

Review

Advancements in Active Journal Bearings: A Critical Review of Performance, Control, and Emerging Prospects

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Abstract

The active or adjustable journal bearings are designed with unique mechanisms to reduce the rotor-bearing system lateral vibrations by adjusting their damping and stiffness. The article provides a comprehensive review of the literature, outlining the structure and findings of studies on active bearings. Over the years, various kinds of adjustable bearing designs have been developed with unique operational mechanisms. Such bearing designs include adjustable pad sectors, externally adjustable pads, active oil injection through pad openings, and flexible deformable sleeves. These modifications enhance the turbine shaft line's performance by increasing the system's overall stability. The detailed review in this paper highlights the characteristics of bearings, along with the key advantages, limitations, and potential offered by active control across different bearing types. The efficiency of any rotor system can be greatly enhanced by optimally selecting the adjustable bearing parameters. These adjustable bearings have demonstrated a unique capability to modify the hydrodynamic operation within the bearing clearances. Experimental studies and simulation approaches were also utilized to optimize bearing geometries, lubrication regimes, and control mechanisms. The use of advanced controllers like PID, LQG, and Deep Q networks further refined the stability. The concluding section of the article explores potential avenues for the future development of active bearings.

Keywords: active bearings; pad adjustments; active oil injection; stability; film pressures



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1. Introduction

Fluid film bearings are mechanical components engineered to facilitate low friction movement between solid surfaces and to support loads in mechanical systems. Bearings are essential in rotating mechanisms that significantly impact the machine's performance, longevity, and reliability. In fluid film bearings, the lubrication mechanism within bearing clearances is crucial for achieving optimal performance in heavy machinery with enhanced load-carrying capacity [1,2]. Alternate forms of bearing geometries were continuously developed over the years to enhance the performance envelope of a rotor bearing system. Bearings with offset half and elliptically shaped geometries, axially grooved bearing surfaces, tilting pad configurations and other bearing designs were widely employed in turbomachinery applications [3–5]. Journal bearing technology has evolved from traditional circular designs to two, three, and four-lobed configurations, which offer improved load-carrying capacity, lower attitude angles, and enhanced static

and dynamic performance. However, their fixed geometries prevent real-time adaptation, limiting their ability to respond to changing loads, speeds, or dynamic disturbances and reducing effectiveness in applications needing active vibration control [6,7]. These bearing geometries lack an essential characteristic of controlling the hydrodynamic operation in bearing clearances. In practice, fluid film bearings with controllable or adjustable features have the potential to overcome such limitations by modifying the dynamic properties of the rotor bearing system. The adjustable journal bearings are designed with unique mechanisms to reduce the rotor-bearing system lateral vibrations by adjusting their damping and stiffness. Over the years, various kinds of adjustable bearing designs have been developed with unique operational mechanisms [8,9]. Such type of bearing designs as illustrated in Figure 1, include adjustable pad sectors, externally adjustable pads, active oil injection through pad openings, and flexible deformable sleeves. These modifications enhance the turbine shaft line's performance by increasing the system's overall stability. The efficiency of any rotor system can be greatly enhanced by optimally selecting the adjustable bearing parameters. These adjustable bearings have demonstrated a unique capability to modify the hydrodynamic operation within the bearing clearances [10].

During operation, the variable features alter the bearing properties to make it safer to operate over a wider range of conditions. As shown in Figure 1a, tilting pad bearings with an active oil injection mechanism have been found to improve damping properties, which helps to reduce vibrations as the rotor reaches its resonant frequency [10–12]. In a variable geometry journal bearing shown in Figure 1b, the pad geometry can be adjusted independently based on the journal's position while the bearing is operational. An additional fluid film thickness was generated within the bearing clearance by displacing the movable bearing half [13,14]. By using such bearings, the speed range of the rotating machinery can be significantly increased by getting rid of the destabilizing effects of cross-coupling. By incorporating sensors and piezoactuators as shown in Figure 1c, the location of the bushing can also be actively varied based on the journal position to attain improved stability [15]. In externally adjustable bearing geometries shown in Figure 1d, the condition of the lubricant film can be actively modified through a controllable mechanism while the bearing is in operation. The controlled pad adjustments can effectively alter the radial clearance and oil film profile. Such variable bearing geometries may easily provide comprehensive control over the bearing action, boosting bearing performance to peak levels over a varied set of speed and load conditions [16–18].

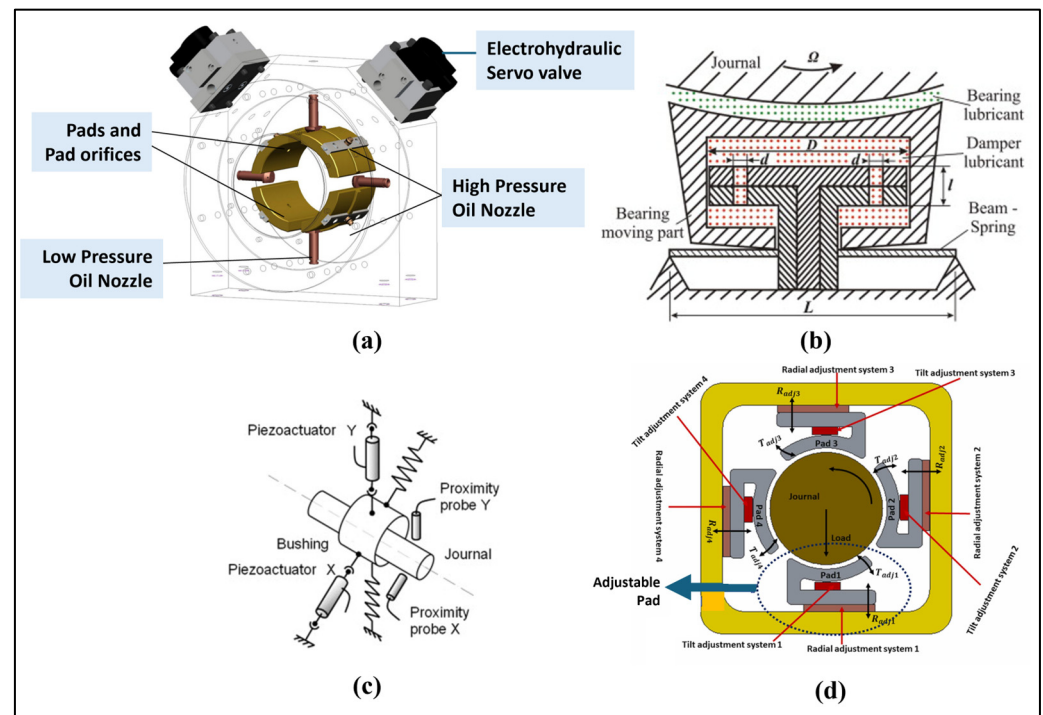


Figure 1. Controllable or adjustable journal bearing geometries (a) Tilting pad bearing with active lubrication [12] (b) Variable geometry bearing with deformable sleeve [13] (c) Bearing with piezo actuators [15] (d) Externally adjustable bearing geometry with square shaped casing for representational purpose [18,19].

2. Design and Testing of Active/Adjustable Journal Bearings

In this review, the detailed analysis of the operating principles and effectiveness of active or adjustable journal bearings is presented by categorizing studies into variable or controllable geometry journal bearings, actively lubricated journal bearings, and active vibration control of adjustable journal bearings which employ different types of actuators and control strategies. Controllable fluid film bearings can be actuated either by applying forces directly to the bearing sleeves or by regulating pressure or flow between the bearing surface and the rotating shaft, influencing different lubrication regimes. Application of forces on bearing sleeves includes additional components such as magnetic and piezo-electric pushers [20–22], hydraulic actuators [23–25], and mechanical actuators [26,27]. Whereas, flow regulation mechanism encompasses actively controlled bearing surface profiles or deformable bushes [28,29], active journal bearings with flexible sleeves [30,31], active lubricated bearings [32,33] among others. These mechanisms facilitate real-time modifications to film thickness, pressure distribution, and stiffness properties, thereby enhancing the overall efficiency of the rotor bearing system. The active control mechanism applied to a rotor bearing system in general is illustrated in Figure 2. During operation, the rotor will be continuously monitored using proximity probes installed at both ends of the bearings. The collected data will be transmitted to a control system, where dedicated algorithms will process it and generate control signals for the actuators. Using a lookup table based on predefined bearing geometry variations, the actuators will adjust the bearing geometry in real time, thereby modifying the rotor position to enhance system stability. Active lubrication techniques, including electrostatically or thermally controlled fluid supply, help prevent issues such as film rupture, cavitation, and excessive wear. Furthermore, the integration of smart materials and adaptive structures into fluid film bearings has strengthened their self-regulating abilities, enabling them to dynamically adjust to varying

loads and rotational speeds. Smart fluid film bearings employing NiTi shape memory alloy springs dynamically tune stiffness to suppress resonance [34,35], while those integrated with giant magnetostrictive actuators actively regulate film dynamics and suppress rotor vibration instabilities [36]. Figure 3 summarizes the research carried out over the years in the field of active and adjustable journal bearings. Approximately 150 articles published between 1980 and the present have been reviewed and classified into the sections outlined in this study.

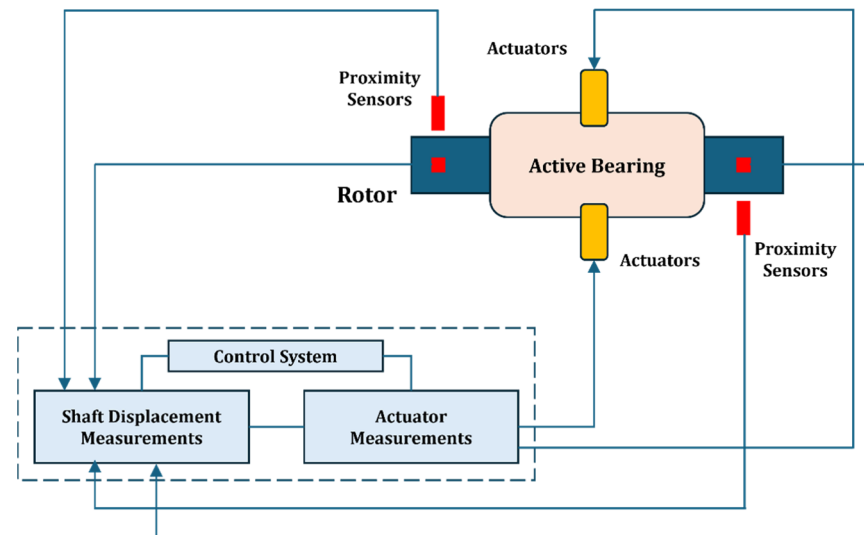


Figure 2. Rotor System with active control mechanism.

