AN AUTOMATICALLY MODE-MATCHED MEMS GYROSCOPE WITH 50 HZ BANDWIDTH

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ABSTRACT

This paper presents the architecture and experimental verification of an automatic mode matching system that uses the phase relationship between the residual quadrature and drive signals in a gyroscope to accomplish and maintain the frequency matching condition. The system also allows controlling the system bandwidth by adjusting the closed loop controller parameters of the sense mode. This study experimentally examines the angle random walk (ARW) and bias instability performances of the fully decoupled MEMS gyroscopes under mismatched (~100Hz) and mode-matched conditions. Moreover, it has been experimentally shown that the performance of the studied MEMS gyroscopes is improved up to 2.4 times in bias instability and 1.7 times in ARW with 50 Hz system bandwidth under the mode-matched condition reaching down to a bias instability of 0.83°/hr and an ARW of 0.026°/√hr.

INTRODUCTION

Mode-matching, i.e., achieving almost 0 Hz frequency split between the drive and sense modes of the gyroscope, provides an improvement in the overall noise floor and bias instability of the sensor [1]. Various approaches have been introduced in the literature to reduce the frequency mismatch between the resonance modes. Some approaches use localized thermal stressing effects [2] or additional fabrication steps, such as selective deposition of polysilicon for the resonance frequency tuning [3]. However, these methods require a manual tuning effort, making them unsuitable in terms of process complexity, cost, and time required for every individual tuning. A more effective approach is the tuning of sense mode frequency by applying a proper DC potential, which relies on the electrostatic spring constant effect [4-8]. Electrostatic mode-matching can be achieved electronically by introducing a square wave dither signal as a quadrature error into the gyroscope and checking its phase across the resonator of the gyroscope [4] or by injecting out-of-band pilot tones into the sense electrodes and monitoring the amplitude difference between the tones [5]; however, the reported performances are limited around 10°/hr. The amplitude and phase information of the residual quadrature signal can also be used to match the drive and sense resonance frequencies, but the current implementations in the literature suffer from either performance [6] or bandwidth [7].

For the first time in the literature, this paper proposes the use of phase information of the residual quadrature signal for automatic mode-matching. This method substantially suppresses the electronic noise of the sense mode electronics and achieves sub-degree per-hour performance without sacrificing the system bandwidth, thanks to the pole-zero cancellation method [8]. This makes the proposed automatic mode-matching system ideal for high end of tactical grade applications. Moreover, this study experimentally demonstrates that the mode-matched condition enhances the bias instability and ARW of the studied MEMS gyroscopes up to 2.4 and 1.7 times with 50 Hz system bandwidth, reaching down to 0.83°/hr and 0.026°/√hr, respectively.

PROPOSED MODE-MATCHING SYSTEM

Figure 1 shows the simplified structure of the fully decoupled MEMS gyroscope studied in this work. The gyroscope structure consists of three suspended frames (drive, proof mass and sense). The drive and sense frames can vibrate along only one direction, whereas the proof mass frame vibrate along two orthogonal directions to transfer Coriolis acceleration induced by rotation to the sense mode. Although the mechanical design theoretically eliminates the coupling between the drive and sense modes completely, fabrication imperfections can lead to an undesired mechanical cross-talk, called quadrature error, between these modes. In the proposed gyroscope design, this quadrature error is cancelled by applying DC potentials to the quadrature nulling electrodes [9]. Despite quadrature nulling, a finite amount of quadrature signal always exists in the mode-matching system. This residual quadrature signal is used to accomplish and maintain the frequency matching condition.

