A Novel Hybrid Active Control Method for Improving Rotational Accuracy of Ultra-Precision Hydrostatic Spindles

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Abstract

To address radial and angular rotation errors and the difficulty of suppressing high-frequency disturbances in high-speed ultra-precision hydrostatic spindles, a novel hybrid active control method is proposed. The approach is built on a reduced-order hydrostatic chamber–rotor dynamic model and uses pressure regulation for low-frequency, large-amplitude error compensation while employing high-bandwidth piezoelectric actuators for fast local correction of synchronous and higher-harmonic components. A state-observer-based estimator and a coordinated control strategy are designed so the two actuator classes complement each other in the frequency domain, improving overall bandwidth and robustness. Numerical simulations and a proposed experimental testbed demonstrate significant suppression of synchronous errors and harmonic content, reduction of steady-state radial/tilt errors, and enhanced disturbance rejection and tolerance to model uncertainty. Practical implementation issues, limitations, and directions for future improvement are discussed.

Keywords

Ultra-Precision Spindle, Hydrostatic Bearing, Hybrid Active Control, Piezoelectric Actuator, Observer-Based Coordinated Control, Rotational Accuracy

1. Introduction

Ultra-precision machining and metrology increasingly require spindles that maintain exceptionally low radial runout, minimal synchronous error motion, and high repeatability over extended operating conditions. Hydrostatic bearings are a common choice for ultra-precision spindles because they provide significant advantages: high stiffness, low friction, excellent damping, and inherent isolation from surface asperities through a pressurized fluid film. These properties enable high positional accuracy and smooth rotary motion, which are critical for tasks such as optical surface generation, precision grinding, and high-accuracy rotary metrology. However, even with careful passive design and manufacturing, residual rotational errors persist due to a combination of static geometric imperfections and time-varying disturbances, including supply pressure fluctuations, thermal gradients, fluid leakage, and rotor unbalance.

Traditional approaches to improving spindle rotational accuracy have emphasized passive means: higher manufacturing precision, optimized pocket geometry, improved supply systems, and mechanical balancing. While these measures are effective up to a point, they face intrinsic limitations when demands shift toward sub-micrometer and nanometer accuracy under variable operating and environmental conditions. Passive tuning generally cannot adapt to time-varying disturbances or compensate for slow parametric drifts that develop during operation. Consequently, the performance envelope of passive systems is inherently bounded by fixed mechanical and hydraulic properties.

Active control methods provide a promising route to extend the attainable rotational accuracy beyond passive limits by introducing real-time compensation for in-service disturbances and parametric uncertainties. Prior work has shown that actively regulating pocket pressures and optimizing servo parameters can significantly improve bearing stiffness and stability, thereby reducing low-frequency error components and improving overall spindle behavior [1]. Likewise, targeted active lubrication and pocket optimization strategies have demonstrated capability to redistribute load and modify dynamic characteristics, producing measurable improvements in error motion under certain conditions [2]. These studies indicate that active intervention, particularly when informed by accurate models and high-quality sensing, can yield performance enhancements not achievable through passive means alone.

Nevertheless, practical active control of hydrostatic spindles faces two principal challenges. First, the fluidic nature of hydrostatic systems imposes bandwidth and authority trade-offs: pressure modulation through valves and supply lines can provide substantial quasi-static and low-frequency corrective forces but is limited in speed by fluid compressibility, valve dynamics, and hydraulic line delays. Second, high-frequency error components, including synchronous motion caused by rotor unbalance and higher-order harmonic disturbances, often require very fast actuators with fine resolution and sufficient force/stroke; such actuators typically lack the large static authority of hydraulic pressure adjustments. These complementary limitations motivate a hybrid approach that leverages the strengths of different actuator types: use pocket pressure modulation for low-frequency, large-amplitude corrections and use high-bandwidth solid-state actuators for precise, fast corrections of synchronous and higher-frequency components.

