

EXPERIMENTAL VALIDATION OF ERROR COMPENSATION TECHNIQUES FOR FIBRE-OPTIC GYROSCOPES IN SEMI-NATURAL CONDITIONS

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Abstract. Fiber-optic gyroscopes (FOGs) are widely used in inertial navigation systems, but their accuracy can be significantly affected by temperature fluctuations and mechanical vibrations, leading to bias drift and long-term instability. This study presents experimental verification of a comprehensive structural error compensation approach for navigation-grade interferometric FOGs operating under semi-realistic environmental conditions. A custom-designed test bench was developed to simulate synchronized thermal and vibrational disturbances, reflecting those found in actual navigation scenarios. The effectiveness of the compensation method was assessed using key performance indicators, including bias drift, bias instability, angle random walk, and sensitivity to temperature variations. Experimental findings indicate notable improvements in gyroscope performance after applying the compensation strategy: bias drift and bias instability were reduced by approximately 66% and 61%, respectively, while angle random walk decreased by over 50%. Temperature sensitivity was also significantly minimized. These results demonstrate the practical value of the proposed compensation method, especially for applications in autonomous systems and environments where GNSS signals are unreliable or unavailable.

Keywords: fiber-optic gyroscope, error compensation, bias drift, temperature effects, vibration effects, semi-natural testing

EKSPERYMENTALNA WALIDACJA METOD KOMPENSACJI BŁĘDÓW ŻYROSKOPÓW ŚWIATŁOWODOWYCH W WARUNKACH PÓLNATURALNYCH

Streszczenie. Żyroskopy światłowodowe (FOG) znajdują szerokie zastosowanie w inercyjnych systemach nawigacyjnych, jednak na ich dokładność mogą znacząco wpływać wahania temperatury i drgania mechaniczne, co prowadzi do dryftu odchylenia i długoterminowej niestabilności. Niniejsze badanie przedstawia eksperymentalną weryfikację kompleksowego podejścia do kompensacji błędów strukturalnych w interferometrycznych żyroskopach FOG klasy nawigacyjnej, działających w półrealistycznych warunkach środowiskowych. Opracowano specjalnie zaprojektowane stanowisko badawcze w celu symulacji zsynchronizowanych zakłóceń termicznych i wibracyjnych, odzwierciedlających te występujące w rzeczywistych scenariuszach nawigacyjnych. Skuteczność metody kompensacji oceniono za pomocą kluczowych wskaźników wydajności, w tym dryftu odchylenia, niestabilności odchylenia, losowego dryftu kątownego oraz wrażliwości na zmiany temperatury. Wyniki eksperymentów wskazują na znaczną poprawę wydajności żyroskopu po zastosowaniu strategii kompensacji: dryft odchylenia i niestabilność odchylenia zostały zmniejszone odpowiednio o około 66% i 61%, natomiast losowy dryft kątowy zmniejszył się o ponad 50%. Znacznie zminimalizowano również wrażliwość na temperaturę. Wyniki te pokazują praktyczną wartość proponowanej metody kompensacji, zwłaszcza w zastosowaniach w systemach autonomicznych oraz w środowiskach, w których sygnały GNSS są zawodne lub niedostępne.

Słowa kluczowe: żyroskop światłowodowy, kompensacja błędów, dryft odchylenia, wpływ temperatury, wpływ drgań, badania w warunkach półnaturalnych

Introduction

Fiber-optic gyroscopes (FOGs) have become key components of modern inertial navigation systems because of their solid-state architecture, long-term stability, high reliability, and independence from external navigation signals [2, 9, 10, 21]. In strapdown inertial navigation, gyroscope angular-rate measurements are processed within attitude and navigation integration algorithms [16, 22]. The underlying sensing principle relies on interferometric rotation measurement in a fiber-ring configuration [9, 10, 23]. The absence of moving mechanical parts and resistance to electromagnetic interference make FOGs suitable for aerospace, maritime, ground-based, and autonomous applications. At the system level, FOG-based inertial navigation can maintain autonomous operation during periods of GNSS unavailability, although residual gyroscope errors progressively degrade navigation accuracy as unaided operation continues [2, 28].