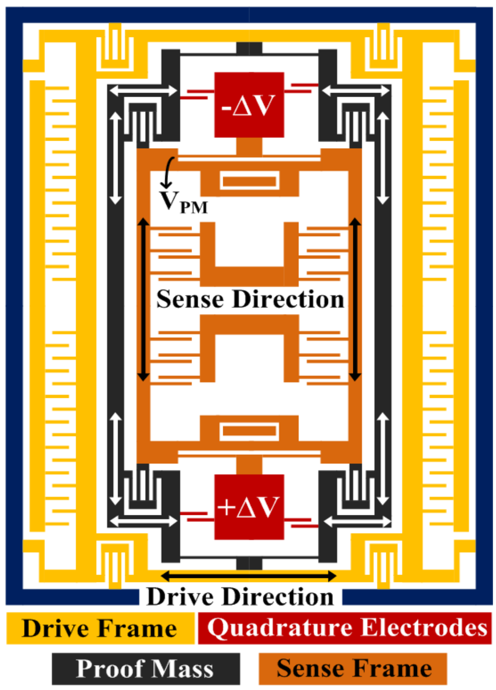

Figure 1: Simplified structure of the fully-decoupled MEMS gyroscope studied in this work.

The main motivation behind the proposed mode-matching system is to automatically tune the sense mode resonance frequency with respect to drive mode resonance frequency by using the electrostatic tuning capability of the sense mode. Figure 2 shows the frequency–voltage characteristics of the drive and sense modes of the studied MEMS gyroscope. The drive mode resonance frequency of the gyroscope remains constant at 14184 Hz, whereas the sense mode frequency of the gyroscope can be electronically tuned in the range of 14496 Hz to 12736 Hz by varying V_{PM} from 8 to 15 V. The resonance mode frequencies are perfectly matched at the proof mass potential of 9.33 V.

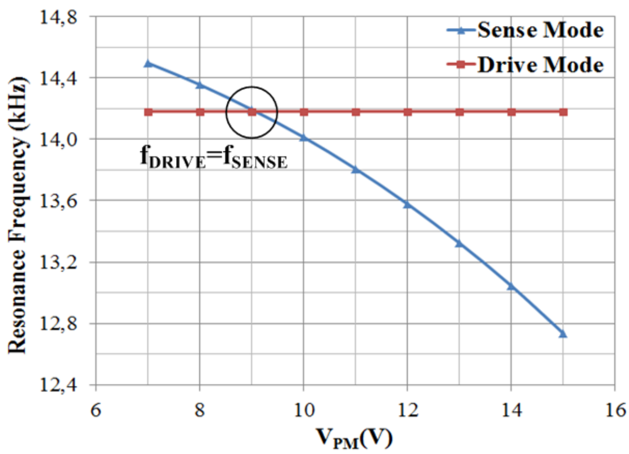

Figure 2: Frequency-tuning characteristic of the sense and drive modes of the studied fully decoupled MEMS gyroscope with changing proof mass potentials.

The automatic mode-matching system operation is mainly based on the phase relationship between the residual quadrature and drive signals in the gyroscope. Figure 3 shows the block diagram of mode-matching control electronics with an analog PI controller that is capable of matching the sense mode resonance frequency to the drive mode by changing V_{PM} by automatically in a range of only ±2.5V, and for an initial frequency split of up to 1 kHz. First, the quadrature and drive signals are directly picked from the sense pick (SP) and drive pick (DP) outputs of the gyroscope through preamplifiers, respectively. The obtained quadrature signal is demodulated with the 90° phase-shifted version of the drive signal and then the output of the demodulator is low-pass filtered to obtain the phase difference information between the drive and quadrature signals. The demodulator together with the low-pass filter equivalently operates as a phase detector. The phase difference information is fed to the PI controller which generates a DC tuning potential to adjust the phase difference between the quadrature and drive signals to the desired value (0°). Next, the DC tuning potential is applied to the proof mass of the gyroscope after summing it with the fixed proof mass potential. The fixed proof mass potential continuously sustains the drive and quadrature signals in the system, required to initiate mode-matching operation. Thus, the proposed mode-matching closed loop controller tunes the sense mode resonance frequency of the gyroscope with a potential range of ±2.5V till the phase difference between the drive and residual quadrature signals converges to zero which ensures that mode-matching has been achieved.

There is always a quadrature signal in the system due to the fabrication imperfections, and this signal has its maximum value at the mode-matched condition. If the quadrature signal is not cancelled, it does not allow the gyroscope to continuously operate at mode-matched condition since the rate output channel would be saturated then. Therefore, the quadrature signal should be reduced down to a certain level to perform the mode-matching operation with the proposed system.

