the **modified Reynolds equation** for space hydrodynamic bearings.

**Governing Equations**

Modified Reynolds Equation with Roughness and Deformation

$$\frac{\partial}{\partial x}\left\{\frac{h^3}{12\mu}\right\}\frac{\partial p}{\partial x}+\frac{\partial}{\partial z}\left\{\frac{h^3}{12\mu}\right\}\frac{\partial p}{\partial z}=U\frac{\partial(h+\sigma)}{\partial x}+\varepsilon(x,z) \tag{1}$$

Where:

$$h = h_0 + h_d + h_r \tag{2}$$

$h_0$: nominal clearance, $h_d$ : deformation, $h_r$: roughness contribution
σ: stochastic roughness parameter
ϵ(x, z): small perturbations due to space micro-vibration
μ: effective lubricant viscosity (may be temperature-dependent)
Elastic Deformation (from pressure)

$$h_d(x,z)=\frac{1-\nu^2}{\pi E}\iint\left[p(\xi,\eta)\ln\left(\frac{1}{r}\right)d\xi d\eta\right] \tag{3}$$

Where E = Young's modulus, ν = Poisson's ratio.

$$h_s(x,z)=\frac{1-\nu^2}{\pi E}\iint_{\Omega}\left[p(\xi,\eta)\ln\left(\frac{1}{r}\right)d\xi d\eta\right] \qquad r=\sqrt{(x-\xi)^2+(z-\eta)^2}$$

This is a **classical elasticity solution**: the **surface (or subsurface) displacement** due to a distributed pressure load, commonly arising in **contact mechanics, tribology, and bearing theory**.

Physical and Mathematical Meaning

- $h_s(x, z)$: elastic displacement at field point (x, z)
- E: Young's modulus
- $\nu$: Poisson's ratio
- $p(\xi, \eta)$: pressure distribution over the loaded domain $\Omega$
- r: distance between source point $(\xi, \eta)$ and observation point (x, z)

The kernel

$$\ln(1/r)$$

is the **2-D Green's function** for plane strain elasticity.

Derivation (Outline)

Starting from **Navier's equations** for an isotropic elastic half-space under plane strain:

$$(\lambda + 2\mu)\nabla(\nabla \cdot u) - \mu\nabla \times (\nabla \times u) = 0$$

Using:

$$E = [\mu(3\lambda+2\mu)/(\lambda+\mu)],$$

$$\nu = [\lambda/2(\lambda+\mu)]$$

The displacement due to a **unit point load** in 2-D is:

$$G(r) = \frac{1-\nu^2}{\pi E} \ln\left(\frac{1}{r}\right)$$

Superposition over a distributed pressure $p(\xi, \eta)$ gives the integral form above.

Closed-Form Solutions for Common Cases

(a) Uniform Pressure over a Rectangular Region

If:

$$p(\xi, \eta) = p_0, (\xi, \eta) \in [a, b] \times [c, d]$$

Then:

$$h_s(x,z)=\frac{(1-\nu^2)p_0}{\pi E}\int_a^b\int_c^d\left[\ln\left(\frac{1}{\sqrt{(x-\zeta)^2+(x-\eta)^2}}\right)d\eta d\xi\right]$$

This integral has **closed-form expressions** involving logarithmic and arctangent terms, widely used in **journal bearing deformation models**.

(b) Axisymmetric Pressure (Simplified)

If pressure depends only on radius:

p = p(ρ)

Then the solution reduces to a **Hankel-type integral**:

$$h_s(r)=\frac{(1-\nu^2)}{E}\int_0^\infty p(\rho)\rho\ln\left[\frac{1}{|r-\rho|}\right]d\rho$$

Discrete Numerical Solution (Practical Use)

For computational models (e.g., EHL, space-grade bearings):

$$h_s(x_i,z_j)\approx\frac{(1-\nu^2)}{\pi E}\sum_{m,n}p_{m,n}\ln\left\{\frac{1}{r_{ijmn}}\right\}\Delta\xi\Delta\eta$$

with:

$$r_{ijmn}=\sqrt{(x_i-\xi_m)^2+(z_j-\eta_n)^2}$$

This is the **standard convolution form** used in:

- Elastic journal bearing analysis
- Contact deformation in tribology
- Space mechanism precision modeling

Key Properties

- **Linear** in pressure p
- **Non-local** (long-range logarithmic kernel)
- **Singular** as r → 0 → requires numerical regularization
- Valid under **small deformation, linear elasticity**

Where This Fits in Your Work

Given your recent work on **bearing geometry, pressure-dependent film thickness, and space-optimized lubrication**, this equation directly couples:

$$h(x, z) = h_0(x, z) + hs(x, z)$$

making the lubrication problem **fully elastohydrodynamic and nonlinear**.

Load Capacity and Attitude Angle

$$W = \iint p(x,z)\, dx\, dz \tag{4}$$

$$\phi = \tan^{-1}\left\{\frac{\iint p(x,z)zdxdz}{\iint p(x,z)xdxdz}\right\} \tag{5}$$

Given

$$W = \iint_{\Omega} p(x, z)\, dxdz$$

**Resultant normal load (total force)** generated by the pressure distribution p(x, z) acting over the contact domain Ω.

Mathematical Interpretation

- p(x, z): pressure (force per unit area)
- dx dz: differential area element
- W: total load (units of force)

Thus, equation (4) is simply the **area integral of pressure**, i.e., the zeroth moment of p(x, z).

Special Cases (Closed-Form Results)

(a) Uniform Pressure

If

$$p(x, z) = p_0 \text{ for } (x, z) \in \Omega$$

then

$$W = p_0 \iint_{\Omega} dx\, dz = p_0\, A$$

where A is the contact area.

