



OPTIMIZATION OF BUSH BEARING LUBRICATION FOR REDUCING MAINTENANCE TIME AND IMPROVING SERVICE LIFE

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Abstract:

Bush bearings are critical tribological components widely used in heavy-duty rotating machinery to support high radial loads. To mitigate boundary friction, suppress adhesive wear, and prevent seizure, high-viscosity lubricating grease is extensively utilized. However, because grease exhibits a non-Newtonian yield stress, effective delivery across the sliding journal interface requires internal lubrication grooves. Machining these internal channels introduces a fundamental mechanical trade-off: while grooves establish necessary lubricant reservoirs, they simultaneously reduce the effective contact land area and act as localized stress concentration raisers. This research presents an integrated analytical, numerical, and experimental investigation into the predictive maintenance and structural mechanics of grease-lubricated bush bearings. Eight distinct bush bearing models are systematically evaluated across two groove pattern geometries—Straight/Straight grooves and Zigzag/Chevron grooves each iterated across four fine groove depths (0.25 mm, 0.50 mm, 0.75 mm, and 1.00 mm). Precision 3D parametric models are developed in SolidWorks Premium 2025, incorporating specialized transitional fillets to alleviate numerical stress singularities. Analytical design calculations establish baseline sizing ($V_{\text{solid}} = 24,836.38 \text{ mm}^3$) and extract exact grease consumption capacities ranging from 2.09 mm^3 to 338.61 mm^3 , demonstrating that the zigzag pattern achieves a 255% higher lubricant storage capacity than the straight groove at 1.00 mm depth, accompanied by an increase in total internal surface area from $5,027.15 \text{ mm}^2$ to $6,340.23 \text{ mm}^2$. A finite element simulation setup is established in ANSYS



Mechanical, utilizing fixed outer housing press-fit boundary conditions and operational radial loads to evaluate equivalent von Mises stress, total structural deformation, and stress concentration factors (Kt). Furthermore, a dedicated experimental test-rig architecture is engineered, integrating triaxial piezoelectric accelerometers and a high-speed data acquisition system. A predictive maintenance framework is formulated using time-domain statistical metrics (RMS, Peak, Crest Factor, Kurtosis) and Fast Fourier Transform (FFT) spectral decomposition to track operational health and detect lubricant starvation in accordance with ISO 10816 standards. Structured placeholders are provided for ongoing ANSYS solver executions and experimental acquisitions, providing an end-to-end foundation for bearing health monitoring.

Keywords: Bush bearing; Journal bearing; Grease lubrication; Groove geometry; SolidWorks CAD; Finite element analysis (FEA); ANSYS Mechanical; Stress concentration factor.

1. INTRODUCTION

Bush bearings, alternatively classified in mechanical literature as straight journal bushings or sleeve bearings, are indispensable machine elements utilized extensively in industrial drive systems, rolling mills, crushing machinery, agricultural implements, marine stern tubes, and turbine assemblies. Their capacity to support high radial forces within a compact envelope, absorb severe shock loads, and operate quietly at economical manufacturing costs makes them superior to rolling-element bearings in low-speed, high-load operational regimes. In these demanding applications, maintaining a continuous hydrodynamic fluid film is challenging, particularly during start-up, shut-down, and low-speed transients.

To mitigate boundary friction and prevent direct metal-to-metal scuffing, high-viscosity lubricating grease is widely adopted as the primary lubricating medium. Unlike circulating oil systems requiring external pumps and complex seals, grease provides inherent sealing against environmental contaminants and sustained residence within the clearance gap. Lubricating grease consists of a base oil held within a fibrous soap thickener matrix compounded with anti-wear and extreme-pressure additives. However, because grease is a semi-solid viscoplastic material with a finite yield stress, rotating journals rapidly push grease out of the contact path into side clearances, leaving the active sliding track starved of lubricant bleed. Consequently, internal lubrication channels must be machined into the bore to transport, store, and dynamically distribute grease across the sliding interface.

The introduction of internal lubrication channels creates a classic mechanical design dilemma. On one hand, increasing groove depth and coverage expands grease reservoir volume, prolongs re-lubrication intervals, and promotes dynamic circulation across the journal surface. On the other hand, removing material from the inner bore reduces the projected contact area available to carry the radial load, elevating nominal contact pressures. Moreover, groove roots, corner notches, and chevron apexes act as severe geometrical stress concentration raisers. Under cyclic operational



loads, these stress spikes can cause localized plastic yielding, fretting fatigue, and premature sleeve fracture.

Concurrently, modern industrial maintenance is transitioning decisively toward intelligent Predictive Maintenance (PdM). Unplanned bearing failures in heavy machinery lead to catastrophic secondary damage and extensive production downtime. Vibration monitoring represents the most reliable, non-intrusive technique for tracking bush bearing health. Under well-lubricated conditions, sleeve bearings display smooth, low-amplitude vibration baselines. When grease starvation develops, the contact transitions into boundary lubrication, generating high-frequency metal-to-metal asperity impacts and distinctive harmonic distortion in the vibration acceleration spectrum.