Mode-matching improves the performance and increases the sensitivity of the gyroscope in the closed and open loop operation; however, it leads to a significant bandwidth limitation in the open loop operation as depicted in the previous work [7]. At mode–matched case, the system bandwidth is theoretically limited by the mechanical bandwidth of the gyroscope in the open loop operation. The use of the proposed closed-loop sense mode controller eliminates the bandwidth limitation with the aid of the PI controller. The PI controller provides an opportunity to adjust the bandwidth of the system, independently from the mechanical sensor bandwidth.

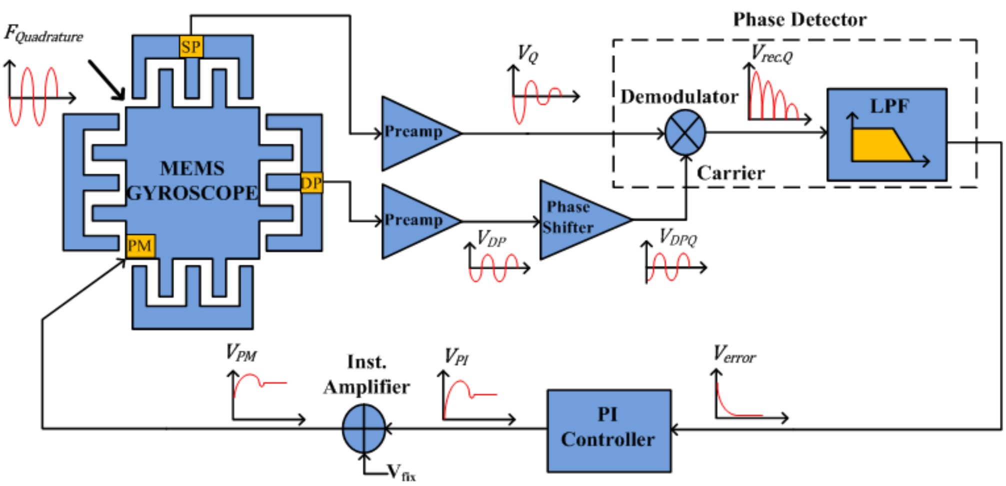

Figure 3: Block diagram of the mode-matching control electronics that is capable of matching the frequency of the sense mode to the drive mode from maximum 1 kHz separation by changing the V_{PM} in a range of ±2.5V.

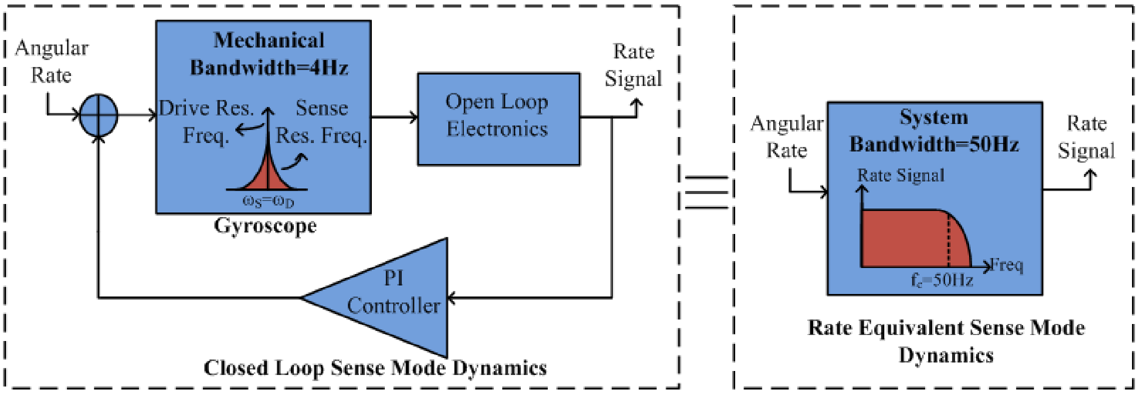

Figure 4: Closed loop sense mode dynamics with 4 Hz mechanical sensor bandwidth (on the left), and its rate equivalent sense mode dynamics with 50 Hz system bandwidth (on the right). The system bandwidth is extended by adjusting the PI controller parameters, independently from the mechanical sensor bandwidth.

