

A MEMS VIBRATING RING GYROSCOPE WITH ON-CHIP CAPACITIVE STRESS SENSORS FOR DRIFT COMPENSATION

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

By
Baha Erim Uzunoğlu
July 2022

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We certify that we have read this thesis and that in our opinion it is fully adequate,
in scope and in quality, as a thesis for the degree of Master of Science.

Erdoğan Tatar(Advisor)

Yusuf Ziya İder

Kıvanç Azgın

Approved for the Graduate School of Engineering and Science:

Orhan Arıkan
Director of the Graduate School

ABSTRACT

A MEMS VIBRATING RING GYROSCOPE WITH ON-CHIP CAPACITIVE STRESS SENSORS FOR DRIFT COMPENSATION

Baha Erim Uzunoglu

M.S. in Electrical and Electronics Engineering

Advisor: Erdinç Tatar

July 2022

MEMS gyroscopes are commonly used for rotation measurement in navigation. Even though the noise performance of these sensors has improved in the last few decades, the long-term drift problem is still prominent for these sensors. Long-term drift error is caused by external factors such as temperature and induced stress on the MEMS chip. With this work, we present an on-chip solution for the compensation of long-term drift. Due to its compact and singular anchor morphology, a vibrating ring gyroscope design was employed. Eight bridge-type capacitive stress sensors were placed periodically at the inner section of the ring surrounding the inner anchor, which adds localized stress measurement capability to the design. Another eight stress sensors were placed at the outer section of the ring surrounding the electrodes of the device. Tensile stress was applied on a testbed, and the output of the stress sensors and the gyroscope were recorded. Then, the gyroscope was subjected to a zero rate output (ZRO) test in mismatch and matched frequency configurations. The compensated output of the device was able to reach $0.008^{\circ}/\text{h}$ in mismatched mode and $0.003^{\circ}/\text{h}$ in matched mode without any signs of drift. The stress and the gyroscope output were partitioned into 12 hour blocks to increase the performance of the least squares fitting algorithm. We have observed a decrease in the compensation performance due to possible nonlinear and hysteresis effects generated during the long-term operation. Finally, we were able to show that the change in temperature wasn't sufficient enough to explain the frequency change of the drive and sense modes.

Keywords: MEMS Inertial Sensors, Stress sensor, Ring gyroscope, Drift, Stress compensation.

ÖZET

UZUN DÖNEM SAPMA DOĞRULAMASI İÇİN ÇİP İÇİ KAPASİTİF STRES SENSÖRLÜ MEMS TİTREK HALKA DÖNÜÖLÇERİ

Baha Erim Uzunoglu

Elektrik ve Elektronik Mühendisliği, Yüksek Lisans

Tez Danışmanı: Erdinç Tatar

Temmuz 2022

MEMS dönüölçer kullanımı navigasyona olan talebin artmasıyla yükselmiştir. Son dönemde yapılan araştırmalarla bu sensörlerin gürültü performansı geliştirilmiş olsa da sensörler uzun süre çalıştırıldıklarında çıktı değerlerinin 0'dan saptığı gözlenir. Uzun dönem sapması olarak da nitelendirilen bu olay MEMS çipine etki eden sıcaklık ve mekanik stres gibi dış etmenlerden kaynaklanmaktadır. Bu çalışmada, uzun dönem sapmasını yok etmek için çip içerisine yerleştirilmiş bir çözüm sunmaktayız. Halkasal tasarım tipi sıkıştırılabilir olduğundan dönüölçerin mekaniksel tasarımında tercih edilmiştir. Stres sensörleri köprü tipi yapıya sahip olup kapasitif ölçümleme yapmaktadır. Halka sekizi içte ve sekizi dışta olan stres sensörleriyle çevrelenmiştir. Bu sayede bölgesel stres ölçümünün daha hassas yapılabilmesi hedeflenmiştir. Stres düzeniğinin üzerine yerleştirilmiş çip kartı gerdirilmiş ve sensör çıktısı kaydedilmiştir. Sonrasında, dönüölçer eşlenmiş ve eşlenmemiş frekans koşullarında sıfır dönü çıktı(SDÖ) testine tabi tutulmuştur. Stres doğrulaması yapıldıktan sonra eşlenmemiş dönüölçer $0.008^{\circ}/\text{saat}$ ve eşlenmiş dönüölçer $0.003^{\circ}/\text{saat}$ değerlerine ulaşmıştır. Aynı zamanda dönüölçer sapma belirtisi de göstermemektedir. Doğrulama en küçük kareler metodu ve kaydedilmiş olan verilerin 12 saatlik sekmelere bölünmesiyle yapılmıştır. Bunun sebebi ise dönüölçer ve stres sensörleri arasındaki ilişkinin zamanla doğrusallığını kaybetmesidir. Son olarak bu araştırma sıcaklığın dönüölçerdeki frekans değişimlerini bire bir olarak eşlemekte yetersiz kaldığını göstermiştir.

Anahtar sözcükler: MEMS Ataletsel Sensörleri, Stres Sensörleri, Halka dönüölçer, Sapma, Stres Doğrulaması.

Acknowledgement

My initial thanks goes to Erdinç Tatar for the opportunity he has given me to study in this fascinating field of research and his wisdom that has guided me throughout the past three years. I have learned a lot from his meticulous attention to detail and approach to solving every unexpected problem. After all the time I have spent working with him, I feel ready to face the awaiting challenges in the next steps of my career.

I am grateful to Yusuf Ziya İder and Kivanç Azgın for the time they have dedicated to evaluate this thesis. All of the evaluations and the comments have improved the quality and made me realize the missing parts of my work.

I acknowledge that this thesis work was funded by TUBITAK and I was financially supported by UNAM and the Electrical and Electronics Engineering department of the Bilkent University. These supports were crucial for me to complete this work.

I would like to thank my parents, Nuran and Yüksel Uzunoğlu, for their vision and their unending support. I'm sorry for all the sleepless nights and the stress that I have projected upon them and I hope to make it up by bad jokes and endless rants on unnecessary topics. There isn't a sufficient amount of "Thank you"s for all your unquestioning support on every decision that I have made in my life and your advice on every problem that I have come across. So thank you once more and I hope to make you folk proud on each passing day.

Lots of gratitude to the friends I have had the chance to meet and know in Bilkent University. Thanks to Murat Güngen and Cem Bülbül for welcoming me to the lab and their advice on how to adjust to the department. Special thanks to Derin Erkan and Can Soygür for their comradeship and all the effort they have put in the lab. I will surely miss the discussions that we had on various topics. Sadly, I wasn't able to mentor them on how to become a good Half-Life player but you win some and you lose some in life. I'd like to thank Tolga Veske and

Ahmet Alp Derin for sparing their time and contributing to the lab work. Best of luck to everyone in their future endeavours. I genuinely believe that they can succeed in whatever they set themselves up for.

Finally, I've saved the most special thanks to the most special lady in my life. Duygu Söylemez was the one who encouraged and inspired me to join the MS program in Bilkent University. I am grateful to her for being there for me every step of the way and sharing the highs and lows. Her take on life and her relentless soul has inspired me to be better and aim higher in life. She has been a true bliss for the last ten years, and I'm excited to share the upcoming experiences we will form together now that I've completed this chapter.

