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AUGUST 2022

An Empirical Study on the Drift Mechanisms of Lissajous FM Gyroscopes: Amplitude, Frequency and Temperature Control

Andrew Sabater
NIWC Pacific

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EXECUTIVE SUMMARY

Frequency modulated (FM) gyroscopes are a relatively novel of inertial sensors that can be used to estimate rotation rate. Based upon simple models, FM gyroscopes should be immune to effect that might cause the rate estimate to drift, but experiments have shown that the rate estimate can drift on the time-scale of hours. This work seeks to empirically demonstrate the test conditions and control system requirements needed to implement an FM gyroscope that does not drift. That is, the design of the amplitude, frequency, and temperature control systems. Different means to implement these controllers are discussed and tested in three different experiments. The key findings are that:

- Amplitude control impacts rate stability on intermediate time-scales (between 10 and 1,000 sec).
- Absolute versus relative amplitude control is believed to be key to further improvements.
- With constant temperature control, relative frequency drift is highly correlated with rate drift.
- It is still unknown what are the needed tolerances of the temperature controller, but some temperature control provides significant improvements.

With some of these questions related to implementation answered, an FM gyroscope that maintains a bias instability below 10 deg/hr on long-time scale is demonstrated in this report. No model is needed to get these results and no trend of increasing bias with time is observed. This work ends with a short description of future work.

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1. INTRODUCTION

Frequency modulated (FM) gyroscopes are a relatively novel class of microelectromechanical (MEMS) sensor that exploit an angular momentum conservation effect to sense rotation versus the Coriolis effect with amplitude modulated (AM) gyroscopes. Nominally similar mechanical structures that can be used to implement an AM gyroscope can be used to implement an FM gyroscope—rings or tuning-fork like structures with degenerate modes. In contrast to an AM gyroscope having a drive mode and a sense mode, both modes of an FM gyroscope are operated at the same time. Based upon a simplified model of FM gyroscopes, one should be able to get an unbiased estimate for rotation rate provided the amplitude of the two modes are equal [1]. That is in theory, FM gyroscopes should be immune to effects that might cause the frequency of the constituent oscillators to drift, for example temperature variation or packaging material aging. However, while opaquely demonstrated, on the time scale of hours, in the absence of constant temperature control, FM gyroscopes have been shown to drift [2]. Building upon prior results [3], this work seeks to clarify the amplitude, frequency, and temperature control requirements needed to implement FM gyroscopes that do not drift. In contrast to earlier work, the goal is to implement a gyroscope that does not need a model to compensate for drift. The questions this work seeks to answer are:

1. What is the impact of amplitude stability on the estimated rotation rate?
2. Can relative amplitude control (control the amplitude of one mode to match the other) be used or is absolute stability for each mode better?
3. For frequency control, does each mode need to be kept at a constant value or can relative frequency control (maintain a constant frequency split) be used?
4. What temperature deviations of the temperature controller are acceptable?

The first section of this work describes the experimental setup. It largely builds upon prior work, but two key improvements are the addition of closed-loop temperature control and digital amplitude control. Section 2 shows experimental results and is broken up into three subsections. The baseline set of experiments are the reference point to compare other control methods and test conditions too. The next experiment added digital amplitude and temperature control. It is found that under these conditions, long-term rate drift is highly correlated with frequency split drift. Degraded amplitude stability due to coarse amplitude control is indicative that intermediate rate stability (between 10 and 1,000 sec) is dictated by absolute amplitude stability. The last experiment studies the impact of relative amplitude, constant frequency split, and constant temperature control. This experiment confirms that under active temperature control, long-term rate drift is due to frequency split drift. On long-time scales (greater than 1,000 sec) bias instability is kept below 10 deg/hr and no trend of increasing bias with time is observed. Relative amplitude control provides an improvement over coarse digital amplitude control, but it is expected that enhanced digital control should negate the need for relative control. Section 4 describes future work and succinctly answers the questions listed in this section.