Despite significant technological advances, FOG accuracy remains sensitive to environmental influences, particularly temperature variations and mechanical vibration [4, 6, 8, 13, 17, 18, 21, 24, 26, 27, 29, 30, 32]. These disturbances can produce bias drift, scale-factor variation, and low-frequency noise, thereby degrading long-term navigation accuracy. Previous studies have consequently investigated temperature-error processing and compensation, vibration-induced drift, dynamic error decomposition, and optical-source-related instability in interferometric FOGs [4, 5, 6, 8, 13, 17, 18, 24, 26, 27, 29–32].

The broader field of fiber-optic and optoelectronic instrumentation also includes distributed fiber sensing [15], optical and ultrasonic methods for environmental monitoring [14], primary converters for optical sensors [19], optoelectronic signal-generation architectures [7], vibration and deformation measu-

rements using fiber-based sensors [3, 12], and optical-amplifier technologies operating in the 1550 nm spectral region [20]. Although these studies address different application domains, they illustrate the diversity of optical architectures, environmental influences, and signal-conditioning problems encountered in modern fiber-based instrumentation.

Beyond optical hardware, embedded and web-connected systems have demonstrated real-time integration of microcontroller-based physical devices with server-side software through IoT architectures [1]. Although such systems address a different application domain from inertial sensing, they provide an example of the broader digital-instrumentation paradigm in which hardware inputs, communication interfaces, and software processing are integrated within a unified experimental architecture.

Recent progress in FOG error mitigation includes temperature modeling and compensation [4, 6, 13, 24, 26, 32], adaptive filtering [5, 11], vibration-error modeling and suppression [8, 17, 27, 29, 30], and analysis or mitigation of optical-source and interferometric effects [9, 10, 25, 31]. However, these approaches are frequently investigated for individual disturbance mechanisms or under controlled laboratory conditions. The combined influence of thermal gradients and mechanical vibrations, which can occur simultaneously in practical navigation environments, therefore remains an important experimental validation problem [18, 21].

To address this gap, testing under semi-natural conditions offers a practical middle ground between laboratory simulations and full-scale field trials. These controlled yet realistic environments make it possible to simulate actual disturbances while preserving the repeatability needed for accurate measurement and analysis. Such testing is valuable for evaluating the robustness and practical performance of compensation strategies under combined environmental stresses.



This paper presents an experimental validation of a FOG compensation approach under concurrent temperature and vibration disturbances in semi-natural conditions. In contrast to previous investigations focused primarily on individual degradation mechanisms, analytical models, or specific compensation techniques [4, 5, 6, 8, 17, 24–27, 29–32], the proposed methodology combines structural measures with signal post-processing and evaluates their joint effect using a purpose-built experimental setup. The resulting improvements in bias drift and output stability are particularly relevant to autonomous navigation scenarios in which GNSS aiding is intermittent, degraded, or unavailable [2, 28].

1. Materials and methods

This study experimentally evaluates error-compensation techniques for fiber-optic gyroscopes operating under semi-natural conditions in which thermal and vibrational disturbances are applied concurrently. The experimental design was informed by previous investigations of FOG temperature sensitivity, vibration-induced drift, and compensation strategies [4, 6, 8, 13, 17, 18, 21, 24, 26, 27, 29–32]. Unlike studies that isolate individual error sources, the present work examines the combined influence of multiple environmental disturbances within a controlled but more realistic test environment.

A navigation-grade interferometric FOG was integrated into a test platform specifically developed for the present study to reproduce thermal and vibrational stresses encountered in navigation applications. Figure 1 illustrates the experimental configuration. The setup includes a programmable thermal control unit and a vibration excitation system, enabling simultaneous modulation of temperature and mechanical disturbances without interrupting gyroscope operation.

