A NOVEL, SIMPLE, AND Q-INDEPENDENT SELF OSCILLATION LOOP DESIGNED FOR VIBRATORY MEMS GYROSCOPES

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ABSTRACT

This paper presents a novel self oscillation loop with a very simple architecture that is independent of quality factor (Q) variations in packaged vibratory MEMS gyroscopes, providing identical start-up performance at different ambient conditions. The new self-oscillation loop circuitry has been fabricated in a 0.6µm CMOS process, tested with a fabricated MEMS gyroscope, and demonstrated start-up characteristics without any overshoot and with a settling time of only 28msec. An angle random walk value of 0.037°/√hr and a bias instability value of 3°/hr are achieved using this new self-oscillation loop.

KEYWORDS

MEMS gyroscopes, self-oscillation loop, drive mode controller.

INTRODUCTION

Stability of the drive motion is very critical in terms of short and long term operations. The Coriolis force directly depends on the amplitude of drive mode oscillation: any drift and instability on the drive mode oscillation cause drifts and instability at the output. In addition, settling time of the drive mode oscillations should be minimized to shorten the overall start-up time of MEMS gyroscope system. However, quality factor of the sensor is very high in order to have less mechanical noise. If the drive motions are not under control, settling time of the sensor will be above tens of seconds due to this high quality factor. On the other hand, for tactical grade applications, settling time of the system should be kept below a few hundreds of milliseconds. Regulation of the drive amplitude is also required for a good bias stability and robust scale factor, which is independent from sensor parameters and ambient conditions.

In the literature, there are several methods to implement the drive mode control. First method is pure analog controllers which are often preferred due to their simple implementation and simple design procedure [1-3]. Second method is digital controllers providing flexible design procedure; on the other hand, these systems are complex due to the necessity of a µ-controller or a FPGA [4-5]. Digital controllers used in the self-oscillation loops can have very low settling times [4] and effective regulation of the drive mode motion at steady state [5]. Third method uses proportional (P) controller at transient and proportional-integral (PI) controller at steady state to reduce the settling time [6]. Fourth method is PLL-based self-oscillation loop reducing the phase errors and phase noise of the drive mode system [3]. These deterministic and stochastic errors degrade the overall system performance if they are not small enough. Another method for the drive mode control is ΔΣ modulator type controller, but the use of such a system is not practical for the drive mode of MEMS gyroscopes [7]. Finally, there is a universal topology which can operate in a wide range of sensor parameters and ambient conditions by using a current commutating switching mixer [8]. This method also suffers from similar complexity as the previous ones [4-8].

In the literature, the simplest implementation for the drive-mode controller uses analog controllers. In these systems, PI controller is mostly used. Use of an integrator in the controller provides zero steady state error which results in strong amplitude regulation of the drive mode oscillations. Moreover, gain of the drive mode is very high due to the operation at vacuum to achieve higher sensitivities. This high gain of the sensor enables to use P controller. Since loop gain of this system is sufficiently high, steady state error is very small even if there is no integral controller. Although, P controller is implemented in the current analog controllers in the literature, these systems include various circuit blocks for the amplitude regulation such as a demodulator, a low-pass filter, an instrumentation amplifier, a controller, and a modulator. In addition, since control of the drive mode oscillation is carried out by the circuits operating at DC, this system is sensitive to offset drifts and Flicker noise.

This paper presents a new and simple self-oscillation loop for MEMS gyroscopes regulating the drive mode oscillation using a proportional controller. This new and simple topology operates at the carrier band, so that it is insensitive to the offset drifts and Flicker noise of the circuitry. In addition, if the sensor operates at vacuum, this new topology provides a Q-factor independent transient performance with a satisfactory settling time and no overshoot.

OPERATION PRINCIPLES

Figure 1 shows the simplified block diagram of the proposed controller system. Operation of the controller is simple compared to conventional drive mode controller systems; in that all the blocks of this controller loop operate at carrier band. Firstly, positive feedback loop provides the self-oscillation. System locks to the resonance frequency of the mechanical sensor with the help of this loop. Secondly, output of the front-end electronics is fed back to the sensor, and it is subtracted from the output of the positive feedback path. This path forms the negative feedback which regulates the drive oscillation amplitude. Actuating signal of the sensor is the difference between the outputs of these positive and negative feedbacks. Its first harmonic can be considered as an error signal, and higher harmonics are rejected by the high-Q dynamics of the mechanical sensor. If the loop gain of the negative feedback is high enough, this error signal is very low such that the output of the negative feedback follows the first harmonic of the positive feedback output. Accordingly, the drive mode oscillation is regulated, because the relation between the drive mode displacement amplitude and negative feedback output amplitude is only a scalar for a certain oscillation frequency.