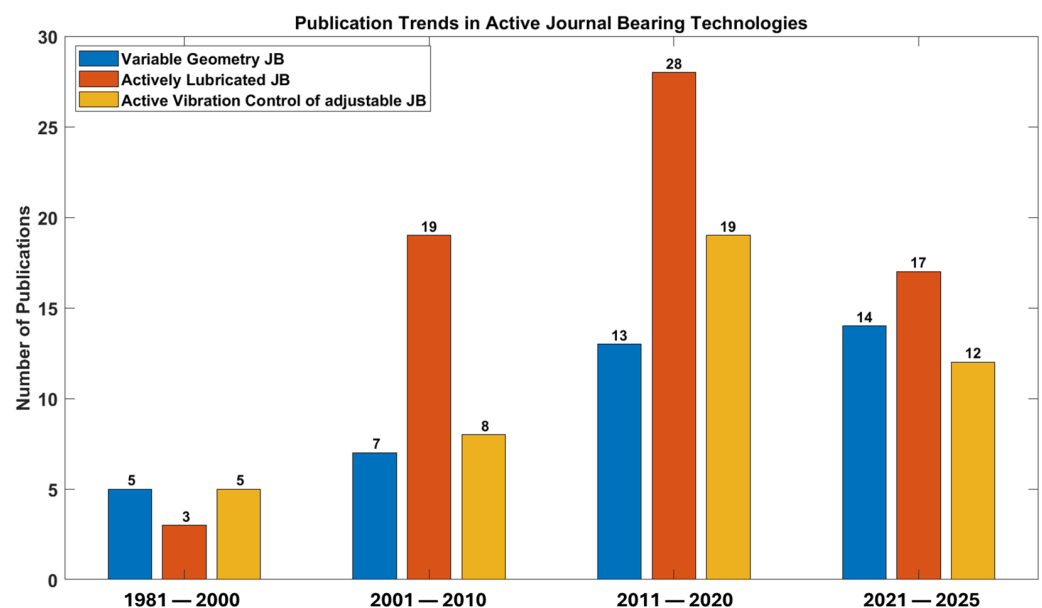


Figure 3. Representation of research work carried out in the field of active journal bearings.

2.1. Variable Geometry Journal Bearings

Over time, a variety of adjustable bearing designs have been developed, each featuring distinct operational mechanisms. Martin and Parkins [37] developed various movable bearing geometries to enhance static and dynamic performance of rotor bearing systems. The studies primarily focused on movable bearings with inverse orientations activated by tapered pins. Two studies explored alternative designs. One featured tiltable shaft segments combined with hydrostatic pockets on the shaft. These segments were connected to tapered pins to allow mechanical adjustments while the hydrostatic pockets influenced

hydrodynamic pressure generation. The other design focused on a pad-type bearing instead of a full bearing and included a novel feature that allows radial and tilt adjustments through mechanical spacers of varying thickness. A finite element (FE) model was built to study the effects of load and segment adjustments on bearing factors, considering non-uniform film thickness [38]. Rotor attitude angle, eccentricities, and dynamic coefficients for various load values and directions were determined. Improved dynamic coefficients with increased segment adjustments, maintaining zero eccentricity were observed under varied conditions. Martin [39] further conducted experimental tests on a variable geometry bearing with adjustable segments using a non-contact electromagnet loading mechanism. Rotor displacements were recorded in real time corresponding to changes in journal position and increasing load values. A significant improvement in the efficiency of adjustable bearings was noted including the suppression of instabilities by controlled variation of bearing dynamic coefficients during operation. In gearbox tests, adjustable bearings on a 190 mm pinion shaft at 1500 rpm reduced journal orbits by over 50% across all load conditions, including zero load. A feasibility study showed that adjustable hydrodynamic bearings in hydro-electric plants could save 14–23 GJ of energy and cut 0.9–1.5 tonnes of CO₂ emissions per day per unit [28]. Shenoy and Pai [29,40] further focused on investigating the static and dynamic characteristics of the proposed adjustable partial bearing subjected to varied L/D ratios, journal eccentricities and pad adjustment positions. Nine different adjustment configurations were considered in the variable geometry bearing. The pad profile can be varied in both radial and tilt directions using mechanical transmission or active means. The tilt profile of the pad produces a non-uniform film profile in the bearing clearance. The steady state analysis was extended to simulate the bearing behaviour under different flow regimes and offset load conditions. Fluid film pressures under negative tilt with radial adjustment were nearly 20 times higher than those with positive tilt, whereas zero adjustment produced pressures about 3–4 times greater than positive tilt. Under maximum eccentricity ratio and offset load conditions, negative adjustments delivered a dimensionless load capacity of 74.36, compared with just 2.56 for zero tilt and 0.63 for positive tilt adjustments, indicating superior steady-state performance with negative adjustments. Even, the influence of shaft misalignment on the performance parameters was also analyzed in detail [41]. The dynamic performance of the proposed bearing was further analyzed using a linearized solution technique for various pad adjustments and flow conditions [42].

Hariharan and Pai [19,43] further proposed a multi-pad adjustable bearing geometry with four pads/segments having features of radial and tilt motion. The adjustable mechanism in radial and tilt direction was applied symmetrically to all four pads in the bearing geometry. Altered film thickness relation for segment translation was developed and the pressure distribution and steady-state characteristics were computed using the finite difference method (FDM) and overrelaxation scheme. Increased film pressures and load capacity were observed with symmetrical inward radial and tilt of pads. Bearing geometry and pad configurations to influence the hydrodynamic performance are detailed in Figure 4. Higher film pressures resulted from reduced pad clearance and film thickness due to inward pad movement. An increase in eccentricity ratios led to lower friction and higher side flow from larger pressure gradients under load. Hariharan and Pai [44] also simulated the multi-pad adjustable bearing by positioning the bearing pads with load-between-pad (LBP) conditions. Bearing pressures formed under the LBP case are notably lower than pressures formed for bearings under LOP case. Peak hydrodynamic pressures (P_{max}) under negative pad adjustments were 20.33 and 24.57 times greater than those under positive adjustments for LOP and LBP orientations, respectively. Load capacity values were positively influenced with a notable increment observed for loads acting on pads compared to the LBP case.

Hariharan and Pai [45] further used a linear perturbation approach to compute the stability and dynamic properties of the proposed adjustable bearing. Simulated stiffness, damping parameters and stability factors noted improved stability margins under inward or negative adjustments. Maximum cross-stiffness occurred at eccentricity ratios of 0.5–0.7 for negative pad adjustments, whereas positive adjustments reached their peak between 1.23 and 1.27. However, pads positioned at radial inward and tilt outward conditions were found to have a notable influence on critical mass parameters under LBP conditions. Ganesha et al. [46,47] further conducted multi-objective optimization using the Taguchi approach and ANOVA to find the best pad adjustment combination for a multi-pad adjustable bearing. The adjustments of the multiple pads were considered asymmetrical in nature when provided with radial and tilt motions. Transformation techniques were used to formulate the film relation and grey relational analysis to find optimal adjustments. Simulation results indicated that radial pad adjustments have higher influence on attitude angle and tilted pad positions significantly influenced the side leakage. Pads under outward tilt and inward radial movement for $\epsilon = 0.4$ were identified as the optimal pad translation combination to attain enhanced steady state bearing performance. Experimental studies were later carried out by Pai and Parkins [48], on an adjustable bearing with four cantilevered variable bearing segments and measured their performance characteristics.

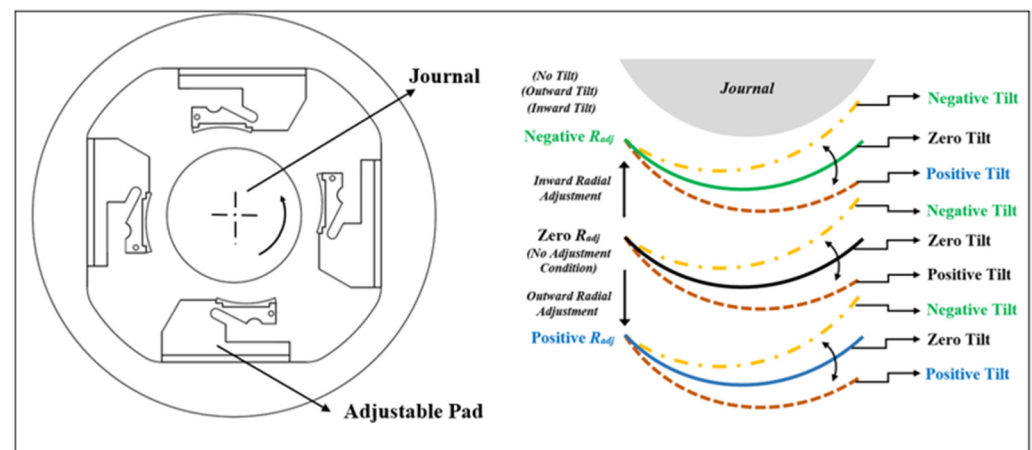


Figure 4. Different adjustment configurations in multi-pad bearing [19].

Krodkiewski et al. [49] modeled an active bearing with a hydraulic damper and a variable sleeve that adjusts during operation. As shown in Figure 5, the deformation of the sleeve was controlled by regulating the oil supply pressures in the underlying chamber, which in turn modified the oil film geometry and pressure distribution, enabling optimization of the film profile and improvement of the bearing's dynamic performance. Precise control of sleeve deformation and optimized hydraulic damper properties have greatly reduced self-exciting rotor vibrations during operation. As the bulk modulus increased from 10^6 to 10^8 Pa, the journal and sleeve vibrations reduced, and stability of the equilibrium position improved. Controlling the capillary diameter, inlet pressure, and keeping the chamber volume small were essential to account for oil film compressibility. Krodkiewski and Sun [50] further utilized the modeling approach to incorporate the active bearing and compute the dynamic properties of a multiple rotor bearing system using both linear and nonlinear models. Linearized model provides details of critical speeds and rotor instability. Stability analysis revealed that at a chamber pressure of 0.94 MPa, the journal entered a large limit cycle, whereas at 1.04 MPa it quickly settled into a stable equilibrium, with 1.0 MPa identified as the threshold of instability. While a nonlinear model details the limit cycles and subharmonic whirling motion of journal caused by

oil film [49,51]. The eigenvalue analysis predicted critical speeds of 28 Hz and 89 Hz, while the nonlinear simulation gave 28 Hz and 80 Hz, demonstrating strong consistency between the two approaches. Sun and Krodkiwski [31] also experimentally investigated the dynamic properties of the active journal bearing with deformable flexible sleeve. Static deformations of flexible sleeve part under different chamber pressure values were measured using eddy current transducers. Experimental tests and numerical simulations show that bearing stability is highly sensitive to hydraulic chamber pressure variations. Experimental verification confirms that mathematical models accurately predict system dynamics, crucial for designing and analyzing rotor-bearing systems. Table 1 presents the different types of variable geometry journal bearings along with a description of their respective principles of operation.

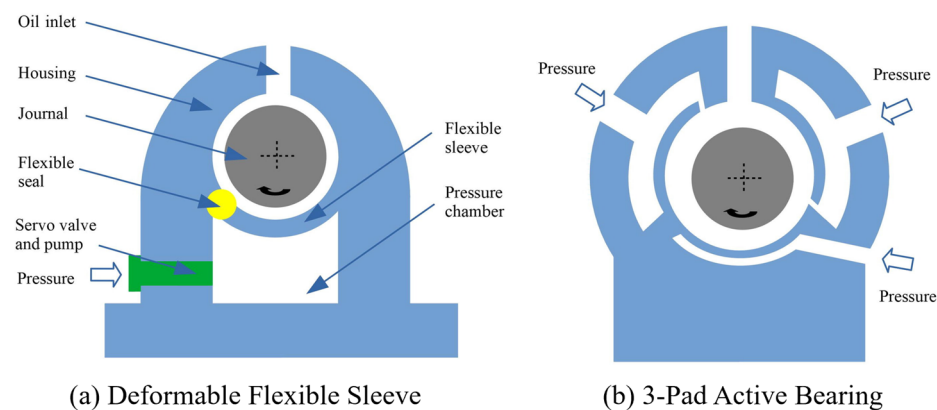


Figure 5. Variable geometry bearing [51].