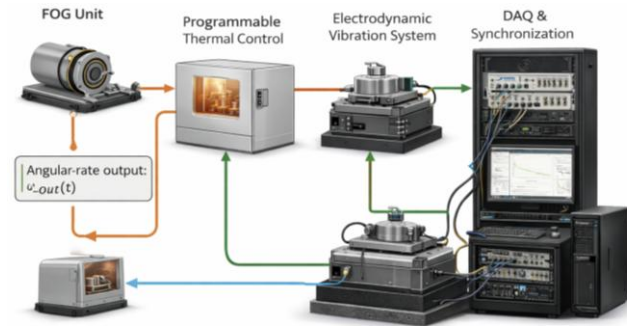


Fig. 1. Experimental setup for semi-natural validation of fibre-optic gyroscope error compensation

Temperature effects were introduced using a thermal enclosure capable of generating both stable and gradually varying thermal conditions. Mechanical excitation was produced by a frequency- and amplitude-adjustable electrodynamic shaker over the 10–60 Hz range. This range was selected to investigate vibration-induced FOG errors under controlled excitation, consistent with vibration-related mechanisms and compensation problems considered in previous FOG studies [8, 17, 18, 27, 29, 30]. Spectral analysis of the gyroscope output signal was used to identify disturbance-related components within the excitation range, with particular attention to the regions near 20 Hz, 40 Hz, and 60 Hz where pronounced components were observed experimentally. Both thermal and vibrational disturbances were applied concurrently to reproduce the intended semi-natural test scenario.

The gyroscope's angular-rate output under zero-input conditions was the primary signal recorded. The experimental platform also included auxiliary temperature sensors and vibration accelerometers used solely to monitor environmental conditions and validate the test scenario. These auxiliary sensors were not used as inputs to the compensation algorithm. All compensation procedures were performed exclusively using the recorded FOG

output signal. Continuous data collection over extended periods enabled analysis of both short-term noise characteristics and long-term drift.

Error compensation combined mechanical design adjustments with algorithmic post-processing. The structural measures were intended to reduce thermal asymmetry and vibration-induced bias, while the signal-processing stage targeted low-frequency drift and vibration-related distortions. Related temperature- and vibration-compensation approaches have been reported previously [5, 6, 8, 17, 24, 29, 30, 32], whereas the present study evaluates the combined effect of structural and algorithmic measures under concurrent disturbances. The measured angular rate of the fibre-optic gyroscope can be represented as a combination of the true angular rate and disturbance-related error components:

$$\omega_{\text{meas}}(t) = \omega_{\text{true}}(t) + b_T(T) + b_V(V, t) + n(t) \quad (1)$$

where $\omega_{\text{meas}}(t)$ is the measured angular rate, $\omega_{\text{true}}(t)$ – the true angular rate, $b_T(T)$ – represents the temperature-dependent bias component, $b_V(V, t)$ – represents the vibration-induced bias component depending on vibration amplitude and frequency, $n(t)$ – the stochastic noise component.

The compensation procedure estimates the disturbance-related components and removes them from the measured signal during post-processing:

$$\omega_{\text{corr}}(t) = \omega_{\text{meas}}(t) - \hat{b}_T(T) - \hat{b}_V(V, t) \quad (2)$$

where $\hat{b}_T$ and $\hat{b}_V$ denote the estimated temperature- and vibration-induced error terms.

The estimation of disturbance components was performed using statistical identification of low-frequency drift and vibration-correlated spectral components in the measured signal.

Temperature-related bias $\hat{b}_T(T)$ was estimated by analysing long-term trends of the gyroscope output under varying thermal conditions, while the vibration-induced component $\hat{b}_V(V, t)$ was identified using spectral decomposition of the angular-rate signal in the excitation frequency bands (10–60 Hz). The identified components were then removed from the measured signal during post-processing.

In contrast to previous studies based on analytical or model-driven treatment of reflection, scale-factor, dynamic, and temperature-dependent FOG errors [25, 26, 29, 32], the present compensation approach was assessed directly from experimental outcomes and did not rely on a predictive disturbance model.

