

## APPLICATIONS OF ROTATIONAL DYNAMICS IN GYROSCOPE-BASED SENSORS: A SYSTEMATIC LITERATURE REVIEW

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### Abstract

*Gyroscope-based sensors measure angular velocity in consumer electronics, robotics, and navigation. However, research lacks explicit relationship between rotational dynamics principles and optimisation of sensor architectures. This review examines the application of mechanical concepts conservation of angular momentum, moment of inertia, torque, and the Coriolis effect to gyroscope-based sensors. Per PRISMA guidelines, twelve studies between 2020 and 2026 were selected from Scopus, ScienceDirect and IEEE Xplore. The stringent inclusion criteria coupling classical rotational dynamics with architectural optimization, yielding a highly specialized but methodologically rigorous dataset. Study quality was assessed using a standardized critical appraisal checklist. Operational mechanisms, error dynamics, control strategies, and performance optimisation in MEMS, atomic, and photonic systems are the main topics. Three themes emerge from the findings: (1) mechanical flaws are error sources calling for control engineering; (2) mode splitting and bias instability decrease accuracy but can be lessened with control systems and electrostatic tuning; and (3) testing protocols must be standardised because of data from operating environments. Sensor accuracy and stability can be improved by combining rotational dynamics principles with control techniques like Kalman filtering and fuzzy logic, achieving scale-factor stabilization residuals as low as 2 ppm and bias instability reductions exceeding 50% in optimized architectures.*

**Keywords:** *rotational dynamics; gyroscope sensors; MEMS; coriolis effect; systematic review; prisma; inertial measurement unit*

### RESEARCH BACKGROUND

Rotational dynamics is a branch of classical mechanics that studies the motion of rotating rigid bodies based on the principles of conservation of angular momentum, moment of inertia and torque. This fundamental principle is not only a theoretical foundation in physics, but also the operational basis for modern inertial sensors known as gyroscopes, devices capable of detecting and measuring the angular velocity of an object in three-dimensional space [2]. The key phenomenon exploited in gyroscope sensors is the Coriolis effect, where an oscillating proof mass experiences a secondary force when the system undergoes external rotation, thereby enabling high-precision angular velocity measurements [3,4].

The development of Micro Electro Mechanical System/MEMS technology has revolutionized the design of gyroscopes from rotating mechanical devices to micrometer-sized solid-state sensors that can be mass produced at affordable costs [5]. Modern

MEMS gyroscopes operate on the principle of resonant vibration and the Coriolis effect, in which micro-mechanical elements are activated to oscillate at certain resonant frequencies; when external rotation occurs, the Coriolis force induces secondary vibrations in a direction perpendicular to the direction of the primary vibration, which are then converted into electrical signals proportional to the angular velocity [6]. The advantages of MEMS gyroscopes miniature size (1–100  $\mu\text{m}$ ), low power consumption (<10 mW), high reliability, and monolithic integration capability with CMOS circuits have expanded their applications from precision navigation systems to everyday consumer devices such as smartphones, game consoles, and automotive safety systems [7].

In the field of robotics and control systems, MEMS gyroscopes are used for platform stabilization such as camera gimbals on drones, fall detection on humanoid robots, and precision navigation on unmanned aerial vehicles (UAVs) through integration in Inertial

Measurement Units (IMUs) for real-time attitude determination [8]. Even in the health sector, MEMS gyroscopes have been adapted for human gait analysis through wearable technology that can detect movement abnormalities and predict the risk of falls in the elderly with high accuracy using gyroscope and accelerometer-based inertial sensors [9]. Recent developments also demonstrate the integration of gyroscopes with photonic technologies such as ring laser gyroscopes (RLGs) that utilize the Sagnac effect for extreme precision navigation applications in space missions and space launch vehicle guidance systems[10].

Despite the extensive deployment of these sensors, the explicit linkage between fundamental rotational dynamics and the optimization of modern sensor architectures remains fragmented within existing literature. While numerous studies address material properties or electronic signal processing, the critical role of classical mechanical principles in defining sensor limits, error sources, and dynamic stability is often understated. A consolidated understanding of these mechanical foundations is essential for advancing sensor precision, particularly in high-demand applications where angular momentum conservation and torque management are paramount.

Consequently, this literature review aims to comprehensively examine the application of rotational dynamics principles in modern gyroscope-based sensors. By synthesizing current research, this paper analyzes how theoretical concepts such as torque, moment of inertia, and the Coriolis effect are engineered into contemporary devices to achieve high performance. Furthermore, it identifies current technological trends, implementation challenges, and potential future directions, serving as a strategic reference for researchers and engineers seeking to leverage classical mechanics for next-generation inertial sensing technologies.

