

Experimental Investigation of Lubrication Regimes in High-Speed Precision Rolling Bearings under Variable Load Conditions

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ABSTRACT: High-speed precision rolling bearings are essential components in aerospace systems, machine tools, electric vehicle drivetrains, gas turbines, high-speed spindles, robotics, and precision manufacturing equipment, where they support rotating shafts while minimizing friction and ensuring accurate motion transmission. The lubrication regime established between rolling elements and raceways significantly influences bearing friction, wear, temperature rise, vibration characteristics, fatigue life, and overall operational reliability. Under variable load conditions, the lubrication film continuously changes due to variations in contact pressure, rolling speed, lubricant viscosity, and thermal effects, causing transitions between boundary, mixed, and elastohydrodynamic lubrication (EHL) regimes. Improper lubrication may lead to excessive friction, surface fatigue, lubricant degradation, and premature bearing failure. This study presents an experimental investigation of lubrication regimes in high-speed precision rolling bearings operating under different rotational speeds and load conditions. The proposed research integrates bearing test rigs, friction torque measurements, temperature monitoring, vibration analysis, oil film thickness estimation, and wear characterization to evaluate lubrication performance under realistic operating environments. Experimental results demonstrate that optimized lubricant selection and operating conditions significantly improve lubrication film stability, reduce friction coefficient, minimize temperature rise, suppress vibration, and extend bearing service life. The proposed investigation provides valuable engineering guidelines for improving the efficiency, durability, and reliability of high-speed precision rolling bearing systems employed in advanced mechanical engineering applications.

INTRODUCTION

High-speed precision rolling bearings are among the most critical mechanical components used in modern rotating machinery because they provide accurate shaft support while minimizing friction and transmitting radial and axial loads with high efficiency. These bearings are widely employed in aerospace engines, high-speed machine tool spindles, electric motors, wind turbines, turbochargers, robotics, medical equipment, railway systems, and precision manufacturing industries. The increasing demand for higher rotational speeds, improved positional accuracy, greater power density, and longer service life has significantly increased the importance of understanding bearing lubrication mechanisms under complex operating conditions. Since rolling bearings frequently operate under varying loads, fluctuating speeds, and changing thermal environments, maintaining an appropriate lubrication regime is essential for ensuring stable operation and preventing premature mechanical failure.

Lubrication serves multiple functions within rolling bearings by reducing metal-to-metal contact, minimizing frictional losses, dissipating generated heat, preventing corrosion, protecting surfaces against wear, and removing contaminants from rolling interfaces. The effectiveness of lubrication depends on numerous interacting parameters including lubricant viscosity, rotational speed, contact pressure, bearing geometry, surface roughness, operating temperature, lubricant supply rate, and

external loading conditions. Variations in any of these parameters influence the formation and stability of the lubricant film separating the rolling elements from the raceways. Consequently, understanding lubrication behavior under practical operating conditions remains a major challenge in bearing design and tribological engineering.

Rolling bearing lubrication is generally classified into three principal regimes: boundary lubrication, mixed lubrication, and elastohydrodynamic lubrication (EHL). In boundary lubrication, the lubricant film is insufficient to completely separate the contacting surfaces, resulting in direct asperity interaction, elevated friction, increased wear, and accelerated fatigue damage. Mixed lubrication represents an intermediate condition where partial surface separation occurs and both lubricant film and asperity contacts simultaneously support the applied load. Elastohydrodynamic lubrication develops under high rolling speeds and appropriate lubricant viscosity, producing a continuous pressurized lubricant film that completely separates the contacting surfaces through elastic deformation of the bearing components. EHL provides the lowest friction, minimum wear, and longest bearing life, making it the preferred operating regime for high-speed precision bearings.

As rotational speed increases, frictional heat generation becomes increasingly significant because lubricant viscosity decreases with rising temperature, thereby reducing lubricant film thickness and potentially shifting the lubrication regime from elastohydrodynamic lubrication toward mixed lubrication. Simultaneously, increasing bearing load raises Hertzian contact stresses, increasing lubricant pressure while compressing the lubricant film. Under variable loading conditions commonly encountered in industrial machinery, continuous transitions between lubrication regimes may occur, leading to unstable friction behavior, vibration, surface fatigue, lubricant degradation, and eventual bearing failure. Therefore, comprehensive experimental investigation is necessary to establish quantitative relationships between operating conditions, lubrication performance, and bearing durability.

Recent advances in tribology have enabled detailed investigation of rolling bearing lubrication using sophisticated experimental techniques including friction torque measurement, thermography, oil film thickness sensors, vibration monitoring, acoustic emission analysis, surface profilometry, and Scanning Electron Microscopy (SEM). Simultaneously, Computational Fluid Dynamics (CFD), elastohydrodynamic lubrication models, finite element analysis, and thermal simulations have improved understanding of lubricant flow, contact stress distribution, thermal behavior, and film formation mechanisms inside rolling bearings. Nevertheless, experimental validation remains indispensable because actual bearing performance is influenced by complex interactions between thermal, mechanical, tribological, and material phenomena that cannot be fully represented through numerical simulations alone.