Contents

1	Introduction	1
1.1	Literature Review	4
1.2	Principals of MEMS Gyroscopes	7
1.3	Gyroscope Performance Parameters	10
1.4	Motivation	11
2	Gyroscope Operation	13
2.1	Gyroscope Design	13
2.2	Stress Sensor Design	20
2.3	FEA Simulation Results	22
2.4	Fabrication	26
3	Readout and Control Electronics	30
3.1	Gyroscope Electronics	30
3.1.1	Gyroscope Drive Stage Electronics	33

3.1.2	Gyroscope Readout Stage Electronics	33
3.1.3	Drive Control Loop	36
3.1.4	Quadrature Cancellation	36
3.2	Stress Sensor Electronics	37
3.3	Test PCBs	41
3.3.1	Main PCB	41
3.3.2	Interface PCB	44
3.3.3	Daughter PCBs	44
3.4	Test Setup	47
4	Test Results	49
4.1	Characterization of the Gyroscope	49
4.2	Characterization of the Stress Sensors	55
4.3	ZRO Tests and the Effectiveness of the Compensation	62
4.3.1	Quadrature Control Off ZRO Test	63
4.3.2	ZRO Test in Mismatched Frequency Operation	66
4.3.3	ZRO Test in Matched Frequency Operation	69
4.3.4	Post Investigation of ZRO Tests	71
4.4	Resonance Lock Tests	73

5 Conclusion and Future Work	78
5.1 Conclusion	78
5.2 Future Work	81
A Additional Figures	87
B Additional Tables	90
C Code	92
C.1 Digital Pin Definitions	92
C.2 Multiplexing and Recording	94

List of Figures

1.1	Spinning Gyroscope (a), Bottom-up view of an HRG structure (b)	2
1.2	Coriolis Force	3
1.3	Gyrosocpe Mechanism	8
2.1	Drive and Sense axis displacements in wineglass mode	14
2.2	Polar coordinates on the ring's cross-section	15
2.3	The top down view of the VRG with parameters	18
2.4	The gyroscope design summary (a), and the SEM image of the gyroscope with the integrated stress sensors (b).	19
2.5	The stress sensor SEM image and the electrical equivalent circuit (a), and the FEA image showing the operation principle (b). . . .	20
2.6	Generated mesh in the Comsol simulation	23
2.7	The Z-axis Inertial Mode at 31374 Hz (a), the Z-axis Tilting Motion 31395 Hz (b), Z-axis Tilting Motion n=2 Mode at 33417 hz (c), XY-plane Acceleration Mode at 47612 Hz (d), Z-axis Tilting Motion n=3 Mode at 50357 Hz (e), XY-plane Torsional Mode at 50647 Hz (f).	24

2.8	The Wineglass Mode $n=2$ at 63345 Hz (a), and the Wineglass Mode $n=3$ at 129286 (b).	25
2.9	The bottom to top view o the VRG's layout	27
2.10	SEM image of the VRG	27
2.11	The gap between the ring and an outer electrode (a), and the ring spoke width and the gaps between a spoke and the inner electrodes (b).	28
2.12	The die observed from the bottom with on the probe station	28
3.1	Overall Control Schematic of Gyroscope	31
3.2	Lock-in Amplifier Connections	32
3.3	Differential Signal Generation Schematic	33
3.4	Readout Circuitry Schematic	34
3.5	Block Diagram of the Drive Resonance	36
3.6	Quadrature Signal Amplifier Schematic	37
3.7	Transimpedance amplifier model of the stress sensor	38
3.8	The stress sensor signal chain	39
3.9	2nd Order Butterworth Low Pass Filter Schematic	40
3.10	Low Pass Filter Spice Simulation	41
3.11	Main PCB	42
3.12	Interface PCB	44

3.13	The wirebonded Gyroscope (a), the populated bottom layer of the daughter board (b), the daughter board with bonded aluminum cap (c).	45
3.14	The Wirebond Connection Map	46
3.15	The Test Setup	47
4.1	Probe Setup	50
4.2	Probe Testing	51
4.3	Drive Pick Sweep Magnitude Plot	52
4.4	Drive Pick Sweep Phase Plot	52
4.5	Sense Sweep Magnitude Plot	52
4.6	Sense Sweep Phase Plot	52
4.7	Time Variant Data of the Rate Output in Mismatched Frequency Condition(a), Rate Table's Velocity vs. Gyroscope Sensitivity in Mismatched Frequency Condition(b)	54
4.8	Time Variant Data of the Rate Output in Matched Frequency Condition(a), Rate Table's Velocity vs. Gyroscope Sensitivity in Matched Frequency Condition(b)	54
4.9	Photo of the aluminum stress test-bed	55
4.10	The cross sectional diagram of the stress testbed diagram	57
4.11	Time Variant Data for 0° axis Screw Test	57
4.12	3D Bar Plot for 0° axis Screw Test	58

4.13 3D Bar Plot for 90° axis Screw Test	58
4.14 3D Bar Plot for 45° axis Screw Test	59
4.15 3D Bar Plot for 135° axis Screw Test	59
4.16 Comsol Simulation of the Screw test for 0° axis	60
4.17 Frequency plot for X Axis Screw Test	61
4.18 Sense Output for X Axis Screw Test	61
4.19 The time domain plot of the temperature and ZRO of the gyro- scope in open loop quadrature condition for 30 hours.	64
4.20 The Allan deviation plots in open loop quadrature control config- uration for different compensation cases.	65
4.21 The time domain plot of the 16 stress sensors, the temperature sensor and ZRO of the gyroscope in mismatched frequency oper- ation for 16 days. The variations over time are plotted, refer to Figure 3.13.a for stress sensor locations.	67
4.22 The Allan deviation plots of the gyroscope in mismatched opera- tion for 16 days for various compensation cases.	68
4.23 The time domain plot of the 16 stress sensors, the temperature sensor and ZRO of the gyroscope in matched frequency operation for 8 days. The variations over time are plotted, refer to 3.13.a for stress sensor locations.	70
4.24 The Allan deviation plots of the gyroscope in matched frequency operation for 8 days for various compensation cases.	70
4.25 The Allan deviation plots for the mismatched operation compen- sated with various stress sensor sets.	72

4.26	The Allan deviation plots for the mismatched operation compensated with different partition periods.	73
4.27	The time domain plots for the drive and sense frequency shifts and temperature changes for 65 hours.	74
4.28	The change of drive frequency vs the change of temperature, hysteresis is visible. The plot is colored with progressing time.	75
4.29	Original and compensated drive frequency with temperature and stress.	76
4.30	Drive frequency compensation in mismatched frequency ZRO test with temperature and stress.	76
A.1	Failure in the vacuuming process	88
A.2	Failure in the metal lithography	88
A.3	Failure in the silicon bonding	89

List of Tables

2.1	Vibrating Ring Paramters	17
2.2	Stress Sensor Paramters	21
2.3	Comsol Simulation Results	23
4.1	Frequency Sweep Results	53
4.2	S3P3-P3P0 Parameters and Values	63
B.1	Interface Board Pin Map	91

Chapter 1

Introduction

Gyroscope was invented in the late 18th century. Initially, these devices utilized rotatory disks that were suspended on freely moving rod and circular rings which can be seen in figure 1.1a . This allowed the structure to maintain its angular momentum when the inner disk is rotated. When an external force is applied on the system, a reactionary force in an opposite direction is generated. The angular momentum is conserved by the reactionary force and it could be measured to obtain the rotation vector applied on the system.