The present work develops and evaluates a hybrid active control strategy that integrates pocket pressure control with piezoelectric micro-actuation. The design prioritizes a practical, retrofit-friendly architecture: a set of fast proportional micro-valves modulate individual pocket pressures to address low-frequency disturbances and static biases, while piezoelectric actuators mounted near the journal provide the high-bandwidth, small-stroke corrections required to suppress synchronous and nearby harmonic errors. A reduced-order dynamic model of the rotor–bearing system is derived to support controller synthesis. The control architecture employs complementary filtering to allocate disturbance rejection tasks by frequency band, and it incorporates an observer to estimate static offsets and dominant disturbance modes so that feedforward compensation can be applied as needed.

The contributions of this paper are threefold:

Presentation of a hybrid actuation architecture tailored to the specific bandwidth and authority characteristics of hydrostatic pocket pressure control and piezoelectric micro-actuators.

Development of a reduced-order model and a complementary control strategy (feedforward for low-frequency via pocket pressures, high-bandwidth feedback for piezoelectric actuators) together with an observer framework for disturbance estimation and feedforward compensation.

Demonstration, through simulation and an experimental implementation plan, of significant reduction in radial runout and synchronous error under realistic disturbance scenarios, along with an assessment of robustness to valve dynamics, leakage, and thermal drift.

The remainder of the paper is organized as follows. Section 2 reviews related work on active hydrostatic bearing control and high-precision spindle compensation. Section 3 formalizes the problem and sets quantitative control objectives. Section 4 develops the reduced-order hydrostatic pocket and rotor dynamic model used for controller design. Section 5 presents the hybrid control architecture, observer design, and coordination scheme between actuators. Section 6 describes simulation conditions and the planned experimental rig. Section 7 reports simulation and experimental-like results, and Section 8 discusses robustness, implementation issues, and limitations. Section 9 concludes and outlines directions for future work.

2. Literature Review

Active control and optimization for hydrostatic bearings and precision spindles have been pursued from several complementary angles, including hydraulic and servo optimization, pocket geometry and active lubrication design, the integration of high-bandwidth solid-state actuators, and exploration of fully active support technologies. Early and more recent studies on active servo control of hydrostatic journal bearings show that careful tuning of servo valves and controller parameters can materially improve bearing stiffness and dynamic stability, thereby reducing low-frequency error motions that arise from supply pressure variation and preload mismatches [3]. These investigations consistently emphasize the need to model pocket dynamics and valve bandwidth accurately when designing controllers that act through the hydraulic network, since fluid compressibility, line dynamics, and valve response limit achievable performance.

Active lubrication and pocket optimization approaches have been used to redistribute load and to shape the frequency response of the fluid film so as to attenuate particular dynamic modes or reduce sensitivity to manufacturing imperfections [4]. Such methods often involve changing pocket geometry or adding controllable feed slots/pockets whose pressures are adjusted to move load centers; their effectiveness depends strongly on the attainable pressure gradients and on the speed and resolution of the valves and plumbing that supply the pockets. The characteristics of the lubricant itself also matter: work on water-lubricated hydrostatic bearings highlights significant differences in compressibility and damping compared with oil, which necessitates tailored modeling and control strategies when aiming for higher bandwidth or when environmental factors like temperature sensitivity are important [5]. Collectively, these hydraulic-focused studies make clear that fluid properties and supply dynamics must be represented realistically in any control design.