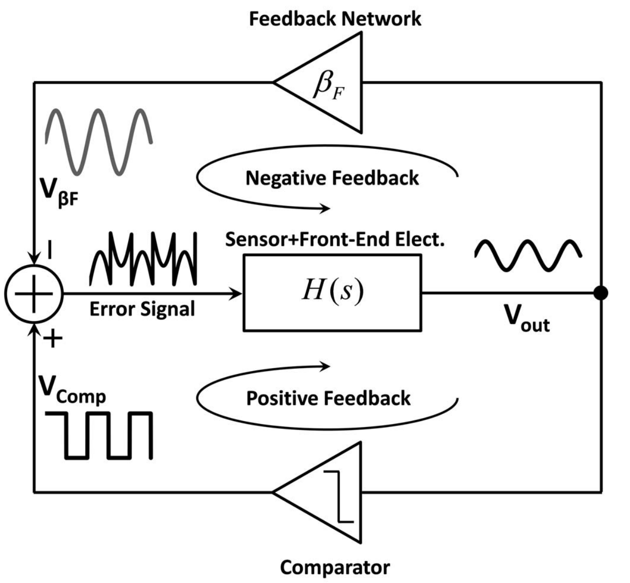

Figure 1: The simplified block diagram of the proposed simple self-oscillation loop controller.

Strength of the oscillation amplitude regulation strictly depends on the loop gain, since the system behaves as a simple proportional controller. In order to strengthen this regulation, loop gain should be increased. The feedback gain factor (β_F), which can be considered as the P controller, is the control parameter to adjust the loop gain for proper control of the drive motion. Mathematical description of this system is simpler than the conventional drive loop's [1]. Envelope model of the sensor can also be used, but it is not necessary for this system, because all the amplitude control operation is performed in high frequency region, not in the base-band. First of all, closed loop gain can be described as follows:

$$G_{CL}(s) = \frac{H(s)}{1 + H(s)\beta_F} \tag{1}$$

where, $H(s)$ is the dynamics of the sensor and front-end electronics, and β_F is the feedback factor. Defining $H(s)$ as in Eq.2, closed-loop transfer function of the over-all system can be obtained as follows:

$$H(s) = \frac{K_{FG} \cdot s}{s^2 + \beta \cdot s + \omega_D^2} \tag{2}$$

$$G_{CL}(s) = \frac{K_{FG} \cdot s}{s^2 + (\beta + K_{FG}\beta_F) \cdot s + \omega_D^2} \tag{3}$$

where, K_{FG} is a scalar composed of several sensor parameters and electronic gains; β is the bandwidth, and ω_D is the natural frequency of the drive mode dynamics.

At resonance frequency, the gain of the closed-loop system is expressed as in Eq. 4.

$$G_{CL}(s)\Big|_{s=j\omega_D} = \frac{K_{FG}}{\beta + K_{FG}\beta_F} = \frac{1}{\beta_F} \cdot \frac{1}{1 + \dfrac{\beta}{K_{FG}\beta_F}} \tag{4}$$

The term $\beta/(K_{FG}\beta_F)$ is sufficiently small for high quality sensors. Using the Taylor's series, steady state percentage error can be found as follows:

$$G_{CL}(s)\Big|_{s=j\omega_D} \approx \frac{1}{\beta_F} \cdot \left(1 - \frac{\beta}{K_{FG}\beta_F}\right) \tag{5}$$

Therefore, percentage steady state error can be expressed as follows:

$$e_{SS,\%} \approx \frac{\beta}{K_{FG}\beta_F} \cdot 100 \tag{6}$$

Amount of this error describes the strength of the regulation. Eq. 5 and Eq. 6 show that if the steady state error is low enough, system response is determined by the feedback factor which is a robust electronic gain. In other words, the system response is insensitive to sensor parameters which are likely to vary with different ambient conditions and process parameters. However, if the amount of the steady state error is not low enough, system will suffer from the drifts of these conditions and parameters.

Steady state error mainly depends on the feedback factor and forward gain as Eq. 6 shows. Especially, if this system has a high-Q, then the system has almost perfect amplitude regulation. In current experiments, quality factors greater than 50000 have been observed for wafer-level vacuum packaged gyroscopes. For these Q-factors, the bandwidth of the system is about 0.24 Hz which corresponds to β =2 rad/sec. Typical value for the forward gain (K_{FG}) is around 10. As a result, steady state error can be below 2% error for feedback factors around 10.