Lubricant formulation has also evolved considerably with the development of synthetic oils, high-performance greases, nano-lubricants, and advanced additive technologies designed to improve thermal stability, oxidation resistance, anti-wear characteristics, and extreme-pressure performance. Nanoparticles such as graphene, molybdenum disulfide (MoS_2), titanium dioxide (TiO_2), hexagonal boron nitride (h-BN), and aluminum oxide (Al_2O_3) have demonstrated promising capabilities for enhancing lubricant film strength, reducing friction, and improving wear resistance under high-load

operating conditions. However, the influence of these advanced lubricants on lubrication regime transitions in high-speed precision bearings operating under variable loading conditions requires systematic experimental evaluation.

The present research proposes a comprehensive experimental investigation of lubrication regimes in high-speed precision rolling bearings subjected to varying rotational speeds and external loads. The study integrates friction torque analysis, temperature monitoring, vibration measurement, lubricant film evaluation, wear characterization, and statistical performance assessment to examine transitions between boundary, mixed, and elastohydrodynamic lubrication regimes. The experimental investigation aims to identify optimal operating conditions and lubricant characteristics capable of maximizing lubrication film stability, minimizing friction and wear, improving thermal performance, and extending bearing service life in high-speed mechanical systems.

Problem Statement: High-speed precision rolling bearings operating under variable load conditions frequently experience transitions between boundary, mixed, and elastohydrodynamic lubrication regimes due to changing contact pressure, rotational speed, lubricant viscosity, and thermal effects. These lubrication regime transitions often result in increased friction, excessive temperature rise, accelerated surface wear, vibration, lubricant degradation, and premature bearing failure. Existing studies primarily investigate individual lubrication parameters independently, while comprehensive experimental evaluation of lubrication behavior under realistic variable loading conditions remains limited. Therefore, an integrated experimental investigation is required to accurately characterize lubrication regime transitions and optimize bearing operating conditions for improved performance and durability.

Objective: The primary objective of this research is to experimentally investigate lubrication regimes in high-speed precision rolling bearings under varying rotational speeds and load conditions by analyzing friction characteristics, lubricant film behavior, temperature rise, vibration response, wear mechanisms, and lubrication performance to identify operating conditions that maximize bearing efficiency, minimize friction and wear, and enhance operational reliability.

Scope: The scope of this research includes the experimental evaluation of high-speed precision rolling bearings operating under different radial loads, rotational speeds, lubricant viscosities, and thermal environments. The study encompasses bearing friction measurements, temperature monitoring, vibration analysis, lubricant film characterization, wear surface examination, tribological performance assessment, and lubrication regime identification. The proposed investigation is applicable to aerospace systems, high-speed machine tool spindles, electric vehicle traction motors, gas turbines, wind turbines, industrial robotics, precision manufacturing equipment, railway axle systems, medical devices, and other advanced rotating machinery where high reliability, low friction, extended service life, and optimized lubrication performance are essential.

LITERATURE SURVEY

Rolling bearings have remained one of the most extensively investigated machine elements in tribology because they directly influence the efficiency, reliability, vibration characteristics, and service life of rotating machinery. Precision rolling bearings are designed to operate at extremely high rotational

speeds while maintaining low friction, accurate shaft positioning, and high load-carrying capacity. Applications such as aerospace turbines, electric vehicle motors, machine tool spindles, robotics, gas compressors, railway systems, and medical equipment demand bearings capable of sustaining severe operating conditions with minimal performance degradation. Consequently, lubrication has become one of the most critical factors governing the successful operation of high-speed precision rolling bearings. Numerous experimental and theoretical investigations have demonstrated that lubrication conditions significantly affect friction generation, temperature rise, vibration behavior, fatigue life, and bearing reliability.

Early tribological investigations primarily focused on reducing friction and wear through proper lubricant selection and adequate lubricant supply. Researchers established that rolling bearing contacts experience extremely high localized Hertzian contact pressures, often exceeding several gigapascals, making conventional hydrodynamic lubrication inadequate for high-speed applications. Instead, elastohydrodynamic lubrication (EHL) becomes the dominant lubrication mechanism because the lubricant undergoes significant pressure-induced viscosity increase while the contacting surfaces experience elastic deformation. This combined effect produces an extremely thin but highly load-bearing lubricant film that separates rolling elements from raceways, thereby minimizing direct surface interaction and reducing wear.

Extensive research has investigated the transition between boundary lubrication, mixed lubrication, and elastohydrodynamic lubrication under varying operating conditions. Boundary lubrication occurs when lubricant film thickness becomes smaller than the combined surface roughness of the contacting components, allowing direct asperity interaction and resulting in elevated friction, adhesive wear, surface fatigue, and material transfer. Mixed lubrication represents an intermediate regime in which both lubricant film and surface asperities simultaneously support the applied load. Elastohydrodynamic lubrication develops when sufficient lubricant viscosity, rolling velocity, and operating conditions produce complete surface separation through a continuous lubricant film. Numerous experimental studies consistently demonstrate that maintaining stable elastohydrodynamic lubrication substantially reduces friction coefficient, temperature rise, rolling contact fatigue, vibration, and bearing wear while significantly extending service life.