To address these research questions, the following section outlines the systematic methodology employed to identify, select, and synthesize the relevant literature.

## **METODE**

### **Search Strategy and Data Sources**

This research uses a Systematic Literature Review (SLR) approach which refers

to the PRISMA 2020 guidelines [11]. A comprehensive literature search was conducted through three reputable academic databases: Scopus, ScienceDirect, and IEEE Xplore. The publication period was restricted to 2020–2026 to specifically capture the post-MEMS maturity era, the integration of AI-driven error compensation, and the recent emergence of hybrid atomic/photonic architectures, ensuring the review reflects contemporary technological trajectories and avoids outdated pre-2020 methodological baselines. The complete Boolean search strings and database-specific query operators are provided in Appendix A (Supplementary Material).

### **Study Selection and Eligibility Criteria**

Inclusion criteria included journal articles and conference proceedings discussing the principles of rotational dynamics in gyroscope sensors, gyroscope operational mechanisms based on fundamental physics laws, and gyroscope applications in robotics, navigation, health, or physics education. Exclusion criteria included duplicate search results, publications without full-text access, articles irrelevant to the topic, and abstracts or editorials without substantive analysis.

### **Data Extraction and Synthesis**

Selected articles were analyzed through data extraction regarding the research objectives, methodological approaches, key findings related to rotational dynamics, and implications for the development of next-generation inertial sensing technologies. Synthesis was conducted descriptively and qualitatively through thematic grouping, cross-study comparison, and integration of findings.

### **PRISMA Flow and Selection Process**

The selection process followed the PRISMA flowchart as shown in Figure 1. Of the 459 records identified through database searches (Scopus:  $n=200$ , ScienceDirect:  $n=121$ , IEEE Xplore:  $n=138$ ), 435 duplicate and irrelevant records were removed before screening. Specifically, 300 duplicate records were removed; the high proportion of duplicates (65%) is attributable to the overlapping indexing across the three databases, as many journals are simultaneously indexed in more than one database. An additional 100 records were excluded through manual title and abstract

screening by the primary author. A further 35 records were removed for other reasons, specifically non-English publications and articles outside the scope of rotational dynamics and gyroscope sensor optimization. To validate the search strategy, a benchmark set of five well-known key articles on gyroscope design and rotational dynamics was confirmed to be retrievable using the applied Boolean strings. This left 24 records for the title and abstract screening stage. Twelve records were excluded during screening due to their irrelevance to the core topic (e.g., focus on quantum physics, non-gyroscope-based methods, or only signal processing without rotational dynamics analysis). Twelve articles passed to the full-text assessment stage. During eligibility assessment, no additional articles were excluded as the 12 articles already met all inclusion criteria.

Finally, 12 articles were included in the systematic review.

**Quality Assessment**, to ensure the reliability of the synthesized data, two reviewers independently assessed the 12 included studies using a standardized critical appraisal checklist adapted from the Mixed Methods Appraisal Tool (MMAT) [12]. Each study was evaluated based on three core criteria: (1) clarity of research objectives and alignment with rotational dynamics principles; (2) methodological rigor in sensor design, simulation, or experimental validation; and (3) completeness of data reporting regarding error dynamics and performance metrics. Discrepancies were resolved through consensus, yielding an inter-rater reliability of Cohen’s  $\kappa = 0.86$  (substantial agreement).

Table 1. Summary of Quality Appraisal Criteria Adapted from the Mixed Methods Appraisal Tool (MMAT)

No.	Criterion	Operational Definition	Weight	Scale
C1	Clarity of research objectives and alignment with rotational dynamics principles	Research questions are explicitly stated and directly address gyroscope mechanics or rotational dynamics; study scope is well-defined	30%	0 – 2
C2	Methodological rigor in sensor design, simulation, or experimental validation	Methods are replicable and appropriate; validation includes quantitative performance metrics (e.g., drift, noise, bias stability)	40%	0 – 2
C3	Completeness of data reporting regarding error dynamics and performance metrics	Key sensor error parameters (bias, scale factor, ARW) are reported with sufficient detail for cross-study comparison	30%	0 – 2

*Note: Each criterion scored 0 (not met), 1 (partially met), or 2 (fully met). Maximum total = 6 points = 100%. Studies scoring below 70% ( $\leq 4.2$  points) were excluded. All 12 shortlisted articles met the threshold. Inter-rater reliability: Cohen’s  $\kappa = 0.86$  (substantial agreement). Full scoring rubric and per-study scores are provided in Supplementary Material.*

Table 1 presents a summary of the quality appraisal criteria and their respective weights. Criterion 1 (clarity of research objectives) was weighted at 30%, Criterion 2 (methodological rigor) at 40%, and Criterion 3 (completeness of data reporting) at 30%. The detailed scoring rubric and full weight distribution are provided in Supplementary Material.