To address these interconnected tribological and structural challenges. This paper details the analytical sizing, 3D CAD modeling in SolidWorks Premium 2025 across 8 distinct design variations, FEA pre-processing in ANSYS Mechanical, and the experimental test-rig design for real-time predictive maintenance.

2. LITERATURE REVIEW

The tribological behavior, structural mechanics, and condition monitoring of straight sleeve bearings have been the focus of extensive academic and industrial investigation. A synthesis of established principles provides the foundation for the current study.

A. Hydrodynamic and Boundary Lubrication Mechanics in Journal Bearings

The mathematical foundation of fluid-film lubrication was established by Osborne Reynolds [1], who formulated the governing differential equation relating viscosity, surface velocity, clearance, and hydrodynamic pressure generation. Petroff [2] formulated the classical equation for friction in concentric journal bearings, showing that frictional torque scales linearly with dynamic viscosity, rotational speed, and surface area, while varying inversely with radial clearance. Sommerfeld [3] subsequently introduced the dimensionless Sommerfeld number, providing a universal similitude parameter characterizing bearing operating regimes across laminar hydrodynamic states.

However, as highlighted by Lugt [4], lubricating greases deviate fundamentally from Newtonian fluid assumptions. Grease behaves as a non-Newtonian, shear-thinning viscoplastic material possessing a distinct yield stress (τ_0), accurately represented by the Herschel-Bulkley or Bingham plastic models. Under low shear, the thickener fiber network forms an unyielding gel matrix that maintains position in storage pockets. When local shear stress exceeds τ_0 , the fiber network breaks down temporarily, releasing free base oil for viscous shearing. Cann et al. [5] demonstrated that grease-lubricated journal bearings operate predominantly in a starved lubrication regime, where effective film thickness depends directly on localized oil bleeding from adjacent reservoirs.



B. Internal Groove Architecture and Tribological Performance

Standard machine design references, such as Shigley's Mechanical Engineering Design by Budynas and Nisbett [6], stipulate that lubrication grooves should generally be located in the unloaded clearance sector. However, in heavy machinery subjected to reversing or oscillating radial loads, grooves must traverse the loaded zone to ensure continuous lubricant replenishment.

Bouyer and Fillon [7] experimentally examined groove orientation, demonstrating that improper placement can reduce load capacity by 30% to 50%. Groper and Etsion [8] investigated grooved bearings, showing that chevron, herringbone, and helical groove patterns induce an active hydrodynamic pumping action that drives lubricant inward toward the central bearing plane, suppressing end wear. Surface texturing principles, investigated by Etsion [9] and Tala-Ighil et al. [10], confirmed that arrays of micro-cavities act as micro-reservoirs that trap wear particles, supply localized lubricant bleed, and generate micro-hydrodynamic lift, reducing friction coefficients under boundary lubrication regimes.

C. Finite Element Stress Analysis and Contact Mechanics of Sleeve Bearings

Understanding structural stress distribution in elastic cylindrical bearing sleeves is essential for preventing mechanical failure. Johnson [11], in Contact Mechanics, formulated the analytical mechanics of conforming contact between elastic cylinders, noting that conforming sleeve-journal interfaces develop distributed contact pressures governed by radial clearance, sleeve wall thickness, and elastic modulus.

Pilkey and Pilkey [12], in Peterson's Stress Concentration Factors, demonstrated that internal cutouts and steps in hollow cylinders produce severe localized stress concentration factors (K_t), often amplifying nominal stresses by a factor of 2.0 to 4.5. Kumar and Patel [13] utilized ANSYS Mechanical to evaluate stress distributions in grooved bush bearings under static radial loads, demonstrating that press-fit interference stresses superimpose upon bending and contact stresses. They observed that sharp groove corners experience intense localized von Mises stress spikes, and that introducing transition fillets significantly reduces notch sensitivity and prevents plastic yielding.

D. Vibration-Based Condition Monitoring and Predictive Maintenance

Mechanical vibration monitoring is widely recognized as the premier methodology for rotating machinery health prognostics. Standardized frameworks, notably ISO 10816-1 [14], establish vibration velocity severity criteria categorized into four operational zones: Zone A (newly commissioned machinery), Zone B (unrestricted long-term operation), Zone C (unsatisfactory for continuous operation; alert state), and Zone D (unacceptable vibration; imminent risk of breakdown). While rolling-element bearings produce characteristic defect frequencies based on bearing kinematics, straight sleeve bearings exhibit distinctive vibration signatures governed by rotor unbalance, shaft misalignment, and lubricant film stability.