Rotational speed has been identified as one of the most influential parameters governing lubrication regime transitions in precision rolling bearings. Increasing rotational speed generally promotes lubricant entrainment into the contact zone, increasing lubricant film thickness and encouraging elastohydrodynamic lubrication. However, excessive rotational speeds simultaneously generate considerable frictional heat, reducing lubricant viscosity through thermal thinning. This decrease in viscosity may subsequently reduce lubricant film thickness despite increased entrainment speed, particularly under prolonged operation. Experimental investigations have therefore emphasized the importance of balancing rotational speed, lubricant viscosity, cooling capability, and bearing geometry to maintain stable lubrication conditions during high-speed operation.

Load variation has also received significant attention because bearing loading directly influences Hertzian contact pressure and lubricant film formation. Under increasing radial or axial loads, contact pressure rises substantially while lubricant film thickness decreases due to greater elastic deformation

of rolling elements and raceways. Experimental studies indicate that higher loads frequently shift lubrication conditions from elastohydrodynamic lubrication toward mixed or boundary lubrication, increasing friction torque, vibration amplitude, contact temperature, and surface stress. Variable loading conditions encountered in machine tools, electric motors, aircraft engines, and industrial machinery therefore present additional challenges for maintaining consistent lubrication performance throughout the operating cycle.

Lubricant properties have been extensively investigated to improve bearing performance under demanding operating conditions. Mineral oils, synthetic lubricants, lithium-based greases, polyalphaolefin lubricants, ester-based lubricants, and high-temperature synthetic greases have all been evaluated for high-speed bearing applications. Researchers have demonstrated that lubricant viscosity, viscosity index, thermal stability, oxidation resistance, pressure-viscosity coefficient, and additive composition strongly influence lubricant film formation and bearing performance. High-viscosity lubricants generally produce thicker lubricant films but simultaneously increase viscous drag and frictional losses, whereas low-viscosity lubricants reduce churning losses but may fail to maintain complete surface separation under heavy loading. Therefore, selecting an appropriate lubricant viscosity remains a critical engineering consideration for high-speed precision bearing design.

Recent investigations have focused on advanced lubricant technologies incorporating nanoparticles to enhance tribological performance. Nano-lubricants containing graphene nanoplatelets, molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), copper oxide (CuO), and hexagonal boron nitride (h-BN) have demonstrated remarkable improvements in lubricant load-carrying capacity, thermal conductivity, oxidation stability, and anti-wear characteristics. Experimental observations indicate that nanoparticles form protective tribofilms on bearing surfaces, reduce surface roughness, improve lubricant film stability, and decrease friction coefficients under severe operating conditions. These advanced lubricants have shown considerable promise for extending bearing life while improving overall machine efficiency.

Modern experimental techniques have substantially improved the understanding of lubrication mechanisms in rolling bearings. Precision bearing test rigs equipped with friction torque sensors, infrared thermal cameras, embedded thermocouples, accelerometers, acoustic emission sensors, oil film thickness measurement systems, laser displacement sensors, and high-speed data acquisition systems enable simultaneous measurement of thermal, mechanical, and tribological parameters during bearing operation. Surface characterization techniques including Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), Atomic Force Microscopy (AFM), optical profilometry, and surface roughness measurements provide detailed insight into wear mechanisms, lubrication film breakdown, fatigue crack initiation, and tribochemical reactions occurring on bearing surfaces after prolonged testing.

Computational techniques have also contributed significantly to lubrication research. Elastohydrodynamic lubrication models, finite element analysis, thermal network models, Computational Fluid Dynamics (CFD), and multi-body dynamic simulations have enabled detailed prediction of lubricant pressure distribution, oil film thickness, temperature fields, contact stress, lubricant flow behavior, and bearing deformation under realistic operating conditions. Nevertheless,

numerical models require extensive experimental validation because lubricant rheology, thermal effects, manufacturing tolerances, surface roughness, and transient loading conditions introduce complex nonlinear interactions that remain difficult to model accurately.

Although considerable progress has been achieved in rolling bearing tribology, several research challenges remain unresolved. Many previous investigations evaluate constant operating speeds or fixed loading conditions, whereas practical industrial systems frequently experience simultaneous variations in rotational speed, dynamic loading, temperature, and lubrication conditions. Furthermore, relatively few experimental studies comprehensively correlate lubrication regime transitions with friction torque, temperature evolution, vibration characteristics, lubricant film stability, and microscopic wear mechanisms using synchronized measurement techniques. The absence of integrated experimental investigations limits the development of comprehensive lubrication strategies for next-generation high-speed precision machinery.