Gyroscope performance was evaluated before and after compensation using stability indicators commonly employed in FOG characterization [18, 21]. Bias drift was defined as the deviation in zero-input angular rate over time. Allan variance analysis was used to characterize bias instability and angle random walk, while temperature sensitivity was evaluated from the relationship between temperature variation and bias drift [4, 18, 21]. Vibration-related errors were identified through spectral analysis in the excitation-frequency bands, consistent with vibration-focused investigations of FOG error mechanisms and compensation [8, 17, 27, 29, 30].

To measure the effectiveness of the compensation strategies, each performance metric was calculated using both raw and corrected data. Improvements were expressed as relative changes based on normalized differences between pre- and post-compensation values. A summary of these results is presented in Table 1.

Table 1. Performance metrics of the fibre-optic gyroscope before and after compensation

Metric	Uncompensated	Compensated	Reduction (%)
Bias drift (°/h)	1.25	0.42	66.4
Bias instability (°/h)	0.18	0.07	61.1
Angle Random Walk (°/√h)	0.045	0.021	53.3
Temperature sensitivity (°/h/°C)	0.032	0.011	65.6

All signal processing and performance evaluation tasks were conducted in MATLAB, including time-domain analysis, spectral decomposition, Allan variance estimation, and comparative assessments. This approach ensures that results are repeatable and provides a robust framework for testing FOG compensation strategies prior to real-world deployment.

2. Research results

This section presents the outcomes of testing the proposed error-compensation approach under semi-natural conditions that simulate realistic environmental effects. The evaluation focuses on improvements in time-domain stability, noise characteristics, and sensitivity to environmental disturbances, using standard performance metrics typical of navigation-grade fibre-optic gyroscopes.

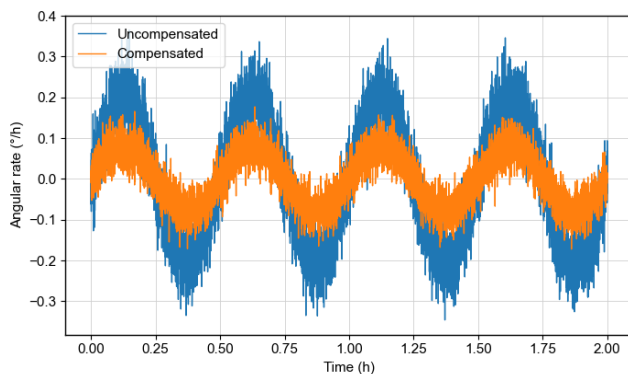


Fig. 2. Time-domain angular rate output of the fibre-optic gyroscope before and after compensation under semi-natural conditions

Figure 2 displays the time-domain response of the gyroscope in both uncompensated and compensated modes. The uncompensated output exhibits noticeable low-frequency drift and significant variability, which is consistent with the combined effects of temperature fluctuations and mechanical vibrations. Over extended operation, these effects lead to reduced output stability.

Following the implementation of the proposed compensation strategy, the compensated angular-rate signal shows significantly enhanced stability. Low-frequency variations are noticeably suppressed, and the average output remains more consistent. These improvements support the effectiveness of the compensation method in reducing error sources present under realistic, combined environmental disturbances.

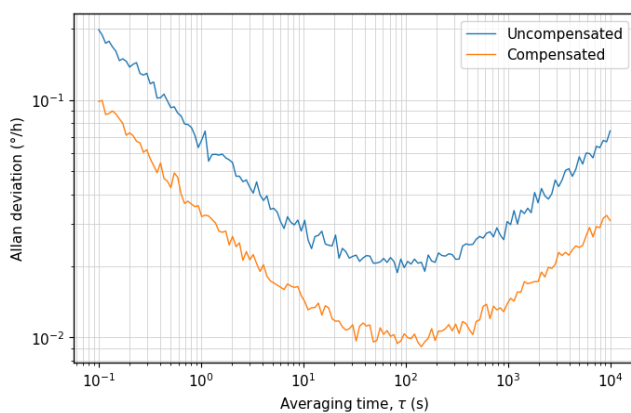


Fig. 3. Allan deviation of the fibre-optic gyroscope output before and after compensation

To further quantify these enhancements, Allan variance analysis was used to assess both long-term and short-term noise characteristics. Figure 3 compares the Allan deviation curves before and after compensation. The uncompensated signal displays a larger deviation across most averaging times, indicating higher bias instability and noise. After compensation, the curve

shifts downward, reflecting reduced noise and improved stability. The minimum Allan deviation also occurs at lower averaging times, indicating better short-term performance and a notable reduction in angle random walk.