Through the pole-zero cancellation method in [8], the closed loop system guarantees a bandwidth extension with sufficiently fast transient response characteristics compared to the open loop system. Therefore, utilizing the pole-zero cancellation method, the PI controller parameters are adjusted to achieve a system bandwidth of 50 Hz. Figure 4 demonstrates the closed loop sense mode dynamics with a 4 Hz mechanical sensor bandwidth, and its rate equivalent sense mode dynamics with 50 Hz system bandwidth.

SIMULATION AND EXPERIMENTS

Performance Results

The performance of the gyroscopes is experimentally tested at room temperature for a drive displacement of 4µm under mismatched (~100Hz) and mode-matched conditions by using the Allan variance technique. Table 1 presents the test results of two different gyroscopes, showing ARW, bias instability, and DC proof mass voltages for mismatched (~100Hz) and mode-matched conditions. Test results demonstrate a substantial performance improvement up to 2.4 times in bias instability and 1.7 times in ARW performances under the mode-matched case compared to the mismatched case.

Table 1: Test results of different gyroscopes under mismatched (100 Hz) and mode matched conditions.

Performance Parameters	Mismatched (~100 Hz) Mode		Matched Mode	
Gyro ID	#1	#2	#1	#2
ARW (°/√hr)	0.044	0.043	**0.026**	**0.036**
Bias Instability (°/hr)	2	2.6	**0.83**	**1.6**
V_{PM} (V)	9.81	10.15	**9.33**	**9.55**

Figure 5 presents the Allan Variance graphs of one of the tested gyroscopes (Gyro #1) under the mismatched (~100Hz) and mode-matched conditions. The gyroscope demonstrates a performance of 0.83°/hr bias instability and 0.026°/√hr ARW, close to the estimated theoretical Brownian noise limit of 0.018°/√hr for this gyroscope, with mode-matching.

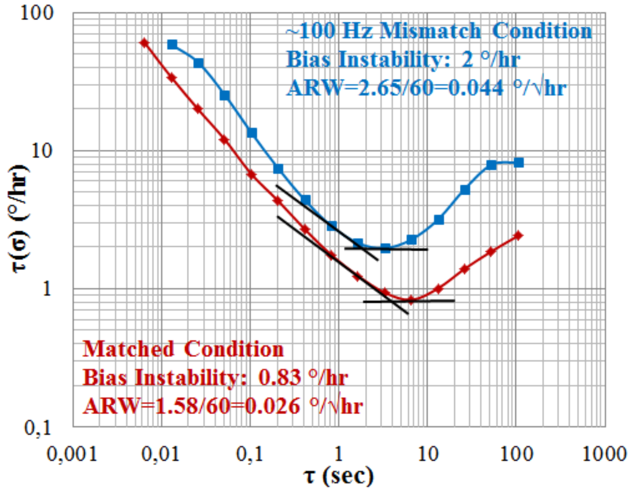

Figure 5: Allan Variance graphs of Gyro ID #1 with a 0.83°/hr bias instability and 0.026°/√hr ARW, close to the estimated theoretical Brownian noise limit of 0.018°/√hr.

Bandwidth Simulation and Experimental Verification

The simulation of the mode-matching system has been carried out by using the complete model of the studied gyroscope and some measured parameters of the system to achieve consistency between the simulation and experiment. Figure 6 shows the simulated bandwidth of the mode-matching system in the presence of a sinusoidal angular rate input whose frequency ramps from 0 to 60 Hz. The corresponding 3 dB point shows that the mode-matching system bandwidth is equal to 50 Hz.

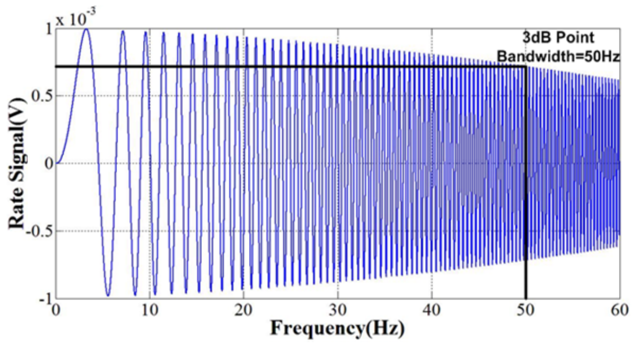

Figure 6: Simulated bandwidth of the mode-matching system in the presence of a sinusoidal angular rate input whose frequency ramps from 0 to 60 Hz.