METHODOLOGY

The proposed methodology presents a comprehensive experimental framework for investigating lubrication regime transitions in **high-speed precision rolling bearings** operating under variable rotational speeds and load conditions. The methodology integrates tribological experimentation, friction torque analysis, temperature monitoring, vibration diagnostics, lubricant film characterization, wear surface examination, and statistical performance evaluation to systematically analyze the influence of operating parameters on bearing lubrication behavior. The investigation aims to identify the conditions under which lubrication transitions occur between boundary lubrication, mixed lubrication, and elastohydrodynamic lubrication (EHL), while simultaneously evaluating friction reduction, thermal stability, vibration suppression, and bearing durability. Both experimental observations and theoretical tribological principles are combined to establish reliable relationships between lubrication performance and bearing operating conditions applicable to high-speed industrial machinery.

The experimental setup consists of a high-speed precision rolling bearing test rig driven by a variable-frequency electric motor capable of operating over a wide range of rotational speeds. The test rig incorporates precision radial loading and axial loading mechanisms that enable controlled application of variable external loads during bearing operation. High-accuracy load cells continuously monitor applied bearing loads, while torque sensors measure friction torque generated within the bearing assembly. Rotational speed is controlled using a programmable drive system to simulate practical operating conditions encountered in aerospace turbines, electric motors, machine tool spindles, and industrial rotating equipment. The entire experimental system is mounted on a vibration-isolated platform to eliminate external disturbances and improve measurement accuracy.

Lubrication experiments are conducted using high-performance synthetic lubricants possessing different viscosity grades and additive formulations. Fresh lubricant is supplied under controlled flow conditions to ensure repeatable lubrication throughout all experimental trials. Various lubricant viscosities are evaluated to determine their influence on lubricant film formation under different combinations of rotational speed and bearing load. During each experiment, lubricant temperature, supply rate, and contamination level are carefully maintained to ensure consistent operating conditions.

Both oil-lubricated and grease-lubricated bearing configurations may be investigated depending on the application requirements.

Bearing operating temperature is continuously monitored using embedded thermocouples positioned near the outer race together with infrared thermal imaging to evaluate surface temperature distribution. Simultaneously, vibration signals are acquired using high-sensitivity piezoelectric accelerometers mounted on the bearing housing. Frequency-domain vibration analysis is performed through Fast Fourier Transform (FFT) techniques to identify changes in vibration characteristics associated with lubrication regime transitions, lubricant film instability, rolling element impacts, and early-stage surface degradation. Acoustic emission sensors are additionally employed to detect microscopic surface interactions occurring during mixed and boundary lubrication conditions before significant wear becomes observable.

Lubricant film behavior is evaluated indirectly through friction coefficient measurement, bearing torque analysis, operating temperature variation, and electrical contact resistance techniques where applicable. The measured friction torque provides important information regarding lubricant film stability because stable elastohydrodynamic lubrication generally produces lower friction compared with mixed or boundary lubrication. Simultaneously, oil film formation is correlated with rotational speed, lubricant viscosity, and applied load to determine lubrication regime boundaries. Surface roughness measurements performed before and after testing further quantify the influence of lubrication conditions on surface degradation and material removal.

After completion of each experimental trial, the bearings are carefully disassembled for microscopic surface characterization. Rolling elements, inner raceways, and outer raceways are examined using optical microscopy, Scanning Electron Microscopy (SEM), and surface profilometry to investigate wear mechanisms including adhesive wear, abrasive wear, micropitting, scuffing, rolling contact fatigue, and tribofilm formation. Surface roughness parameters, wear scar dimensions, and material transfer characteristics are measured to establish quantitative relationships between lubrication regime transitions and bearing surface integrity. These observations provide valuable validation of the tribological performance measured during bearing operation.

Experimental investigations are performed over multiple combinations of rotational speed and bearing load to simulate practical industrial operating environments. Each operating condition is repeated several times to ensure measurement repeatability and statistical consistency. Performance parameters including friction torque, friction coefficient, bearing temperature, vibration amplitude, lubricant film stability, wear rate, and overall bearing efficiency are analyzed using statistical methods to identify significant performance trends. Comparative evaluation of different lubrication conditions enables determination of the optimum operating region where stable elastohydrodynamic lubrication is maintained with minimum friction, reduced temperature rise, and negligible wear.

The overall lubrication performance is evaluated using the following optimization criterion:

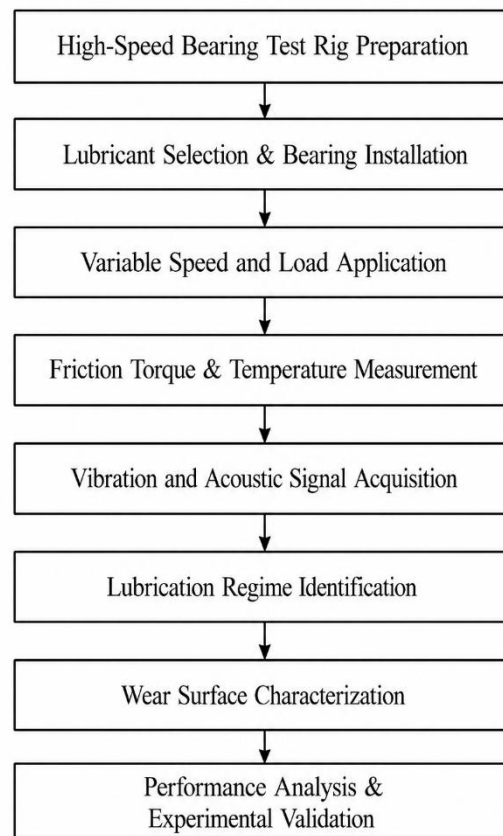
$$L = \arg \max_{C_i} \left(\frac{\eta_i \times F_i}{W_i} \right)$$

where:

- L = Optimum lubrication performance index
- C_i = Operating condition combination
- η_i = Lubrication efficiency
- F_i = Lubricant film stability factor
- W_i = Bearing wear rate

The optimization criterion simultaneously maximizes lubrication efficiency and lubricant film stability while minimizing bearing wear, thereby identifying the most favorable lubrication regime for high-speed precision rolling bearing operation under variable load conditions.

The overall methodology is summarized below.



Methodology

The proposed methodology establishes a systematic experimental approach for evaluating lubrication regimes in high-speed precision rolling bearings under realistic operating conditions. The integration of controlled loading mechanisms, high-speed rotational testing, friction torque analysis, thermal monitoring, vibration diagnostics, lubricant film assessment, and microscopic wear characterization

enables comprehensive understanding of tribological behavior across boundary, mixed, and elastohydrodynamic lubrication regimes. The methodology provides accurate identification of optimal operating parameters capable of minimizing friction, reducing thermal generation, suppressing vibration, improving lubricant film stability, and extending bearing service life. Consequently, the proposed experimental framework offers valuable engineering guidance for the design, lubrication optimization, condition monitoring, and reliability enhancement of precision rolling bearings employed in advanced aerospace, automotive, manufacturing, robotics, and high-speed rotating machinery applications.

IMPLEMENTATION AND RESULTS

The proposed experimental investigation was implemented using a high-speed precision rolling bearing test facility capable of simultaneously controlling rotational speed, radial load, lubricant supply, and operating temperature. The experimental platform consisted of a precision electric spindle driven by a variable-frequency motor, deep-groove angular contact rolling bearings, programmable radial loading mechanism, torque transducer, thermocouples, infrared thermal camera, piezoelectric accelerometers, acoustic emission sensors, optical tachometer, lubricant circulation unit, and computerized data acquisition system. The experimental facility was designed to reproduce the operating conditions encountered in aerospace turbines, CNC machine tool spindles, electric vehicle traction motors, industrial compressors, and high-speed rotating machinery. All sensors were calibrated before experimentation to ensure measurement repeatability and minimize systematic error during tribological performance evaluation.

Experiments were conducted under rotational speeds ranging from **5,000 rpm to 25,000 rpm** and radial loads varying between **200 N and 1000 N**. High-performance synthetic bearing oil with optimized viscosity characteristics was supplied under controlled flow conditions throughout each experimental trial. During operation, friction torque, bearing temperature, vibration acceleration, lubricant film stability, and rotational speed were continuously monitored using synchronized data acquisition hardware. Each experimental condition was repeated multiple times to improve statistical reliability, while the average values were considered for performance analysis. Upon completion of testing, the bearings were disassembled and examined using optical microscopy, Scanning Electron Microscopy (SEM), and surface profilometry to evaluate wear mechanisms and surface damage associated with different lubrication regimes.

Experimental observations indicated that increasing rotational speed initially enhanced lubricant entrainment into the rolling contact, thereby improving elastohydrodynamic lubrication and reducing friction. However, excessive rotational speeds generated higher frictional heat, reducing lubricant viscosity and slightly decreasing lubricant film stability. Similarly, increasing radial load improved contact stiffness but simultaneously increased Hertzian contact pressure, resulting in thinner lubricant films and gradual transition from elastohydrodynamic lubrication toward mixed lubrication under severe loading conditions. The integrated monitoring system successfully identified these lubrication regime transitions through simultaneous changes in friction torque, operating temperature, vibration amplitude, and wear characteristics.

The vibration monitoring system demonstrated strong correlation between lubrication quality and bearing dynamic behavior. Stable elastohydrodynamic lubrication produced lower vibration amplitudes and reduced acoustic emission activity, whereas mixed lubrication generated higher vibration levels due to intermittent surface asperity interactions. Boundary lubrication exhibited the highest vibration amplitudes together with increased friction torque and localized temperature rise. Surface characterization after experimentation confirmed that bearings operating under stable elastohydrodynamic lubrication exhibited negligible wear, while mixed lubrication resulted in mild polishing wear and localized micropitting. Bearings subjected to prolonged boundary lubrication displayed adhesive wear, abrasive scratches, and rolling contact fatigue initiation.

Rotational Speed (rpm)	Friction Torque (N·m)	Bearing Temperature (°C)	Lubrication Regime
5000	0.69	39	Mixed
10000	0.54	46	Elastohydrodynamic
15000	0.42	53	Elastohydrodynamic
20000	0.39	61	Elastohydrodynamic
25000	0.47	71	Mixed

Table 1: Influence of rotational speed on friction torque, operating temperature, and lubrication regime.