The gyroscope technology has evolved throughout the history. The demand for inertial sensors for the navigation tools have fueled the innovation in the field. In the recent decades, the state of the art technology for gyroscopes has been the Hemispherical Resonating Gyroscope(HRG)[1]. The hemispherical shell fitted on to singular rod resembles a structure shaped of an umbrella which can be seen in 1.1b. The shell is surrounded by the perfectly fitted electrodes which generate the electric field that initiates and maintains the resonance of the structure. The type of resonance utilized by this structure is described as the wineglass resonance or $n=2$. The description stems out of the motion that a wineglass generates when the wineglass is used as a musical instrument. By rubbing the top of the wine glass the structure can be driven into resonance and create a unique sound[2]. The HRG's handcrafted structural design is produced with minimal amount of

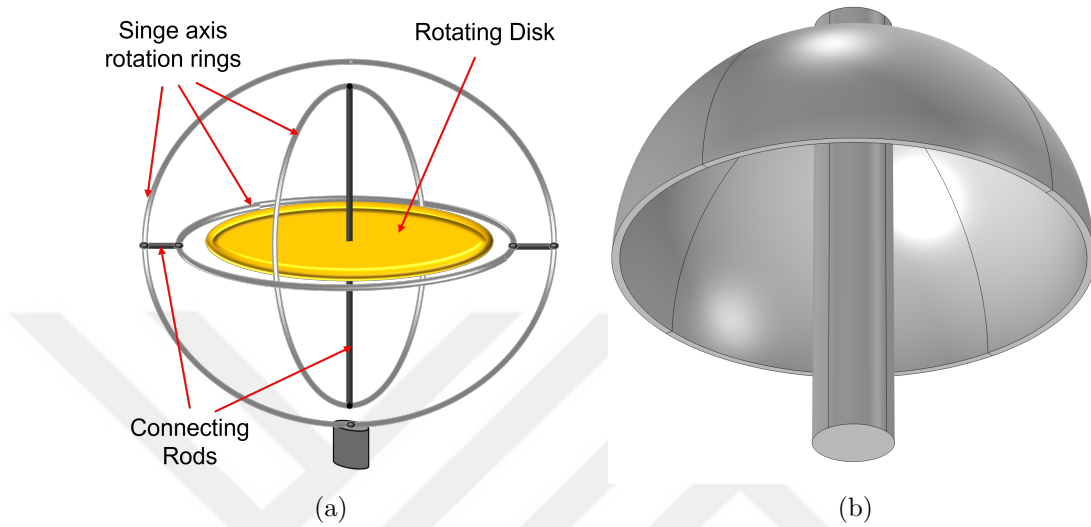


Figure 1.1: Spinning Gyroscope (a), Bottom-up view of an HRG structure (b)

errors and provides high performance and low noise in sensing. The drawback of this technology has been its high cost and low scalability for mass production. Due to this fact, the use of this type of gyroscope has been limited to aviation and the space industry. The high throughput for the gyroscopes have been with the realization of the MEMS industry. The use of MEMS accelometers for the airbags in the automotive industry paved the way[3] for the gyroscopes to be manufactured in mass by the MEMS fabrication techniques.

The MEMS device design is achieved by layer by layer basis. In general, the mechanical design is etched into the silicon layer and then it is released to allow free movement of the mass in 3-D space while being held by a group of beams. The desired motion of the proof mass is achieved by an electric field which is generated by electrodes. This way the compliant mechanism is moved in the desired direction. The magnitude and the direction of the force is dictated by the voltage difference between the proof mass and the surrounding electrodes. The metalization layer is also present in some of these designs to provide connectivity for the electrodes. The collection of these layers are finally wrapped by a package to protect them from the external environmental effects and provide a vacuum to enhance performance.

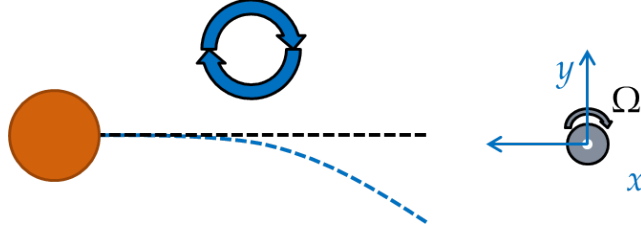


Figure 1.2: Coriolis Force

The developed fabrication methods presented the MEMS designers to manipulate the mass in a small diameter which is the most important requirement to realize a gyroscope in the MEMS field. A MEMS gyroscope functions when a constant motion is provided to the proof mass as it can be seen in figure 1.2. To understand the subject matter one can think of the proof mass motion on xy plane. Commonly, the proof mass is driven into resonance in a single axis. In this example, we can think of the resonance or the drive axis as the x axis. The Coriolis force is generated on the perpendicular axis y, when the device is subjected to a rotational vector in z-axis. In a MEMS Gyroscope, the proof mass is displaced in the x axis periodically to utilize the Coriolis force. The displacement caused by the Coriolis force acting on the body can be measured by the change in capacitance in the sensing electrodes. The relation between the change of capacitance and the rotation vector is found by applying a predetermined rotation input to the device and observing the change in the output of the sense electrodes.

When the theory is put in practice however the device becomes subjected to factors that limit its performance. One of the most crucial factors in MEMS gyroscope performance is the inherit noise of the device. The noise can be generated by various sources. The thermally coupled and the stress induced noise on the mechanical structure are two of the most dominant mechanical noise sources in the system. The accumulation of these noises generate long term drift or the Rate Random Walk(RRW) in the long term operation of the Gyroscope. The goal of this thesis is to present a Circular MEMS Gyroscope design that achieves long term drift compensation with on-chip stress sensor and off-chip temperature sensors.

1.1 Literature Review

In recent years, the innovations in MEMS gyroscope design, readout circuitry and the fabrication techniques has improved the performance in terms of the output noise. The improvement was achieved by focusing different aspects of the MEMS gyroscope design. The circular resonating ring topologies have gained traction in the last decade by demonstrating high performance and stability. In 2014 Boeing Disc Resonator Gyroscope was introduced [4]. It featured concentric rings that were attached to one another by supporting spokes which are located 45 degrees apart surrounding an inner supporting disc. These spokes are alternated by 22.5 degrees for each concentric ring to obtain maximum displacement in xy plane. This design was able to achieve $0.012^\circ/\text{hr}$ bias instability. The honeycomb design in [5] replaces the concentric rings with arcs that forms hexagonal spaces within the proof mass. The honeycomb design was able to reach $0.015^\circ/\text{hr}$ bias instability. The vibrating ring design has also found commercial success with Silicon Sensing's CRS39A[6] which achieves bias stability less than $0.03^\circ/\text{h}$. At the other side of the spectrum, the rectangular gyroscopes have also presented high performance and stability. Northrop Grumman LITEF GmbH[7] developed the dual mass arrangement of the gyroscope design has achieved bias instability smaller than $0.03^\circ/\text{hr}$. Another tuning fork design[8] which employs out of plane motion was able to reach $0.006^\circ/\text{hr}$. There has been interest in minimizing the die size without waiving the performance of the Gyroscope. In [9] the device demonstrated $0.02^\circ/\text{hr}$ bias instability within a die size of 1.3mm^2 . The implementation of HRG's design in the MEMS domain was achieved by the newly developed fabrication techniques. 3D fused-silica micro Precision Shell Integrating gyroscope was able to achieve $0.0014^\circ/\text{hr}$ [10] bias instability. These designs were able to introduce or perfected features that optimise the stability of the device. However, the interest in each design aimed to increase the stability in short term operation and the devices were subjected to long term drift when the output is not compensated. This shift is visible in Allan variance plots where the long averaging times start to rise in [5][10].

