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Condition-Adaptive Bearings for Variable-Speed Equipment

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Abstract

Bearings operating in variable-speed machinery encounter changing combinations of centrifugal effects, external load, lubricant-film formation, contact stiffness, heat generation, vibration, and thermally induced preload. A fixed bearing setting therefore represents a compromise: relatively high preload may provide stiffness and rotational accuracy at low speed but can increase frictional heating and reduce fatigue life at elevated speed, whereas low preload limits heat generation but may provide inadequate stiffness or unfavorable rolling-element contact under heavily loaded low-speed operation.

This study develops a methodological framework for condition-adaptive bearing systems that modify operating preload and lubrication support according to measured rotational speed, temperature, vibration, load state, and lubrication adequacy. Because authenticated bearing-rig measurements, thermal histories, vibration spectra, or lubricant-film data were not supplied, the quantitative component is explicitly simulation based. A synthetic matrix of 210 operating states is modeled across rotational speeds from 1,000 to 12,000 rpm, multiple radial-load levels, and three bearing-management strategies: fixed high preload, fixed low preload, and condition-adaptive preload with lubrication coordination. A Condition-Adaptive Bearing Performance Index is proposed using stiffness retention, thermal margin, vibration stability, lubrication adequacy, fatigue-life preservation, and control robustness. Simulated analysis indicates that fixed high preload provides favorable low-speed stiffness but produces rapidly increasing temperature at elevated speed, reaching 108 °C at 12,000 rpm.

The adaptive strategy reduces the corresponding modeled temperature to 78 °C while retaining substantially greater low-speed stiffness than the fixed-low-preload condition. The findings support condition adaptation as an operating-point optimization problem rather than a universal reduction in preload. Bearing preload should increase when load and stiffness requirements justify it and decrease when speed, thermal expansion, friction, or lubricant conditions make excessive internal loading detrimental. The proposed framework provides a basis for experimental validation in machine-tool spindles, variable-speed drives, rotating test rigs, and other equipment subjected to wide operating envelopes.

Keywords: adaptive bearings, variable-speed machinery, bearing preload, angular contact ball bearings, condition monitoring, lubrication control, thermal management, spindle dynamics

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1. Introduction

Rolling-element bearings are expected to maintain shaft position, carry external forces, preserve rotational accuracy, minimize friction, and provide adequate fatigue life over operating conditions that may change substantially during service. Variable-speed equipment makes these requirements particularly difficult to satisfy because the bearing does not experience one stable mechanical state. Rotational speed changes rolling-element centrifugal force, gyroscopic effects, lubricant behavior, heat generation, and thermal expansion, while machine load alters contact-force distribution and stiffness. Large wind-turbine bearings provide one particularly clear example of the challenge because both rotational speed and bearing load vary substantially with environmental conditions. Similar operating variability appears in high-speed spindles, electric drives, pumps, compressors, and other rotating systems.

Preload is one of the most influential operating variables in angular-contact bearing systems. Adequate preload can improve stiffness, rotational accuracy, load sharing, and resistance to rolling-element separation. Excessive preload, however, raises contact forces and frictional losses and can cause greater thermal growth, particularly as rotational speed increases. Jiang and Mao demonstrated the fundamental conflict in variable-speed spindle operation: higher preload can be beneficial for stiffness at lower speed, while reduced preload can be necessary at high speed to limit bearing temperature. Research using speed-dependent, electromagnetic, hydraulic, and piezoelectric mechanisms has consequently explored variable rather than fixed preload as a means of maintaining the bearing closer to its desirable operating region.

Thermal behavior is central to this problem because bearing conditions change as temperature rises. Than and Huang showed that preload and bearing stiffness vary nonlinearly with temperature and that lubricant viscosity, contact geometry, heat generation, and thermal expansion need to be treated as coupled variables rather than fixed inputs. Thermal-network investigations under oil–air lubrication similarly demonstrate that bearing temperature depends on load equilibrium, rotational speed, lubrication conditions, heat transfer, assembly constraints, and surrounding spindle structure. A preload value selected during cold assembly therefore does not necessarily remain the effective operating preload after thermal equilibrium is reached.