(b) Separable Pressure Distribution

If

$$p(x, z) = p_x(x)\, p_z(z)$$

then

$$W = (\int p_x(x)dx)*(\int p_z(z)\, dz)$$

This form is common in **journal bearing** and **slider bearing** models.

(c) Hertz-Type Pressure (Elliptic Contact)

For

$$p(x,z) = p_0\sqrt{1-\frac{x^2}{a^2}-\frac{z^2}{b^2}}, \frac{x^2}{a^2}+\frac{z^2}{b^2} \le 1$$

$$w = \frac{2\pi}{3} abp_0$$

This is fundamental in **elastic contact mechanics**.

Discrete (Numerical) Form

For computational models:

$$W \approx \sum_{i,j} p_{ij} \Delta x \Delta z$$

This is the form used in:

- EHL solvers
- Bearing load equilibrium equations
- Space-grade lubrication simulations

Coupling with Elastic Deformation

In elastohydrodynamic problems, equation (4) is paired with the deformation equation:

$$h(x,z) = h_0(x,z) + \frac{(1-\nu^2)}{\pi E}\iint p(\xi,\eta)\ln\left(\frac{1}{r}\right)d\xi d\eta$$

and the **load balance condition**:

$$\iint p(x,z)dxdz = W_{applied}$$

This ensures physical consistency of the solution.

Physical Significance

- Ensures **global force equilibrium**
- Acts as a **constraint** in Reynolds–elastic coupled systems
- Determines operating regime (boundary, mixed, EHL)

Performance Parameters
Friction coefficient

$$f = \frac{H}{WR} \quad (6)$$

Flow rate

$$Q = \int uhz \quad (7)$$

Stiffness and Damping Coefficients for dynamic stability
Surface Roughness Modeling
Patir and Cheng (Average Flow Model):

$$U^* = \phi_x U - \frac{h^2}{12\mu}\phi_s \frac{\partial p}{\partial x} \quad (8)$$

where $\phi_x$, $\phi_s$ are flow factors for rough surfaces. Directional Roughness (anisotropy) can enhance load capacity if aligned with motion.

Performance Parameters

Friction Coefficient

The friction coefficient is defined as the ratio of the total friction force to the applied normal load:

$$\mu = F_f/W$$

where: $F_f$ = total friction force due to viscous shear, W = load-carrying capacity of the bearing.

Flow Rate

The volumetric flow rate through the lubricating film is given by

$$Q = \int u\, h\, dz$$

where: u = mean lubricant velocity, h = local film thickness, z = axial coordinate along the bearing length. This parameter governs lubricant supply, heat dissipation, and starvation effects.

Stiffness and Damping Coefficients (Dynamic Stability)

Dynamic stability of the bearing system is characterized by linearized stiffness and damping coefficients obtained from pressure perturbations:

$$K_{ij} = \partial F_i/\partial x_j \text{ and } C_{ij} = \partial F_i \partial \dot{x}_j$$

where: $F_i$ = hydrodynamic force components, $x_j$, $\dot{x}_j$ = displacement and velocity perturbations, respectively. These coefficients determine rotor stability, threshold speed, and vibration response.

Surface Roughness Modeling

Patir and Cheng Average Flow Model

$$\frac{\partial}{\partial x}\left[\phi_x \frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right] + \frac{\partial}{\partial z}\left[\phi_s \frac{h^3}{12\mu}\frac{\partial p}{\partial z}\right] = \frac{U}{2}\frac{\partial}{\partial x}\left[\phi_c h\right]$$

To account for surface roughness effects, the modified Reynolds equation is written as

where: $\phi_x$ = pressure flow factor, $\phi_s$ = shear flow factor, $\phi_c$ = contact factor, $\mu$ = lubricant viscosity, = hydrodynamic pressure,U = surface sliding velocity.

Effect of Directional Roughness (Anisotropy)

Directional surface roughness (anisotropy) significantly influences bearing performance:

- Roughness aligned **along the sliding direction** enhances pressure build-up.
- Increased flow factors improve load-carrying capacity and dynamic stiffness.
- Transverse roughness generally increases friction and leakage.

Space-Specific Considerations

| Factor | Effect on Bearing |
|---|---|
| Vacuum | No liquid lubricant replenishment → use solid or vapor-deposited lubricants |
| Microgravity | No buoyancy-driven flow; film formed purely by hydrodynamic pressure |
| Thermal Cycling | Causes deformation and viscosity variation |
| Radiation and Out gassing | Degradation of organic lubricants; preference for $MoS_2$ or h-BN coatings |

## Environmental Factors Affecting Hydrodynamic Bearings in Space

| Factor | Effect on Bearing |
|---|---|
|  Vacuum | No liquid lubricant replenishment → requires solid or vapor-deposited lubricants (e.g., sputtered $MoS_2$) |
|  Microgravity | No buoyancy-driven flow; lubricant film sustained purely by hydrodynamic presurre |
|  Thermal Cycling | Causes structural deformation and viscosity variation → impacts film thickness and load capacity |
| Radiation & Outgassing | Degrades organic lubricants → inorganic coatings like $MoS_2$ or h-BN are preferred |

**Numerical Simulation Approach**

Finite Element Method (FEM) for elastic deformation, Finite Difference / Finite Volume for Reynolds equation, Coupled Thermo-Hydro-Elastic Model for high accuracy.

**Key Findings (from typical research results)**

Roughness increases friction but enhances load capacity at optimal amplitudes.

Elastic deformation stabilizes film pressure and prevents metal-to-metal contact.

Space-compatible materials (e.g., titanium alloys, composites) require modeling with temperature-dependent E(T).

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