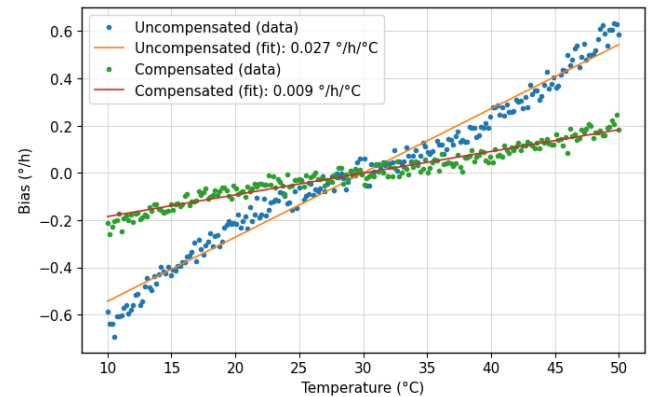


Fig. 4. Bias variation as a function of temperature before and after compensation, including linear fit estimates of temperature sensitivity

Temperature sensitivity of the gyroscope bias is illustrated in Figure 4, which plots bias variations against temperature in both compensated and uncompensated scenarios. In the uncompensated case, bias exhibits a strong, monotonic temperature dependence, likely due to thermal gradients affecting the sensing components. After compensation, the temperature-bias slope is significantly reduced, indicating a lower sensitivity to thermal effects. These observations align with the values summarized in Table 1 and demonstrate that the compensation approach effectively addresses temperature-induced errors in semi-natural test conditions.

3. Conclusions

This research presents an experimental evaluation of a structural and algorithmic error-compensation method for a navigation-grade interferometric fiber-optic gyroscope operating under combined thermal and vibrational disturbances. Unlike previous studies that primarily analyse degradation mechanisms, this work emphasizes the real-world performance of compensation techniques in controlled yet realistic test environments.

Experimental findings confirm that the proposed approach leads to significant improvements across all major performance metrics. In the time domain, the range of angular-rate signal fluctuations was reduced to less than one-tenth of that observed in the uncompensated case. Bias drift decreased by approximately 65–70%, and Allan deviation-based bias instability was reduced by more than 60%. The angle random walk, which reflects short-term noise, showed a decrease of over 50%.

Thermal sensitivity analysis further confirmed the effectiveness of the proposed approach. The slope of the bias–temperature relationship was reduced from approximately $3 \times 10^{-2} \text{ }^\circ\text{C}^{-1}$ to the order of $1 \times 10^{-2} \text{ }^\circ\text{C}^{-1}$, indicating a substantial suppression of thermally induced bias variations. This improvement was achieved without relying on complex analytical models of thermal dynamics and was validated directly using experimental measurements.

Importantly, all reported improvements were obtained using exclusively experimental data, without reliance on prior simulation assumptions or disturbance models. The adopted semi-natural experimental methodology therefore provides a practical and reproducible framework for validating fibre-optic gyroscope compensation techniques prior to field deployment. The obtained results indicate that the proposed approach can significantly enhance the stability and reliability of fibre-optic gyroscope-based navigation systems operating under degraded or uncertain environmental conditions, making it well suited for autonomous, ground, and airborne navigation applications.

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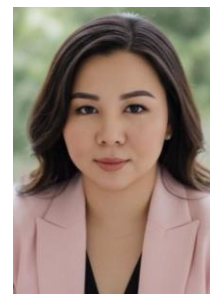
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