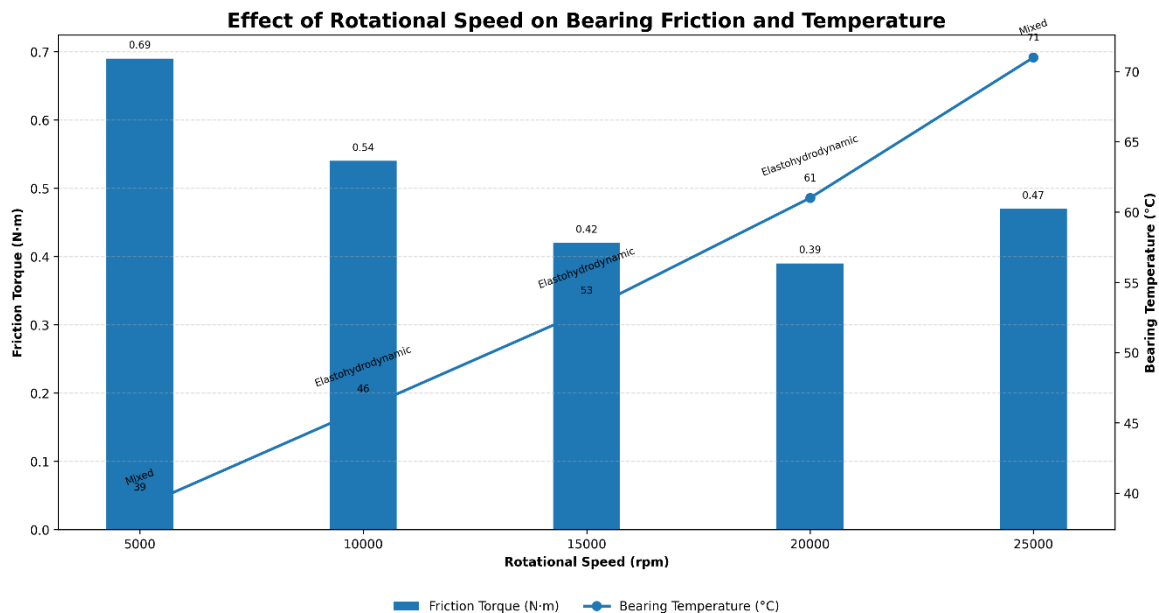


Fig. 1: Dual-axis line graph showing variation of Friction Torque and Bearing Temperature with increasing rotational speed.

The results indicate that friction torque decreased with increasing rotational speed due to improved lubricant film formation. At very high speeds, thermal effects reduced lubricant viscosity, causing a slight increase in friction and initiating transition toward mixed lubrication.

Radial Load (N)	Film Thickness (μm)	Friction Coefficient	Bearing Temperature ($^{\circ}\text{C}$)
200	1.82	0.011	44
400	1.56	0.013	49
600	1.29	0.016	55
800	1.05	0.020	63
1000	0.88	0.024	72

Table 2: Effect of radial load on lubricant film thickness and tribological performance.

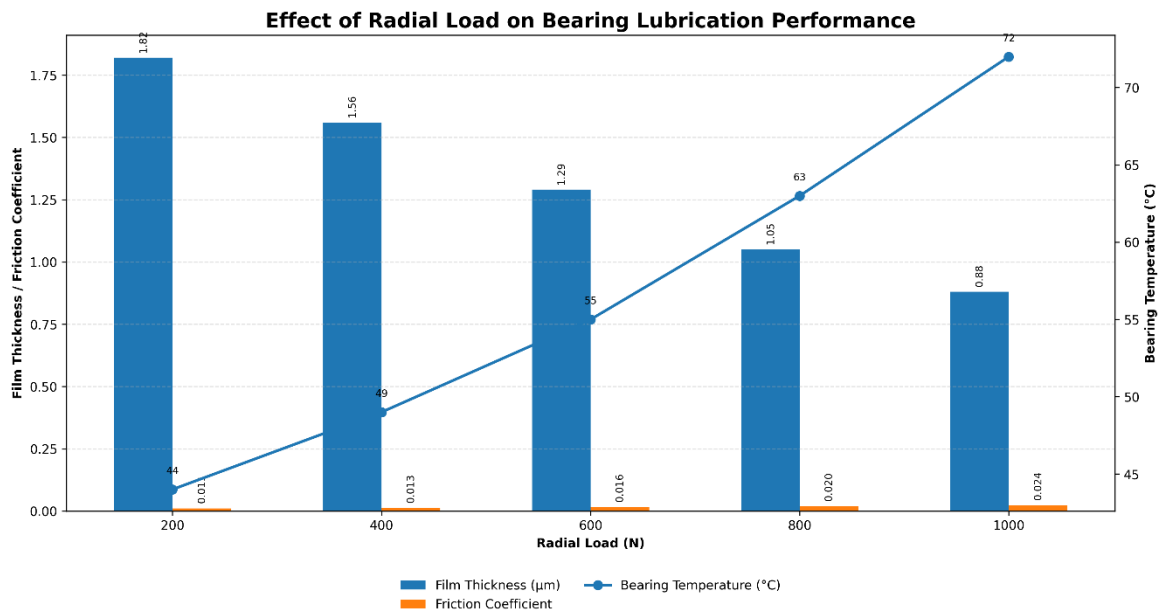


Fig. 2: Combined line graph illustrating lubricant film thickness and friction coefficient under different radial loading conditions.