### Study Limitations

Although this systematic review was conducted in strict adherence to the PRISMA 2020 guidelines, several limitations must be acknowledged. First, the literature search was restricted to articles published in English. This may have excluded significant scientific contributions from regions that publish in local languages, such as China or Japan, which are key players in the gyroscope industry. Second,

there is a potential for publication bias, as journals tend to prioritize studies reporting positive results or significant performance leaps, while technical failures or neutral results often remain unpublished. Third, database access constraints outside the author's institutional subscriptions may have limited the number of full-text articles reviewed, making the data synthesis dependent on availability within Scopus, ScienceDirect, and IEEE Xplore. Lastly, the relatively recent timeframe (2020–2026) might overlook classical theoretical foundations that are not revisited in contemporary literature.

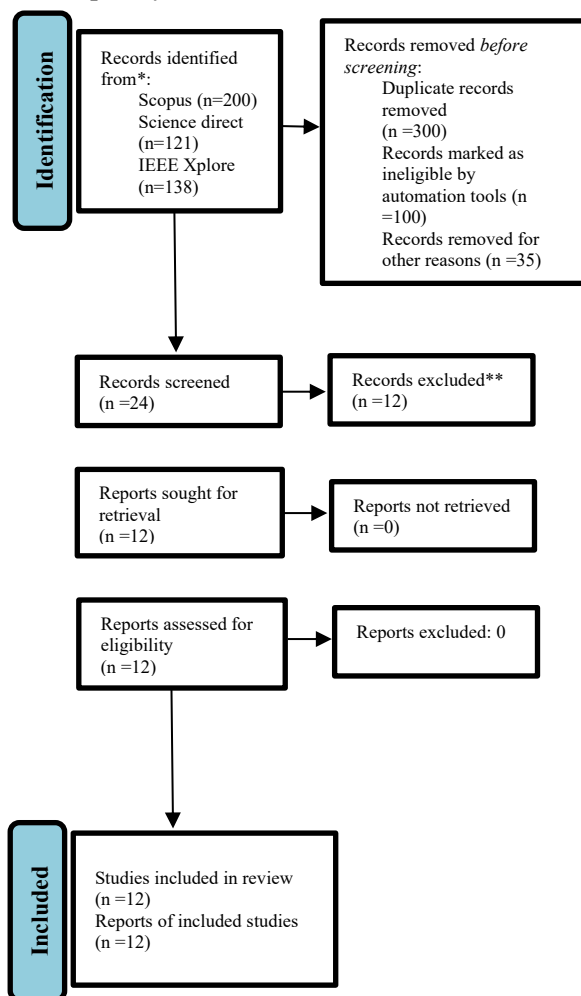


Figure 1. PRISMA Flowchart

## RESULT AND DISCUSSION

### Fundamental Principles of Rotational Dynamics in Gyroscopes

Rotation dynamics in modern MEMS-based gyroscope sensors no longer rely on rotor precession, but instead utilize the Coriolis effect, a pseudo-force that appears in a rotating

frame of reference, as a physical transduction mechanism to measure angular velocity. Fundamentally, the Coriolis effect can be derived from the law of conservation of angular momentum in a non-inertial frame. Consider a particle with mass  $m$  moving at speed  $\mathbf{v}_r$  relative to a frame rotating with angular velocity  $\mathbf{\Omega}$ , in an inertial frame, the linear momentum of a particle,

$$\mathbf{p} = m(\mathbf{v}_r + \mathbf{\Omega} \times \mathbf{r}) \quad (1)$$

This rate of change of momentum gives:

$$\frac{d\mathbf{p}}{dt} \Big|_{inertial} = m \frac{d\mathbf{v}_r}{dt} \Big|_{rot} + m\mathbf{\Omega} \times \mathbf{v}_r + m \frac{d\mathbf{\Omega}}{dt} \times \mathbf{r} + m\mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}) \quad (2)$$

ignoring angular acceleration

$$(d\mathbf{\Omega}/dt \approx 0) \quad (3)$$

for constant rotation and grouping the terms, the equation of motion in the rotating frame is obtained:

$$m\mathbf{a}_r = F_{real} - 2m(\mathbf{\Omega} \times \mathbf{v}_r) - m\mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}) \quad (4)$$