The long term drift or rate random walk can be observed in vibratory MEMS

gyroscopes due to the accumulation of noise in long duration operations. The gyroscope is needed to be tested for a period of days or even weeks to observe the long term drift clearly. Even though prominent in almost all types of Gyroscope designs, the long term drift is a relatively unexplored topic. However, the interest in this field has been increasing in the last decade. The factors that trigger the long term drift are discovered to be the external factors. Primarily the change in temperature and induced stress on the silicon layer [11]. There are different approaches to eliminate the long term drift. One of these approaches aims to eliminate the long term drift with machine learning algorithms. Especially with the increasing demand for low cost IMUs, new machine learning algorithms try to compensate the long term drift with the temperature data. Chong et al. aims to model the drift based on genetic-Elman neural network in [12]. In the paper, utilized network provides a minor improvement over the uncompensated output. Somehow the algorithm manages to remove the white noise of the sensor yet, the long term drift is observable even after the compensation. One can also observe that the compensation method fails to track the output changes in time varying plot. In [13] various neural networks were used to compensate the IMU output in the case of 20K temperature change in a period of three minutes. Even though, the paper reports a successful compensation method it's hard to observe long term drift condition in most of the IMUs, let alone in a state of the art MEMS vibratory gyroscopes within a period of 3 minutes. Also, it's hard to imagine an environment where a typical gyroscope operation is subjected to such an aggressive change in temperature. Another approach to suppress the amount of drift in gyroscope has been the temperature calibration. Most of the high-end IMUs and gyroscopes go through a calibration process post fabrication. The Boing DRG is ovenized within 1mk with an ovenized crystal in [14]. The ovenized gyroscope has a suppressed drift but the residual long term drift can be observed. The temperature is a good starting point for compensation but it isn't adequate to eliminate the drift completely on its own. In a different approach Ge et al.[15] pairs two DRGs so that they are operating in different modes for compensation. The compensation improves the stability of the gyroscope operating at $n=2$ mode and increases the duration before the initiation of the drift. However, the long term drift can be observed in the compensated gyroscope output.

Long term drift has been investigated mainly on the scope of temperature. The impact of stress on long term drift remains unknown compared to the effects of temperature. In [16] a gyroscope's response was simulated under predetermined stress. The FEA simulation reports a linear change in quadrature error and ZRO due to stress induced gap mismatches. In [17] Zhang et al. created a simulation model which simulates the effects of stress on a plastic mold packaged MEMS device. The MEMS device design is adjusted accordingly by the simulation results. The findings of the paper shows that the optimized design's output is less susceptible to the changes in temperature compared to the non-optimized design. These studies paint a clear picture on the effects of stress and are good starting point in terms of decreasing these effects. However, the amount of induced stress and the type of stress can vary depending on the fabrication process and the type of die to package attachment[18]. These findings show the necessity of on-chip stress sensing for the elimination of long term drift.

The first time that on-chip stress monitoring was used for monitoring and the compensation of stress can find in Tatar's work in [19]. Piezoresistive type stress sensors were employed on the periphery of the mode matched vibratory-rate-gyroscope. The results of this paper has shown that the long term drift compensation is possible and has room for future development for increased performance in long term stability. On-chip stress measurement can be achieved by using different methods. One method is to use piezoresistive materials to measure the stress. To measure the stress a long beam that is fixed on two ends are released on the silicon layer. The beam's resistivity changes depending on the applied pressure and a simple wheatstone bridge can be used to monitor the change in conductivity to measure the applied pressure. Piezoresistive sensor's performance is highly dependent on the fabrication method and the type of layers that are used. Especially, in highly conductive SOI wafers the piezoresistive sensor requires a large silicon real estate to measure the stress change accurately. As it was mentioned earlier, the piezoresistive stress sensor has been used for stress measurement in the industry. In [20] the piezoresistive stress sensor are used to measure the stress built up in IC packages after the production. The study shows the importance of stress monitoring to increase yields in chip production.

Common use of piezoresistive stress sensors has been to measure pressure[21]. The accurate measurement of pressure has been shown to be possible and the methods that are used for pressure sensing can be applied to stress measurement. The integration of these sensors with an inertial sensor has been a challenge. The inertial sensors are fabricated with thick ($>10\mu\text{m}$), highly conductive silicon layer to eliminate the out of plane modes of the lumped mass. Additionally, the calibration is required due to the temperature dependence of the silicon[22]. The capacitive array stress sensor design is more compact compared to piezoresistive stress sensor and is compatible with the inertial sensors. The trade-off of capacitive sensors is the comparatively complex readout circuitry. The readout circuitry requires a demodulation step which is similar to the gyroscope's readout step. Capacitive stress sensor design is consist of a complaint mechanism that converts the applied pressure to mechanical displacement. Commonly used fork design offers high capacitive cross-sectional area for high stress sensitivity. Some of these devices can be found in [23], [24]. The capacitive design requires low power and has low temperature dependence since the detrimental material properties for the functionality of the sensor design are unaffected by the temperature change. All in all, the small silicon real estate that these type of stress sensors allow precise and directional stress reading. Due to this prominent fact, a capacitive stress sensor design was used in this study that is derived from a capacitive sensor which can be seen in [25].

1.2 Principals of MEMS Gyroscopes

The MEMS Gyroscopes rely on the phenomena named Coriolis Effect to function. The Coriolis force is expressed as:

$$F = -2m(\Omega \times V) \quad (1.1)$$

where Ω expresses the rotational vector existent on the plane around a rotation axis. The V is the velocity vector perpendicular to the rotation axis. In figure

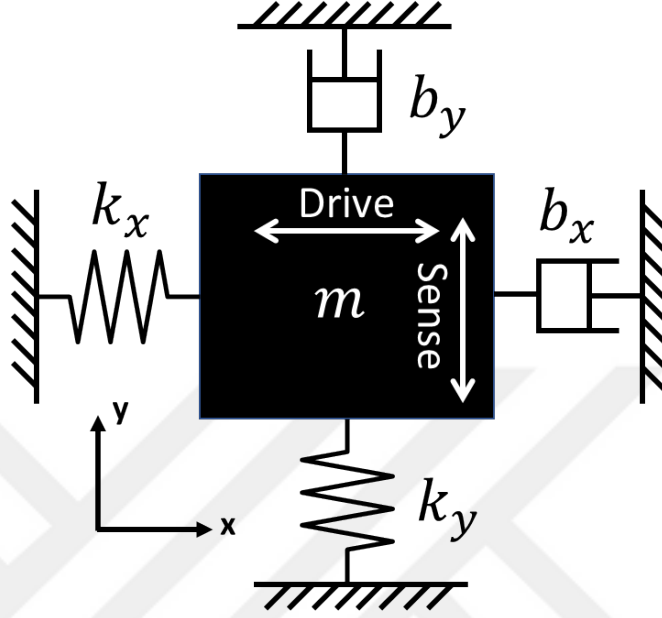


Figure 1.3: Gyrosocpe Mechanism

1.2 the movement of a mass on rotating plane is depicted. The velocity in the positive x axis direction combined with the rotation vector around the positive z axis generates a reactionary force in the direction of negative y axis. The force exerted on the mass causes a deviation from the expected path.

Figure 1.3 shows the simplified mechanical mechanism of a MEMS Gyrosocpe. The micro machined gyroscope with sense and drive axes can be modeled as two degrees-of-freedom(DoF) spring-mass-damper system. For this example the drive and sense axis are allocated to x and y axis respectively. The relation between the applied force on the proof mass and the displacement in each axis for an ideal case where the mass is the same for drive axis and sense axis can be expressed as [26]:

$$m\ddot{x} + b_x\dot{x} + k_x x = F_D + 2\Omega\dot{y} + m\Omega^2 x + m\dot{\Omega}y \quad (1.2)$$

$$m\ddot{y} + b_y\dot{y} + k_y y = -2\Omega\dot{x} + m\Omega^2 y + m\dot{\Omega}x \quad (1.3)$$

Where the m refers to mass, the spring and damping coefficients are expressed as k and b . F_D is the drive force. Subletters denote the axis names x and

y. The force components are smaller compared to the applied drive force thus, in the proceeding equations these can be neglected. By dividing each side of these equations with m we obtain a simpler version of these equations. Also, we obtain an important characteristic of the gyroscope, ω_m as the natural resonance frequency of the proof mass's mode.

$$\ddot{x} + \frac{b_x}{m}\dot{x} + \frac{k_x}{m}x = \frac{F}{m} \quad (1.4)$$

$$\ddot{y} + \frac{b_y}{m}\dot{y} + \frac{k_y}{m}y = \frac{-2\Omega\dot{x}}{m} \quad (1.5)$$

$$\omega_x = \sqrt{\frac{k_x}{m}}, \quad \omega_y = \sqrt{\frac{k_y}{m}} \quad (1.6)$$