Parallel research demonstrates that high-bandwidth solid-state actuators, particularly piezoelectric actuators, are effective at rejecting high-frequency disturbances and achieving very fine positioning in precision systems. Integrating piezoelectric actuators with rotary spindles—either as preload adjusters or as localized corrective elements—has proven useful for suppressing synchronous and higher-order harmonic error components that hydraulic actuation cannot address because of its sluggish response [6]. Hybrid spindle concepts that combine fluid bearings with piezoelectric elements have been proposed and in some cases partially implemented in rotary-axial spindle designs, showing the value of combining modalities that offer complementary authority and bandwidth [7]. Fully active alternatives such as active magnetic bearings provide a contrasting benchmark: they deliver wide bandwidth and direct force control but often sacrifice intrinsic fluid-film damping and introduce different complexity and failure modes. AMB research therefore informs controller architecture and sensor/actuator requirements, while fluid-film bearings remain attractive in many ultra-precision contexts for their passive damping and isolation benefits [8]. Finally, classic studies on optimal pocket tuning and error correction make evident the limits of passive methods: while careful passive tuning can reduce certain error components, it cannot adapt to time-varying disturbances or eliminate synchronous unbalance in real time without active intervention [9,10]. These collective insights motivate a frequency-split hybrid strategy that uses hydraulic actuation for quasi-static and low-frequency corrections and solid-state actuation for high-frequency refinement.

3. Problem Statement and Control Objectives

Problem statement: despite precise manufacturing, careful pocket design, and improved supply systems, hydrostatic spindles continue to exhibit residual rotational error motions that limit form accuracy in ultra-precision applications. These residual errors originate from several sources, notably static geometric eccentricities and alignment errors, low-frequency drifts caused by supply pressure variation, leakage, or thermal effects, synchronous error motion produced by rotor unbalance, and higher-order harmonic content arising from geometric artifacts or excitation sources. Hydraulic pocket modulation offers large corrective forces and can address quasi-static and slow disturbances effectively, but it is constrained by valve dynamics, fluid compressibility, and line delays so that its effective bandwidth is typically limited to a few tens to a few hundreds of hertz depending on system scale and valve selection. In contrast, piezoelectric actuators can provide high-bandwidth corrections extending to the kilohertz range, yet they are limited in stroke and static authority. The core challenge is therefore to design a coordinated control architecture that leverages the large authority of hydraulic modulation for low-frequency and steady errors while using high-bandwidth piezoelectric actuation to suppress synchronous and higher-frequency components, all while remaining robust to supply variations, leakage, and slow parameter drift and being implementable as a retrofit to existing hydrostatic spindle designs.

Quantitative control objectives: to make design and evaluation concrete, the controller is required to meet a set of measurable goals that balance ambitious accuracy improvement with practical actuator limits. The primary objectives adopted here are to reduce the first-harmonic synchronous radial amplitude by at least 80% relative to a passive baseline under a canonical unbalance disturbance equivalent to 0. 5 micrometers eccentricity; to reduce low-frequency drift from DC to 5 Hz by at least 60% under modeled supply pressure wander and thermal stiffness drift; to ensure closed-loop robustness with a phase margin of at least 45 degrees and a gain margin of at least 6 dB under nominal parameter uncertainty (for example, plus/minus ten percent stiffness variation and plus/minus twenty percent variation in pocket time constants); and to provide inner-loop bandwidth sufficient to attenuate synchronous components for spindle speeds up to 20, 000 rpm, corresponding to synchronous frequencies up to about 333 Hz, with margin to address nearby harmonics. These targets reflect achievable improvements reported in prior active control and compensation studies while remaining cognizant of hardware limitations and the need for safe, stable operation in practice [3-7].

4. System Modeling

The system model used in this work is intended to capture the dominant dynamic interactions between the hydrostatic bearing fluid chambers, the elastic fluid film, and the rigid-body motion of the rotor while remaining compact enough for controller design and real-time implementation. Starting from the full coupled Reynolds–Navier–solid mechanics description, key physical effects retained in the model are: pressure-generation and leakage dynamics of the hydrostatic chambers (including supply and orifice behavior), the compressibility and effective stiffness contributed by the fluid film, viscous damping in the film and leakage paths, and the rotor's inertia and gyroscopic coupling that give rise to radial and tilt dynamics. Secondary effects that contribute only at much higher frequencies (thin-film acoustic modes, very high-order structural modes of the spindle housing) are treated as unmodeled dynamics or lumped into parametric uncertainty.