Chasalevris and Dohnal [52] designed a journal bearing model with variable geometry to effectively vary the bearing dynamic properties and reduce rotor vibrations at resonance. The bearing is designed with a movable component that shifts when the fluid film forces exceed a certain threshold. This displacement creates an additional layer of lubricant within the pad clearances, effectively increasing the local fluid film thickness. As a result, the pressure distribution and stiffness of the bearing are modified, enhancing damping and reducing vibration amplitudes, especially near critical rotational speeds. The adjustability concept was designed to activate as the rotor operates under critical speed conditions. By setting the external stiffness to 7.5% of the nominal bearing stiffness and the external damping to 25% of the nominal damping capacity, the vibration response at resonance was significantly reduced. Using these self-adaptable bearings, the rotor disk exhibited approximately a 70% reduction in vertical and an 80% reduction in horizontal resonance amplitudes compared to conventional plain journal bearings. Chasalevris and Dohnal [53] further mounted the variable bearing geometry on a large scale rotor bearing system operated for a range of medium speeds. External spring and damping parts of variable bearing get self-activated as the fluid forces exceed a preload setting of external spring element. Variable bearing geometry design has been proven to be beneficial in reducing the maximum stresses that develop during resonance. External damper has negligible effect on damping proving that major portion gets dissipated in the fluid film itself. Chasalevris and Dohnal [13] built and installed the variable bearing prototype in an experimental bearing test setup. Various startup and shutdown conditions of the system were tested for different cases of variable bearing geometry settings. During start-up, the moving part of the VGJB experienced a maximum displacement of 3.35 times the bearing's radial clearance. Dynamic behaviour was measured, which highlights the bearing effectiveness in limiting the rotor vibrations at resonance. As shown in Figure 6, partial adjustable bearing prototypes were developed and tested for different operational conditions. At the critical speed, the disc's

response amplitude was reduced by nearly 50% vertically and 30% horizontally, while the journal's response increased by 10% in the vertical and 40% in the horizontal directions. Experimentally verified the effectiveness of variable bearing geometry on the suppression of rotor vibrations [14,53].

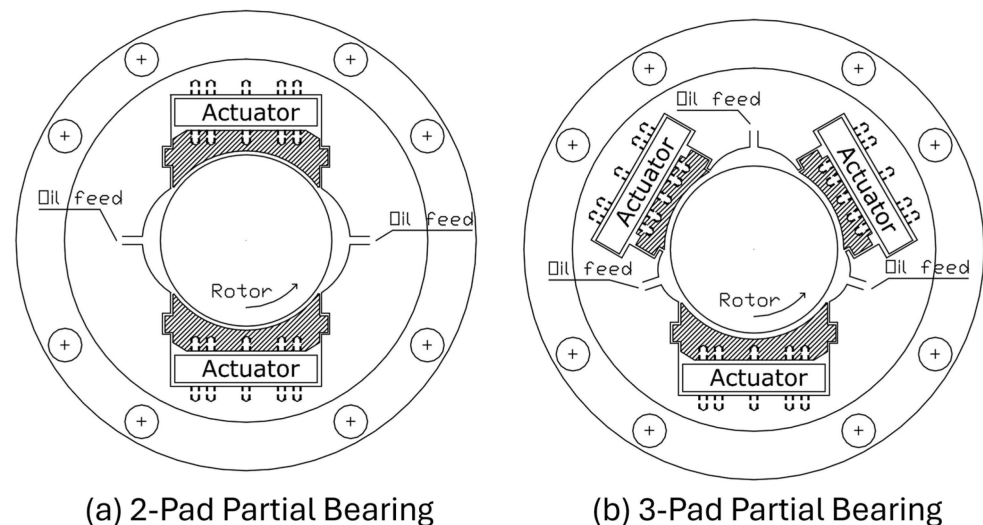


Figure 6. Variable Pad Bearings with actuator controls [14].

Table 1. Different types of variable geometry journal bearings and its principle of operation.

Authors	Year	Type of Study	Type of Adjustable Feature	Principle of Operation	Findings
Martin [8,39]	2001, 2004	Experimental	Flexible pad geometry and deformable shaft segments	Rotor dynamics tested using magnetic loading and adjustable fluid film bearings on a fixed shaft.	Displacement data confirmed that adjustable bearings increased stiffness via higher direct coefficients allowing precise repositioning, repeatable resets under 1.9 kN loads
Martin [28]	2011	Experimental	Shaft segment variation through external adjustments using Pins	Adjustable tilting-pad bearings allow active control of rotor position and film shape	Adjustable bearings achieved over 50% orbit suppression, lower oil temperatures, upto 20% torque reduction, and energy savings of 14–23 GJ/day
Shenoy and Pai [40,54]	2011, 2008	Numerical	Radial and tilt adjustable single pad geometry using external means	Single pad adjustable bearing under radial and tilt motion	Negative pad adjustments improved bearing performance by increasing stiffness and damping coefficients, raising stability margins, and suppressing half-frequency whirl
Hariharan and Pai [55–57]	2021, 2022	Numerical	Radial and tilt adjustable multiple pad geometries under symmetrical adjustments	Multi-pad adjustable geometry with symmetrical adjustments to control film profile under normal and misaligned conditions	Negative pad adjustments increased peak pressures (2.16 times), lowered attitude angles, enhanced load capacity, and improved the four-pad geometry's misalignment tolerance
Ganesha et al. [46,47]	2021	Numerical	Radial and tilt adjustable multiple pad geometries under asymmetrical adjustments	Adjustable bearings modify film thickness in real-time via flexible elements for precise journal control.	ANOVA results showed that radial adjustment had highest influence on attitude angle (62.8%), followed by eccentricity ratio (16.8%), while tilt adjustment contributed only 3.8%.

Table 1. Cont.

Authors	Year	Type of Study	Type of Adjustable Feature	Principle of Operation	Findings
Krodzkiwski and Sun [50,58]	2000, 1998	Numerical and Experimental	Flexible sleeve modification by chamber pressure variation	A pressure-controlled sleeve adjusts film shape to actively influence rotor dynamics.	Increasing bulk modulus from 10^6 to 10^8 Pa reduced journal and sleeve vibrations, while chamber pressure adjustment enhanced rotor stability and dynamic response
Chasalevris and Dohnal [14,59]	2016	Numerical and Experimental	Radially movable partial arc pads to alter film thickness	Adjustable partial-arc bearings enable real-time control of rotor position	Optimized external stiffness and damping enhanced rotor stability, suppressed resonance, and reduced vibration response by up to 80% compared to plain bearings.
Chasalevris and Guignier [60]	2019	Numerical	Quasi-statically displaceable bearing pads in partial-arc bearings	Bearing pads are shifted to adjust the journal center and bore profile, enhancing rotor-stator alignment, and stability.	Effectively reduced rotor-stator eccentricity and whirling, improved bearing loading, and suppressed oil-whirl/whip in 50 MW and 200 MW turbines
Zhang et al. [61,62]	2022, 2025	Numerical and Experimental	Adjustable single pad through Mechanical transmission mechanism	Radial clearance is actively adjusted to modulate oil film pressure and stabilize rotor dynamics.	Reducing clearance from 90% to 30% cut vibration amplitudes by upto 64% (horizontal) and ~61% (vertical) at 3600 rpm, while increasing clearance from 30% to 70% at 12,000 rpm eliminated oil whip and restored stable orbits
Shutin [63]	2023	Physics-based Modeling, Machine Learning, and Experimental	Adjustable bearing geometry using mechanical Adjustments	Combines physics-based wear modeling and machine learning to predict Remaining Useful Life (RUL) under active thermal control.	Ambient lubricant stabilization extended service life by only 3%, whereas sub-ambient cooling markedly improved viscosity and life
Zhang et al. [64,65]	2019, 2020	Numerical and Experimental	Elliptical ratio adjustment by varying tip clearance actively	Adjusting the elliptical ratio alters oil film stiffness and pressure to control rotor vibrations.	Suppresses forced, resonance, and self-excited vibrations, with suppression rates up to 60% depending on load and rotor type.
Jin et al. [66]	2019	Numerical	Passive Mechanical Adjustment in tilting pad bearing (TPB) via elastic pivot	Elastic pivot enables self-adaptive preload that adjusts film thickness and vibration response under varying conditions.	Elastic pivot TPB provided 18.7% and 27.0% higher minimum film thickness under static and unbalance conditions, but with 9–11 times greater vibration amplitudes than the rigid pivot TPB.

2.2. Actively Lubricated Journal Bearings

Controllable hydrodynamic lubrication regimes in journal bearings enabled by flow control mechanisms effectively regulate fluid film pressure and lubricant flow to reduce friction and enhance the thermal, static, and dynamic performance of sliding bearings [17]. To control vibrations in rotating machinery, Santos [23] developed and tested two configurations of active tilting pad bearings. In one design, the tilting pads were integrated with a hydraulic chamber system equipped with two control valves, allowing dynamic adjustment of the clearance between the rotor and pads by varying chamber pressure. This mechanism effectively modified the bearing's dynamic characteristics, reducing rotor vibration amplitudes near critical speeds and enhancing damping and overall bearing stability by directly influencing oil film kinematics. Santos and Russo [32] further explored this active lubrication concept theoretically, examining the feasibility of modifying hydrodynamic forces using electronically controlled lubricant injection through pad orifices. Simulations

indicate that radial oil injection at 3.5–4.5 bar boosts hydrodynamic forces by 52–89% and bearing load capacity, whereas 0 bar injection lowers both, with rotor speed (50–100 Hz) and Sommerfeld number (140–280) influencing pressure distribution and rotor equilibrium. In actively lubricated tilting pad bearings, Nicoletti and Santos [11] implemented both linear and nonlinear control systems to modify damping coefficients and adjust rotor equilibrium positions. Simulations were conducted to evaluate the effectiveness of these control strategies and to assess the unbalanced and frequency responses of the rotor-bearing system. The results from the unbalance response analysis were promising, showing that all control systems successfully regulated rotor vibrations. Additionally, the controllers effectively suppressed whirl instabilities across various operating conditions. Nicoletti and Santos [67] also conducted an in-depth study on the methodology used to calculate the gains of an active feedback control system designed for vibration attenuation in flexible rotors. Output-feedback control at bearing positions reduces flexible rotor vibration amplitudes by up to 50% at maximum displacement and approximately 25% at the bearings. Shaft displacements are kept within 4% of the bearing gap, while control signals remain within the linear range of active lubrication actuators. Santos et al. [68] later found that selecting an appropriate set of control gains can significantly extend the operational frequency range while also enhancing stability margins. Santos and Scalabrin [69] later conducted experimental investigations on the proposed active oil injection technique using a relatively lightweight rotor operating under various rotational speeds and bearing configurations. Nicoletti and Santos [70] extended frequency-domain experiments show that active lubrication with a proportional controller reduces resonance peak amplitudes of the rotor-tilting pad bearing system by up to 30% at 900–1800 rpm. The linearized coefficient approach overestimates resonance peaks by 40% because it neglects the frequency-dependent behavior of the active lubrication system, whereas the use of global dynamic oil film coefficients accurately accounts for these effects, yielding predictions that closely align with experimental results. Further enhancement in vibration suppression was achieved by implementing more advanced control strategies. Haugaard and Santos [71] later examined the dynamic behavior of bearings by incorporating pad deformation effects alongside active lubrication. Their initial studies focused on single, centrally located pad orifices, which were later expanded in [72] to include configurations with four and six orifices combined with a control system (refer Figure 7). The findings revealed that multi-orifice configurations enhance bearing performance, particularly when the orifices are positioned away from the pivot point under active elastohydrodynamic lubrication conditions.