In the above relations, regulation of the drive mode oscillation is implicitly shown by expressing the regulation of the output of $H(s)$. On the other hand, the relation between the amplitudes of the drive mode oscillation and output of $H(s)$ (V_{out}) is only a scalar as it is shown in follows:

$$x_d = \frac{V_{out}}{K_{Elect} \cdot K_{X/I}} \tag{7}$$

where, x_d is the drive mode oscillation amplitude, V_{out} is the amplitude of $H(s)$ output, K_{Elect} is the electronic gain, and $K_{X/I}$ is the displacement to current conversion gain of the sensor. In addition, the negative feedback system is actuated by a square voltage whose first harmonic yields the input force of this system. Therefore, the amount of the drive mode oscillation amplitude can be written as:

$$x_d = \frac{4 \cdot V_{Comp}}{\pi \cdot \beta_F \cdot K_{Elect} \cdot K_{X/I}} \tag{8}$$

where, V_{Comp} is the level of the actuating voltage generated by the comparator.

Closed-loop system identified in Eq. 3 is also a second order system whose envelope behavior can be expressed as follows [1]:

$$\widetilde{G}_{CL}(s) = \frac{1}{2} \cdot \frac{K_{FG}}{s + \frac{1}{2} \cdot (\beta + K_{FG}\beta_F)} \qquad (9)$$

As a result of this envelope behavior, this system settles to its steady state value in an exponential manner. Settling time for 1% error band is described in the following equation:

$$t_{set} = 4.5 \cdot \frac{2}{\beta + K_{FG}\beta_F} = \frac{9}{\beta + K_{FG}\beta_F} \approx \frac{9}{K_{FG}\beta_F} \qquad (10)$$

Eq. 10 shows that if the term of $K_{FG}\beta_F$ is much higher than the bandwidth of the sensor (β), settling time is almost independent from the quality factor. In addition, envelope behavior of this system is first-order; hence, there is no overshoot during start-up.

CONTROLLER PROPERTIES

The proposed self-oscillation topology has several benefits comparing with conventional approaches presented in the literature. Firstly, this new system is very simple, since it is only composed of an electronic gain stage and a comparator in addition to the preamplifier. If the sensor has a differential force-feedback electrodes in the drive mode, subtraction of the negative and positive feedback can be performed in the mechanical sensor. Otherwise, an extra subtractor circuit, which can be implemented with a single Op-Amp, is required for this operation. Secondly, this system does not require any off-chip component such as large capacitors which are necessary in the low-pass filters used in conventional self-oscillation loops. Thirdly, this system only operates at the carrier band; therefore, the oscillation amplitude is insensitive to the electronic drifts and Flicker noise. On the other hand, conventional loops in the literature are sensitive to the errors at DC, which degrades the bias instability and scale factor repeatability especially for CMOS implementations. Finally, this system has an identical start-up performance with low settling time and no overshoot for different ambient conditions providing that the quality factor is high enough. This feature seems to have a restriction on the quality factor, but for high performance MEMS gyroscopes quality factor is needed to be high enough in order decrease Brownian noise and noise contribution of the electronics at the system output. In fact, even if the sensor operates at atmosphere, this system can still operate theoretically if the $K_{FG}\beta_F$ product is sufficiently high. Nevertheless, this will cause stability problems and/or decrease the drive mode oscillation amplitude.

TEST RESULTS

Proposed system is implemented with discrete electronics and in a 0.6µm standard CMOS technology. Figure 2 shows the die photograph of the fabricated chip including the proposed self-oscillation loop circuitry and sense control electronics.

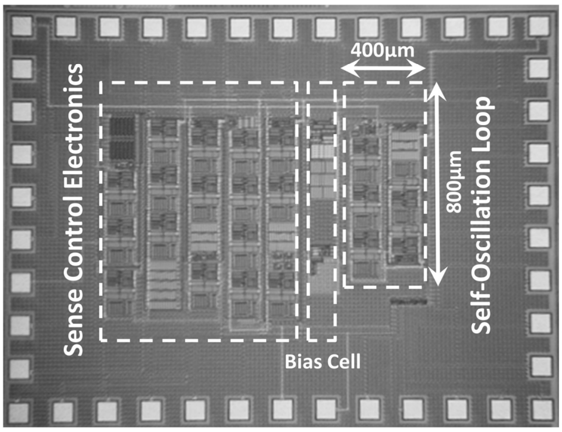

Figure 2: The die photograph of the fabricated CMOS chip including the proposed self-oscillation loop controller circuitry.

Table 1 shows the sensor and system parameters used in the tests. Figure 3 shows the scope view of the steady state waveforms of the proposed simple self-oscillation loop controller circuitry. It is verified that the output of the negative feedback loop is regulated by the actuating voltage which is the positive feedback loop output. It is observed that the negative feedback output is almost equal to the first harmonic of the actuating signal as Figure 3 shows. The percentage of the measured steady state error is 5%. This error is larger than the expected result due to the phase errors coming from the electronics which is also observed in Figure 3. These phase errors can be minimized by improvements in the self-oscillation loop circuitry. The oscillation amplitude, which is shown in Figure 3, corresponds to the approximately 2.5µm displacement amplitude of the drive resonator mass. Figure 3 also shows the error signal which directly feeds the mechanical sensor.