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2. EXPERIMENTAL SETUP

The experimental setup used in this work builds upon the one documented in [3]. The heart of an FM gyroscope is a resonator with two orthogonal vibration modes. In this work, each mode has a natural frequency of about 4 KHz with about a 60 Hz split or difference between them. To sustain the oscillations of each mode, a negative feedback loop consisting of a phase shifter and inverter/buffer was used. The control of the gyroscope was implemented with a Red Pitaya STEMLab125-14 [4]. Rate and quadrature data is encoded as a frequency modulation at the split frequency. To extract the phase reference, the displacement of both modes were multiplied together and then low-pass filtered. To tune the phase reference, the phase reference was adjusted so that the mean value of quadrature error was maximized during the trial (e.g. during a zero rate input test, the assumption is that the effect that causes frequency modulation is due to quadrature error).

To maintain the amplitude at a constant value, a proportional-integral (PI) design automatic gain control (AGC) circuit was implemented. In the prior work, an analog design was implemented where the controller would adjust the supply voltage of the inverter/buffer. With testing shown in this work, it was found that while ideally PI control should provide good long-term stability, the amplitude would tend to drift on the time scale of hours. The source of amplitude drift is unknown but it could be related to $1/f$ noise from the amplifier used to estimate amplitude error or drift from the integrator circuit. Recent works have noted the use of I-type control [5] and that in practical application, an integrated circuit may be needed. To mitigate drift from the analog AGC, a prototype digital PI controller was implemented. To estimate the amplitude of a given mode, the displacement of a given mode was multiplied by itself and then low-pass filtered. As this filtered value is quadratically related to the actual displacement, the setpoint of the digital PI control was selected by this nonlinearly related value for amplitude. The digital to analog (DAC) on the Red Pitaya is only 14 bits, so to enhance the voltage resolution, 1 KOhm by 10 KOhm voltage divider was used. This divided output was then connected to the error voltage on the analog AGC circuit and the integral error voltage was grounded.

In regards to frequency and temperature control, this is also documented in other works. To enable large displacement frequency control, shaped combs were designed with considerations of the limits of the fabrication method [3]. In [6], active temperature control was implemented by co-packaging a temperature sensor and heating elements with the resonator. To retroactively enable temperature control, one of the packages with the components for closed-loop temperature control was epoxied to the bottom of the interface electronics board. While issues related to thermal gradients are expected due to the distance between the sensor and the resonator, this is a significant improvement over the prior work. That is, tests could be conducted for days, effects due to the cycling of the air conditioning system are not clear in the rate data, and the test duration is now limited by the memory of the Red Pitaya.

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3. EXPERIMENTAL RESULTS

To answer the questions in section 1, three different experiments were conducted. The baseline or reference experiment was defined based on similarity to published works. To control for temperature and amplitude variation effects, a second experiment was conducted. While the long-term absolute amplitude stability was improved, the crude digital amplitude control degrades short-term amplitude stability. Under constant temperature control, it is shown that long-term rate drift is linearly related to frequency split drift. To confirm that long-term rate drift is related to frequency split drift, a third experiment was conducted with relative frequency split control. Also in this third experiment, relative amplitude control was implemented that removed some of the short-term noise associated with all digital amplitude control. Under constant temperature and relative frequency split control, long-term stability may be related to absolute amplitude stability, but further work to implement a better amplitude controller is needed to test this.

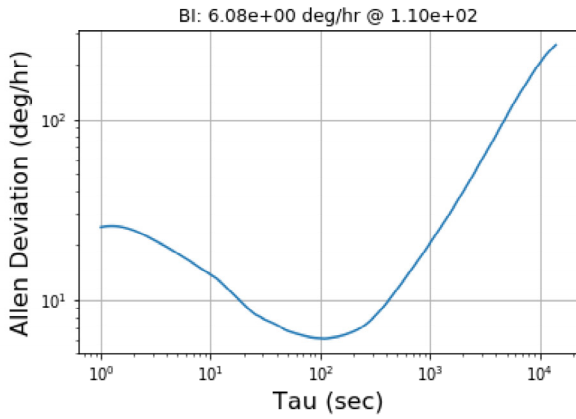
3.1 TEST 1: BASELINE–ANALOG AMPLITUDE CONTROL

The first set of experiments conducted in this work where the amplitude is controlled via an analog method, no active frequency control is used, and tests were conducted at ambient temperature are considered the baseline or reference as it is similar to prior published work [7]. One major difference is integral control was used to compensate for amplitude drift as tests with a proportional controller immediately drifted, but more recent works have also considered this [5].