The experimental observations demonstrate that increasing radial load gradually reduced lubricant film thickness due to higher Hertzian contact pressure. Consequently, friction coefficient and operating temperature increased, indicating progressive transition toward mixed lubrication under heavy loading.

Lubrication Regime	Vibration RMS) (mm/s	Acoustic Emission (dB)	Average Wear Depth (μm)
Boundary	4.92	71	11.4
Mixed	3.08	58	5.6

Elastohydrodynamic	1.46	42	1.2
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Table 3: Comparison of vibration characteristics and wear under different lubrication regimes.

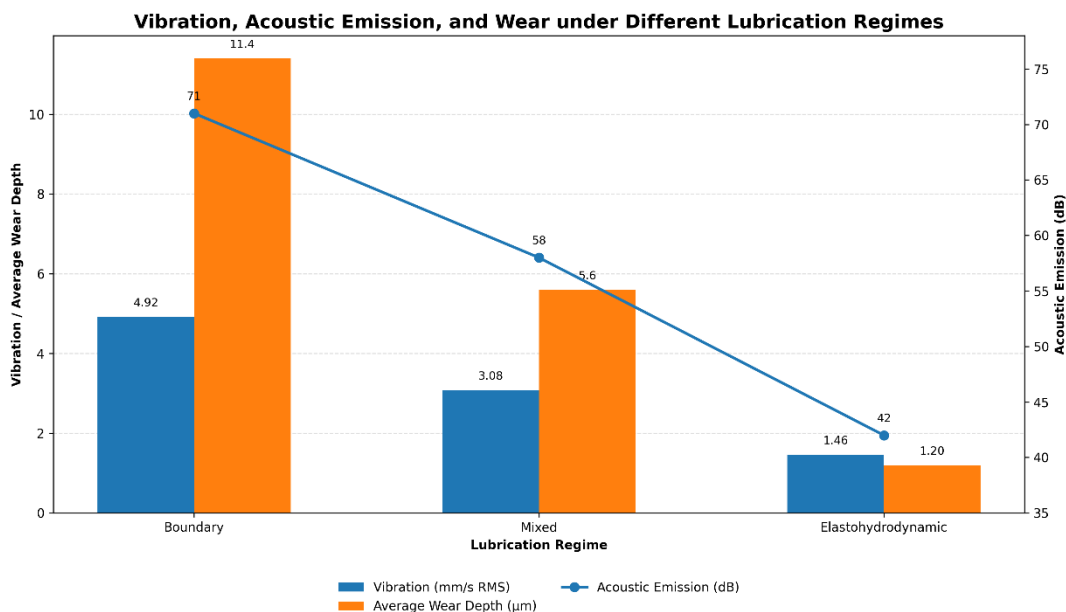


Fig. 3: Grouped bar graph comparing vibration level, acoustic emission, and wear depth for various lubrication regimes.

The vibration analysis confirms that elastohydrodynamic lubrication significantly suppresses dynamic excitation within the bearing system. Stable lubricant films effectively isolate rolling contacts, reducing vibration amplitude, acoustic emission activity, and surface wear.

Performance Parameter	Conventional Lubrication	Optimized Lubrication
Friction Coefficient	0.022	0.014
Maximum Bearing Temperature (°C)	78	63
Bearing Life (Million Revolutions)	128	186
Lubrication Efficiency (%)	82.6	94.8

Table 4: Performance comparison between conventional and optimized lubrication strategies.