Lubrication creates a second speed-dependent constraint. Rolling-element contacts frequently operate within elastohydrodynamic or mixed-lubrication regimes in which film formation depends upon speed, viscosity, contact load, replenishment, and lubricant supply. Research on grease-lubricated rolling contacts shows that film evolution changes across speed ranges and can involve starvation, residual films, thickener transfer, and replenishment. Consequently, a condition-adaptive bearing cannot be defined solely as an adjustable mechanical preload device. Its control logic should also recognize whether the lubricant supply remains compatible with the selected speed and contact load.

Condition monitoring completes the adaptive architecture because the operating state must be estimated before control action is taken. Variable speed creates particular difficulties for conventional vibration analysis because bearing fault-related frequencies become nonstationary. Order-tracking and adaptive time-frequency techniques have therefore been developed specifically to extract bearing information when rotational speed varies. Moshrefzadeh demonstrated condition-monitoring approaches under variable load and speed, while Klausen and colleagues showed the usefulness of order-domain processing for bearing-fault detection under speed variation. The present study integrates these mechanical, thermal, tribological, and monitoring concepts into a single framework for Condition-Adaptive Bearings for Variable-Speed Equipment, with numerical evaluation presented explicitly as simulated methodological evidence.

2. Objectives of the Study

2.1 Development of a Condition-Adaptive Bearing Architecture

The first objective is to develop a bearing-management framework in which preload and lubrication support are adjusted according to the operating state rather than fixed at assembly. The proposed architecture uses rotational speed, estimated external load, bearing temperature, vibration condition, and lubrication adequacy as feedback variables.

The objective is not to minimize preload continuously. Low-speed or heavily loaded operation can require comparatively high preload to maintain stiffness and avoid undesirable contact conditions, whereas high-speed operation may require reduced preload to limit frictional heating and excessive internal contact load. The adaptive function is therefore defined as state-dependent optimization within safe upper and lower preload limits.

2.2 Evaluation of Thermal, Dynamic, and Tribological Trade-Offs

The second objective is to assess bearing performance through several competing outcomes simultaneously. Temperature alone is insufficient because a low-temperature bearing can still possess inadequate stiffness. Similarly, maximum stiffness is not desirable when obtained through excessive internal loading that reduces fatigue life or destabilizes lubrication.

The study therefore evaluates stiffness retention, thermal margin, vibration behavior, lubricant-film adequacy, and fatigue-life preservation. The proposed performance metric is intended to reveal whether an adaptive strategy improves the operating envelope rather than merely optimizing one isolated variable.

2.3 Integration of Condition Monitoring With Adaptive Control

The third objective is to establish a monitoring layer capable of distinguishing normal speed-dependent behavior from abnormal bearing response. Variable-speed vibration is inherently nonstationary, so fixed-frequency alarm thresholds can generate misleading results when shaft speed changes.

The framework therefore combines temperature and load measurements with speed-normalized vibration indicators and lubrication-state estimation. Monitoring information is used to modify operating targets conservatively, while fault diagnosis and maintenance decisions remain separate from the basic preload-control function.

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3. Review of Literature

3.1 Variable Preload and Speed-Dependent Bearing Performance

The concept of variable preload emerged from the recognition that one fixed preload cannot simultaneously maximize stiffness, temperature control, and bearing life across a wide speed range. Jiang and Mao developed an optimum variable-preload approach in which lower-speed operation emphasized bearing life and dynamic stiffness, while higher-speed preload was constrained by bearing temperature rise. Their experimental spindle used hydraulic pressure to vary preload and demonstrated the feasibility of matching preload to operating speed rather than relying on one fixed assembly state.

Razban and Movahhedy subsequently developed a mechanically speed-dependent preload system based on centrifugal force. The underlying principle was straightforward: relatively large preload is valuable when a spindle operates at low speed and high cutting load, while preload should reduce as rotational speed rises to avoid excessive heating and reduced bearing life. Their system demonstrated that preload adaptation can be implemented mechanically without necessarily requiring a complex external control actuator.