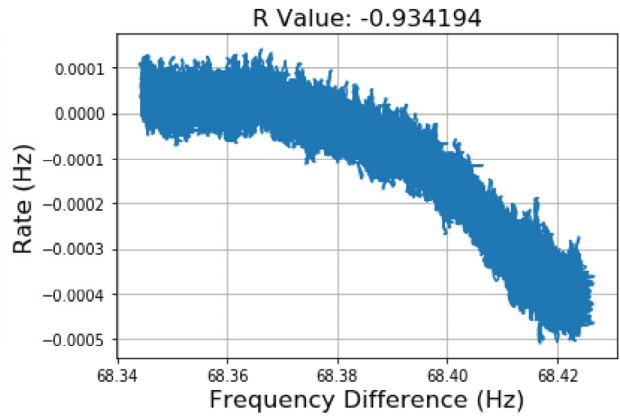
As shown in Figure 1a, the rate output tends to drift on time scales of about 100 sec. Long-term rate drift (greater than 1,000 sec) seems to be nonlinearly related to frequency split drift. Shown in Figure 1b is a scatter plot of the rate estimate versus frequency split difference. The correlation coefficient or R value is shown in the title of the plot. While the scale factor, defined as

$$SF = \frac{1}{2} \left(\frac{a_1}{a_2} + \frac{a_2}{a_1} \right), \quad (1)$$

where a_1 and a_2 are the amplitudes of mode 1 and 2, respectively, is about constant, the amplitude of both modes tends to drift also at 100 sec. While not conclusive, the similar drift of rate and absolute amplitude drift may be indicative that the transition of the rate estimate from white to another noise process (e.g. temperature induced drift or 1/f noise) maybe be govern by absolute amplitude stability. Figure 2 shows Amplitude stability data for Test 1 which includes Allen deviation of amplitudes and Allen deviation of scale factor for Figure 2.

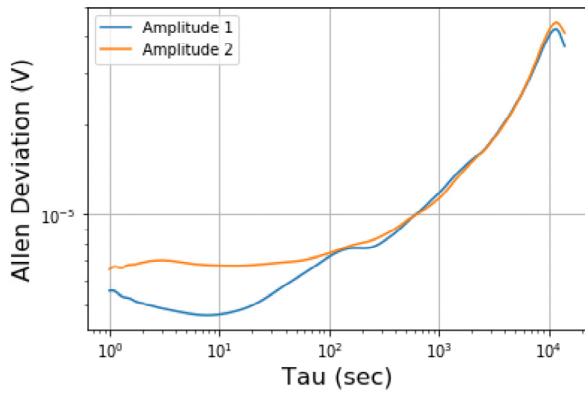


(a) Allen deviation of rate estimate.

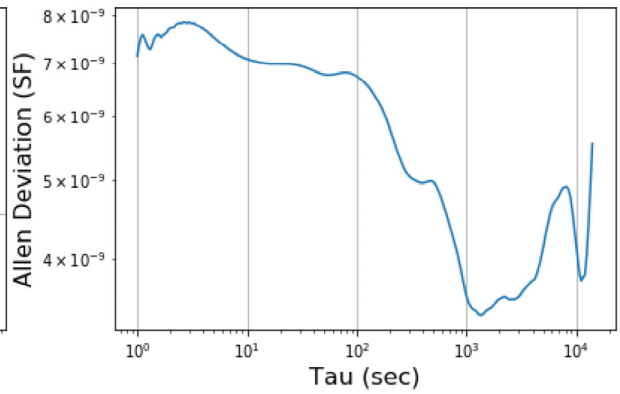


(b) Rate estimate versus frequency difference.