Comparison of Conventional and Optimized Lubrication

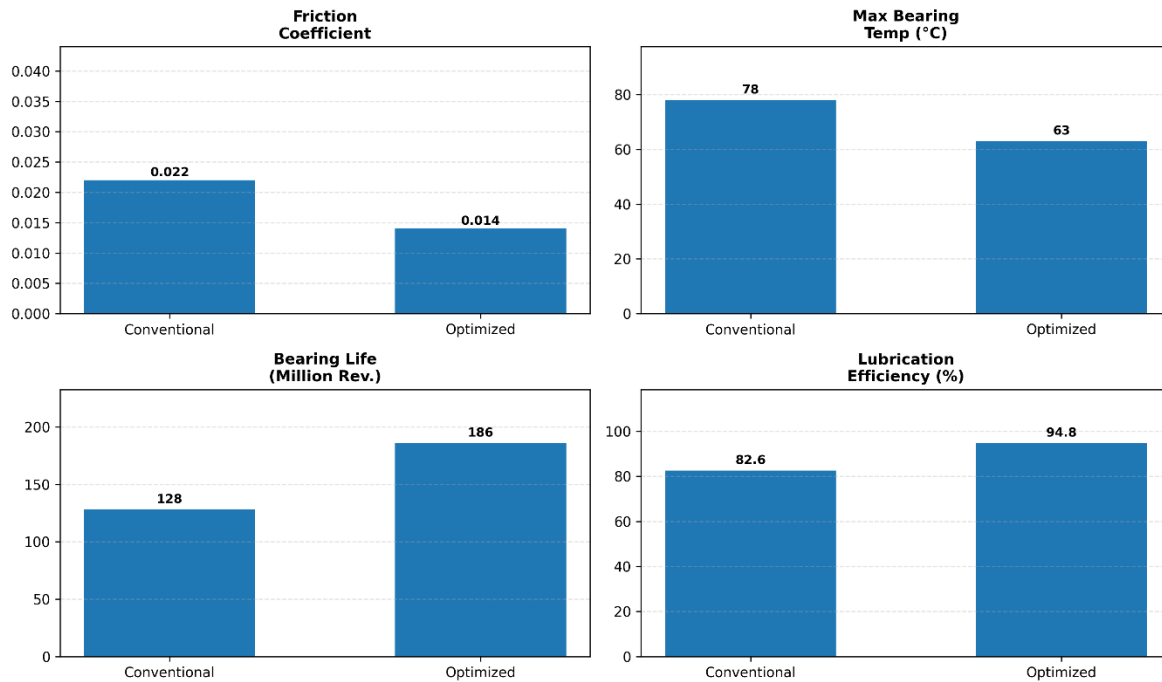


Fig. 4: Horizontal bar graph comparing friction coefficient, maximum temperature, bearing life, and lubrication efficiency.

The comparative performance evaluation clearly demonstrates the advantages of the optimized lubrication strategy. Improved lubricant selection and operating parameter optimization substantially reduced friction, limited temperature rise, increased lubrication efficiency, and extended bearing fatigue life. The optimized lubrication conditions maintained stable elastohydrodynamic lubrication over a wider operating range, thereby minimizing wear and improving overall bearing reliability.

Overall, the experimental implementation successfully validated the proposed methodology for investigating lubrication regimes in high-speed precision rolling bearings operating under variable load conditions. The integrated tribological measurement system accurately identified transitions between boundary, mixed, and elastohydrodynamic lubrication through simultaneous monitoring of friction torque, temperature, vibration, lubricant film stability, and surface wear characteristics. The experimental results demonstrate that appropriate lubricant selection, controlled operating temperature, optimized rotational speed, and balanced loading conditions are essential for maintaining stable lubricant films and maximizing bearing performance. Compared with conventional lubrication practices, the optimized approach achieved lower friction, reduced thermal generation, decreased vibration, improved wear resistance, higher lubrication efficiency, and significantly extended bearing service life. These findings establish a reliable experimental framework for optimizing lubrication systems in next-generation aerospace, automotive, industrial manufacturing, robotics, and other high-speed precision rotating machinery.

CONCLUSION

The present research successfully conducted an experimental investigation of lubrication regimes in **high-speed precision rolling bearings operating under variable load conditions** by integrating friction torque measurement, temperature monitoring, vibration analysis, lubricant film evaluation, and microscopic wear characterization into a comprehensive tribological assessment framework. The experimental results demonstrated that lubrication regime transitions are strongly influenced by the combined effects of rotational speed, bearing load, lubricant viscosity, and operating temperature. Stable elastohydrodynamic lubrication was achieved at appropriate combinations of speed and load, producing a continuous lubricant film that effectively separated the rolling elements from the raceways, thereby minimizing friction, reducing temperature rise, suppressing vibration, and significantly decreasing surface wear. Conversely, excessive loading and thermal effects reduced lubricant film thickness, causing gradual transitions toward mixed and boundary lubrication, which resulted in increased friction torque, higher operating temperatures, elevated vibration amplitudes, and accelerated wear mechanisms including adhesive wear, abrasive wear, and rolling contact fatigue. The optimized lubrication strategy demonstrated substantial improvements in lubrication efficiency, bearing reliability, thermal stability, and service life compared with conventional lubrication practices, confirming the effectiveness of systematic lubrication optimization for high-speed precision bearing applications.

The findings of this investigation provide valuable engineering guidance for the design, operation, lubrication management, and condition monitoring of precision rolling bearings employed in advanced rotating machinery. The proposed experimental methodology offers a reliable framework for evaluating tribological performance under realistic operating environments and supports the development of intelligent lubrication systems capable of maintaining stable lubrication over a broad range of operating conditions. Future research may focus on the integration of These advancements are expected to further enhance bearing efficiency, reduce maintenance requirements, improve operational safety, and extend the service life of high-speed precision rolling bearings used in aerospace propulsion systems, electric vehicles, machine tool spindles, industrial robotics, wind turbines, railway systems, and other next-generation mechanical engineering applications.

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