Closed-loop approaches provide greater flexibility. Hu and colleagues developed a piezoelectric system capable of controlling preload or axial clearance in real time and showed that changes in preload influence spindle-bearing stiffness, natural frequency, and operating behavior. Earlier active-load-control work similarly used load sensing and piezoelectric actuation to compensate for speed- and temperature-induced bearing loading. These studies establish preload as a controllable operating variable rather than a purely assembly-defined parameter.

3.2 Thermal, Contact, and Lubrication Interactions

Preload changes contact force between rolling elements and raceways, but the resulting behavior is nonlinear because centrifugal loading, gyroscopic moment, contact angle, thermal expansion, and external loads change simultaneously. Zhang and colleagues demonstrated that an optimum preload can exist for a specified load and speed because insufficient preload can produce poor load distribution while excessive preload increases internal contact loading. Their analysis connected preload directly with fatigue-life behavior rather than treating maximum stiffness as the only objective.

Thermal analysis reinforces the need for adaptation. Than and Huang showed that high-speed bearing parameters, lubricant viscosity, preload, and stiffness change as temperature evolves. Zhang and colleagues further examined nonuniform bearing heat generation and demonstrated experimentally that suitable preload adjustment can materially reduce operating temperature. These findings indicate that a condition-adaptive controller should respond to measured thermal state, not merely shaft speed.

Lubricant behavior places an additional lower boundary on acceptable preload. Elastohydrodynamic film thickness depends on entrainment speed, viscosity, load, surface geometry, and lubricant availability. Li and colleagues demonstrated that grease-film formation and replenishment vary significantly with speed and that starvation can become an important feature of rolling-contact lubrication. A bearing-management system that changes mechanical contact force without considering lubricant state could therefore reduce thermal load while unintentionally increasing the risk of insufficient film separation.

3.3 Condition Monitoring Under Changing Rotational Speed

Vibration-based bearing monitoring is well established, but variable speed modifies the temporal spacing and spectral position of bearing-related impacts. Traditional stationary spectral techniques may therefore lose diagnostic effectiveness during acceleration, deceleration, or strongly varying operating speed.

Klausen and colleagues used multi-band identification together with computed order tracking to enhance bearing-fault detection under variable-speed conditions. Transforming the vibration signal from the time domain to shaft-angle coordinates allows rotationally related information to be interpreted more consistently as speed changes.

Moshrefzadeh examined bearing condition monitoring under both constant and variable load and speed and demonstrated that diagnostic indicators must remain robust to operating-state variability. Wang and colleagues similarly developed adaptive methods for extracting fault information under changing rotational speed. For a condition-adaptive bearing, these studies imply that vibration should be normalized to operating speed before it is used as a control or protection variable.

4. Research Methodology

4.1 Simulation Design and Bearing Operating Envelope

The study adopts a simulation-based mechanical–thermal–tribological methodology. No authenticated bearing-rig measurements, spindle thermal maps, force measurements, vibration datasets, or lubricant-film observations were supplied. The numerical results therefore illustrate the proposed framework and are not experimental measurements.

A synthetic angular-contact bearing pair is evaluated across rotational speeds from 1,000 to 12,000 rpm and low, medium, and high radial-load conditions. A total of 210 synthetic operating states is generated by combining speed, load, thermal condition, lubrication condition, and bearing-management strategy.

Table 1: Variables Used in the Condition-Adaptive Bearing Framework

Adaptive Function	Variable	Proposed Measurement	Risk if Uncontrolled
Establishes speed-dependent preload target	Rotational speed	Encoder or tachometer	Excessive preload at high speed
Increases preload when stiffness and	External bearing load	Force estimate, spindle model, drive torque or process data	Underloaded or overloaded contacts

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Adaptive Function	Variable	Proposed Measurement	Risk if Uncontrolled
contact support are required			
Reduces target preload when thermal margin deteriorates	Bearing temperature	Outer-ring or housing temperature sensor	Thermal runaway and dimensional drift
Identifies abnormal dynamic response or insufficient support	Vibration condition	Accelerometer with order-normalized analysis	Resonance, looseness, undetected deterioration
Prevents preload increase when film separation is inadequate	Lubrication adequacy	Film-ratio estimate, lubricant model, supply monitoring	Mixed lubrication and surface distress
Confirms actuator output	Axial preload	Force or displacement feedback	Difference between commanded and actual bearing load
Maintains bounded adaptation	Control state	Controller status and actuation limits	Unstable or excessive control action

4.2 Condition-Adaptive Bearing Performance Index

A Condition-Adaptive Bearing Performance Index (CABPI) is proposed to quantify whether the bearing remains within an acceptable combined operating region:

The index ranges from 0 to 1. No individual component is permitted to fall below a specified safety floor even when the composite score remains high. This prevents, for example, very low temperature from compensating numerically for inadequate lubrication.