Figure 1. Rate estimate and frequency difference data for Test 1.



(a) Allen deviation of amplitudes.



(b) Allen deviation of scale factor.

Figure 2. Amplitude stability data for Test 1.

3.2 TEST 2: DIGITAL AMPLITUDE AND CONSTANT TEMPERATURE CONTROL

To mitigate the amplitude and temperature drift effects with the first experiment, a second experiment was conducted. Tests were also conducted at 40 C to control for temperature sensitive effects. The digital amplitude controller described in section 2 was used. As shown in Figure 4, the absolute and relative amplitude stability is degraded on short-time scales. However, on long-time scale, the trend is that as the averaging time is increased, stability is improved. Thus, it is expected that with a higher resolution DAC, digital control should be able to improve both short and long-term stability.

Comparing the rate data in Test 2, as shown in Figure 3, to the data from Test 1, the bias instability is worsen and bias drift occurred around 10 sec. This drift around 10 sec is believed to be related to absolute amplitude drift—in the prior test, the absolute amplitude stability at 100 sec was below 10^{-5} V, while in Test 2, the absolute amplitude stability at 100 sec was above 10^{-5} V. On longer time scales, rate drift is linearly related to frequency split drift. Shown in Figure 3b is a scatter plot of the estimated rate versus frequency split. There is a clear linear relationship between the two values. Using a simple linear model, the rate estimate can be calibrated using the frequency split. This is shown in Figure 3a as the calibrated data. The current theory is that with stable amplitude and temperature, frequency drift is only dependent on packaging material aging. Thus, under these conditions, frequency split drift provides a means to observe rate estimate drift. To test this, Test 3 implemented relative frequency control to maintain a constant frequency split.

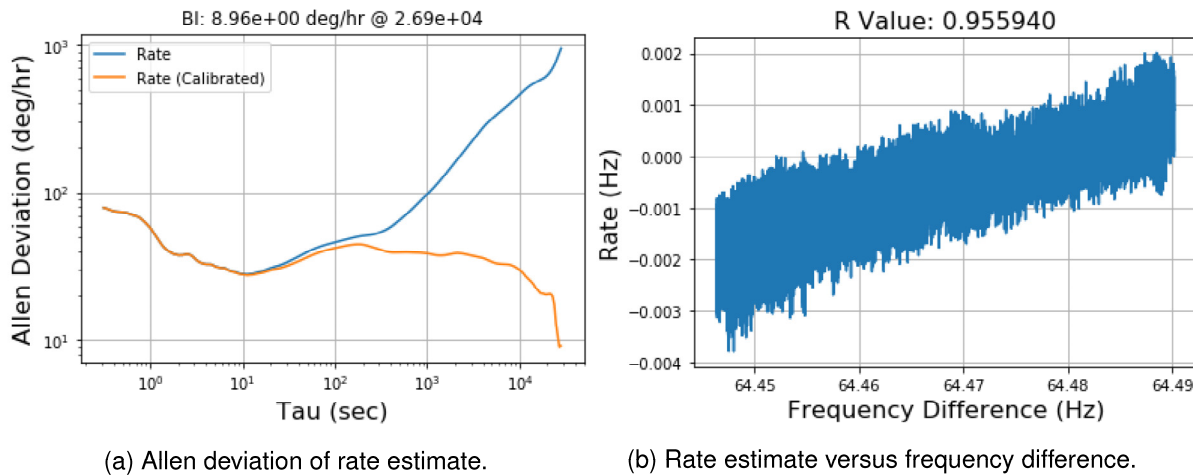


Figure 3. Rate estimate and frequency difference data for Test 2.