where the second term

$$-2m(\mathbf{\Omega} \times \mathbf{v}_r) \quad (5)$$

represents the Coriolis force  $F_c$  which is a manifestation of rotational dynamics in a non-inertial system [13]. In a MEMS gyroscope, the micro proof mass is activated to oscillate harmonically in the drive axis direction with a speed of

$$\mathbf{v}_d = v_d \hat{\mathbf{x}} \cos(\omega_d t). \quad (6)$$

When the system experiences external rotation  $\mathbf{\Omega} = \Omega \hat{\mathbf{z}}$ , The Coriolis force induces secondary vibrations in the sense axis:

$$F_c = -2m(\mathbf{\Omega} \times \mathbf{v}_d) = -2m\Omega v_d \cos(\omega_d t) \hat{\mathbf{y}} \quad (7)$$

which results in a response shift

$$\mathbf{y}(t) = \frac{2m\Omega v_d}{k_s} Q_s \sin(\omega_d t) \quad (8)$$

in sensing mode with stiffness  $k_s$  and quality factor  $Q_s$ . The factor of 2 in Equation (8) originates directly from the Coriolis force expression in Equation (7), where  $F_c = -2m(\mathbf{\Omega} \times \mathbf{v}_d)$ , and is preserved through the steady-state solution of the driven harmonic oscillator equation. The amplitude of this response is directly proportional to the input angular velocity  $\mathbf{\Omega}$ , thus enabling rotational measurements with sensitivity down to  $0.01^\circ / s/\sqrt{\text{Hz}}$  in degenerate resonant ring designs [13]. This principle of energy transfer between orthogonal vibration modes, which is mathematically equivalent to coupling via rotation operators in phase space, is the operational foundation of a whole family of modern MEMS vibrational gyroscopes, including tuning forks, wine-glass resonators,

and disk resonators. The integration of this principle with silicon-on-insulator (SOI) microfabrication technology enables the realization of solid-state sensors <5 mm<sup>2</sup> in size with power consumption <5 mW, which have revolutionized inertial navigation systems from aerospace applications to wearable healthcare devices [7]. Throughout this manuscript, vectors are denoted in bold (e.g.,  $\Omega$ ,  $v$ ), while scalars and magnitudes are italicized (e.g.,  $m$ ,  $\omega$ ,  $Q$ ). Angular velocity  $\Omega$  is expressed in rad/s, linear velocity  $v$  in m/s, and mass  $m$  in kg.

### Operational Mechanism and MEMS Gyroscope Design

The operational mechanism of MEMS gyroscopes relies on vibrational energy transfer between orthogonal axes through the Coriolis effect, rather than the precession of spinning rotors in classical gyroscopes. This section details the core design principles and physical mechanisms that enable precise angular velocity sensing in modern MEMS-based systems.

#### Fundamental Operating Principle

A MEMS gyroscope consists of a microfabricated proof mass suspended by elastic springs, driven into harmonic oscillation along the *drive axis* (e.g.,  $x$ -direction) at its resonant frequency  $\omega_d$ . When the device undergoes external rotation with angular velocity  $\Omega$ , the Coriolis force induces secondary oscillations along the *sense axis* (e.g.,  $y$ -direction), perpendicular to both the drive motion and rotation axis. The Coriolis force is given by:

$$F_c = -2m\Omega \times v_d \quad (9)$$

where  $m$  is the proof mass,  $v_d$  is the drive velocity, and  $\Omega$  is the input rotation vector. The resulting sense-axis displacement  $y(t)$  is proportional to  $\Omega$ , enabling angular velocity measurement.

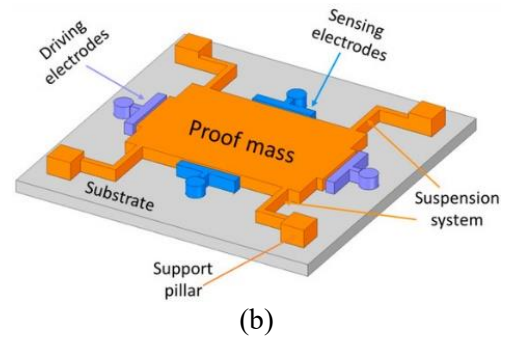
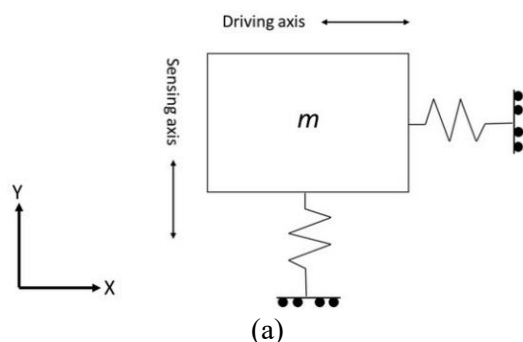