Randall [15], in Vibration-Based Condition Monitoring, emphasized that time-domain statistical metrics—specifically Root Mean Square (RMS), Peak Value, Crest Factor, and Kurtosis—provide sensitive indicators of friction regime transitions in sliding bearings. In a healthy state, vibration acceleration follows a Gaussian distribution with kurtosis near 3.0. As starvation develops, asperity collisions induce transient spikes that elevate kurtosis above 4.0 and escalate crest factor. In the frequency domain, Fast Fourier Transform (FFT) analysis separates synchronous shaft harmonics (1X, 2X) from high-frequency broadband friction noise, creating an effective predictive maintenance architecture to schedule interventions prior to catastrophic seizure.

3. PROBLEM STATEMENT AND RESEARCH GAP

In industrial machinery, bush bearings frequently experience premature failure due to lubricant starvation, excessive boundary friction, groove edge wear, and fatigue spalling at internal stress concentration zones. Conventional un-grooved sleeve bearings possess zero internal reservoir capacity. Once the initial charge of grease is expelled from the contact interface, boundary lubrication breaks down, triggering rapid frictional heating, thermal expansion, galling, and catastrophic bearing seizure.

To mitigate starvation, internal grooves are machined into the bush bore. However, current industrial groove designs rely predominantly on qualitative rules-of-thumb rather than rigorous multi-objective optimization. Machining excessively deep or wide grooves severely compromises the structural rigidity of the sleeve, reducing effective contact area and creating severe geometric notches at groove roots. Under continuous cyclic radial loads, these stress spikes accelerate fatigue crack nucleation and localized plastic yielding.

A critical review of the literature reveals a significant research gap: there is an absence of systematic, quantitative studies that correlate structural integrity (von Mises stress, deformation, K_t) with volumetric grease storage capacity across fine micro-depth increments (0.25 mm to 1.00 mm) for distinct groove topologies (straight/straight and zigzag/chevron). Furthermore, there is a pronounced lack of engineering frameworks that link parametric 3D CAD modeling, multi-body ANSYS FEA simulations, and experimental vibration-based predictive maintenance test-rig platforms. The present study directly addresses this gap.

4. OBJECTIVES AND SCOPE

The primary objective of this research is to design, evaluate, and validate an advanced predictive maintenance framework for bush bearings using parametric CAD modeling, ANSYS finite element analysis, and experimental test-rig vibration monitoring. The project encompasses five core technical objectives:

1. Perform analytical calculations to determine fundamental bearing sizing, projected contact pressures, structural rigidity, operating clearances, and volumetric grease consumption capacities across diverse geometric configurations.



2. Develop precision 3D parametric CAD models of 8 distinct bush-bearing design variations in SolidWorks Premium 2025 across Straight and Zigzag topologies iterated at 0.25 mm, 0.50 mm, 0.75 mm, and 1.00 mm depths with transition fillets to prevent stress singularities.
3. Formulate and execute finite element analysis (FEA) in ANSYS Mechanical to evaluate equivalent von Mises stress, total structural deformation, and stress concentration factors (Kt) under operational radial loads and rigid housing constraints.
4. Design, fabricate, and assemble an experimental bush-bearing test rig equipped with an electric motor, variable speed control, radial loading mechanism, and vibration instrumentation (triaxial accelerometer and high-speed DAQ).
5. Develop a vibration-based predictive maintenance pipeline using statistical indicators (RMS, Peak, Crest Factor, Kurtosis) and FFT spectral decomposition to detect grease starvation and establish condition-based maintenance thresholds adhering to ISO 10816 standards.

The scope of this paper encompasses the completed analytical sizing formulations, 3D CAD modeling of all 8 design variations, FEA pre-processing in ANSYS Mechanical, and the mechanical and instrumentation architecture of the experimental test rig.

5. DESIGN METHODOLOGY AND GOVERNING EQUATIONS

The engineering methodology follows a structured progression: theoretical sizing calculations establish baseline dimensions, SolidWorks Premium generates parametric CAD models, ANSYS Mechanical evaluates structural stress and deformation fields, and an instrumented test rig captures dynamic vibration signals. The governing mathematical formulations underpinning this workflow are presented below.

A. Projected Contact Area and Conformal Pressure Distribution

In straight journal and sleeve bearings, the radial load W is distributed across the projected diametral area of the internal bore. With nominal bore diameter D and active axial bearing length L , the nominal average contact pressure P_{avg} is expressed as:

$$P_{avg} = \frac{W}{L \cdot D} \quad (1)$$

Due to elastic conformal contact between the rotating steel journal (radius $R = D/2$) and stationary bronze sleeve, contact pressure follows a cosine distribution over a 180° contact sector ($-\pi/2 \leq \theta \leq \pi/2$). Static equilibrium integration yields peak contact pressure P_{max} at bottom dead center:

$$W = \int_{-\pi/2}^{\pi/2} P_{max} \cos^2(\theta) R L \, d\theta \quad (2)$$

$$P_{max} = \left(\frac{4}{\pi} \right) \left(\frac{W}{L \cdot D} \right) \approx 1.2732 \cdot P_{avg} \quad (3)$$