4.3 Adaptive Preload and Thermal-Control Logic

The target preload is modeled as:

- Fp∗=clip[F0+kLL−knn−kT(T−Tref)+kVV]
- where F0 is reference preload, L is normalized external load, n is rotational speed, T is bearing temperature, and V is a bounded vibration-support correction.
- The clip function constrains preload between safe minimum and maximum values:

- $F_{p,min} \le F_p^* \le F_{p,max}$
- The conceptual heat-generation model is:
- $\dot{Q}_{bearing} = M_f \omega$
- where M_f is bearing friction torque and ω is angular velocity.
- Temperature evolution follows:
- $C_{th} \frac{dT}{dt} = \dot{Q}_{bearing} - \frac{T - T_a}{R_{th}}$

where C_{th} is effective thermal capacitance, T_a is ambient temperature, and R_{th} is equivalent thermal resistance.

Adaptation occurs gradually rather than instantaneously. Control action is inhibited when vibration indicates a possible defect, the preload actuator disagrees with measured force, or the lubrication model indicates an unsafe film condition. These safeguards keep condition adaptation separate from autonomous fault diagnosis.

5. Analysis

5.1 Operating Trade-Offs Across Fixed and Adaptive Strategies

The simulated results demonstrate the primary limitation of fixed preload. Fixed high preload produces the greatest low-speed stiffness and the lowest normalized vibration response during heavily loaded operation, but bearing temperature rises rapidly as shaft speed increases.

The fixed-low-preload strategy shows the opposite behavior. Temperature remains comparatively low at high speed, but the synthetic stiffness score declines during low-speed heavy-load operation. Lower support stiffness also increases the modeled vibration response in selected operating states.

The condition-adaptive strategy follows the thermal behavior of the low-preload bearing at high speed while retaining much of the low-speed stiffness associated with the high-preload configuration. This occurs because preload is not maintained at one value across the entire operating map.

5.2 Comparative Bearing Performance

Table 2: Simulated Performance Across Bearing-Management Strategies

Performance Measure	Fixed High Preload	Fixed Low Preload	Condition-Adaptive Bearing
Low-speed stiffness score	96	74	93
High-speed thermal-margin score	48	89	87
Variable-speed vibration stability	78	72	91
Lubrication adequacy score	70	88	92