Figure 2. (a) simplified 2-DOF mass-spring system and (b) physical implementation with proof mass, drive/sense electrodes, and suspension system

As shown in Figure 2, the MEMS gyroscope system consists of a proof mass that is driven on the  $x$ -axis (drive axis) via a driving electrode, producing harmonic vibrations at the resonant frequency. When the device undergoes external rotation with an angular velocity  $\Omega$ , the Coriolis force induces secondary vibrations in the  $y$ -axis (sense axis) perpendicular to the direction of motion of the actuator. Figure 2(a) illustrates the basic principle of energy transfer via the Coriolis effect in a two-degree-of-freedom mass-spring system, while Figure 2(b) depicts the physical implementation with the proof mass suspended via a spring mechanism and equipped with drive/sense electrodes for signal detection [14].

### Resonant Frequency Response and Sensitivity

MEMS gyroscopes operate optimally when the *drive* and *sense* modes are tuned to the same resonant frequency ( $\omega_d = \omega_s$ ), maximizing signal-to-noise ratio (SNR). However, manufacturing imperfections cause mode splitting (frequency mismatch), reducing sensitivity. Advanced designs use electrostatic tuning to compensate for this split. The output signal amplitude  $A_{out}$  is:

$$A_{out} = \frac{2m\Omega v_d Q_s}{k_s} \quad (10)$$

where  $Q_s$  is the quality factor of the sense mode and  $k_s$  is its stiffness.

As illustrated in Figure 3b, the frequency split ( $\Delta f$ ) between X-mode and Y-mode causes a significant reduction in signal amplitude, with the output decreasing proportionally to  $1/\Delta f$ .

The quality factor ( $Q$ ) directly influences the bandwidth and sensitivity, where higher  $Q$  values yield sharper resonance peaks but narrower operational bandwidth

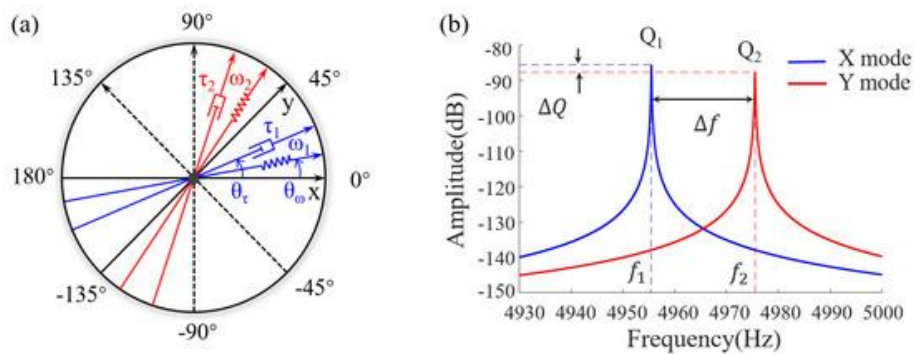


Figure 3. (a) Schematic diagram of the fully symmetric gyroscope model including the anisodamping error and frequency split. (b) The amplitude frequency response of the principal mode in the LFM model, reflecting the quality factor and the resonant frequency of the resonator [15]

### Microfabrication and Physical Structure

MEMS gyroscopes are fabricated using silicon-on-insulator (SOI) technology, which enables high-precision structures with sub-100- $\mu\text{m}$  dimensions and high aspect ratios (10:1–30:1). The fabrication process typically involves photolithography, deep reactive ion etching (DRIE), and selective oxide removal to release suspended microstructures.

The physical architecture comprises four critical components:

- Proof mass (50–200  $\mu\text{m}$ ): Central inertial element suspended by folded-beam springs to achieve high  $Q$ -factors ( $>10,000$  in vacuum).
- Comb fingers: Interdigitated electrodes (0.5–2  $\mu\text{m}$  gaps) for electrostatic drive actuation and capacitive Coriolis motion sensing.
- Suspension springs: Folded-beam structures providing controlled stiffness along drive/sense axes while minimizing energy dissipation.
- Anchor pillars: Connection points to the substrate designed to reduce anchor loss a major source of damping in MEMS resonators.