By taking the Laplace transform of the formula shows the relation between displacement and the external force in frequency domain can be written as:

$$\frac{X(s)}{F(s)} = \frac{\frac{1}{m}}{s^2 + 2\zeta\omega_x s + \omega_x^2} \quad (1.7)$$

Where ζ is defined as the damping factor, the quality factor Q and the bandwidth BW can be written together as:

$$\zeta = \frac{b}{2m\omega_x}, \quad Q = \frac{m\omega_x}{b}, \quad BW = \frac{\omega}{Q} \quad (1.8)$$

The quality factor is defined as the maximum ratio of amplitude to the static deflection[27]. For $\omega = \omega_x$ and $s = j\omega_x$ case the relation can be written as:

$$X(s) = -j\frac{Q_x}{k_x}F(s) \quad (1.9)$$

By inserting 1.9 in 1.5 the sense axis displacement can be written as:

$$Y(s) = -2\Omega\frac{Q_x}{k_x}\frac{\omega_x}{(\omega_y^2 - \omega_x^2) + \frac{\omega_y}{Q_y}j\omega_x}F(s) \quad (1.10)$$

Depending on the resonance frequency of the sense mode the displacement function in the sense axis can be written for two conditions. If the gyroscope is operated in mode match condition $BW \gg 2|\omega_x - \omega_y|$

$$Y(j\omega_x) \approx \frac{-2\Omega j\omega_x X}{jBW\omega_x} = \frac{-2X\Omega}{BW} \quad (1.11)$$

In the mismatch case where $BW \ll 2|\omega_x - \omega_y| = 2\Delta\omega$

$$Y(j\omega_x) \approx \frac{-2X\Omega}{\Delta\omega} \quad (1.12)$$

The rotational rate of the gyroscope's output is determined by the displacement in the sense axis. As $\Delta\omega \gg BW$ the matched rate of the gyroscope is much larger than the mismatched rate. The Bandwidth of the Gyroscope is determined by the quality factor of the gyroscope thus the matched response is directly correlated with the Quality factor

1.3 Gyroscope Performance Parameters

The MEMS Vibratory Gyroscopes are analyzed by certain parameters that are set by the IEEE Standards to obtain their universal performance. It's important for the reader to get a grasp on these parameter definitions before moving forward with this study. The full documents that contain the standard definition can be reached from [28]

Angular Random Walk: Expresses the accumulated angular rotation noise that is generated due to white noise sources in the gyroscope such as thermal noise and the Brownian motion of the mechanical sensor. This error is typically expressed in degrees per square root of hour ($^\circ/\sqrt{h}$).

Bias Instability: The random variation in bias as computed over a specific

period of time. It's expressed by the 1/f power spectral density function. Expressed in degrees per hour ($^{\circ}/h$).

Rate Random Walk: The accumulation of drift due to the white noise in angular acceleration. This error is typically expressed in degrees per hour ($^{\circ}/h$).

Rate Gyro: A gyroscope that returns angular rotation proportional to inertial space.

Scale Factor: The ratio change in the output of the Gyroscope that is proportional to the input angular velocity change. Usually obtained by measurement and cross fitting the output values with a linear line according to the incrementally changed input.

Bandwidth: The frequency band where the Gyroscope's displacement response is higher than the cut-off points.

Input Range: The region between the upper and lower limit where the gyroscope output can be measured.

1.4 Motivation

This thesis aims to come up with a method to accurately assess the on-chip stress built up on a MEMS gyroscope and aims to compensate the long term drift noise of the MEMS gyroscope by utilizing the measured stress change. As it was mentioned earlier, earliest study on this topic was presented in the Tatar's work in [29]. Tatar has shown that the improvement in the long term drift is possible by employing on-chip stress sensors around the periphery of the MEMS gyroscope. However, in that particular study the piezoresistive stress sensors were used which are inadequate to measure the localized stress vector. Another room for improvement was the anchors that support the gyroscope. A rectangular design was chosen for the gyroscope which requires multiple points of support to be held freely on 3D space. We have realized that a circular design can be

supported by a single central anchor. We hypothesize that a single anchor is likely to be subjected to a uniform stress distribution over the proof mass of the gyroscope. We also aim to introduce capacitive stress sensors that can be fit into a small Silicon estate. The capacitive stress sensors will be placed at the inner and the outer periphery of the circular ring to separately measure the stress induced upon the central anchor of the Gyroscope and the electrodes. The fabricated design will be subjected to a Zero Rate Output(ZRO) test at which the the gyroscope will not be subjected to a rotation input and the base noise of the system will be measured, The long term drift of the device will be presented by an Allan variance plot and compensation method will be applied to improve the performance of the gyroscope in a long term operation.

This thesis includes the design of the vibrating ring gyroscope(VRG) and the design of the stress sensor. In chapter 2 the simulations results of the designed structure, fabrication method and its results. The testing equipment and the control mechanism used will be explained in chapter 3. The readout electronics will be explored thoroughly and the employed PCB designs will be shared with the reader. The chapter 4 will present the test results. The gyroscope's characteristics will be reported and the stress sensor outputs will be analyzed where they are subjected normal and shear stress vectors. The uncompensated and compensated gyroscope outputs will be presented for ZRO tests. Finally, overall summary will be presented in the chapter 5.

Chapter 2

Gyroscope Operation

The Gyroscope's performance is determined by its mechanical design. As the motivation of this study aims to utilize a circular design we will focus on ring based structures for the design. In this chapter, the parameters of the gyroscope and stress sensor design will be investigated. The simulation results will be presented and the fabricated devices will be shared.

2.1 Gyroscope Design

The resonance mode utilized for the circular gyroscope is different compared to resonance mode that is employed on a three folded mechanical structure. The ring structure bends at nodal points in wineglass ($n=2$) mode compared to displacement of the mass in a single axis. Figure 2.1 shows the bending of the ring in the drive and the sense axis during wineglass mode. The structure bends from four points in wineglass mode. The displacement is expanding in x-axis while the circular structure is compressed on the corresponding y-axis and vice versa. Thus, the displacement on the ring must be investigated for each point on the polar coordinates. The displacement vector of the ring can be expressed as[30]:

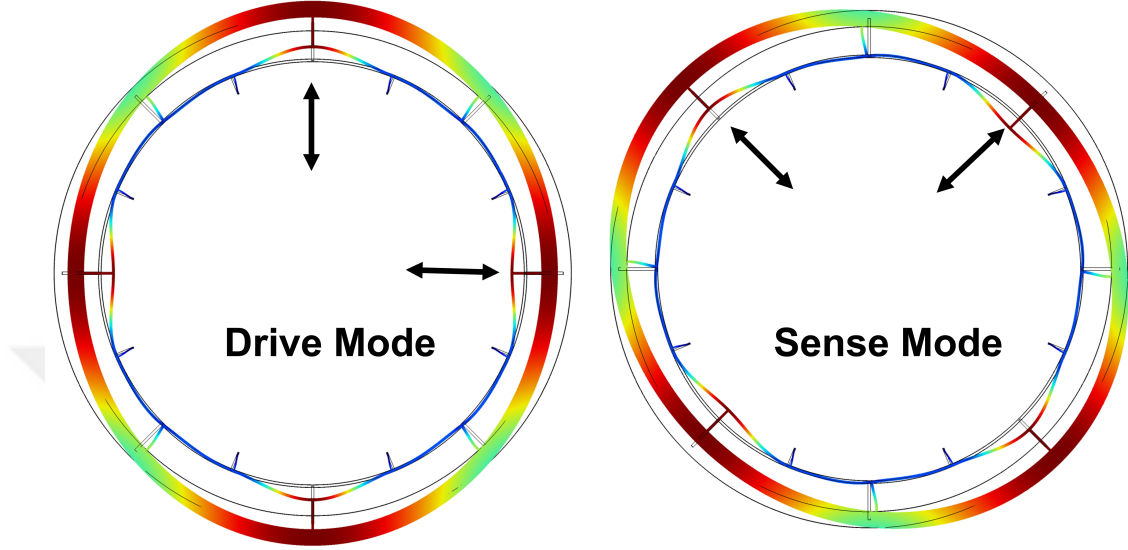


Figure 2.1: Drive and Sense axis displacements in wineglass mode

$$\begin{bmatrix} w \\ u \end{bmatrix} = Q_{11}(t) \begin{bmatrix} n \sin n\theta \\ \cos n\theta \end{bmatrix} + Q_{12} \begin{bmatrix} n \cos n\theta \\ -\sin n\theta \end{bmatrix} \quad (2.1)$$