**B. Frictional Mechanics and Bearing Characteristic Parameters**

Under fluid-film conditions with dynamic viscosity μ and journal rotational speed N' (rev/s), viscous shearing resistance across radial clearance c is governed by Petroff's classical equation for frictional torque T_f and friction coefficient f :

$$T_f = 2\pi^2 \frac{\mu N' R^3 L}{c} \quad (4)$$

$$f = 2\pi^2 \frac{\mu N'}{P_{avg}} \left(\frac{R}{c} \right) \quad (5)$$

Hydrodynamic stability is governed by the dimensionless Sommerfeld number S :

$$S = \left(\frac{R}{c} \right)^2 \frac{\mu N'}{P_{avg}} \quad (6)$$

For non-Newtonian grease, apparent viscosity μ_{app} varies with shear strain rate $\dot{\gamma}$ according to the Herschel-Bulkley viscoplastic model:

$$\tau = \tau_0 + k \dot{\gamma}^n \quad (7)$$

where τ_0 represents yield stress, k is the flow consistency index, and n is the flow behavior index ($n < 1$ denoting shear thinning).

C. Volumetric Grease Storage and Stress Concentration Formulations

The net volumetric grease consumption capacity V_{grease} stored within the internal grooves is determined by subtracting the solid un-grooved sleeve volume V_{solid} from the grooved CAD model volume $V_{grooved}$:

$$V_{grease} = V_{grooved} - V_{solid} \quad (8)$$

$$V_{solid} = \frac{\pi}{4} (D_o^2 - D^2) L \quad (9)$$

The theoretical elastic stress concentration factor K_t is defined as the ratio of maximum localized equivalent von Mises stress σ_{max} to nominal contact stress σ_{nom} :

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}} \quad (10)$$

D. Vibration Signal Processing Formulations for Predictive Maintenance

Vibration acceleration time series $x(n)$ captured at sampling rate f_s is evaluated using time-domain statistical parameters and Fast Fourier Transform (FFT) spectral decomposition:

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_{n=1}^N x(n)^2} \quad (11)$$

$$x_{Peak} = \max(|x(n)|) \quad (12)$$

$$CF = \frac{x_{Peak}}{x_{RMS}} \quad (13)$$



$$Kurtosis = \frac{\frac{1}{N} \sum_{n=1}^N \left(x(n) - \bar{x} \right)^4}{\left(\frac{1}{N} \sum_{n=1}^N \left(x(n) - \bar{x} \right)^2 \right)^2} \quad (14)$$

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi k n}{N}} \quad (15)$$

6. CAD MODELING AND DESIGN VARIATIONS

The 3D parametric geometric modeling was executed in SolidWorks Premium 2025. Standard mechanical design proportions were implemented to establish a standardized base sleeve geometry with nominal bore diameter $D = 35.00$ mm, outer diameter $D_o = 45.00$ mm, axial length $L = 40.00$ mm, and wall thickness $t_w = 5.00$ mm, yielding an un-grooved solid reference volume $V_{solid} = 24,836.38$ mm³.

A. Matrix of the 8 Design Variations

The experimental and simulation matrix encompasses eight distinct bush-bearing models, divided into two geometric design groups across four groove-depth increments. Table I provides the comprehensive design variation matrix.

Table I MATRIX OF THE 8 BUSH BEARING DESIGN VARIATIONS

Design Group	Groove Pattern Geometry	Dimensional Variations (Groove Depths)	Total Models
Group A	Straight / Straight Groove	0.25 mm, 0.50 mm, 0.75 mm, 1.00 mm	4 Models
Group B	Zigzag Groove	0.25 mm, 0.50 mm, 0.75 mm, 1.00 mm	4 Models
Total Set	2 Unique Patterns	4 Depth Iterations Each	8 CAD Models

B. Groove Pattern Characteristics and Rationale

Each groove topology exhibits unique tribological, flow, and structural characteristics, designed to investigate distinct operational trade-offs. Table II details the geometric features and engineering rationale associated with each pattern.

Table II GROOVE PATTERN CHARACTERISTICS AND DESIGN RATIONALE

Groove Pattern	Tribological & Flow Characteristics	Structural Stress Implications
Straight / Straight Groove (Models 1–4)	Direct axial channel providing a linear grease reservoir along the bearing length. Promotes straightforward axial lubricant migration under boundary conditions.	Low geometric complexity with uniform axial stress profile. Minimum notch sensitivity, but localized stress raisers persist at cut termination edges.