Table 1: The sensor and system parameters used in the tests

f_D	β	Q-factor	K_{FG}	β_F
12815.6Hz	1.73rad/sec	46600	12.7	10

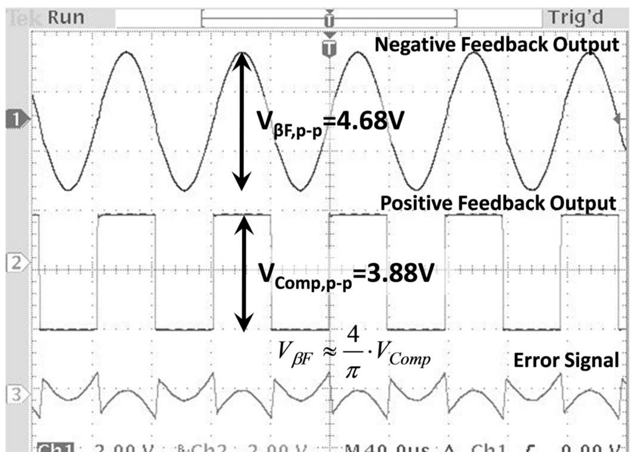

Figure 3: Scope view showing steady state waveforms of the proposed simple self-oscillation loop controller circuitry.

Figure 4 gives the scope view of the settling of the proposed self-oscillation loop controller circuitry. These results demonstrate that the start-up has a settling time of 70msec without any overshoot. This is the expected value which is in accordance with the analytical calculations given in Eq. 10 and the parameters given in Table 1. This settling time can further be improved by increasing the electronic feedback factor (β_F) at the expense of reduction in the drive mode oscillation amplitude. A settling time of 28msec is obtained with a larger β_F value around 25. These settling times are very good comparing to the reported results in the literature [1-8].

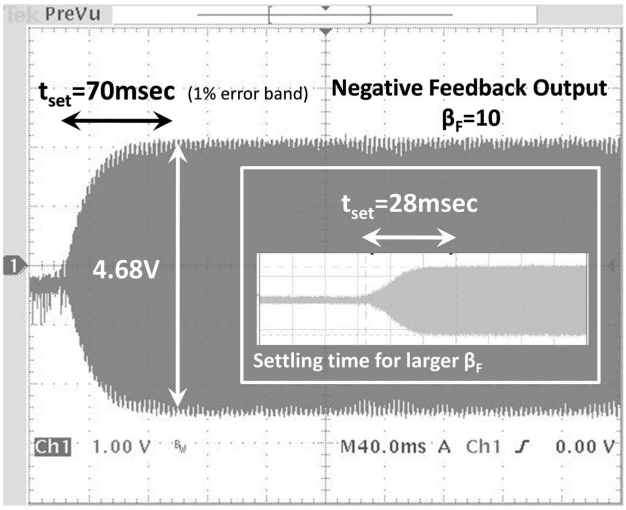

Figure 4: Scope view from the time measurements of the proposed simple self-oscillation loop controller circuitry.

Finally, Figure 5 shows the Allan variance test result of the complete system with the new self-oscillation loop controller circuitry. An angle random walk value of 0.037°/√hr and a bias instability value of 3°/hr are obtained, which makes this system usable for tactical grade applications.

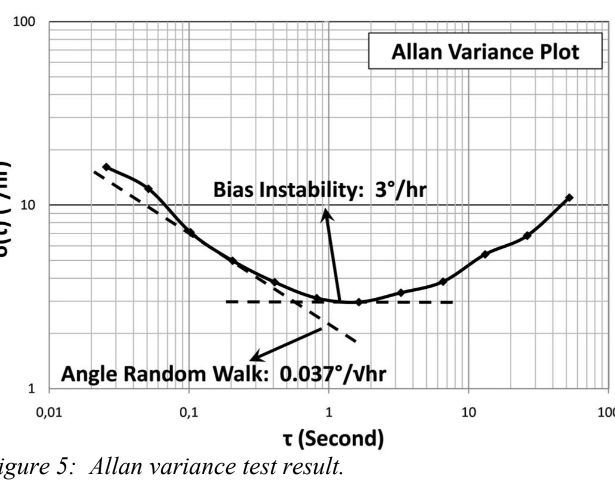

Figure 5: Allan variance test result.

CONCLUSION

This paper reports the development of a new self-oscillation loop for the drive mode oscillation regulation with a simple architecture. The proposed loop control circuitry is insensitive to variation in quality factor value, resulting in a predictable startup performance. This new system is implemented in a 0.6μm CMOS technology. A settling time of 28msec is achieved without any overshoot. Finally, performance tests are carried out; and an angle random walk value of 0.037°/√hr, and a bias instability value of 3°/hr are obtained.

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