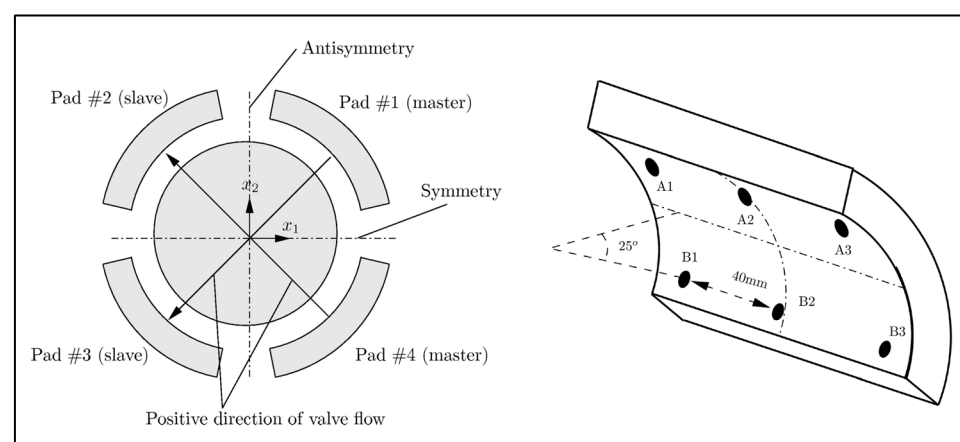


Figure 7. Representation of the pad bearing with valve orientation and orifice locations [72].

Varela and Santos [25] further investigated the controllable oil injection mechanism and its impact on the thermal and dynamic performance of a tilting pad bearing model. Their

theoretical analysis demonstrated significant benefits, including reduced oil temperatures and improved damping ratios, achieved by repositioning the oil inlet hole closer to the leading edge of the tilting pads. The actively lubricated tilting pad bearing proved effective in generating controllable forces across a broad range of operating frequencies. Building on this capability, Varela and Santos [73] explored the feasibility of utilizing these bearing models as calibrated shakers for identifying dynamic parameters in rotating machinery. Experimental and theoretical investigations show that the active tilting-pad bearing can produce measurable forces up to 200 Hz, with a phase lag of up to 45° influenced by the dynamics of the pipelines and pads. Maintaining high frequency response function coherence while preserving the system's original dynamic behavior necessitates precise tuning of the supply pressure and input signal amplitude. Varela and Santos [74] later validated their mathematical model using experimental data obtained from a test rig equipped with an actively controlled single-pad bearing configuration. The use of a proportional-derivative controller to generate control signals proved more effective in modulating bearing impedance compared to a fixed control system. Varela et al. [75] extended the active lubrication concept to a tilting pad bearing design incorporating a groove lubrication mechanism at the leading edges of the pads. This innovative design enabled adjustments to the rotor equilibrium positions based on control signals from both open- and closed-loop configurations.

Salazar and Santos [76] conducted experimental studies on an active bearing with control. They designed and implemented a proportional derivative (PD) controller to operate the active lubrication mechanism through multiple high frequency servo valves. An active lubrication mechanism using PD controller system was able to limit the vibrations of flexible rotors. Such vibration quenching near the journal equilibrium conditions highly depends on the operating conditions and desired orthogonal directions. Salazar and Santos [77] performed experimentation to analyze the dynamic behavior of active bearings under different kinds of lubrication control mechanisms-feedback, passive and hybrid. Hydraulic control system consisted of high-pressure supply units, servo valves, nozzle, displacement sensors and controllers. Minimal frequency dependence is observed in the stiffness coefficients identified under passive lubrication across the study range. Experiments show that hybrid and feedback-controlled lubrication can boost vertical stiffness by up to 30% above 50 Hz, reduce cross-coupling stiffness by an order of magnitude, and increase damping up to 10 times, significantly lowering rotor vibrations. Salazar and Santos [78] mathematically reviewed the modeling of a flexible rotor system with an active tilting pad bearing, assessing various lubrication mechanisms. Used a beam FE approach for the rotor and elasto thermohydrodynamic methods for bearing matrices. Under hybrid lubrication at 2000 rpm, supply pressures of 60 and 90 bar improved the system's dynamic performance over passive lubrication, particularly around the 210 Hz resonance, with higher pressures lowering vibrations by about 30%. Gong and Cao [79] also modeled an active hybrid tilting-pad bearing with an unsymmetrical flexible rotor and hydraulic system. Pressurized oil was used for active lubrication and applied a proportional-integral (PI) controller with pressure variation computed using the FDM. Using PI controller, the vibration magnitudes of rotor bearing system were notably limited especially in the ranges experiencing whirl instability. Active bearing system was found to be effective in improving the rotor stability and compensating small rotor misalignments. Table 2 presents the various active lubrication principles employed in journal bearings, highlighting the mechanisms through which each method enhances bearing performance.

Salazar and Santos [12] focused on synthesizing model-based Linear Quadratic Gaussian (LQG) optimum controllers for lubrication with feedback mechanism. Experimental tests compare system response with LQG and Proportional-Integral-Derivative (PID)

controllers. From experimental study, the LQG controller was found to perform well to describe the dynamics of rotor system. Rehman et al. [80] utilized PID and Integrator backstepping control approaches to enhance the active bearing performance with servo control. Dynamic behavior of bearing was analyzed for varied conditions of speed, lubricant viscosity, load, and radial clearances of bearing. The four-pocket hydrostatic journal bearing with active lubrication achieved up to 50% faster response and reduced vibration amplitudes by 40% compared to conventional bearings, while integrator backstepping control outperformed PID control, improving load rejection and stiffness by approximately 20–30%. Gong and Qin [81] designed a PID controller to regulate equilibrium locations in an unsymmetrical flexible rotor system with tilting pad bearings and active lubrication. Used FDM to determine pressure distribution on each tilting pad surface. An effective suppression of flexible rotor vibrations was noted with the implementation of PID controller. Active lubrication mechanism with injection of pressurized oil through orifices was found to broaden the operational speed range and limit whirl instability. Kazakov et al. [82] developed PI, adaptive PI, and Deep Q network (DQN) controllers to limit frictional torque in a conical bearing. Constructed the bearing to allow axial shaft motion for controlling clearance via oil supply, and built a MATLAB R2016b model including the rigid shaft, axial reaction coupling, and conical bearing modules. The DQN agent outperforms other controllers in minimizing friction torque, resulting in lower values and shorter adjustment times. Adaptive PI controller shows predicted pulse effects, while the DQN agent achieved greater trajectory amplitudes and minimized friction torque in the conical bearing. Rahmatabadi et al. [6,7] study examines 2, 3, and 4-lobe bearings using micropolar fluids, demonstrating that micropolarity improves static performance, with the enhancement becoming more pronounced at higher coupling numbers and varying with bearing configuration. Bearing orientation and preload notably affect performance, with fewer-lobed bearings more sensitive to orientation and preload influencing attitude angle and load capacity [83]. Couple stress lubricants in three-lobed bearings enhanced load capacity, decreased attitude angle, and strengthened dynamic stability, with higher couple stress raising critical mass and lowering whirl frequency [84,85].

Table 2. Various types of active lubrication principles utilized in journal bearings.

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Nicoletti and Santos [11,70,86]	2003, 2005, 2001	Numerical and Experimental	Pressurized oil injection—Pad orifices	Pressurized oil is injected via pad orifices to actively counteract rotor vibrations using control algorithms.	Active lubrication reduced vibration amplitudes by up to 30%, suppressed whirl, and shifted resonance peaks associated with the first rigid mode, thereby enhancing rotor stability.
Santos and Watanabe [87]	2004	Theoretical	Hydraulic pressure modulation	Active lubrication adjusts hydrostatic pressure to influence bearing dynamics.	Active lubrication with proportional–derivative (PD) controllers increases direct stiffness through proportional control and enhances direct damping through derivative control.
Hashimoto and Ochiai [88,89]	2009, 2010	Experimental and Theoretical	Passive supply control (via starved lubrication)	Reduced oil supply and orientation adjustment enhance stability by minimizing destabilizing forces.	Starved lubrication with optimized orientation ensured stability up to 4500 rpm, while controlled transition to flooded lubrication maintained stability at 5500–6500 rpm.

Table 2. Cont.

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Salazar and Santos [90,91]	2015, 2017	Experimental	Radial oil injection via servo-valves	Integral controller adjusts journal position through controlled oil injection to influence bearing dynamics.	Experiments demonstrated that with injection pressures up to 12 bar, the I-controller repositioned the journal within 24–27% of clearance and minimized tracking oscillations.
Uretta et al. [92,93]	2010, 2019	Experimental and Numerical	Magnetorheological (MR) fluid-based actuation	MR fluid viscosity is varied by magnetic field to modulate pressure and stiffness in a hybrid journal bearing.	50% gain in load and stiffness; effective at low frequencies, but too slow for high-speed response.
Bompos and Nikolakopoulos [94–97]	2011, 2014, 2016	Numerical and experimental	Magnetorheological actuation via a steady magnetic field applied to the lubricant	Magnetic particles in the MR fluid and nano MR fluid increases lubricant's viscosity and actively regulate the bearing's steady state and dynamic properties.	Under magnetic field, the MR fluid increased the attitude angle by 0.7–37.4%, raised friction coefficients by 0.2–28%, and reduced fluid flow by 0.16–5.5%.
Estupinan and Santos [98,99]	2012	Numerical simulation	Piezoelectric and mechanical oil injectors	Active lubrication combines hydrodynamic film with controllable radial oil injection to adapt fluid film pressure and thickness.	Controlled oil injection enhanced minimum film thickness by up to 90%, limited maximum film pressure to the injection pressure, and reduced both vibration amplitudes and cyclic power losses.
Wang et al. [100,101]	2017	Experimental	Electromagnetic actuation via external magnetic field	MR fluid lubricated smart bearings control stiffness and damping by varying fluid viscosity under a magnetic field.	Under 2.4 A magnetic field, the floating ring bearing outer stiffness, damping, and added-mass rose up to 283%, 1220%, and 463%, while inner coefficients stayed mostly constant
Zhan et al. [102]	2021	Experimental and Modeling	Active lubrication with hydrostatic pressure control	Segmented linear models simplify multiple-input multiple-output dynamics for small shaft motions in hydrostatic rotor bearing model.	Identified model accurately captures position-dependent dynamics, with validation fits of 91.35% (horizontal) and 87.44% (vertical), and impulse-response fits of 84.13% and 78.41%.
Li et al. [103]	2022	Experimental	Piezoelectric microjet	Piezoelectric actuator ejects microdroplets of lubricant on demand via rectangular wave excitation.	Enables long-term, precise, low-power active lubrication for space bearings with 0.012 μL /pulse accuracy and >20-year service life.
Kazakov et al. [82]	2022	Simulation	Control of supply pressures	Friction torque minimized by regulating axial shaft displacement via pressure control using PI, adaptive PI, and DQN agents.	DQN agent reduces friction torque by up to 25% and shortens adjustment times (0.3–0.48 s), outperforming PI and adaptive PI controllers in torque minimization
Jensen and Santos [104,105]	2022, 2023	Theoretical and Experimental	Radial oil injection	Model-based control using a digital twin of rotor-bearing-foundation system to attenuate vibrations	Up to 75% vibration reduction achieved at bending mode; strong integral action causes low-frequency amplification.