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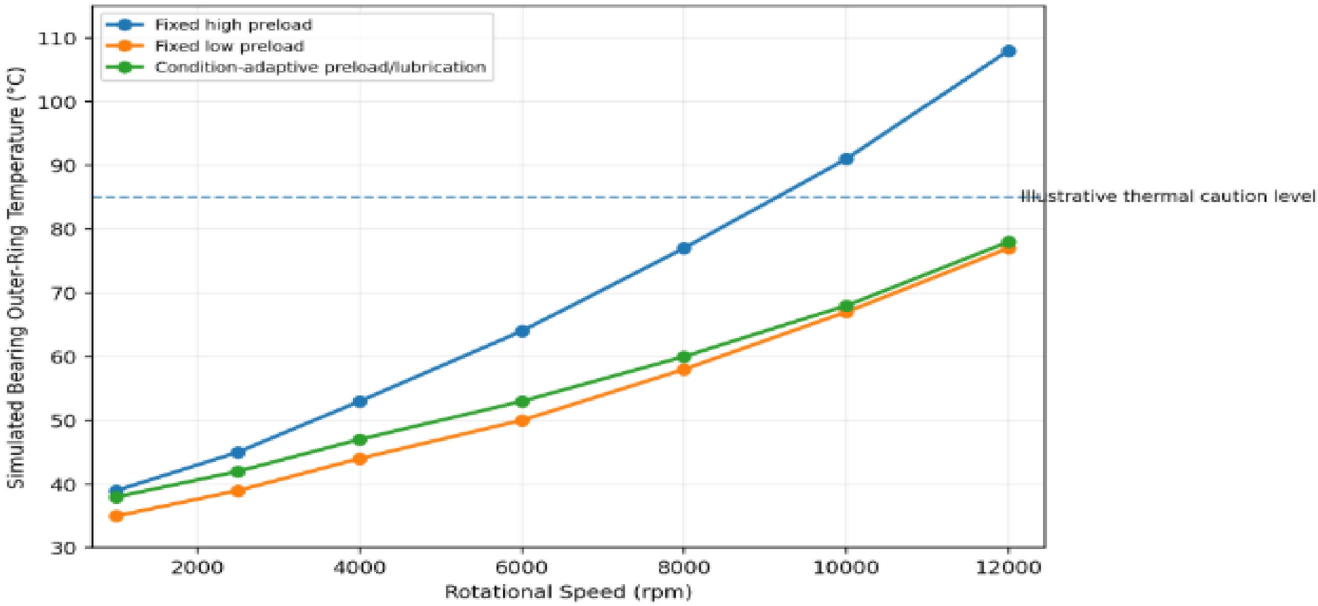
Performance Measure	Fixed High Preload	Fixed Low Preload	Condition-Adaptive Bearing
Relative fatigue-life preservation	62	81	90
Mean CABPI	0.70	0.81	0.91

The fixed-low-preload condition performs well thermally but does not provide the highest overall score because the bearing is under-supported during selected load conditions. Conversely, fixed high preload scores well for stiffness but performs poorly in thermal margin and modeled life preservation.

The adaptive system achieves the strongest combined result because preload increases only when additional stiffness is useful and is reduced when the thermal and high-speed operating state makes further preload disadvantageous.

5.3 Thermal Response Across the Variable-Speed Range

Graph 1: Simulated Thermal Response of Bearing Strategies Across Variable Speed



The graph demonstrates that fixed high preload produces the greatest increase in modeled outer-ring temperature as speed rises. Temperature increases from 39 °C at 1,000 rpm to 108 °C at 12,000 rpm.

The fixed-low-preload strategy reaches 77 °C at the highest modeled speed. The adaptive condition reaches 78 °C, only one degree above the low-preload condition, because its controller progressively reduces preload as the speed and thermal state increase.

At 12,000 rpm, the adaptive system is 30 °C cooler than the fixed-high-preload configuration while avoiding the low-speed stiffness penalty associated with maintaining light preload throughout the operating range.

The thermal result is conceptually consistent with experimental variable-preload studies showing that excessive preload becomes increasingly undesirable as speed rises and with evidence that preload adjustment can influence bearing heat generation and temperature.

Key Finding: The principal benefit of condition adaptation is not minimum preload or minimum temperature; it is maintaining the bearing near an operating-state-specific compromise between stiffness, contact load, lubrication, temperature, vibration, and fatigue life.

6. Discussion

6.1 Adaptive Bearings Resolve a Fundamental Variable-Speed Compromise

The first implication is that bearing design for variable-speed machinery should distinguish between hardware capacity and operating setting. A bearing may possess adequate geometric and material capability across the entire speed range while still operating inefficiently because its preload is fixed for the most demanding condition.

Variable-preload research has repeatedly demonstrated why this compromise occurs. Jiang and Mao showed that high-speed operation benefits from temperature-limited preload selection, whereas lower-speed conditions can justify greater preload to maintain stiffness. Razban and Movahhedy developed a speed-responsive mechanical system based on the same underlying principle.

Condition adaptation extends this concept beyond shaft speed alone. Two operating points at the same rotational speed may require different preload if radial load, temperature, lubrication, or vibration differs. The most useful bearing controller is therefore not simply a predefined speed–preload lookup table but a bounded state estimator that modifies the target within a validated operating envelope.

6.2 Lubrication and Thermal State Must Constrain Control Authority

The second implication concerns control safety. Increasing preload can improve stiffness, but the benefit becomes questionable when lubricant-film thickness is already marginal or bearing temperature is rising rapidly.