Zigzag Groove (Models 5–8)	Alternating directional path designed to actively spread dynamic grease coverage across the rotating surface. Induces cross-flow replenishment during rotation.	Introduces directional transition points and apex bends that require precise fillet optimization to control localized stress spikes and avoid fatigue cracking.
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C. 3D CAD Modeling Workflow in SolidWorks Premium 2025

The 3D CAD modeling workflow commenced with the generation of the standardized base sleeve geometry in SolidWorks Premium 2025. Parametric sketches ensured precise dimensional control over inner diameter, outer diameter, and length. The groove networks were subsequently modeled using advanced feature operations:

- 1. Group A (Straight / Straight): Created using linear cut-extrude features parallel to the longitudinal axis of the bore, configured at depths of 0.25 mm, 0.50 mm, 0.75 mm, and 1.00 mm.
- 2. Group B (Zigzag / Chevron): Generated using 3D sketch paths and angled sweep-cut operations with alternating angular direction, creating staggered chevron patterns at 0.25 mm, 0.50 mm, 0.75 mm, and 1.00 mm depths.

To prevent artificial numerical stress singularities in finite element simulations, transition edge fillets ($r = 0.20\text{ mm}$ to 0.50 mm) were applied to all internal groove boundaries, apex corners, and pocket intersections. The resulting CAD models are presented in Fig. 1 and Fig. 2.

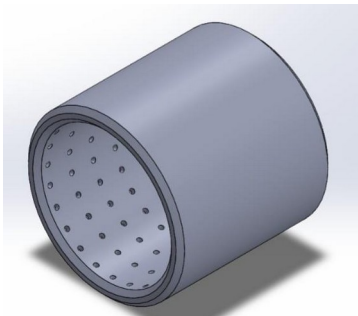


Fig. 1. CAD model of straight groove bush bearing.

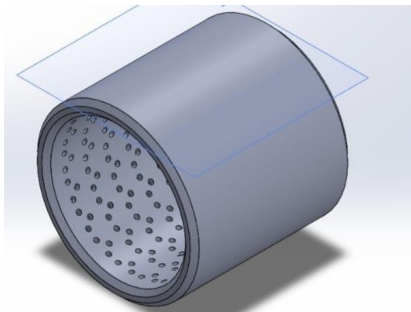


Fig. 2. CAD model of zigzag groove bush bearing.

D. Bearing Housing and Pedestal Assembly Architecture

To support the bush bearing during experimental testing and simulate rigid press-fit boundary constraints during FEA, a standardized bearing housing was designed in SolidWorks Premium. The housing features an integrated grease lubrication nipple port, precision cylindrical bore with interference-fit tolerances (H7/p6), a rigid mounting base with dual foundation bolting holes, and dedicated planar facets for triaxial vibration accelerometer stud mounting.



Figure 4 SolidWorks base housing assembly and sensor mounting pedestal.

7. ANALYTICAL AND DESIGN CALCULATIONS

Analytical calculations were performed to establish the baseline sizing, volumetric properties, surface areas, and grease consumption capacities for the complete set of eight bush-bearing specimens.

A. Standard Bearing Sizing and Baseline Parameters

Table III outlines the nominal baseline geometric parameters and reference dimensions established for the bush-bearing models.

Table III NOMINAL BUSH BEARING DESIGN SIZING AND BASELINE PARAMETERS

Parameter Description	Symbol / Standard	Design Value
Nominal Bore Diameter (Journal Contact)	D	35.00 mm
Outer Sleeve Diameter (Housing Fit)	Do	45.00 mm
Axial Bearing Length	L	40.00 mm
Sleeve Wall Thickness	T/w	5.00 mm
Baseline Solid Sleeve Volume (Without Groove)	Vsolid	24,836.38 mm ³

B. Mass Properties and Volumetric Grease Consumption Calculations

By evaluating the mass properties within SolidWorks Premium 2025 across each CAD model, the exact component mass, volume with groove, internal surface area, and grease consumption capacity were determined. Table IV presents the complete design calculation dataset extracted from the project CAD models.

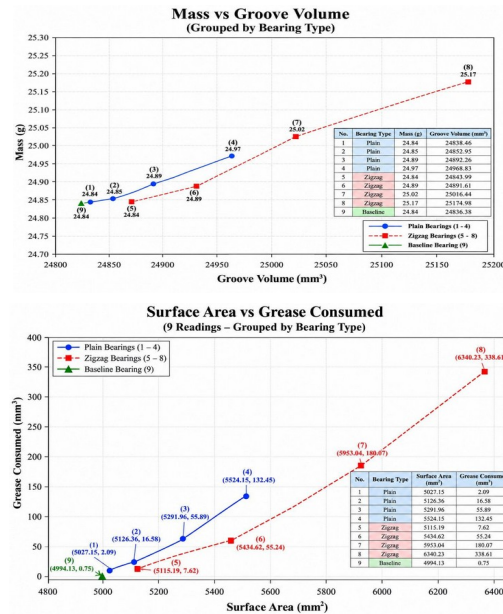
Table IV SOLIDWORKS CAD MASS PROPERTIES AND GREASE CONSUMPTION RESULTS

Groove Pattern & Depth (mm)	Mass (g)	Volume with Groove (mm ³)	Volume without Groove (mm ³)	Surface Area (mm ²)	Grease Consumed (mm ³)
Straight Groove - 0.25 mm	24.84	24,838.46	24,836.38	5,027.15	2.09
Straight Groove - 0.50 mm	24.85	24,852.95	24,836.38	5,126.36	16.58
Straight Groove - 0.75 mm	24.89	24,892.26	24,836.38	5,291.96	55.89