Table 2. Cont.

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Li et al. [106]	2022	Theoretical and Experimental	Servo valve-based hydrostatic pressure control	Servo valves adjust supply pressure to control journal position and minimize disturbances via active hydrostatic forces.	Machine Learning (ML)-based Model Predictive Controller (MPC) outperforms cut steady-state friction torque by ~10% and stabilize rotor displacements under 20 N impulses at 1500 rpm, outperforming PID and LQG controllers in tracking, disturbance rejection
van der Meer et al. [107]	2023	Experimental and Numerical	Magnetorheological (MR) fluid with localized magnetic field	Locally magnetized, low-viscosity MR fluid regulates bearing stiffness, damping, and load.	MR-lubricated bearings showed ~30% lower friction at 500 rpm and ~25% reduced transition speed using locally magnetized, low-particle MR fluid
Shutin and Kazakov [108] and Shutin [109]	2023, 2024	Numerical and Experimental	Hydraulic (active lubrication via servo valves)	Actively adjusts shaft position and pressure distribution to reduce shear stress in the lubricant film	Significant friction reduction (up to 6×) and 50% decrease in flow rate; 4-lobe geometry proved most effective.
Tomar et al. [110,111] and Sahu et al. [112,113]	2023, 2024	Numerical	MR and Electro-rheological (ER) fluid with textured surfaces	Bearing stiffness and stability are improved through the combined effects of smart fluid behavior and surface texturing.	Combined textured surfaces and MR fluid increase minimum film thickness by ~3.5%, stiffness by ~25.6%, and stability threshold speed by ~7%

2.3. Active Vibration Control of Adjustable Journal Bearings

Rotor instability is a major issue in high-speed rotors with sliding bearings, worsening as machine parameters increase. Active Vibration Control (AVC) using adjustable mechanisms entails dynamically altering system parameters like stiffness, damping, or geometry in real time to suppress unwanted vibrations. Glavatskih and Glund [114] studied tribotronics for active tribology, highlighting its role in smart machines. A Tribotronic system consists of four key components such as sensors, actuators, control system, and bearing geometry and typically uses these elements along with control algorithms to continuously adapt to varying operating conditions. Sensors monitor parameters like temperature, pressure, friction, and oil properties. The control unit processes signals using tribological algorithms to determine necessary actions, which actuators then implement. This autonomous system enables real-time self-adjustment of bearings for optimal performance. Actuators used in active vibration control systems are diverse, including piezoelectric stacks, shape memory alloy (SMA) springs, hydraulic cylinders, electromagnetic devices, and giant magnetostrictive materials, with each type chosen according to required bandwidth, force capacity, and precision. Similarly, bearing geometries vary widely, encompassing tilting-pad, wave, and multi-pad hydrodynamic designs, as well as gas-lubricated and shape-morphing configurations. Such variety in actuators and bearing designs enables tailored control strategies that enhance load capacity, vibration suppression, and rotor stability, showcasing the adaptability of modern tribotronic systems, as detailed in this section. Another example is a tilting-pad bearing whose pads adjust their inclination with changing operating conditions to maintain optimum load capacity. Such passive self-adjusting feature ensures excellent performance, and researchers have further improved it by developing actively controlled bearings (Figure 8). In these designs, the oil film geometry is actively adjusted by moving the pads radially using pressurized hydraulic cylinders, piezoelectric actuators, or mechanical devices. Such controlled changes enhance the bearing's dynamic performance

and load capacity. Such AVC control techniques improve system stability, minimize noise, and boosts performance in applications like precision engineering and rotating equipment.

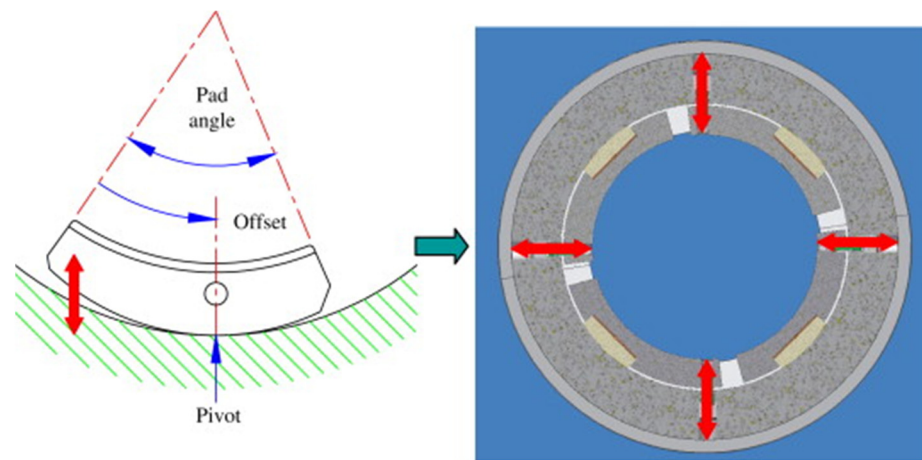


Figure 8. Actively adjustable tilting-pad journal bearing with arrows indicated for radial pad translation [114].

Tuma et al. [15] studied active vibration control of journal bearings using piezoactuators and developed a prototype. The controllable bearing incorporates a variable geometry adjusted by piezoactuators, which respond to proximity probe signals measuring vibrations to actively suppress them. Figure 9 shows the test rig with bearings for active vibration control. The test shaft was driven by a high-frequency motor through an elastic membrane coupling and monitored by eddy-current and capacitive proximity probes. Adding one or two discs varies the bearing load and rotor mass, but instability occurs at lower speeds with minimal load. Using low-viscosity VG10 oil, the rotor instability onset occurred at 4300 rpm, which was increased to 7300 rpm with active vibration control and delayed to approximately 6200 rpm at half the open-loop gain, significantly extending the stable operating speed range. The active vibration control system adjusts the bushing position based on the difference between the actual and desired shaft positions to suppress rotor instability [115,116]. The piezoelectric patch-based active vibration control effectively suppressed lower rotor vibration modes, reducing the unbalance response amplitude X_7 by 52.44% at the first critical speed in steady-state and by 54.9% at the first resonance during run-up. Wu et al. [117] proposed a model-based control for active tilting-pad bearings, which use linear actuators to adjust pad positions during operation. A nonlinear dynamic model was further developed, modeling hydrodynamic forces as a damper with spring. Experiments confirmed that active control improves performance over passive operation and achieves similar regulation to PID control with lower energy consumption. Kalligeros et al. [118] presents a hydraulically actuated, shape-morphing three-wave journal bearing designed to actively control vibrations and noise in rotating machinery. The bearing actively adjusts its internal geometry in real time through hydraulic pockets, allowing it to function as a wave bearing with tunable dynamic characteristics. CFD and FSI analyses confirmed that the inner ring deforms closely to the nominal wave profile with minimal effect on lubricant pressure, ensuring reliable operation. Dynamic simulations showed that the shape-morphing bearing can fully suppress shaft oscillations and induce anti-resonance, especially in low-stiffness systems.

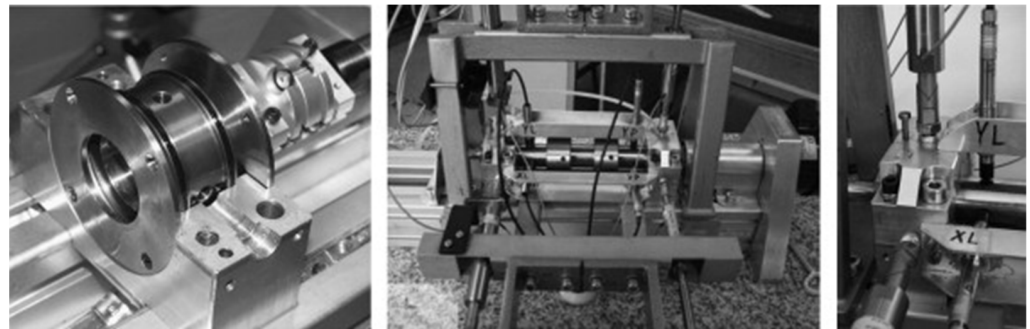


Figure 9. Test rig for active vibration control research [15].

Cai et al. [119] developed a dynamic model of active tilting-pad bearings with actuator forces for radial translation as control inputs and a feedback controller. Hydrodynamic film forces were modelled as a spring-damper by considering the dynamic coefficients as unknown, slow-varying parameters. They utilized adaptive control systems to help improve bearing behavior over conventional passive operation. Uncertainty in lubricant force coefficients were efficiently managed. The proposed control design framework also easily accounts for uncertainty in rotor/pad/pivot mass [120]. Wu and De Queiroz [117] further proposed an active bearing with feedback system to adjust pad angular velocity based on operating conditions. They designed a model-based controller using rotor position, pad velocities, and tilt angles to maintain zero rotor eccentricity. In the passive tilting-pad bearing, the journal reached a limit cycle with an eccentricity ratio of 0.15 after 1.6 s, whereas the proposed active control stabilized the journal concentrically within just 30 ms. Pad motion was found to possess sufficient bandwidth to control journal dynamics, as the pad mass is less than the rotor mass.

By incorporating stacked linear piezoactuators for bearing shell motion, Tuma et al. [121] focussed on stabilizing the high-speed rotors by reducing frictional losses and increasing the stable operational ranges and radial stiffness of the bearing. Active vibration control reduced the friction losses of the journal bearing at 7000 rpm by 27% and increased its effective radial stiffness by up to 36 times reaching approximately 100 kN/m, comparable to precision rolling bearings. Borges et al. [35,122] employed springs acting as actuator elements using shape memory alloy (SMA) material to establish an active control rotor bearing system. SMA spring elements were found to be capable enough to alter the natural frequency of the SMA bearing system through variation in temperatures of actuators using fuzzy control method. SMA spring-based control reduced the rotor-bearing displacement amplitude by about 60–62% at the first natural frequency. The proposed control technique was utilized to overcome the heating and cooling issues rising in SMA bearing. SMA springs took roughly 25 s to heat and 29 s to cool between 30 °C and 70 °C, setting the system's stiffness adjustment response time during ramps. To limit the rotor vibrations, the effectiveness of flexible patch piezo actuators bonded to a shaft surface was also tested, which generated bending moments to counteract the rotor deformation [115]. Recently, Jungblut et al. [123] presented an alternate design of piezoelectric active bearing with rotating actuation elements. A model-free active vibration control system was developed based on the transform domain least mean squares algorithm, where delay compensation was considered by an additional efficient algorithm. Experiments were conducted to establish the functionality of the piezoelectric bearing through manual feedback and passive rotor run-up conditions. Similar concept of efficient vibration attenuation in tilting pad bearings was implemented using an active pad bearing mechanism. The active bearing with three rotating piezo actuators cut the first forward whirl vibrations by around 50–55%, although the third-order vibrations rose as a result of actuator hysteresis.