where the w is the radial displacement on the ring, u is the tangential displacement on the ring, θ shows the angular position of the point on the ring and n is the number of nodal diameters. The displacement vectors can be seen in figure 2.2. The relation between the tangential and radial displacement is expressed in [31] by the normal strain as:

$$\epsilon(0) = 0 = \frac{du}{dx} - \frac{w}{R} \quad (2.2)$$

$$U = W/n \quad (2.3)$$

The resonance frequency of the VRG can be calculated using Lagrange's method. The maximum kinetic energy of the structure must be equal to the maximum strain energy. The kinetic energy of the ring can be written as:

$$\frac{1}{2}mV^2 = \int_0^{2\pi} \frac{1}{2}\rho R d\theta A(\dot{v}^2 + \dot{w}^2) \quad (2.4)$$

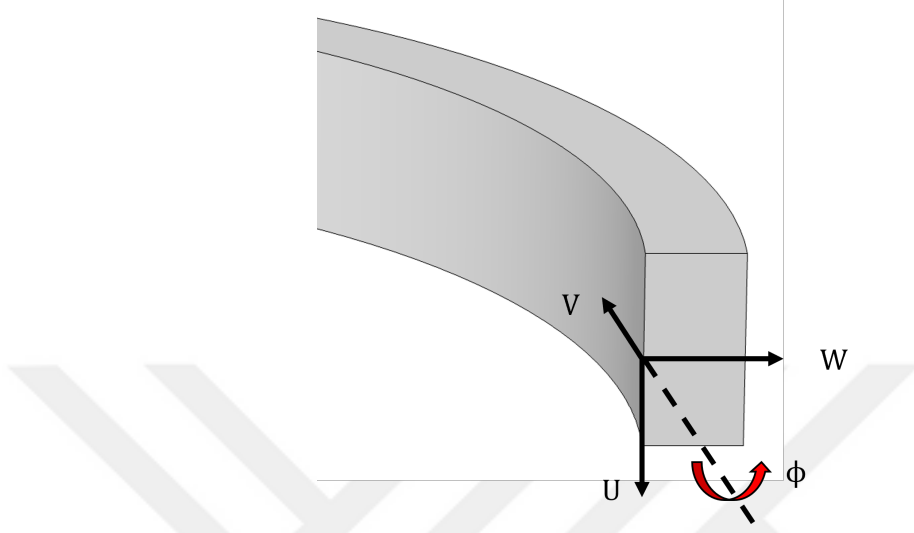


Figure 2.2: Polar coordinates on the ring's cross-section

$$\dot{w} = \dot{Q}_{11}n \sin n\theta + \dot{Q}_{12}n \cos n\theta \quad (2.5)$$

$$\dot{v} = -\dot{Q}_{12} \sin n\theta + \dot{Q}_{11} \cos n\theta \quad (2.6)$$

$$= \frac{1}{2} \rho R A \int_0^{2\pi} (\dot{Q}_{11}(n \sin n\theta + \cos n\theta)^2 + \dot{Q}_{12}(n \cos n\theta + \sin n\theta)^2) d\theta \quad (2.7)$$

The integration eliminates the odd function on the 0 to 2π band. so the sin and cos elements are found to be 0.

$$E_{Kin} = \frac{1}{2} \rho R A \pi (n^2 + 1) (\dot{Q}_{11}^2 + \dot{Q}_{12}^2) \quad (2.8)$$

The strain energy is written as:

$$U = \frac{I_z}{2R^3} \int_0^{2\pi} E \left(\frac{\delta^2 w}{\delta \theta^2} + w \right)^2 d\theta \quad (2.9)$$

$$w = Q_{11}n \sin n\theta + Q_{12}n \cos n\theta \quad (2.10)$$

$$\frac{\delta^2 w}{\delta \theta^2} = -Q_{11}n^3 \sin n\theta - Q_{12}n^3 \cos n\theta \quad (2.11)$$

$$U = \frac{I_z}{2R^3} \int_0^{2\pi} E (Q_{11}(n \sin n\theta - n^3 \sin n\theta) + Q_{12}(n \cos n\theta - n^3 \cos n\theta))^2 d\theta \quad (2.12)$$

$$U = \frac{I_z}{2R^3} \int_0^{2\pi} E (Q_{11}n \sin n\theta(1 - n^2) + Q_{12}n \cos n\theta(1 - n^2))^2 d\theta \quad (2.13)$$

$$U = \frac{2\pi I_z}{2R^3} E \left(\frac{Q_{11}^2 n^2 (1 - n^2)^2}{2} + \frac{Q_{12}^2 n^2 (1 - n^2)^2}{2} \right) \quad (2.14)$$

$$E_{Strain} = \frac{\pi EI_z}{2R^3} (Q_{11}^2 + Q_{12}^2) n^2 (n^2 - 1)^2 \quad (2.15)$$

The resonance frequency of the ring can be obtained by equivalence of the kinetic and the strain energy. Q_{11} and Q_{12} can be assumed to be:

$$Q_{11} = B \sin wt, \quad Q_{12} = C \sin wt \quad (2.16)$$

where w is the frequency of the motion. By placing these values in the equation 2.8 and equation 2.15 we obtain:

$$\frac{1}{2} \rho R A \pi (n^2 + 1) (B^2 w^2 + C^2 w^2) = \frac{\pi EI_z}{2R^3} (B^2 + C^2) n^2 (n^2 - 1)^2 \quad (2.17)$$

$$w^2 = \frac{\frac{\pi EI_z}{2R^3} (B^2 + C^2) n^2 (n^2 - 1)^2}{\frac{1}{2} \rho R A \pi (n^2 + 1) (B^2 + C^2)} \quad (2.18)$$

$$w^2 = \frac{I_z}{R^4} \frac{E}{\rho A} \frac{n^2 (n^2 - 1)^2}{n^2 + 1} \quad (2.19)$$

where I_z and A is expressed as where R is the radius of the ring and R_i is the inner radius of the ring:

$$I_z = \frac{h(R - R_i)^3}{12}, \quad A = (R - R_i) \cdot h \quad (2.20)$$

$$w^2 = \frac{h(R - R_i)^3}{R^4} \frac{E}{\rho w h} \frac{n^2 (n^2 - 1)^2}{n^2 + 1} \quad (2.21)$$

$$w = \frac{R - R_i}{R^2} \sqrt{\frac{E}{12\rho} \frac{n(n^2 - 1)}{\sqrt{n^2 + 1}}} \quad (2.22)$$

The design's mechanical analysis is investigated more thoroughly in [32].