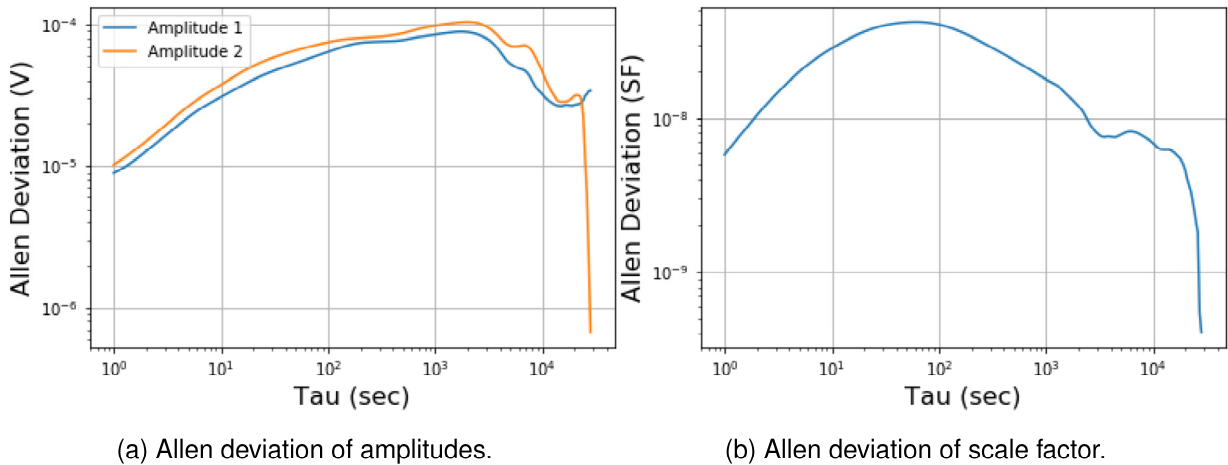


Figure 4. Amplitude stability data for Test 2.

3.3 TEST 3: RELATIVE AMPLITUDE, CONSTANT FREQUENCY SPLIT, AND CONSTANT TEMPERATURE CONTROL

In the final experiment, three control loops were implemented: constant temperature, relative amplitude, and relative frequency control. With relative amplitude control, one mode was controlled via the analog controller and the other was digitally controlled to match the other. The reduction in noise from using one less digital amplitude controller pushed the transition from white to correlated noise to the same time scale as all analog amplitude controller. Relative amplitude control does not appear to directly impact long-term stability. However, as the need for relative amplitude control arises from drift from the analog controller, and amplitude noise degrades rate short-term noise, implementing an amplitude controller with better stability on all time scales would be optimal.

With relative frequency split control, the frequency of one mode was adjusted to maintain a constant frequency difference. With constant temperature and relative frequency control, long-term drift due to material packaging aging is removed and confirms the hypothesis that long-term rate drift is related to relative frequency drift versus drift of each mode. No modeling was needed to get result shown in Figure 5. Bias instability is kept below 10 deg/hr and no trend of increasing bias with time is observed. Figure 6 shows Amplitude stability data for Test 3.

In regards to temperature variations and the impact, there are still questions to be answered. Shown in Figure 7 are scatter plots of mode frequency versus heater temperature. On the left is data from Test 3. On the right is data from the -1 g accelerometer test from [6]. Importance differences between the two tests are that in the accelerometer tests, the thermal gradient between the temperature sensor and resonator was much lower and a room temperature die bonding process was used. To minimize the thermal gradient, the temperature sensor and heaters were placed within a few cm of the resonator. For the gyroscope, the heater assembly was placed on the backside of the interface electronics board. Between the heater assembly and the gyroscope resonator was the printed circuit board, a DIP socket, and a DIP package. While the gyroscope resonators were bonded at room temperature, wire bonding was conducted at 150 C, so effects related to thermal cycling could be present.