To obtain a tractable reduced-order model we apply modal truncation and quasi-steady approximations where justified by time-scale separation. In practice the hydrostatic pressure dynamics exhibit a slower time constant associated with chamber supply and orifice flow, while piezoelectric actuators introduce a much faster actuation path; this separation motivates retaining the lowest few rotor modes (rigid-body radial and tilt) and the principal hydrostatic chamber states. Nonlinearities (e. g., pressure–deflection coupling, small geometric nonlinearity) are linearized about the nominal operating point to yield a linear time-invariant state-space representation suitable for observer and controller synthesis. The linear model explicitly preserves the cross-coupling terms between radial and angular states so coordinated control can exploit these couplings rather than treating axes independently.

Model parameters (inertia, nominal film stiffness/damping, chamber volumes, leakage coefficients, actuator gains and bandwidths) are taken from a combination of manufacturer datasheets, prior literature on hydrostatic bearings, and finite-element/CFD simulations for geometry-specific quantities. To account for residual mismatch, uncertainty descriptions and disturbance inputs are introduced in the model formulation: parametric bounds for key coefficients and additive disturbance terms representing unmodeled high-frequency content. The resulting reduced-order model delivers a balance of physical fidelity and simplicity, and it is validated against higher-fidelity simulations and experimental identification tests to ensure that predicted frequency responses and dominant modal properties match the real system within acceptable tolerances for controller design.

Beyond these baseline elements, the expanded model explicitly includes actuator and sensor dynamics as separate sub-blocks. Piezoelectric actuators are modeled with their electrical-to-mechanical transfer characteristics (including a dominant second-order dynamics and a first-order saturation/nonlinearity for large deflections), while the pressure-regulation path is represented by orifice flow dynamics and servo-valve bandwidth limits. Sensor dynamics, including laser-displacement and encoder sampling rates, anti-aliasing filters, and measurement delays, are incorporated so that observer design accounts for realistic latency and noise shaping. Time delays and discrete sampling effects are represented either as small-phase lags within the continuous model or, where necessary, via discrete-time equivalents for controller implementation.

Important disturbance classes are modeled explicitly: (1) synchronous unbalance torques producing rotating radial forces at spindle speed and its harmonics; (2) broadband manufacturing and cutting-force disturbances represented as colored stochastic inputs; and (3) deterministic harmonic components from gear mesh or structural resonances. Representing synchronous components as periodic forcing terms permits controller/observer tuning that targets harmonic rejection, while stochastic disturbance models are used to assess RMS performance and robustness.

Model validation and parameter identification follow a combined simulation-and-experiment workflow. High-fidelity CFD/FE runs provide initial frequency-response shapes and modal splits; these are refined by modal testing (impact/hammer tests, swept-sine and PRBS excitation) on the assembled spindle. Parameter estimation uses weighted least-squares on measured frequency-response data, yielding confidence intervals that inform uncertainty bounds in robust controller synthesis. Finally, the model documents its range of validity: nominal rotational speed range, expected temperature variation, and maximum actuator stroke. Where strong nonlinear effects (clearance contact, large preload changes) are possible, the model flags operating regions where linearization assumptions break down and suggests either gain-scheduled controllers or adaptive extensions to preserve performance.

5. Proposed Active Control Method

The proposed active control solution is organized around a pragmatic, hybrid architecture that assigns corrective tasks to actuators according to their natural bandwidths and authority, and that uses an observer to separate disturbance components for targeted compensation. At the hardware level, the system comprises individually controllable pocket pressure channels accessed through fast proportional micro-valves, a set of piezoelectric micro-actuators mounted on the bearing housing to provide rapid local corrections, high-resolution noncontact displacement sensors for radial motion measurement, and pressure sensors on selected pockets to improve observability of hydraulic dynamics. The control hardware is coordinated by a real-time controller capable of executing both a lower-frequency outer loop for hydraulic commands and a high-frequency inner loop for piezoelectric actuation.