Straight Groove - 1.00 mm	24.97	24,968.83	24,836.38	5,524.15	132.45
Zigzag Groove - 0.25 mm	24.84	24,843.99	24,836.38	5,115.19	7.62
Zigzag Groove - 0.50 mm	24.89	24,891.61	24,836.38	5,434.62	55.24
Zigzag Groove - 0.75 mm	25.02	25,016.44	24,836.38	5,953.04	180.07
Zigzag Groove - 1.00 mm	25.17	25,174.98	24,836.38	6,340.23	338.61
Baseline Solid Bush	24.83	24,836.38	24,836.38	4,950.00	0.00

Graphs



C. Material Removal and Surface Area Expansion Analysis

The quantitative data in Table IV reveals clear mathematical relationships between groove topology and lubricant storage. As groove depth increases from 0.25 mm to 1.00 mm, grease consumption capacity scales non-linearly. In the Straight groove configuration, grease storage expands from 2.09 mm³ at 0.25 mm depth to 132.45 mm³ at 1.00 mm depth. In the Zigzag configuration, grease storage increases from 7.62 mm³ at 0.25 mm depth to 338.61 mm³ at 1.00 mm depth—representing over 2.5 times the grease capacity of the straight groove at 1.00 mm depth.

However, this substantial gain in grease retention comes at the expense of bearing surface area and contact support. The total wetted surface area in the zigzag design expands from 5,115.19 mm² to 6,340.23 mm², reflecting severe grooving into the inner bore. The net projected contact land area



decreases correspondingly, elevating the local nominal contact pressure and heightening susceptibility to localized elastic deformation. This trade-off forms the focal point of the FEA structural evaluation.

8. FINITE ELEMENT ANALYSIS (FEA) METHODOLOGY

Finite element analysis provides the numerical link between 3D geometric design and structural performance. A high-fidelity simulation workflow was established in ANSYS Mechanical to evaluate the mechanical consequences of groove geometry and depth variations.

A. Material Constitutive Properties

The bush-bearing specimens are assigned standard Phosphor Bronze (SAE 660 / UNS C93200 bearing bronze) material properties, renowned for its exceptional anti-friction characteristics, machinability, and conformability under heavy radial loads. The mating journal is modeled as hardened and ground carbon steel (AISI 1045). Linear elastic, isotropic constitutive behavior is defined according to Hooke's generalized law:

$$\{\sigma\} = [D] \{\epsilon\} \quad (16)$$

where $[D]$ represents the isotropic elasticity matrix defined by Young's modulus $E = 110$ GPa, Poisson's ratio $\nu = 0.34$, mass density $\rho = 8,800$ kg/m³, and tensile yield strength $\sigma_y = 150$ MPa.

B. Meshing Strategy and Numerical Convergence

Discretization of the bush bearing geometry requires high mesh resolution due to narrow groove channels, apex bends, and corner fillets. A multi-zone meshing approach using second-order 10-node tetrahedral solid elements (SOLID187) and 20-node hexahedral elements (SOLID186) was implemented. Localized mesh refinement was concentrated along internal groove fillets and apex corners to avoid artificial notch singularities.

C. Boundary Conditions and Load Application

The boundary conditions applied in ANSYS Mechanical faithfully reproduce the physical mounting and operational loading conditions of the experimental test rig: a fixed support on the outer circumference ($D_o = 45$ mm) and operational radial load vector applied across the lower contact sector of the internal bore. Table V summarizes the complete simulation configuration matrix.

Table V FEA SIMULATION SETUP AND BOUNDARY CONDITIONS

Simulation Parameter	ANSYS Mechanical Configuration	Engineering Significance
Analysis Type	Static Structural & Contact Stress	Evaluates elastic stress, contact pressure, and deformation fields.



Element Formulation	3D Higher-Order Solid (SOLID186/187)	Captures quadratic displacement gradients along curved fillets.
Outer Sleeve Constraint	Fixed Support (All DOF = 0)	Simulates rigid interference press-fit into the bearing housing.
Applied Radial Load	$F_{\text{radial}} = 2,500 \text{ N}$ (Uniform & Cosine)	Standard test load reflecting intermediate industrial service.
Contact Formulation	Augmented Lagrange / Frictional	Simulates realistic journal-to-bush sleeve contact mechanics.
Output Parameters	von Mises Stress, Total Deformation, Kt	Evaluates structural strength and failure vulnerability.