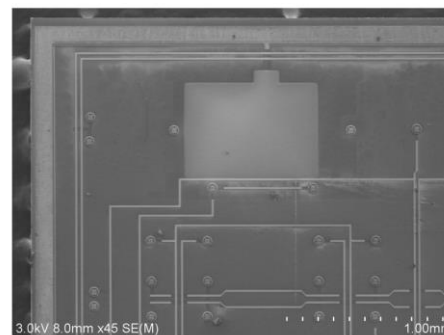


Figure 4. SEM image of fabricated gyroscope CAP wafer [16]

As shown in Figure 4, the SEM image reveals a fully released proof mass centered within comb finger arrays, connected to anchor pillars via folded-beam springs. The 100- $\mu\text{m}$  scale bar confirms the microscale dimensions required for high-frequency resonant operation (typically 5–20 kHz). Manufacturing imperfections such as critical dimension variations, sidewall angle deviations, and residual stress can cause mode mismatch between drive and sense frequencies, directly degrading sensitivity and bias stability. Advanced SOI processes with precise etch control and post-fabrication annealing minimize these effects, enabling commercial-grade performance in compact form factors suitable for consumer electronics and aerospace applications.

### Signal Processing Chain

The signal processing chain of MEMS gyroscopes converts mechanical motion into precise digital angular rate measurements through a series of critical stages. As illustrated in Figure 4, the system begins with analog signals from capacitive sensing electrodes that capture the Coriolis-induced displacement of the proof mass. The signal undergoes switched-phase sensitive demodulation to extract angular rate information while rejecting noise, followed by low-pass filtering to remove high-frequency components. The demodulated signal then

enters a single-bit quantized sigma-delta ( $\Sigma\Delta$ ) modulator that provides high linearity in the digital output. This bitstream is processed through a fifth-order cascade filter (comprising third-order CIC and second-order IIR filters) that suppresses quantization noise and converts it into a clean 24-bit digital output signal. The resulting high-resolution digital output enables precise angular rate measurement with a signal-to-noise ratio (SNR) of 111.56 dB and nonlinearity of only 0.03% over the full-scale range, as verified in experimental results.

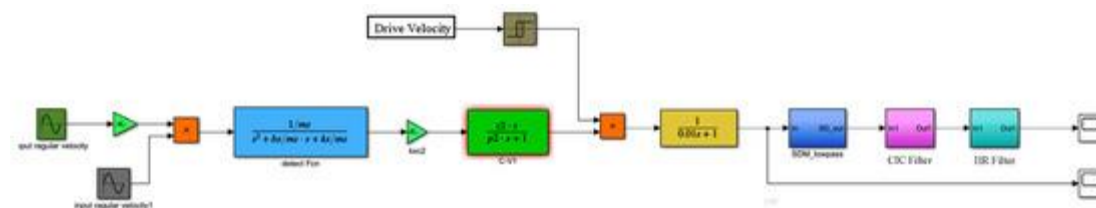


Figure 5. Signal processing chain of MEMS gyroscope sense circuit [17]

### Synthesis Literature Finding

Table 2 synthesizes findings from 12 included studies published between 2020 and 2026. Of the 12 studies, 6 (50%) focused on MEMS-based gyroscopes, 3 (25%) on Control Moment Gyroscopes (CMG), 2 (17%) on atomic/NMR systems, and 1 (8%) on Ring Laser Gyroscopes (RLG). The majority of studies (67%) were published in IEEE and Elsevier journals, reflecting the dominance of these publishers in inertial sensing research.

Quality scores reported in Table 2 were calculated based on the three weighted criteria established in the Quality Assessment section (Table 1), where C1 (clarity of research

objectives) was weighted at 30%, C2 (methodological rigor) at 40%, and C3 (completeness of data reporting) at 30%. Each criterion was scored on a scale of 0 (not met), 1 (partially met), or 2 (fully met), yielding a maximum raw score of 6 points. The final percentage score was derived using the formula: Quality Score (%) = (weighted sum / 6) × 100. Studies achieving ≥85% were classified as High quality, 70–84% as Medium quality, and <70% as Low quality. All 12 included studies met the minimum threshold of 70%, confirming the methodological soundness of the synthesized evidence.

Table 2. Synthesis of Included Studies on Gyroscope Technologies (2020–2026)

References	Gyroscope Type	Testing Method	Research Focus	Key Performance	Key Findings	Quality Score
[18]	Cold-Atom Gyroscope based Point-Source Interferometry (PSI)	Kalman Filter Simulation	Real-time rotational scale-factor calibration using CG-assisted compensation	Scale-factor stabilization: mean residual 2ppm, std dev 230ppm; enables high-dynamic operation	Kalman filter effectively tracks scale-factor drift; CG-based decoupling enables PSI operation in dynamic environments	High (92%)
[19]	3-DOF Control Moment Gyroscope	Lyapunov stability analysis, Simulink simulation, experimental CMG platform	Hybrid LQR, interval type-3 fuzzy logic control for robust stabilization under disturbances	Tracking errors converge to small residuals; reduced chattering; lower RMSE vs. PID/LQR/T2-FLC	IT3-FLS outperforms T1/T2 for uncertainty modeling; online adaptation compensates tuning errors; observer	High (88%)