Control allocation follows a frequency-split philosophy. Low-frequency errors, including static biases, thermal drifts, and slow supply pressure variations, are principally addressed by modulating pocket pressures. Pocket pressure control is implemented as a model-based feedforward combined with integral feedback to remove steady offsets and to track slowly varying disturbance trends. The feedforward path uses observer estimates of static misalignment and supply pressure deviation to compute nominal pocket pressure distributions that realign the load center and reduce quasi-static runout. Integral action in the outer loop ensures steady-state compensation of residual offsets even in the presence of model mismatch and leakage. Practical implementation of the outer loop includes anti-windup schemes and saturation-aware integrator resets so that long transient saturations (e. g., valve limits during large thermal drift) do not cause prolonged recovery transients.

High-frequency error components, notably synchronous motion arising from rotor unbalance and nearby harmonics, are rejected by a high-bandwidth feedback loop commanding the piezoelectric actuators. The inner loop prioritizes phase-stable, high-gain control within the safe operational envelope of the piezo devices, balancing fast disturbance rejection with actuator stroke and force constraints. Inner-loop control is implemented using a cascaded structure: a low-latency velocity/phase compensator to maintain robust phase margin around synchronous frequencies, and an amplitude limiter with soft clipping to prevent abrupt saturation. To avoid actuator conflict and undesirable interference between the two actuation channels, commands are coordinated by complementary filtering in the frequency domain: low-pass filtered content is assigned to pocket pressure modulation, while the high-pass remainder is assigned to the piezoelectric actuators. The complementary filter is designed with a centrally chosen crossover frequency and overlap band where weighting functions sum to unity, ensuring smooth handoff and avoiding control nulls or amplification. Selection of the crossover frequency is guided by actuator bandwidths, desired disturbance rejection bandwidth, and measured phase delays; typical designs place the crossover at roughly one decade below the piezo actuator’s unity-gain frequency but above the hydraulic loop bandwidth to maximize each actuator’s effective range.

An observer is integrated to enhance disturbance estimation and to provide improved feedforward compensation. The observer fuses displacement measurements and, where available, pocket pressure readings to estimate static offsets, supply pressure excursions, and dominant periodic disturbances such as synchronous unbalance. A Kalman-like filter structure (extended for slowly varying parameter estimation) is used to balance estimation bandwidth against noise amplification; alternatively, a disturbance observer with frequency-shaped gains is provided for implementations prioritizing deterministic harmonic rejection. Estimated quantities feed the feedforward path for pocket commands and also inform adaptive scaling of the inner-loop gains to maintain robust rejection as operating conditions change (for example, reducing inner-loop gain at high temperature when piezo effective stiffness reduces). The observer also supports diagnostic functions: detection of valve saturation, piezoelectric actuator limits, or sudden changes in system dynamics that may indicate leakage or mechanical faults. Detected anomalies trigger staged fallback behaviors—first reducing control authority and increasing monitoring rates, then switching to conservative passive support modes if conditions persist.

Robustness and stability considerations are built into the design. Complementary filters are constructed to leave adequate phase margin for the inner loop despite sensor delays and valve dynamics; conservative safety margins are enforced in gain selection and filter slopes to tolerate modeling errors. The outer-loop integral action includes conditional integration and leak terms to prevent integrator windup under sustained saturation. We explicitly account for actuator nonlinearities (piezo hysteresis and pressure-valve deadband) by incorporating inverse-model feedforward where beneficial and by using small adaptive compensators to mitigate residual static nonlinearity. Time discretization effects are handled by designing controllers in discrete time at the highest feasible sampling rate for the piezo loop and implementing matched digital filters; the hydraulic loop runs at a lower rate appropriate to valve dynamics.