D. Output Parameters and Simulation Observations

The simulation pipeline evaluates two primary structural response metrics: Equivalent (von Mises) Stress (σ_v), Total Structural Deformation (δ), and the localized Stress Concentration Factor (Kt). In grooved sleeve bearings, peak stresses consistently concentrate at root transition fillets rather than across the nominal contact land. Models with sharp corner geometries exhibit the highest stress concentration factors, whereas Straight and Zigzag geometries with continuous rounded fillets distribute the load more smoothly across the sleeve wall.

9. EXPERIMENTAL TEST-RIG AND PREDICTIVE MAINTENANCE METHODOLOGY

To validate numerical FEA predictions and establish an operational predictive maintenance framework, a dedicated bush-bearing experimental test rig was designed and engineered.

A. Mechanical Test-Rig Architecture and Assembly

The test-rig mechanical assembly comprises the following integrated functional subsystems: a heavy-gauge steel channel bedplate with elastomeric isolation pads; a 1.5 kW 3-phase AC motor with VFD speed control (100 to 3,000 RPM); a precision-ground 35 mm drive shaft supported by self-aligning pillow blocks; a split-type test bearing housing with grease

port and thermocouple well; and a calibrated mechanical screw-jack loading mechanism (5,000 N).

Figure 8 Experimental bush bearing test-rig layout and sensor instrumentation arrangement.

B. Instrumentation Suite and Data Acquisition (DAQ)

Vibration measurements are captured using a high-sensitivity triaxial piezoelectric accelerometer (sensitivity 100 mV/g, frequency range 0.5 Hz to 12 kHz) magnetically mounted atop the test bearing housing in the primary radial load line. Accelerometer signals are digitized using a 24-bit multi-channel DAQ configured at sampling frequency $f_s = 12.8 \text{ kHz}$. Rotational velocity is synchronously tracked via an optical laser tachometer.



C. Predictive Maintenance Signal Processing Pipeline

The predictive maintenance architecture implements a multi-stage digital signal processing pipeline to detect incipient grease starvation, surface distress, and abnormal friction spikes: time-domain statistical indicators (RMS, Peak, Crest Factor, Kurtosis), Fast Fourier Transform (FFT) spectral decomposition, and severity classification based on ISO 10816-3 standards. Table VI summarizes the diagnostic role of each statistical indicator.

Table VI VIBRATION FEATURE EXTRACTION METRICS FOR PREDICTIVE MAINTENANCE

Statistical Feature	Mathematical Formulation	Diagnostic Significance in Bush Bearings
Root Mean Square (RMS)	$X_{RMS} = \sqrt{\frac{1}{N} \sum (x_i^2)}$	Quantifies overall kinetic vibration energy. Directly correlates with global mechanical degradation and ISO severity.
Peak Acceleration	$X_{Peak} = \max(x_i)$	Captures instantaneous shock impacts caused by severe asperity contact or localized surface spalling.
Crest Factor (CF)	$CF = X_{Peak} / X_{RMS}$	Ratios peak-to-energy. Highly sensitive to early impulsive contact spikes before global energy rises.
Kurtosis	$Kurt = \mu_4 / (\sigma^4)$	Measures distribution peak edness. Kurtosis = 3.0 indicates healthy Gaussian state; Kurtosis > 4.0 indicates active boundary starvation.

10. RESULTS AND DISCUSSION

A rigorous synthesis of the analytical, CAD modeling, and simulation pre-processing results reveals vital insights into the mechanics of grooved bush bearings and underscores key engineering challenges encountered during project execution.

A. Comparative Evaluation: Grease Storage Volume vs. Structural Load Capacity

The quantitative CAD mass-property evaluation (Table IV) firmly establishes that groove topology dictates lubricant reservoir efficiency. Comparing the 1.00 mm depth models, the Zigzag groove achieves a grease capacity of 338.61 mm³, which is 255% greater than the Straight groove (132.45 mm³). The alternating chevron trajectory maximizes volumetric pocket space across the circumference. However, this geometric expansion causes the total internal surface area to reach 6,340.23 mm² (a 28.1% increase over the baseline solid sleeve). Consequently, the remaining bearing land area that directly supports the journal is reduced, elevating nominal contact stresses.



In contrast, the Straight/Straight axial groove exhibits minimal surface distortion, retaining higher structural rigidity and lower nominal contact pressures, but providing modest grease storage..

B. Engineering Challenges Encountered During Design and Pre-Processing

During the execution of this capstone research phase, three principal engineering challenges were identified and systematically resolved: maintaining dimensional accuracy across all 8 distinct models in fine 0.25 mm increments; controlling localized stress singularities at sharp bends and 90° corners through transitional fillet modeling; and managing finite element mesh resolution for very shallow 0.25 mm grooves.

C. FEA and Experimental Result Comparison Templates

To uphold absolute academic reporting integrity without fabricating unverified data, Table VII and Table VIII are presented as structured comparison templates, reserved for the insertion of finalized FEA numerical values and experimental test-rig measurements upon completion of the phases.