Table 2.1: Vibrating Ring Paramters

Parameter Name	Parameter Variable	Parameter Value
Outer ring max radius	R_O	$1600\mu m$
Inner ring max radius	R_I	$1325\mu m$
Outer ring width	ω_O	$100\mu m$
Inner ring width	ω_I	$16\mu m$
Length of connecting beam	l_c	$175\mu m$
Length of supporting beam	l_s	$110\mu m$
Width of connecting beam	ω_c	$16\mu m$
Width of supporting beam	ω_s	$10\mu m$
Thickness of the Si Layer	t	$35\mu m$
Mass density	E	$2329kg/m^3$
Young's Modulus	ρ	$170GPa$

The vibrating ring design that will be studied in this thesis consist of two concentric rings which are connected to one another by spokes that are placed with the interval of 45 degrees around the circumference of the ring. The outer ring is surrounded by differential electrode pairs at its inner and its outer side. The gap between the electrode and the ring is set to $3\mu m$. The inner and the outer differential electrode pairs are matched by their span length of $630\mu m$ for the drive and sense electrodes. The electrode length is crucial for inserting the same amount of drive force from the positive and the negative terminals. As it holds a similar importance for the sense electrodes to obtain a clear output signal. The inner ring has a width of $16\mu m$ and an outer radius of $1325\mu m$. The outer ring and the inner ring is connected to each other with a rectangular spoke that has a length of $180\mu m$ and the width of $16\mu m$. The parameters of the ring can be find in table 2.1 and the VRG's parameters is marked on the figure 2.3.

The resonance frequency of the wineglass mode is set to 63.2kHz. The ring's in-plane resonance modes are proportional to $w \approx 1/R^2$ [31]. The allocated regions for the stress sensor necessitates a compact design for the gyroscope. Due to these reason, the resonance frequency of the gyroscope is much higher compared to a typical operational range of 10kHz. The design of the ring is optimized to separate the wineglass mode from the acceleration mode of the ring. The modal mass of the acceleration mode is larger compared to wineglass mode due to the topology of the design. The resulting mode space shows a smaller resonance frequency for

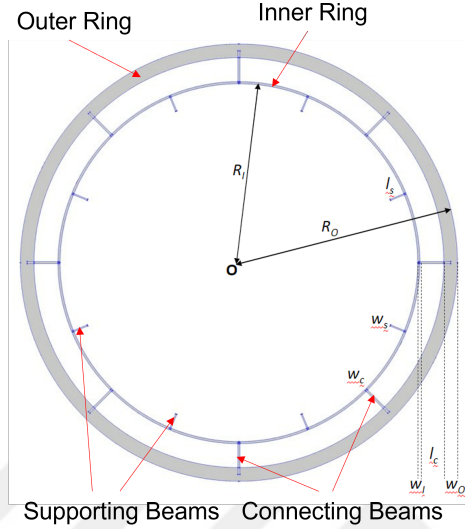


Figure 2.3: The top down view of the VRG with parameters

the acceleration mode compared to the wineglass mode. The separation of these modes is critical to optimize the performance of the ring hence the inner circle's spring coefficient was increased by stiffening the inner circle's suspension. Thus, the resonance frequency of the $n=1$ acceleration is set to 47.3 kHz. By achieving large band separation between each mode resonance frequency the effect of coupling between each mode is minimized. The mode space of the VRG will be explained thoroughly in section 2.3.

The gyroscope is operated through the differential electrode pairs. Each electrode and its location can be seen in figure 2.4a. The differential input and output is necessary to cancel the in-plane vibrations of the ring to the first order. The Drive(D+/-) and Drive Pick(DP+/-) electrodes are responsible for driving the structure in to resonance in drive axis. A differential sinusoidal input signal is applied to the D electrodes to start the resonance. While the DP electrodes generate an output current due to change of capacitance. This signal is amplified and then demodulated as a 180° phase shifted signal. The DP signal is necessary to keep the resonance motion at a constant displacement level. The sense axis's nodal diameter is set along the 45° and 135° axis the magnitude of the displacement in the sense axis is 10-20 times smaller depending on the angular velocity input. Thus, the signal generated at the sense electrodes is small and prone to

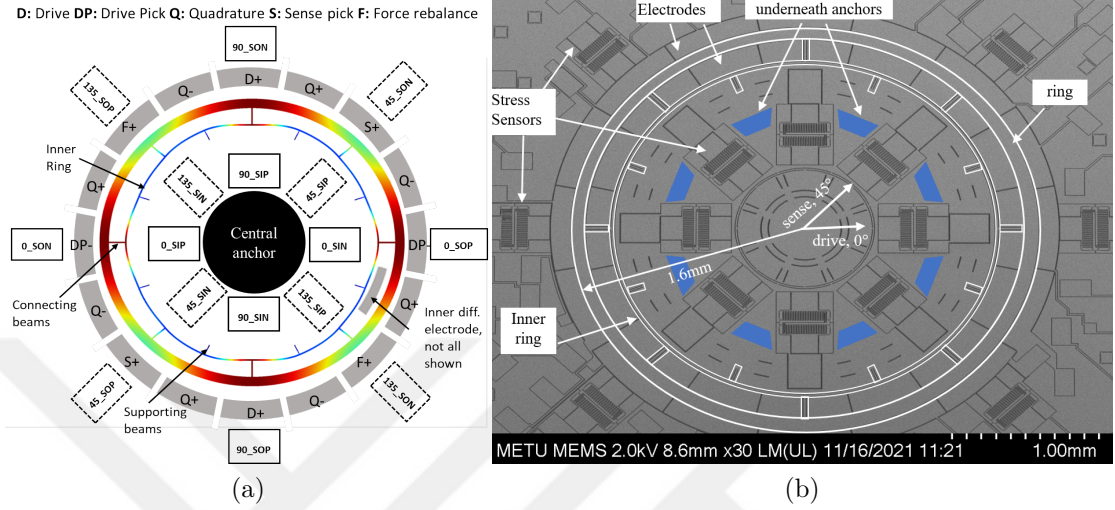


Figure 2.4: The gyroscope design summary (a), and the SEM image of the gyroscope with the integrated stress sensors (b).

the noise sources in the system. Force rebalance(F+) electrode are placed as an outer electrode while the Ftune electrode is placed at the inner side. The F+ electrodes can be used to negate the displacement at the sense axis by operating the gyroscope in the closed loop operation. The magnitude bandwidth of the rotation input can be increased when operating in closed loop configuration but in this study we will not utilize this electrode. A DC voltage is supplied to the Ftune electrode which generates an offset electrostatic force that changes the frequency mismatch between the drive and sense modes. The Q+ and Q- are the quadrature cancellation electrodes which are also supplied with a DC voltage which is controlled by the lock-in amplifier which will be investigated thoroughly in section 3.1.4.

The design parameters of the ring was limited by the fabrication methods that were used in the production. The fabrication of the device was outsourced from METU-MEMS and a deviated version of fabrication process in [33] was used for the fabrication. The device consist of three layers which are the anchor glass layer, the silicon(Si) layer that consist of the lumped mass of the stress sensors and the gyroscope and the metalization layer that etched off from the deposited gold(Au) layer.

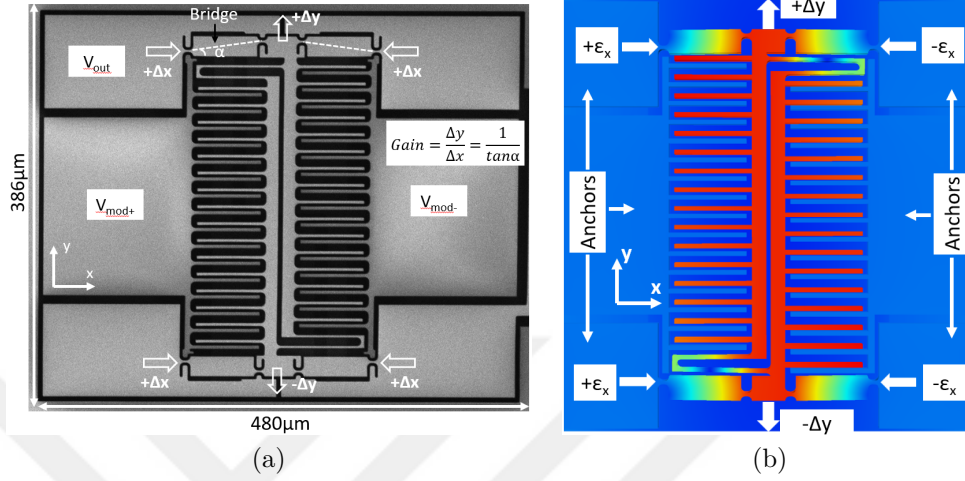


Figure 2.5: The stress sensor SEM image and the electrical equivalent circuit (a), and the FEA image showing the operation principle (b).