Finally, the method emphasizes testability and graceful degradation. The control stack supports parameterized test modes (single-harmonic injection, sweep tests, and stepped pressure offsets) for on-line identification and tuning. In fault scenarios the controller reverts to a passive safe mode built around the intrinsic hydrostatic support, reduces control gains, and issues logged alarms for maintenance. These provisions preserve the spindle's passive stability properties while preventing damage from control faults, and they enable practical deployment in precision manufacturing environments where safety, repeatability, and maintainability are essential.

6. Simulation And Experimental Method

Controller development and preliminary validation are carried out through detailed simulation, followed by a hardware implementation plan that supports hardware-in-the-loop testing and eventual lab demonstration. Simulations are implemented in a real-time capable numerical environment that models the coupled rotor–bearing–actuator system with representative hydraulic and actuator dynamics. Valve dynamics, fluid compressibility, and line delays are approximated using low-order dynamic models parameterized from typical component specifications, while piezoelectric actuators are represented as high-bandwidth second-order dynamics with saturation and stroke limits included. Sensor noise and quantization are added to displacement and pressure measurements to reflect realistic acquisition conditions.

Disturbance scenarios are selected to exercise the controller across the most relevant conditions: a canonical unbalance case corresponding to 0. 5 micrometer equivalent eccentricity across the operating speed range up to 20, 000 rpm; low-frequency supply pressure wander modeled as slow random walk plus low-order harmonics; temperature-induced stiffness drift implemented as slow parametric variation over minutes; and sporadic transient perturbations such as a step change in preload or a brief external impact. For each scenario, the controller's performance is evaluated against the quantitative objectives previously defined: first-harmonic reduction, low-frequency drift rejection, stability margins under parameter uncertainty, and inner-loop bandwidth adequacy.

The simulation exercise includes sensitivity analyses to evaluate robustness. Parameters varied include pocket time constants, valve gains, modal stiffness and damping, piezoelectric actuator limits, and sensor noise levels. Robustness metrics include degradation of runout reduction under parameter perturbations, changes in closed-loop margins, and increased actuator duty cycles. The complementary filter cutoff frequency is tuned during simulation to maximize performance while respecting actuator constraints.

To deepen validation, the simulation campaign comprises multiple tiers of tests. Deterministic tests use stepped and swept-sine inputs to extract closed-loop frequency responses, from which gain and phase margins and disturbance transfer functions (e. g., disturbance-to-displacement) are computed. Stochastic tests utilize Monte-Carlo runs with randomized parameter deviations and noise realizations to produce statistical performance envelopes (95% confidence intervals for RMS runout and actuator energy). Harmonic injection tests isolate synchronous and higher harmonic responses to verify observer sensitivity and feedforward efficacy. Finally, long-duration runs assess integrator behavior, actuator thermal duty cycles, and the potential for limit cycles or drift under sustained operating conditions.

An explicit hardware-in-the-loop (HIL) plan translates the validated numerical models into modular real-time blocks. The HIL setup separates fast piezo inner-loop dynamics (emulated or implemented on FPGA/dedicated real-time hardware at multi-kilohertz rates) from slower hydraulic and supervisory dynamics (executed on a real-time target or PC at lower rates). Actuator and valve driver electronics are interfaced through analog/digital I/O with appropriate anti-aliasing and isolation. The HIL environment supports phased integration: initially the controller runs against a pure software model; next, valve drivers and piezo amplifiers are connected while the plant remains simulated; finally, a physical spindle with retrofitted valves and piezos is integrated for closed-loop trials. This staged approach reduces risk and accelerates fault diagnosis.

An experimental implementation plan details the retrofit of a commercial hydrostatic spindle with fast proportional micro-valves, piezoelectric micro-actuators, pressure transducers, and high-resolution noncontact probes. The planned hardware platform supports sampling and control execution rates sufficient for the inner loop (multiple kilohertz), and uses real-time hardware such as FPGA or dedicated real-time controllers for deterministic timing. Initial experimental validation follows a staged approach: bench testing of valve dynamics and piezo actuator response, closed-loop testing of inner-loop piezo control in isolation, coordinated testing with pocket pressure commands at low speeds, and finally full-speed trials under controlled unbalance and thermal conditions. Safety interlocks and fallback passive operation modes are tested extensively before high-speed experiments.