Figure 7 shows the frequency response of the mode-matching system that is experimentally measured up to 42 Hz, limited by the rate table used in the tests, and then overlapped with the simulated data. The measured and simulated data are consistent with each other which evidently indicate and verify the system bandwidth as 50 Hz.

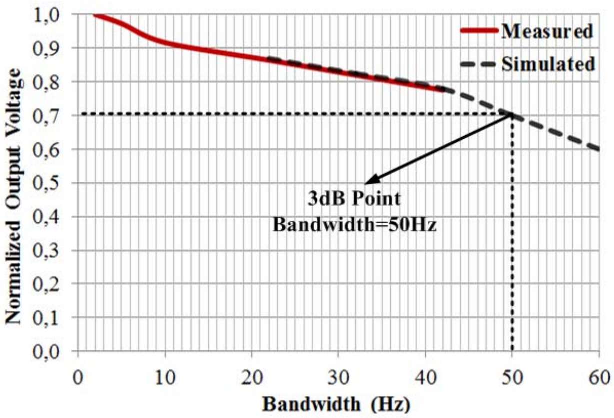

Figure 7: Frequency response of the mode-matching system that is measured up to 42 Hz and then overlapped with the simulated data.

Figure 8 shows the measured sense mode output in response to two different angular inputs. The first input has 2π °/s amplitude with a frequency of 20 Hz, and the second input has the same amplitude with a frequency of 40 Hz. The amplitude of the sidelobes, corresponding to 20 Hz and 40 Hz of angular rate signals, is about 20.1 and 18.1 mV_{rms}, respectively. These amplitudes agree with the measured system frequency response of Figure 7. The central peak at the drive mode resonance frequency corresponds to the measured sum of the in-phase and quadrature offset signals. The amplitude of the central peak is quite small compared to the amplitude of the sidelobes. This ensures the functionality of our mode-matching system because if it does not work properly then the quadrature signal would not be cancelled since the phase relationship in the closed loop quadrature cancellation controller will be inconsistent for proper operation.

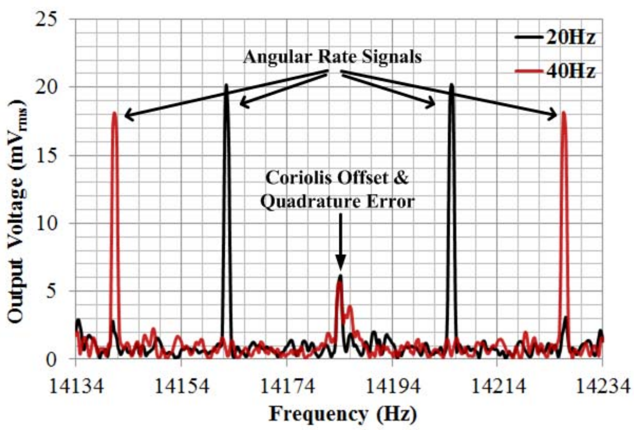

Figure 8: Measured sense mode output in response to sinusoidal angular rate inputs with amplitudes of 2π °/s and frequencies of 20 and 40 Hz.

CONCLUSION

This paper proposes the usage of the phase relationship between the residual quadrature and drive signals in the gyroscope for the automatic mode-matching which improves the bias instability and angle random walk (ARW) performances of the gyroscope in the closed loop system with a bandwidth of 50 Hz for the first time in the literature. It has been experimentally shown that the performance of the studied MEMS gyroscopes is improved up to 2.4 times in bias instability and 1.7 times in ARW under the mode-matched condition with 50 Hz system bandwidth. The bias instability of 0.83°/hr and ARW of 0.026°/√hr, close to the estimated theoretical Brownian noise limit of the studied gyroscope (0.018°/√hr), has been achieved by mode-matching.

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