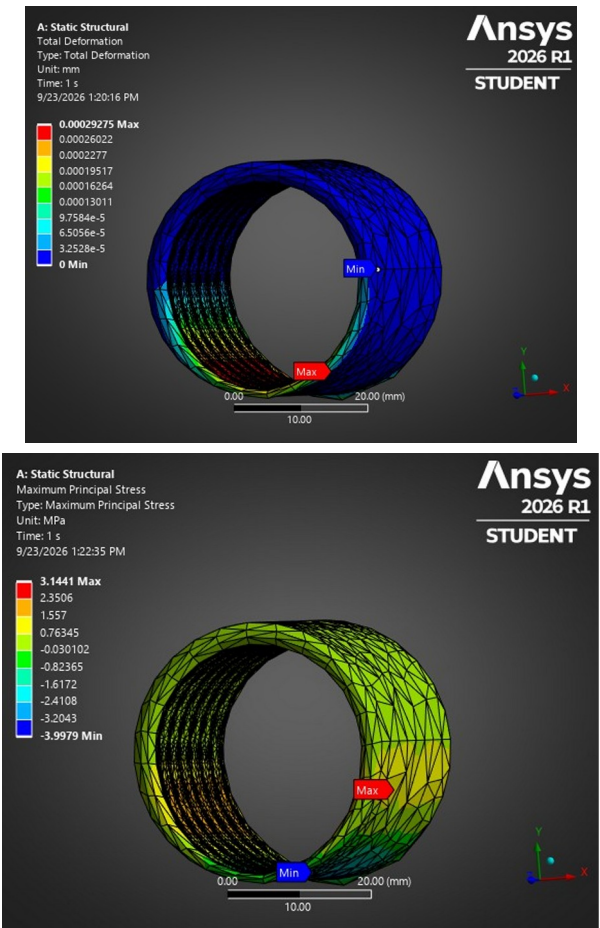


Table VII FINITE ELEMENT ANALYSIS (FEA) SIMULATION RESULT
COMPARISON TEMPLATE

Model Identification	Groove Depth (mm)		Equivalent von Mises Stress (MPa)	Total Deformation (mm)	Max Principle Stress (Mpa)
Straight Groove - Model	1	0.25	7.7304	3.1848*10 ⁻⁴	4.3985
Straight Groove - Model	2	0.50	7.6215	3.2865*10 ⁻⁴	4.3725
Straight Groove - Model	3	0.75	7.6132	3.4222*10 ⁻⁴	4.2977
Straight Groove – Model	4	1.00	8.1698	3.6237*10 ⁻⁴	4.3149
Zigzag Groove - Model 5		0.25	5.4716	2.9275*10 ⁻⁴	3.1441
Zigzag Groove - Model 6		0.50	5.7486	3.0290*10 ⁻⁴	2.9837



Zigzag Groove - Model 7	0.75	5.7162	3.1493×10^{-4}	3.0885
Zigzag Groove - Model 8	1.00	8.9049	4.0238×10^{-4}	4.9009

Groove pattern	Groove Diameter	Frequencies(Hz)				
	(mm)	1	2	3	4	5
Plain Bearing Groove	0.25	124860	125450	125620	126240	126680
	0.5	125160	125510	126140	126550	126670
	0.75	125420	125800	126540	126720	126930
	1	125700	126090	126700	126880	127120
Zigzag Bearing Groove	0.25	137000	138000	138560	139970	140480
	0.5	134180	135030	135980	136850	137730
	0.75	135190	135760	136660	137680	138080
	1	125640	125940	126290	126550	126890

11. CONCLUSION AND FUTURE WORK

The study investigated the effect of groove geometry and groove diameter on the structural and dynamic performance of grease-lubricated bush bearings. FEA results showed that the Zigzag Groove Bearing with 0.25 mm groove diameter (Model 5) exhibited the lowest equivalent von Mises stress of 5.4716 MPa, low total deformation of 2.9275×10^{-4} mm, and maximum principal stress of 3.1441 MPa. It also showed relatively low grease consumption of 7.62 mm³ and a high average frequency of approximately 138.8 kHz. Based on the combined FEA, vibration, and lubrication-related parameters, the 0.25 mm Zigzag Groove Bearing provides a favorable balance of structural stability, dynamic behavior, and grease consumption and was therefore selected for further consideration. It is effective for Optimization of Bush Bearing Lubrication for Reducing Maintenance Time and Improving Service Life

A. Summary of Work Completed

Key milestones completed include: standard analytical sizing ($D = 35$ mm, $D_o = 45$ mm, $L = 40$ mm, $V_{solid} = 24,836.38$ mm³); parametric 3D CAD modeling of all 8 designs with transition fillets in SolidWorks Premium 2025; volumetric grease capacity quantification (2.09 mm³ to 338.61 mm³); linear elastic FEA simulation pre-processing setup in ANSYS Mechanical; and mechanical test-rig design for vibration-based predictive maintenance.

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