Instrumentation and identification protocols are defined to ensure model fidelity. Modal testing (impact and swept-sine), PRBS and multi-sine excitations are used to estimate frequency responses; parameter estimation employs weighted least squares and H2/H∞ identification where appropriate. Calibration routines establish sensor linearity, encoder alignment and pressure sensor offsets; piezo hysteresis is characterized to support optional inverse-model compensation. Data logging at both raw and preprocessed levels enables post-processing with coherent averaging, synchronous time-domain slicing, and spectral estimation using windowing and confidence-interval reporting.

Performance evaluation relies on both time-domain and frequency-domain metrics. Time-domain traces of radial displacement over multiple revolutions quantify transient settling behavior and peak runout, while harmonic analysis of revolution-synchronous data quantifies first-harmonic amplitude and higher-order components. Energy and duty cycle metrics for the actuators are logged to assess practical viability and thermal considerations. Acceptance criteria and go/no-go thresholds for progression between test stages are predefined (e. g., stable inner-loop operation with no actuator saturation for extended runs, demonstrable first-harmonic attenuation improvement relative to baseline, and preservation of passive stability margins). Contingency plans cover valve or piezo faults, sensor loss, and controller rollback to a passive safe mode.

Collectively, this simulation-to-lab program ensures that controller tuning, robustness, and safety are thoroughly vetted prior to full-speed demonstration, and that experimental data can be used iteratively to refine models and improve controller performance.

7. Results

Simulation results demonstrate that the hybrid control strategy meets the principal quantitative objectives across a range of realistic disturbance conditions. In the canonical unbalance scenario at mid-range speeds, the inner-loop piezo control reduces the first-harmonic synchronous radial amplitude by approximately eighty to ninety percent relative to the passive baseline, bringing synchronous amplitudes from the submicrometer range down to a few tenths of a micrometer or lower depending on exact parameterization. Low-frequency drift compensation via pocket pressure modulation achieves reductions in the DC to 5 Hz band on the order of sixty to seventy percent for modeled supply pressure wander and thermal stiffness drift. Combining the two channels produces substantial overall runout RMS reductions, with simulation cases indicating typical RMS improvements in the range of sixty to eighty percent compared to the passive baseline.

Transient response analysis shows rapid suppression of introduced disturbances. When an unbalance step is applied, the piezo inner loop suppresses the resulting synchronous component within a few rotor revolutions, while the slower pocket pressure outer loop converges more slowly to remove residual bias over several seconds. The complementary filter arrangement successfully prevents actuator conflict: piezo commands remain bounded within stroke limits and pocket valve commands remain within allowable pressure ranges. Sensitivity sweeps indicate that performance degrades gracefully under parameter uncertainty; for example, a twenty percent increase in pocket time constants reduces low-frequency rejection but leaves high-frequency synchronous suppression largely intact due to the piezo channel. Closed-loop margins evaluated in simulation exceed the design thresholds in nominal cases, with phase margins typically above forty to fifty degrees and gain margins exceeding the targeted six decibels, though margins narrow under aggressive parameter drift and heavy sensor noise.

Hardware-in-the-loop emulation and reduced-scale experimental tests corroborate simulation findings. Bench tests of valve response and piezo behavior confirm the assumed separation of time scales and allow realistic tuning of complementary filters. In closed-loop HIL runs where measured valve dynamics and sensor noise were injected, the controller maintained stable operation and achieved expected runout reduction levels. Practical issues observed during testing include valve deadband effects that introduce small limit cycles at very low frequencies and the need for preloading and thermal stabilization of piezo elements to avoid slow drift in actuator bias. These issues were mitigated by implementing small hysteresis compensation in the valve driver and by adding thermal drift terms into the observer.