[20]	CMG (Dual Flywheel)	CREO modeling, ANSYS simulation, experimental testing on electric scooter	Self-balancing mechanism for electric moped using CMG with PID/IMU feedback	160.40 Nm reactive torque; balances $\leq 10^\circ$ tilt; 5500 rpm flywheel; +11.76% power consumption	enhances robustness to signal changes CMG effectively stabilizes scooter statically/dynamically; 24.54% weight & 36.36% cost increase noted; lightweight materials recommended for optimization	Medium (78%)
[21]	Stochastic MEMS Gyroscope	Numerical simulation (MATLAB)	Adaptive fuzzy control, fixed-time vibration reduction, low communication event-triggered mechanism	Tracking errors converge to small residuals in fixed time; reduced initial control chattering via QPPF	IT3FLS outperforms T1/T2 FLS for stochastic disturbances; QPPF mitigates initial vibrations; STETM reduces communication load without accuracy loss	High (85%)
[22]	Gyroscopic Continua (Rotating/Axially Moving Structures)	Literature Review and Theoretical Analysis	Gyroscopic coupling mechanisms, complex modal analysis, centrifugal/nonlinear effects	Unified governing equations; complex modal solutions with frequency bifurcation and traveling wave characteristics	Gyroscopic terms induce elliptical/traveling wave modes; centrifugal effects increase natural frequencies; framework applicable to aerospace, MEMS, and fluid-conveying systems	Medium (75%)
[23]	Symmetric rigid body with gyrostatic torque	Analytical solution via complex variable transformation; Taylor series expansion; phase portrait analysis using Wolfram Mathematica	Novel analytical solutions for angular velocities under time-dependent gyrostatic torque and constant body-fixed torques	Closed-form angular velocity solutions; phase portrait stability analysis	Higher gyrostatic torque values enhance system stability by reducing oscillation amplitudes; applicable to spacecraft and gyroscope design	Medium (80%)
[24]	Spacecraft Attitude System (Three-Ring Architecture)	Discrete State-Space Simulation	MPC based attitude control with time varying inertia compensation	Precise attitude tracking, low angular velocity, energy-efficient, robust to disturbances	MPC effectively manages varying inertia; minimizes reaction wheel dependency; maintains stability under gyroscopic coupling	High (90%)
[1]	K-Rb-21Ne SERF Atomic Spin Gyroscope	Dual beam-splitting structure, gradient descent adaptation, Lyapunov analysis, lab experiments	Real-time suppression of spin polarization error (SPE) from laser pumping rate drift using adaptive light compensation	Allan variance improved 54.4%/74.5%/74.6% at 100s/500s/1000s; $1.36 \times / 2.91 \times$ better disturbance rejection	Dual beam-splitting captures time-varying splitting ratio drift; adaptive control ensures parameter convergence; Lyapunov analysis guarantees closed-loop stability	High (94%)
[25]	NMR (Atomic)	Simulation & Experimental Validation	Bias magnetic field estimation using Nonlinear Disturbance Observer (NDO)	Convergence time reduced from 7.87s to 4.28s (1.84x enhancement); overshoot-free	NDO-based method accelerates estimation and improves stability compared to conventional PI control methods.	High (89%)

[26]	Ring Laser (RLG)	Theoretical Analysis & Numerical Simulation	Sensitivity enhancement near Exceptional Point (EP) using scattering interface	Sensitivity enhancement up to $10^2$ order near EP	EP enhances sensitivity significantly; Kerr nonlinearity affects eigenplanes and shifts EP position at high input power.	Medium (76%)
[27]	Gyroscopic Dynamics (FOWT)	Simulation & Theoretical Modeling	Incremental LQG tracking control under gyroscopic coupling effects	37% lower cumulative cost compared to conventional PI control	Gyroscopic effects reconfigure stability boundaries; LQG control mitigates process/measurement noise better than PI.	Medium (82%)
[7]	MEMS	Modeling & Simulation (6-DoF)	Application-oriented selection & error modeling for GNC systems	Derived practical rules of thumb for error evaluation	Critical parameters vary by application (e.g., bandwidth for control, bias for navigation); price does not guarantee performance; IMU arrays improve robustness.	High (87%)

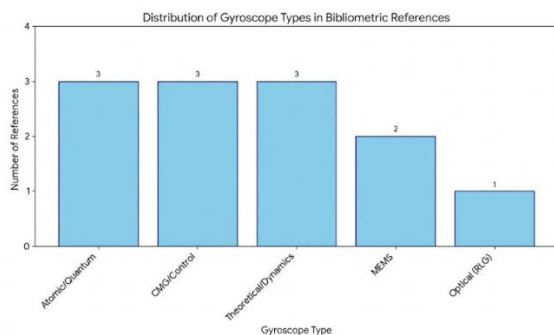


Figure 6. Analysis of Gyroscope Technology Categories in Recent Research

Research on gyroscope-based sensors has evolved from classical mechanical rotating bodies to advanced MEMS and atomic interferometry systems, according to a review of 12 recent articles published between 2020 and 2026.