Increasing the number of actuators to five cut the third-order vibration amplitude by approximately 67%, demonstrating that vibration excitation diminishes with more actuators. Electromagnetic actuators fitted on the tilting pads control the angular motion of the pads, which thereby modifies the dynamic behavior of the rotor bearing system [33,118]. Table 3 provides an overview of the different types of piezo actuator-driven adjustable journal bearings, detailing the underlying principles of their operation.

Zhang and Xu [124] investigated the bearing performance with variable clearances and under laminar and turbulent flow conditions. Oil film pressures were developed only in the lower bearing bush for 80% radial clearance and a notable improvement in lubrication near upper bearing bush was noted as the clearance was further reduced to 70%. Adjustable bearing exhibited improved lubrication behavior under laminar regime than noted under turbulent flow. Stable velocity ranges determined were found to be unstable under turbulent flow regimes. System stability was directly influenced by radial clearance, with a reduction in clearance leading to improved stability. Marcinkevicius [125] studied hydrodynamic tilting-pad journal bearings with automatic control. A three-pad bearing was analyzed, revealing challenges in maintaining small clearance at high rotation speeds. Without control, dry friction at startup causes rapid wear and high motor load. Increasing the neck diameter from 14 mm to 16 mm lowered the measurement displacement, resulting in approximately a 21% reduction in sensitivity. The combined stiffness of the pin head and neck reached $705 \text{ N}/\mu\text{m}$, restricting elastic deflection under a 26,722 N load to $37.9 \mu\text{m}$, while automatic clearance control could nullify the initial interference force, ensuring smooth journal rotation. The proposed automatic system regulates clearance by measuring and adjusting pad load, improving bearing performance (Figure 10) [51].

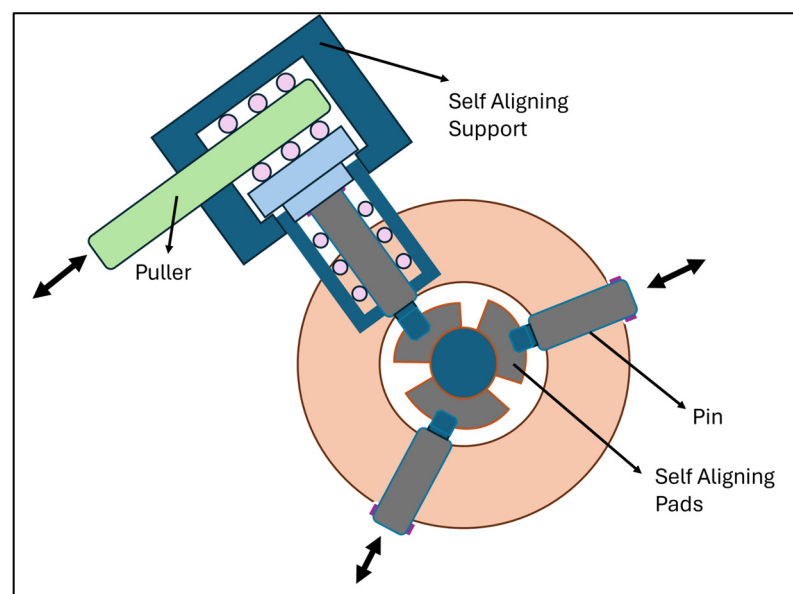


Figure 10. Automatically-controlled bearing [51].

Viveros and Nicoletti [126] analyzed lateral vibration attenuation in shafts supported by tilting-pad journal bearings with embedded electromagnetic actuators. These bearings combine hydrodynamic load capacity with electromagnetic actuation, allowing smaller actuators than magnetic bearings. Numerical and experimental analysis with PD control showed vibration reductions of 11% at 600 rpm and 18% at 1100 rpm, aligning with the mathematical model. The bearing's control capacity is competitive with other active bearings. The proof of concept test setup utilized to test the active bearing with electromagnetic actuators is represented in Figure 11. Experimental results show that rotor motion can

be controlled by sending reference signals to the bearing actuators, allowing harmonic motion under various conditions and frequencies in open-loop tests [118,127]. Deckler et al. [22] studied the simulation and control of an active tilting-pad journal bearing with a feedback system to regulate shaft orbit. Linear actuators behind each pad enable real-time radial motion. Control design uses state-variable feedback with optimized gains based on a quadratic performance index. A linear spring-mass model, incorporating pad stiffness and damping, is derived from nonlinear Reynolds equation simulations. The nonlinear model verifies the control's effectiveness, showing that design parameters can regulate system stiffness, damping, and shaft orbit. The tilting pad bearings were also operated by injecting high-pressure oil through radially drilled holes in the pads, allowing adjustment of the injection pressure to modify the bearing's static and dynamic properties as needed. In the experimental test rig shown in Figure 12, the tilting pad bearing design with location of position sensors and high pressure nozzles illustrates the active lubrication concept for improved rotor dynamic performance [24].

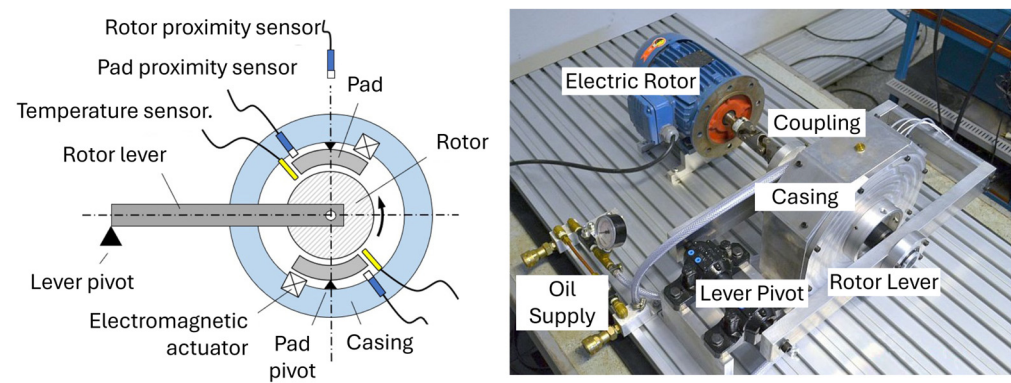


Figure 11. Hydrodynamic bearing with embedded electromagnetic actuators and tilting-pad [33].

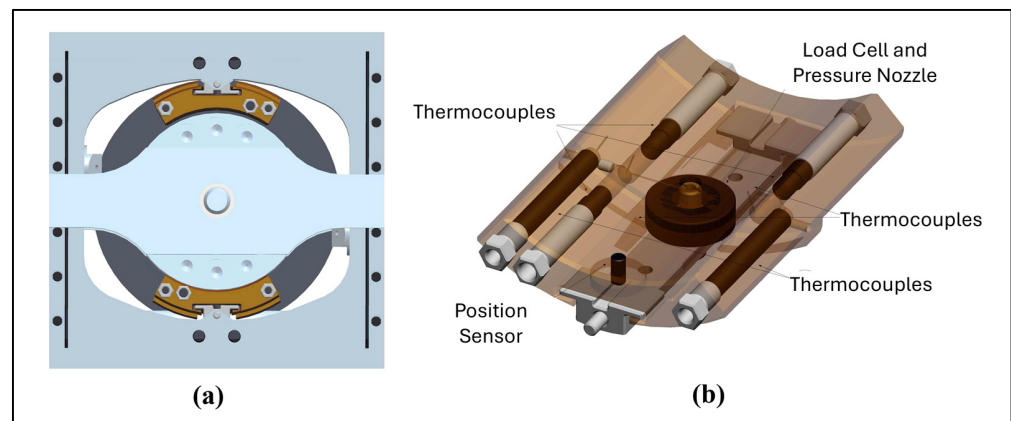


Figure 12. Active tilting pad bearing with bearing with embedded electromagnetic actuators and tilting-pad (a) Test bearing with two tilting pads (b) Tilting pad with nozzles and load cell [24].

Simoes et.al [128] studied modal active vibration control of a rotor using piezoelectric stack actuators. Simulations on an FEM model confirmed feasibility, while experimental tests on a rotor test rig showed good agreement with numerical results, validating the control approach. Piezoelectric actuators, orthogonally mounted at one bearing, enabled effective vibration suppression. The LQR controller lowered vibration levels by up to 20 dB at the first critical speed, shortened settling time by 83% from 0.3 s to 0.05 s, and reduced transient motion vibrations by 90%. Carmignani et.al [129] proposed active control of rotor vibrations using a hydrodynamic bearing with piezoelectric actuators. A mobile bearing housing, actuated in two orthogonal directions, generates corrective forces to reduce

unbalance-induced bending. A test rig validated this alternative to magnetic bearings, showing effective vibration reduction and good agreement between experiments and simulations, confirming feasibility for large rotating machines. Using finite element approach, Jungblut et al. [123,130] modeled a gyroscopic rotor system with multiple piezoactuators enabling dynamic manipulation of the rotational axis. The proposed approach theoretically enables active control of rotor displacements while keeping bearing forces low, even in the self-centering zone. Applying additional weighting to the controller helps suppress force-free resonances and removes the discrepancy between absolute and relative displacement control, as confirmed by test rig experiments shown on Figure 13. Displacements are determined using position sensors, while the bearing forces are captured with piezoelectric load cells installed on each piezo actuator and amplified with load amplifiers. The active bearing successfully reduced the first forward whirl order by about 50% of the disc's eccentricity, while slightly increasing the first backward whirl order. The rotating piezo actuator design achieved over 90% lower power consumption than conventional active piezoelectric bearings, using only a fraction of the voltage. Wang et al. [36] investigated the feasibility of using giant magnetostrictive material (GMM) actuators for control of a bearing. Frequency response tests were conducted to assess system performance at various speeds. The proposed active control concept, utilizing orthogonally placed GMM actuators, demonstrated effective real-time stabilization, minimizing eccentricity and vibration. Controlling the smart journal bearing with GMA excitation eliminated self-excited whirling vibrations at 210 rad/s and increased the system's unstable speed from 282 rad/s to 400 rad/s, extending the stable operating range by over 40%.

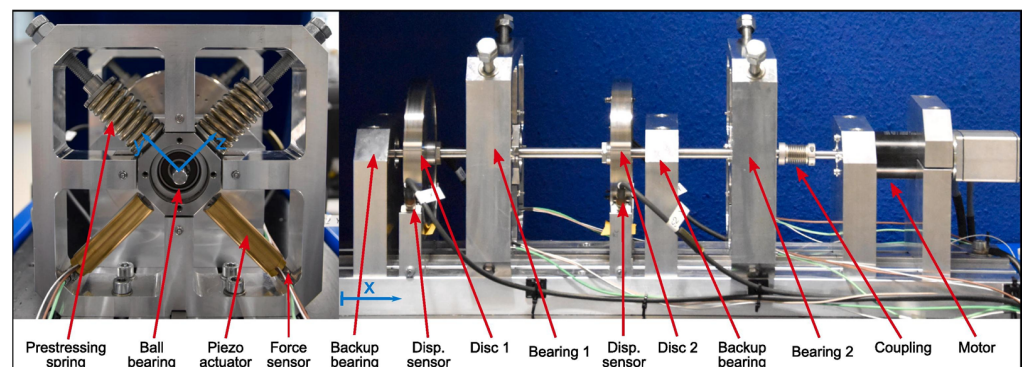


Figure 13. Rotor test setup with active bearings and piezoactuators with X, Y and Z representing the local coordinates [130].