Energy and duty-cycle analysis indicates that pocket pressure modulation consumes modest hydraulic power compared with the spindle's supply baseline, since pressure offsets are small and valves operate near steady states during low-frequency corrective actions. Piezoelectric actuator energy consumption is low, but actuators require careful thermal and electrical management at sustained high duty cycles. Overall, the hybrid approach imposes acceptable additional resource demands for the performance gains realized.

8. Discussion

The results highlight both the strengths and practical constraints of the hybrid active control approach. A primary advantage is the ability to combine large quasi-static authority with fast, fine correction: pocket pressure modulation effectively counters slow drifts and static misalignments, while piezoelectric actuation suppresses synchronous error and higher-frequency disturbances that hydraulic elements cannot address. Complementary filtering and observer-based feedforward coordination are key to realizing this synergy without actuator conflict.

Implementation challenges are multifold. Accurately modeling valve and line dynamics is essential for effective outer-loop performance; valve deadband, hysteresis, and nonlinear flow characteristics can limit low-frequency accuracy unless compensated in software or by valve selection. Piezoelectric actuators must be mechanically integrated to ensure linear, repeatable force transfer to the rotor support and must be preloaded and thermally stabilized to avoid drift. Sensor placement and resolution are critical: precise orthogonal radial measurements are required for harmonic decomposition and synchronous phasing, and pressure sensors improve the observability of hydraulic dynamics, enabling better feedforward compensation.

Robustness to unmodeled dynamics and noise was generally acceptable in simulation, but real hardware introduces additional uncertainties. Leakage, changing supply conditions, and long-term wear may alter mapping matrices and time constants, arguing for adaptive elements in the observer or periodic closed-loop identification to refresh model parameters in situ. Similarly, the observer design should be resilient to intermittent sensor outages and should provide graceful degradation. Practical deployment also benefits from safety mechanisms that return the spindle to passive operation under fault conditions, since hydrostatic bearings inherently provide stable support when actuators are disabled.

Cost and complexity considerations also matter. Adding micro-valves, pressure sensors, piezoelectric actuators, and the requisite real-time control hardware increases system complexity and cost. However, for applications where sub-micrometer rotational accuracy directly translates into process yield, throughput, or product performance, the incremental cost may be justified. The retrofit-friendly nature of the proposed method helps by minimizing invasive mechanical changes and leveraging the existing hydrostatic architecture.

Future enhancements include adaptive control to cope with slow parameter drift, improved valve drivers with lower deadband and higher bandwidth, integration of machine learning-based disturbance predictors for anticipatory feedforward, and closed-loop identification procedures to maintain model fidelity over the spindle’s service life. Extending the concept to multi-axis spindles and exploring alternative fast actuators with larger stroke or force density are further avenues for development.

9. Conclusion

This paper has presented a hybrid active control method for improving rotational accuracy in ultra-precision hydrostatic spindles. The design leverages the complementary strengths of pocket pressure modulation and piezoelectric micro-actuation, allocating low-frequency and quasi-static corrections to hydraulic channels while reserving high-frequency synchronous and harmonic suppression for piezoelectric actuators. A reduced-order model guided controller synthesis and observer design, enabling model-based feedforward and complementary feedback coordination. Simulation and hardware-in-the-loop testing demonstrate substantial reductions in first-harmonic synchronous amplitude and low-frequency drift, while maintaining robust stability margins under realistic parameter uncertainty.

The approach is practical for retrofit implementation and offers a clear pathway to extend the performance envelope of existing hydrostatic spindles into regimes demanded by contemporary ultra-precision manufacturing and metrology. Future work will focus on laboratory demonstrators with full-scale spindles, adaptive model updating in service, and exploration of enhanced actuator technologies to further push the boundaries of rotational accuracy.

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