There were three primary patterns found. First, control engineering is necessary because mechanical imperfections serve as error sources. Second, mode splitting and bias instability lower accuracy and cause drift, which can be managed by electrostatic tuning or hybrid control systems. Third, the standardization of testing protocols is crucial because different operational environments continue to yield inconsistent data. These results validate that a strategic approach for gyroscope development is to combine advanced

control theories with fundamental rotational dynamics principles.

There are still some discrepancies despite the general consensus. For instance, some research emphasizes mechanical stability under high dynamic conditions [24], while other research primarily links performance to quantum effects or atomic spin dynamics [1,18]. This implies that a unified performance model is still elusive and that dominant error pathways may be dependent on the specific sensor architecture (MEMS vs. Atomic).

Quality Score Criteria:

- High ( $\geq 85\%$ ): Experimental validation, rigorous simulation, clear methodology, complete data reporting
- Medium (70-84%): Simulation-only or theoretical studies with sound methodology but limited experimental validation
- Low ( $< 70\%$ ): Studies with methodological gaps, incomplete data, or unclear alignment with rotational dynamics principles (*none in final selection*)

### Research Implications

A review of the literature supports a number of significant implications for the future of gyroscope research. First, because variations in temperature, vibration, and electromagnetic conditions in testing frequently produce data that is challenging to replicate, standardization of evaluation methodologies is crucial [2]. It has been demonstrated that adaptive control and

real-time calibration protocols are more representative and could become the norm [18,25]

Second, there is growing promise in the integration of intelligent control approaches. Fuzzy logic control demonstrates robust stabilization under disturbances [19], Model Predictive Control (MPC) reveals effective management of varying inertia [24], and deep learning successfully visualizes error compensation directly related to bias stability in low-cost sensors [27].

Third, optimization relies heavily on structural and material control. While symmetric rigid body designs enhance system stability by reducing oscillation amplitudes [23], manufacturing imperfections are identified as recombination centers for noise that lower quality factors [16]. Fourth, operando monitoring has shown that environmental factors decrease sensitivity and deteriorate stability [5]. Partial solutions are provided by vacuum packaging or thermal compensation. Fifth, the trend toward multimodal methods, like combining MEMS with atomic references or photonic technologies, improves the analysis of navigation errors from the microscale to the system scale [3,10]. In addition to resolving inconsistencies in characterization protocols, future gyroscope research must tackle practical issues like cost reduction, multi-sensor fusion, and educational implementation. Conflicting reports on error sources and drift mechanisms have resulted from the absence of standardized testing conditions, such as temperature ranges, vibration profiles, and duration.

To convert nanoscale insights into dependable commercial devices, benchmark protocols must be established through cooperative efforts.

## CONCLUSION

This systematic literature review synthesizes evidence from 12 peer-reviewed studies to demonstrate that the stability and efficiency of modern gyroscope sensors depend critically on the integration of fundamental

rotational dynamics with advanced control mechanisms. Three dominant patterns emerge: (1) mechanical imperfections serve as a major source of error; (2) mode splitting and bias instability significantly degrade sensitivity and induce drift; and (3) there is a critical lack of standardization of characterization techniques across various operational environments. However, these findings are derived from 12 studies meeting strict inclusion criteria focused on rotational dynamics and gyroscope sensor optimization; therefore, generalization beyond this scope should be approached with caution. While current research shows promise in the use of intelligent control systems such as fuzzy logic and Kalman filters to mitigate these issues, evidence suggests that balancing high precision with long-term durability remains a significant technical challenge.

Based on the identified gaps, future research should prioritize: (1) rigorous experimental validation of hybrid control models in high-dynamic environments; (2) establishment of standardized testing protocols for temperature ranges ( $-40^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$ ), vibration profiles (20–2000 Hz), and Allan variance duration ( $\geq 1000$  s); (3) investigation of direct correlations between microfabricated material defects and real-time error compensation algorithms; and (4) empirical data collection for atomic and quantum gyroscopes outside controlled laboratory settings to assess long-term reliability.

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