Pinte et.al [131] studied a piezo-based bearing for active structural acoustic control in rotating machinery. As shown in Figure 14, the modular bearing, equipped with piezostacks, introduces secondary forces to reduce structure-borne noise. On an experimental setup with a rotating shaft and a noise-radiating plate, the system achieved more than 10 dB noise reduction below 1 kHz through feedback and repetitive control. The design integrates collocated piezo actuators and sensors in a ring-shaped module, enabling force generation in all radial directions to control vibration transmission effectively. The preloaded piezoactuators apply bidirectional forces, with power and charge amplifiers handling actuation and sensing. The design ensures force transmission through the piezostacks while preventing shear stress. Two SISO controllers regulate the bearing, which is tested on an experimental setup. Research has also explored the potential of using active lubrication in gas journal bearings. This concept works by producing controllable forces through the radial injection of lubricant, which is regulated by piezoelectric actuators installed behind the bearing sleeves. Morosi and Santos [132,133] established the theoretical foundation for implementing active control in gas-lubricated journal bearings. The active piezoelectric

injection system lowered the rotor's synchronous vibration amplitude by up to 90% relative to passive operation, while effectively eliminating half-frequency whirling at speeds exceeding 18,000 rpm. Furthermore, the active control enhanced transient response, reducing peak vibration amplitudes by more than 80% during sudden shocks. The prototype active gas journal bearing shown in Figure 14 consists of a rigid sleeve with four equally spaced orifices at the axial mid-plane and four piezoelectric actuators that control the flow between the pressure supply and the journal-sleeve gap. Figure 15 illustrates the piezoelectric injection system, where a voltage-driven piezo stack moves an injection pin to control air flow from the supply reservoir to the bearing, aided by Belleville washers for return motion and O-rings to limit air leakage. Qiu et al. [134] examined self-excited vibration control in a rotor system with active gas bearings (Figure 16). The setup includes externally pressurized thrust bearings for axial support and tilting-pad journal gas bearings with embedded piezoelectric actuators for radial control. A feedback system with gap sensors and PID controllers effectively suppresses vibrations when optimally tuned. The key studies on active vibration control in journal bearings are summarized in Table 3, highlighting the control strategies, implementation methods, and their impact on system performance.

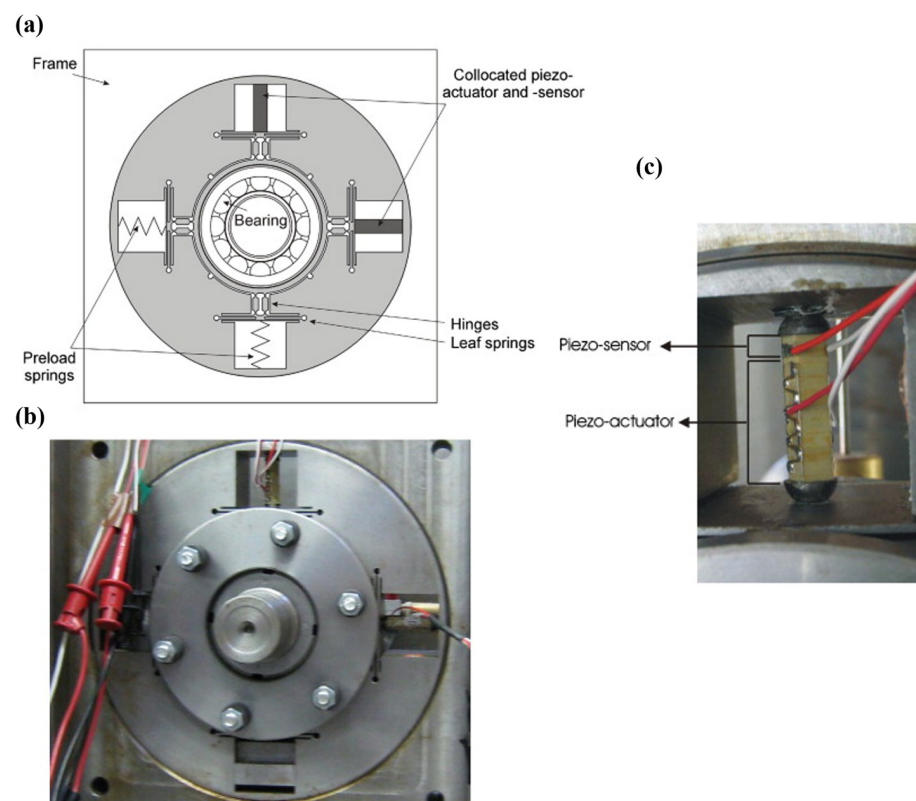


Figure 14. Piezoactive bearing system (a) Schematic drawing (b) Experimental setup (c) Piezoactuator [131].

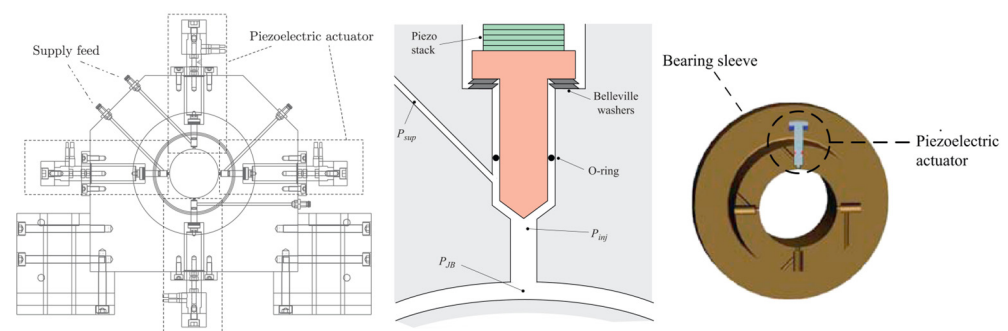


Figure 15. Active gas journal bearing prototype and piezoelectric injection system [132].

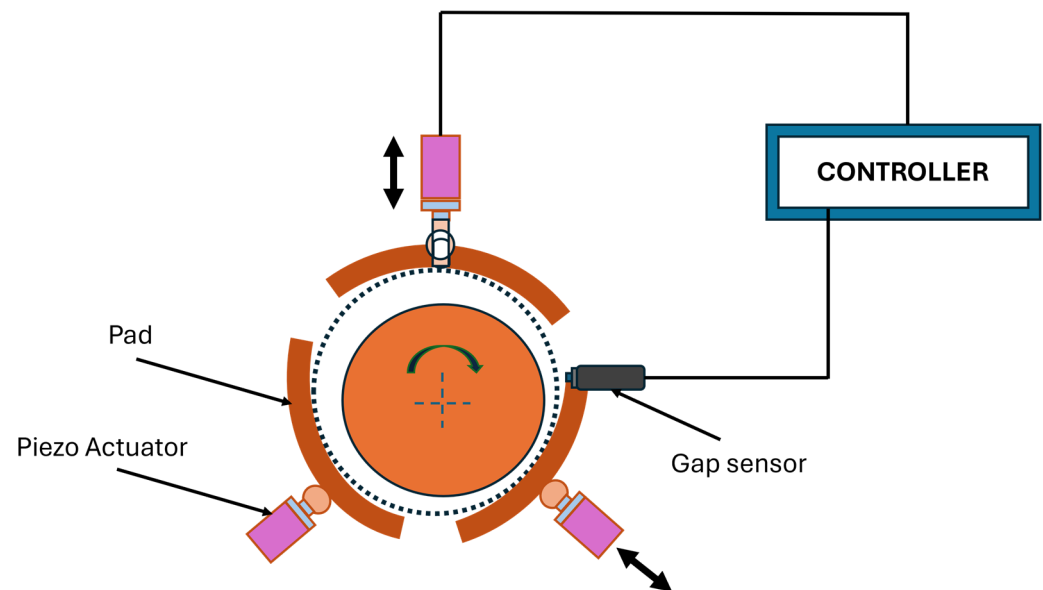


Figure 16. Configuration of the tilting-pad journal gas bearings [51].

Table 3. Various types of active vibration control mechanism in journal bearings and its principle of operation.

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Stanway and Burrows [135]	1981	Theoretical modeling	Active control applied at critical rotor locations	Stabilization achieved through control inputs at strategic rotor points, analyzed under system constraints.	Study reveals trade-offs in actuator placement, sensing, and system identification, exposing conflicting control requirements.
Burrows et al. [136]	1989	Experimental and theoretical	Magnetic actuator	Uses a single magnetic actuator to estimate system response and apply optimal force to reduce synchronous vibration	Effectively reduced first critical speed vibrations by 80–90% using a single electromagnetic bearing and sparse measurements, while enabling on-line parameter estimation.
Yu et al. [137] and Shao et al. [138]	1998, 2021	Experimental and theoretical	Active magnetic bearing (electromagnetic actuator)	Applies optimized electromagnetic force using feedforward self-optimizing control for fast vibration suppression.	Attains $\geq 70\%$ vibration reduction within 1 s and sustains performance under speed variations without relying on complex models.
Przybylowicz [139,140]	2000, 2004	Numerical	Piezoelectric (PZT) actuation to movable shell	Piezo actuators adjust the bearing shell based on journal motion, tuning the oil gap and damping.	Piezoelectric jacks dynamically adjusting the bearing shell doubled the system's critical speed, greatly extending its stable operating range.
Carmignani [129]	2001	Experimental and Numerical	Piezoelectric actuators	Harmonic motion from piezo-actuated housing generates corrective forces to counter shaft unbalance.	Demonstrated effective vibration suppression via adaptive bearing actuation, with corrective moments validated by strong experimental–numerical agreement.
Cai et al. [119]	2003, 2004	Simulation-based modeling	Linear actuators translating tilting pads.	Adaptive control uses actuators to reposition pads, stabilizing the rotor despite uncertainties in fluid film behavior	The adaptive controller reduced rotor displacement by over 95% compared to passive operation, while maintaining control forces within ± 2000 N

Table 3. Cont.