Shown in the titles of the plots are the slopes relating frequency to heater voltage. As the heater voltage is dependent on ambient temperature, the assumption is that this slope is related to temperature sensitivity. Significant caveats are that frequency could also drift due to bonding material aging and that the while both resonators are made of the same material, they are operated using different modes. Reducing the thermal

gradient, however, clearly reduces the temperature sensitivity. To clarify the impact of what temperature deviations are acceptable, gyroscope resonators need to be co-packaged with the components needed for closed-loop temperature control. The resolution of the current temperature sensor is also only 0.01 C, so the resolution of this may also be needed to be improved.

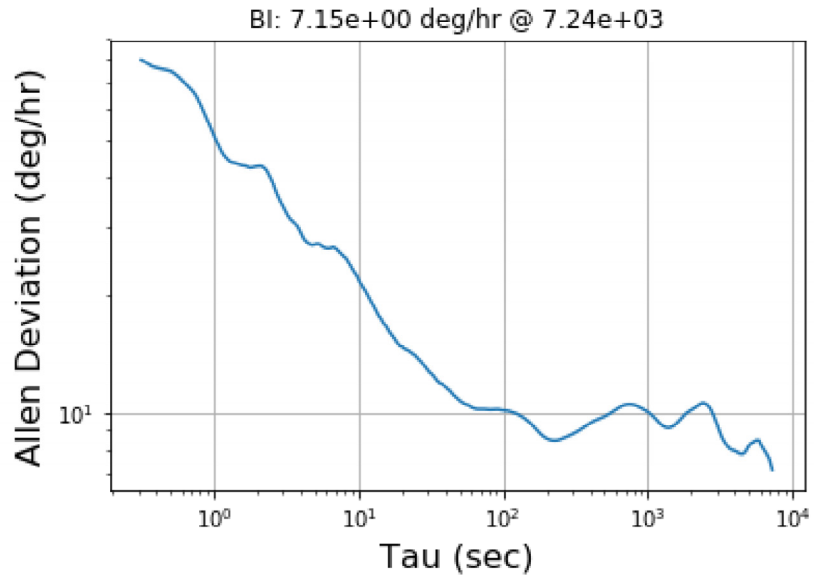
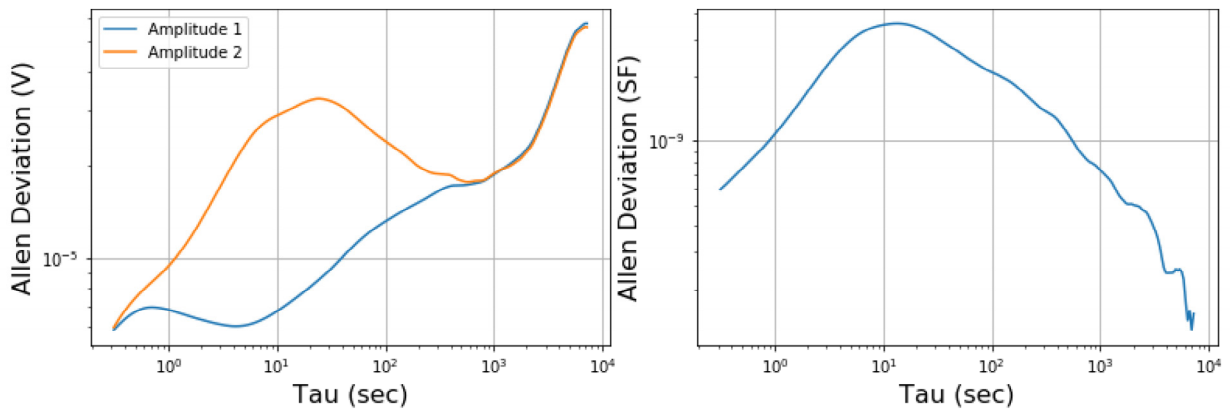