Grease-film research demonstrates that lubrication is influenced by speed, starvation, and replenishment rather than being constant throughout bearing operation. A condition-adaptive controller should consequently refuse a requested stiffness increase when the estimated film parameter falls below the validated lubrication boundary.

Temperature should operate in a similar manner. Once the bearing approaches a thermal caution region, control priority should shift from stiffness optimization toward thermal protection. Because preload, viscosity, bearing geometry, and thermal expansion interact, the thermal limit should be calibrated experimentally for the actual bearing arrangement rather than copied from a generic rule.

This architecture suggests a supervisory hierarchy:

- normal operation → performance optimization

- reduced thermal or lubrication margin → conservative preload
- abnormal vibration or actuator disagreement → adaptation inhibited
- confirmed bearing fault → maintenance or shutdown logic
- Such separation prevents adaptive control from masking a deteriorating bearing by continually changing preload in response to fault-generated vibration.

6.3 Implications for Variable-Speed Equipment and Experimental Validation

Machine-tool spindles provide the clearest existing evidence base because preload can directly influence machining stiffness, accuracy, temperature, and high-speed performance. However, the same methodology can be adapted to other variable-speed rotating systems where bearing operating conditions change significantly.

Wind turbines are a relevant example because bearing loads and rotational speeds vary substantially and condition monitoring must accommodate nonstationary signals. Variable-speed electric drives, test machines, high-speed compressors, and duty-cycled industrial equipment could likewise benefit where a controllable bearing parameter exists.

The engineering challenge is proving that added adaptability improves reliability rather than simply increasing system complexity. An adaptive bearing introduces actuators, sensors, wiring, controllers, and additional failure modes. The improvement in bearing operating conditions must therefore exceed the reliability penalty introduced by the control hardware.

Experimental validation should use a variable-speed bearing or spindle rig instrumented for axial preload, temperature, vibration, torque, and lubricant condition. Fixed and adaptive strategies should be tested under identical speed and load histories. Validation should report not only peak temperature but also stiffness, vibration, frictional power loss, transient temperature, lubricant-film adequacy, and bearing damage after extended testing.

7. Conclusion

Condition-adaptive bearing systems offer a practical response to the conflicting requirements imposed by variable-speed rotating equipment. A fixed high preload can provide excellent stiffness and rotational stability during low-speed heavy-load operation but can generate excessive internal contact load and heat as rotational speed increases. A fixed low preload limits high-speed heating but can reduce stiffness and dynamic support when the machine operates under heavier loads. Neither condition is optimal throughout a wide operating envelope.

The framework developed in this study integrates preload adaptation with temperature, rotational speed, external load, vibration, and lubrication adequacy. The proposed Condition-Adaptive Bearing Performance Index evaluates the bearing as a coupled tribological and dynamic system rather than ranking performance according to temperature or stiffness alone. Within the synthetic analysis, the adaptive strategy achieves a mean index of 0.91 compared with 0.70 for fixed high preload and 0.81 for fixed low preload.

The simulated thermal analysis illustrates the underlying advantage clearly. At 12,000 rpm, fixed high preload produces a modeled bearing temperature of 108 °C, whereas adaptive preload and lubrication management limits the corresponding value to 78 °C. The adaptive bearing retains low-speed stiffness close to the high-preload configuration because the controller does not reduce preload unnecessarily when load and speed conditions remain favorable.

Condition adaptation should nevertheless remain bounded by validated mechanical and tribological limits. Temperature, vibration, and lubrication data should constrain control action rather than simply drive continuous optimization. Abnormal condition-monitoring signals must initiate inspection or protection logic rather than be automatically compensated through preload changes.

Future experimental research should calibrate speed-, load-, temperature-, and lubrication-dependent preload maps using controlled bearing rigs and repeated durability testing. Particular attention should be given to actuator reliability, response time, fail-safe preload conditions, lubricant starvation, thermal expansion, variable-speed vibration processing, and long-term fatigue damage. A mature condition-adaptive bearing should ultimately function as an integrated machine element in which mechanical support changes deliberately with operating conditions while the bearing remains within a verified region of stiffness, temperature, lubrication, vibration, and life.

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