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Alizadeh et al. [141]	2003	Experimental with control design and simulation	Piezoelectric ssactuators at bearings	Actuators apply corrective forces based on integral force feedback or robust control to suppress rotor vibrations.	Piezo-actuator damping reduced rotor orbit amplitudes by >80%, maintained ~90% stiffness, while both control strategies proved effective, with robust μ -synthesis offering superior handling of system uncertainties.
Wu and Queiroz [21] and Wu et al. [117]	2007, 2010	Theoretical modeling and Experimental	Linear and rotary actuators	Pad positions or tilt angles are adjusted in real-time via feedback control to regulate rotor motion and enhance stability.	Nonlinear tilt-angle control kept the journal centered without limit cycles, needing only sub-milliradian resolution and a few N·m torque, outperforming PID in efficiency.
Tuma et al. [15,116]	2011	Experimental and Numerical	Active—Piezoelectric Actuators	Journal vibrations detected by proximity probes are countered by piezoactuators adjusting a movable bushing.	Active control delays instability, extending stable speed to 23,000 rpm with just one actuated bushing.
Lau et al. [142]	2012	Experimental	GMM based actuators	GMM actuators control journal bearing position via self-tuning P control under a PID algorithm.	GMM actuators reduced shaft orbit size by over 35% across all tested speeds, with fluctuations limited to ~2 mm from a 20 mm uncontrolled orbit confirming feasibility for vibration suppression and positioning.
Viveros and Nicoletti [126]	2014	Numerical and experimental	Electromagnetic actuators	PD-controlled electromagnetic actuators reduce rotor vibrations using hydrodynamic support.	Achieved up to 18% vibration reduction; system shows competitive control capacity with smaller actuators.
Fang et al. [143]	2015	Theoretical and experimental	Active Magnetic Bearing (AMB)	Feedforward control with phase correction aligns rotor axis, minimizing vibrations.	AVC strategy reduced rotor vibration forces and torques by over 99% and halved displacement amplitudes, demonstrating high effectiveness for AMB-based devices
Pierart and Santos [144]	2016	Theoretical and Experimental	Piezoelectrically controlled radial oil jet	Proportional control of radial oil injection improves damping by adjusting gas film pressure.	Proportional controller enhanced the rotor-bearing damping factor up to $6\times$, with natural frequency errors under 5% and damping deviations within 50% between theory and experiment.
Ambur and Rinderknecht [145]	2018	Experimental and simulation	Piezoelectric actuators	Self-sensing piezo actuators detect bearing deflection, enabling unbalance estimation via frequency-domain parameter estimation	Robust fault detection was achieved using Weighted Least Squares, with all fault parameters identified in stationary tests, as outliers reduced accuracy by ~45% in magnitude and ~33° in phase
Hu et al. [146]	2018	Experimental and Simulation	Piezoelectric actuators	Piezo actuators regulate preload or clearance via pressure/position control using closed-loop PI control.	Variable position preload achieved up to ~90% higher axial stiffness and ~28% higher first-order natural frequency than variable pressure preload under the same conditions

Table 3. *Cont.*

Authors	Year	Type of Study	Type of Actuation	Principle of Operation	Findings
Preto et al. [147]	2023	Experimental	SMA thermal actuation	SMA wires at bearings adjust stiffness via Joule heating to alter system dynamics.	SMA rotor system reduced bearing and disc horizontal displacements by 20–30% compared to the elastic setup, while also increasing stiffness and raising the critical frequency.
Xu et al. [148,149]	2023, 2025	Experimental and numerical	Hydrostatic gas supply with PID and fuzzy PID control	External gas supply boosts film stiffness in air foil bearings, enabling active vibration control through pressure tuning.	Increasing the gas supply to 0.50 MPa cut rotor vibration by ~6.8 μm , suppressed low-frequency oscillations, and increased critical speed to 6200 r/min.
Li et al. [150]	2023	Theoretical and Experimental	Active Hybrid Bearings (AHBs) with PI and nonlinear controllers	Uses PI and adaptive nonlinear control to manage rotor vibration and viscous friction in AHB systems.	Active hybrid bearings cut rotor oscillations by several times and lower viscous friction losses by up to 19% via optimized rotor position control.

3. Applications and Future Prospects of Active Bearing Technologies

Actively controllable bearings have advanced from lab-scale concepts to viable engineering solutions, providing real-time adaptability in stiffness, damping, and alignment. Unlike passive bearings, their key advantage is the capacity to adjust dynamically to varying loads, speeds, and operating conditions. Actively controllable bearings offer significant advantages in various engineering applications, including precision machining, high-speed rotating machinery, and vibration-sensitive systems. Detailed review of active bearing technologies shows that they can reduce vibration amplitudes by over 60–70%, enhance damping factors by up to sixfold, and markedly raise critical speeds, thereby broadening the stable operating range. Piezoelectric-actuated bearings show fast response and effective vibration suppression in high-speed rotors and precision micro-machining tools, while electromagnetic and magnetic bearings are extensively used in turbomachinery, vacuum pumps, and power-generation turbines, providing non-contact operation, minimal wear, and reliable performance under extreme conditions. Controlled fluid injection in actively lubricated bearings has been shown to enhance pressure distribution and dynamic stability, with experiments demonstrating significant improvements in load capacity and damping.

Several active bearing technologies are moving toward industrial adoption, though their levels of advancement differ. Magnetic bearings are the most developed, with established use in gas turbines, flywheel energy storage, and MRI-compatible medical pumps. Their demonstrated reliability and widespread commercialization position them at the highest stage of technological readiness. In contrast, piezoelectric and magnetostrictive bearings remain at pilot or pre-commercial stages tested in aerospace rigs and precision manufacturing but not yet broadly adopted. Active lubrication techniques are even less advanced, showing promising laboratory results but facing limited uptake due to fluid control complexity and integration challenges. Overall, this highlights that while magnetic bearings are already industrially established, other concepts are still progressing from research toward practical application. Despite their advantages, a key limitation to widespread adoption is the added cost and complexity from actuators, sensors, and controllers, as well as increased energy consumption during continuous operation, especially in piezoelectric and electromagnetic systems. Integration into compact housings demands sophisticated design and dependable real-time feedback, while developing accurate control models remains computationally intensive. Additionally, industries expect decades-long

service life, so active bearings must prove comparable durability and robustness in harsh environments before gaining wider acceptance.

To address these challenges, current research is aimed at simplifying models for real-time predictive control, creating adaptive and AI-driven algorithms that self-adjust to changing conditions, and employing advanced materials to improve load capacity and thermal resilience. Figure 17 details the future development of active journal bearings. Research is also advancing toward miniaturizing actuators and sensors for seamless integration and creating scalable, modular systems that can serve diverse sectors like energy, aerospace, and advanced manufacturing. While magnetic bearings have already reached industrial maturity, other active bearing concepts are progressively advancing toward practical use. Study findings shows that actively controllable bearings are advancing from lab-scale prototypes to practical technologies, offering significant potential to enhance the performance and reliability of rotating machinery.

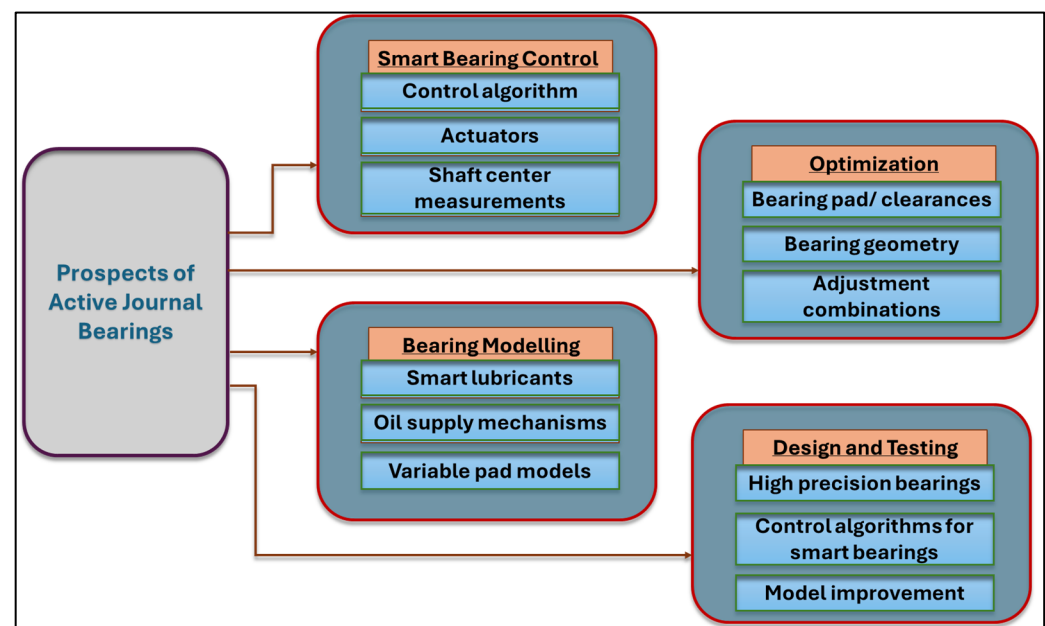


Figure 17. Future development of active journal bearings.

The key emerging trends in active bearing development include:

- i. Smart bearing control focuses on enhancing the adaptability and responsiveness of active journal bearings. This involves the development of advanced control algorithms, the integration of precise actuators, and the use of real-time shaft center measurements to enable adaptive operation. Both classical controllers, such as PI, PD, and PID, and advanced methods like artificial neural networks, fuzzy logic, and adaptive/self-tuning techniques are employed to maintain optimal bearing performance under varying operating conditions.
- ii. Optimization in active journal bearings aims to enhance dynamic performance, efficiency, and stability by fine-tuning both the bearing design and its operating parameters. This involves adjusting bearing pads, clearances, and overall geometry, as well as optimizing pad-clearance combinations and pressure distribution. Component-level improvements, such as refining lubrication gaps, supply systems, and miniaturizing sensors and actuators, contribute to more compact, efficient, and reliable bearing systems.
- iii. Bearing modelling focuses on accurately representing the behavior of active journal bearings under diverse operating conditions to improve performance and reliability. This includes incorporating smart lubricants and advanced oil supply mechanisms, as well as developing variable pad models that can simulate the bearing's dynamic

response. Continuous refinement of these simulation models ensures that the bearings perform optimally and reliably across different loads and operating environments.

- iv. Design and testing of active journal bearings focus on translating advanced models and control strategies into high-performance, reliable hardware. This involves manufacturing high-precision bearings specifically tailored for active operation, developing and validating control algorithms for smart bearings, and conducting continuous testing and refinement to ensure optimal performance, reliability, and safety under real operating conditions.

4. Conclusions

- i. Active or adjustable bearing systems have evolved from theoretical concepts to practical engineering solutions, significantly enhancing rotor dynamics and vibration control. Early studies focused on hydraulic dampers, variable sleeves, and controllable fluid film bearings, while modern developments extend these concepts to high-speed and multi-rotor systems with precise real-time control.
- ii. Modern active bearings incorporate magnetic and piezoelectric actuators, flexible sleeves, deformable bushes, and advanced fluid supply systems, enabling real-time adjustment of film thickness, pressure distribution, and stiffness. Studies show they can reduce vibration amplitudes by 60–70%, increase damping up to sixfold, and raise critical speeds, greatly enhancing the stable operating range.
- iii. Active control frameworks integrating proximity probes, adaptive algorithms, and actuator-driven adjustments allow rotor position correction, dynamic compensation, and mitigation of cavitation, wear, and other adverse phenomena. Adjustable clearances, optimized lubrication, and adaptive materials provide self-regulating capabilities, ensuring enhanced stability, reliable vibration suppression, and improved dynamic performance.
- iv. Despite substantial advancements, challenges remain in managing system complexity, reducing energy consumption, achieving compact integration, and ensuring long-term industrial reliability. Ongoing research focuses on hybrid bearing systems, AI-driven adaptive control, miniaturized sensors and actuators, and advanced materials to enhance load capacity, thermal stability, and overall operational performance.
- v. Emerging trends in active bearing development focus on enhancing adaptability, dynamic performance, and reliability through advanced control algorithms, real-time monitoring, optimized geometries, and component-level improvements. Additionally, accurate bearing modelling, smart lubrication, high-precision manufacturing, and rigorous testing ensure that active bearings deliver stable, efficient, and robust performance across diverse operating conditions.

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