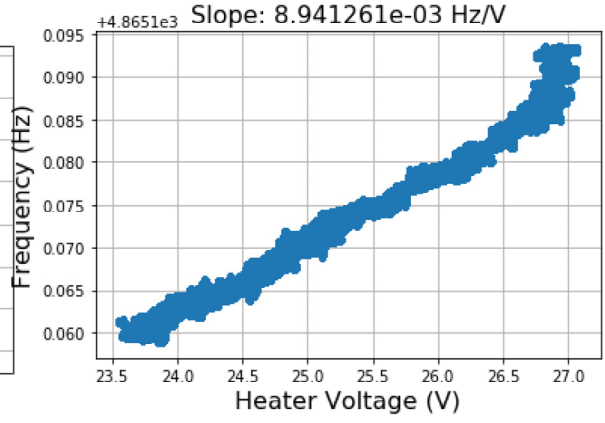
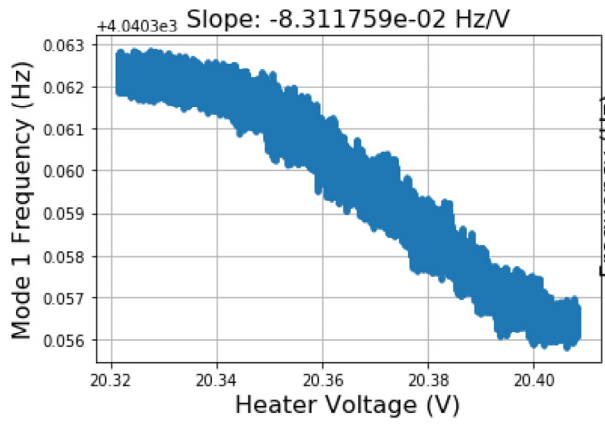
Figure 5. Allen deviation for Test 3.



(a) Allen deviation of amplitudes.

(b) Allen deviation of scale factor.

Figure 6. Amplitude stability data for Test 3.



(a) Heater temperature versus mode 1 frequency.

(b) Heater temperature versus accelerometer frequency.

Figure 7. Temperature sensitivity data.

4. CONCLUSIONS AND FUTURE WORK

Depending on the implementation, FM gyroscopes have been demonstrated to have excellent long-term stability. However, a wide range of FM gyroscopes have been demonstrated using different control methods and test conditions. Due to the challenges of assessing the impact of these methods and conditions theoretically, this work has attempted to empirically determine the amplitude, frequency, and temperature control requirements of FM gyroscopes. Section 1 lists four questions this work hoped to clarify, but succinct answers are listed below:

1. With the implemented system, amplitude stability impacts rate stability on time-scales between short and long periods (between 10 and 1,000 sec). When other drift mechanisms are controlled for, amplitude noise effectively provides an upper bound for the rate stability. The $1/f$ noise in the rate estimate after 100 sec is believed to be from amplitude noise. On long time-scales (greater than 10,000 sec), is it unknown what amplitude requirements are needed to maintain a Gaussian rate estimate.
2. It is possible that relative amplitude control can provide some improvements, but the need for relative versus absolute amplitude control is derived from drift from the amplitude controller. For further improvements, it is expected that better absolute amplitude control will be needed.
3. When amplitude and temperature drift is controlled, long-term rate drift (greater than 1,000 sec) is highly correlated with frequency split drift. Active frequency split control can be used to mitigate long-term rate drift.
4. It is unknown what are the tolerances of the temperature controller needed to implement an FM gyroscope that is insensitive to ambient temperature variations. This is a future area of work, but the current hypothesis is that below a certain tolerance, further improvements to temperature stability do not impact the gyroscope.

In regards to future work, to push beyond the presented results, enhanced amplitude, frequency, and temperature controllers are planned. Digital amplitude control seems promising, but the current implementations has rather coarse resolution. The DAC used for the frequency controller may be sufficient, however the limits of this control loop are due to ADC of the frequency detector. When the resolution of the frequency detector is improved, it is expected that the resolution of the associated DAC will also need to be improved. As for the temperature controller, besides increasing the resolution of the temperature sensor, decreasing the thermal gradient between the sensor and resonator is also needed. This has already been demonstrated by co-packaging the resonator with the components needed for active temperature control.

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