2.2 Stress Sensor Design

A stress sensor is a mechanical structure that converts the built up stress into an electrical signal. The highly used silicon and the compact design favors the capacitive stress sensor design over a piezoresistive one. The capacitive sensor can be placed at the inner part of the ring and encircle the proof mass anchor. Since stress is not distributed on the die linearly we believe that the distribution of the stress sensors will assess the stress built up more accurately.

The design of stress sensor is inspired the bridge-type flexure hinge[25]. The sensor has a rectangular morphology, spans an area of $480\mu\text{m} \times 386\mu\text{m}$ and separated to three different electrode blocks. The two middle section at each side supported by the anchors house the fixed capacitive electrode plates. These plates has a limited movement capability compared to the hinge plates. The third electrode is comprised of the flexure hinge design and the moving plates. The flexure hinge amplifies the horizontal stress on the anchors to vertical displacement of the plates in the center as it can be seen in the figure 2.5b. The distance change between the fixed and the moving plates changes the capacitance and can be measured to obtain the built up stress.

Table 2.2: Stress Sensor Paramters

Parameter Name	Parameter Variable	Parameter Value
Hinge length	l_x	$65\mu m$
Hinge width	l_y	$21\mu m$
Pivot length	l_a	$10\mu m$
Pivot width	t	$3\mu m$
Flexure degree	α	7°
Thickness of the Sensor	h	$35\mu m$
Finger length	l_f	$65\mu m$
Finger gap	d_0	$2\mu m$

The hinge design amplifies the displacement on the anchors by the displacement gain of:

$$R_{amp} = \frac{l_a \cos \alpha}{\cos \alpha \frac{t^2 \cos \alpha}{6l_a \sin \alpha} + l_a \sin \alpha} \quad (2.23)$$

Since t is small we can express the displacement gain as:

$$R_{amp} \approx \cot \alpha = 6.5 \quad (2.24)$$

The displacement per strain is found by the multiplication of the gain and the total width of the stress sensor as:

$$\Delta y = 170\mu m \cdot 106^{-6} \cdot 6.5 = 1.105 \cdot 10^{-9} \quad (2.25)$$

The Comsol simulations also show that the per strain for displacement as $1.05nm$ which is matching result to our theoretical calculations. The distance between the finger gaps are discovered to be $2.85\mu m$ by the SEM imaging. So, the output voltage per strain on the stress sensor can be written as:

$$V_{out} = \frac{n\epsilon A}{C_0} \frac{2\Delta y}{d_0} V_{mod} \quad (2.26)$$

The derivation of the equation 2.26 is given in the section 3.2. The output voltage change per strain for $C_0 = 1pF$ and an input simgal of $V_{mod} = 1V$ we obtain:

$$V_{out} = \frac{16 \cdot 8.85 \cdot 10^{-12} \cdot 65 \cdot 10^{-6} \cdot 35 \cdot 10^{-6}}{10^{-12}} \frac{2 \cdot 1.1 \cdot 10^{-9}}{2.8 \cdot 10^{-6}} 1 \quad (2.27)$$

$$V_{out} = 0.09mV \quad (2.28)$$

The stress sensors are placed 8 at the inner part and 8 at the outside of the ring as it can be seen in the figure 3.13.a. The name of the stress sensors are according to their location. First the axis degree regarding the x-axis is given. S stands for the stress sensor. O or I refers to the inner or outside. P and N shows the polarity of the stress sensor. The stress sensor design has a polarity so that the for the same type of stress the distance between the capacitive fingers changes reversely. Thus for the compressive stress applied on a P type stress sensor the capacitive between the positive clock and the output of the stress sensor is diminishing while the gaps between the negative clock signal and the output electrode is increasing. For the N type stress sensor the opposite condition is true. This time when a compressive force is applied on the stress sensor the capacitive gap between the negative clock signal and the output electrode decreases. Thus the magnitude of the negative voltage increases while the positive decreases.

2.3 FEA Simulation Results

A complaint mechanical structure can have various resonance frequency modes. The structure start to resonate when a proper force in a specific direction is applied on it on its resonance frequency. The circular topology of the gyroscope makes it difficult to compute the exact resonance frequency values of the different types of resonance mods. To calculate and observe these modes an FEA simulation tool is required. Comsol multiphysics tool was used as the FEA simulation tool to simulate the structure characteristic of the ring gyroscope. The moving structure was modeled on the simulation tool by assigning parameter to the ring structure's spoke and ring radius. As it can be seen in the figure 2.6 only the moving parts of the VRG structure is simulated to reduce the workload of the simulation tool. The inner surface of the inner spokes are fixed to the location they are located in the 3d space. The remaining volume is arranged to be freely moving.

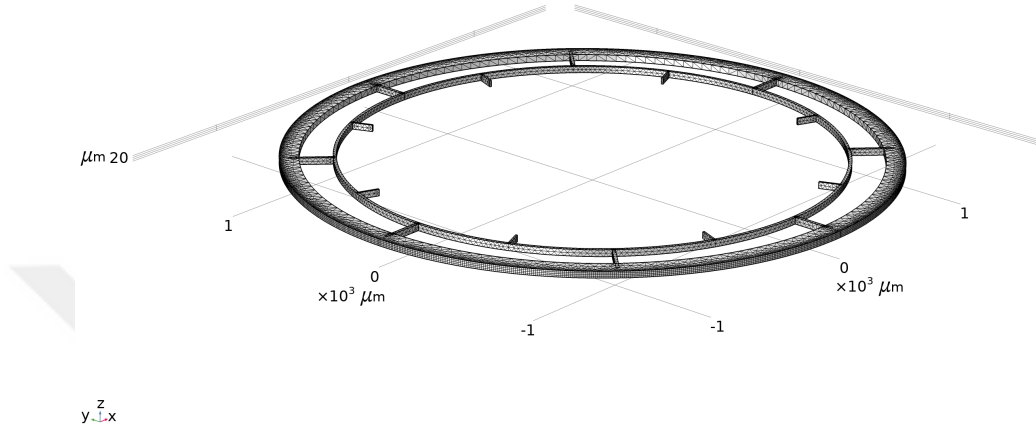


Figure 2.6: Generated mesh in the Comsol simulation

Table 2.3: Comsol Simulation Results

Mode Name	Obtained Resonance Frequency
Z-axis Inertial	31374
Z-axis Tilting Motion	31395
Z-axis Tilting Motion n=2	33417
XY-plane Acceleration	47612
Z-axis Tilting Motion n=3	50357
XY-plane Torsional	50647
Wineglass Mode in Sense Axis	63345
Wineglass Mode in Drive Axis	63477
Wineglass Mode n=3	129286

One of the most important setting that needs to be arranged for an FEA simulation is the meshing. FEA simulation calculate the eigenfrequency of the design by computing the spring coefficient of the structure point by point. The point location on the volume is decided by the mesh. The separation uniformity of these points is crucial to obtain a correct result otherwise the displacement vector of the structure can be misaligned. To properly generate a mesh a layer boundary was defined on the outer ring's outer sidewall surface. Since the actuation and the sensing is measured from this sidewall it was important to protect the uniformity on the sidewall and the remaining points were assigned by free tetrahedra algorithm. The generated mesh on VRG can be seen on the figure 2.6.

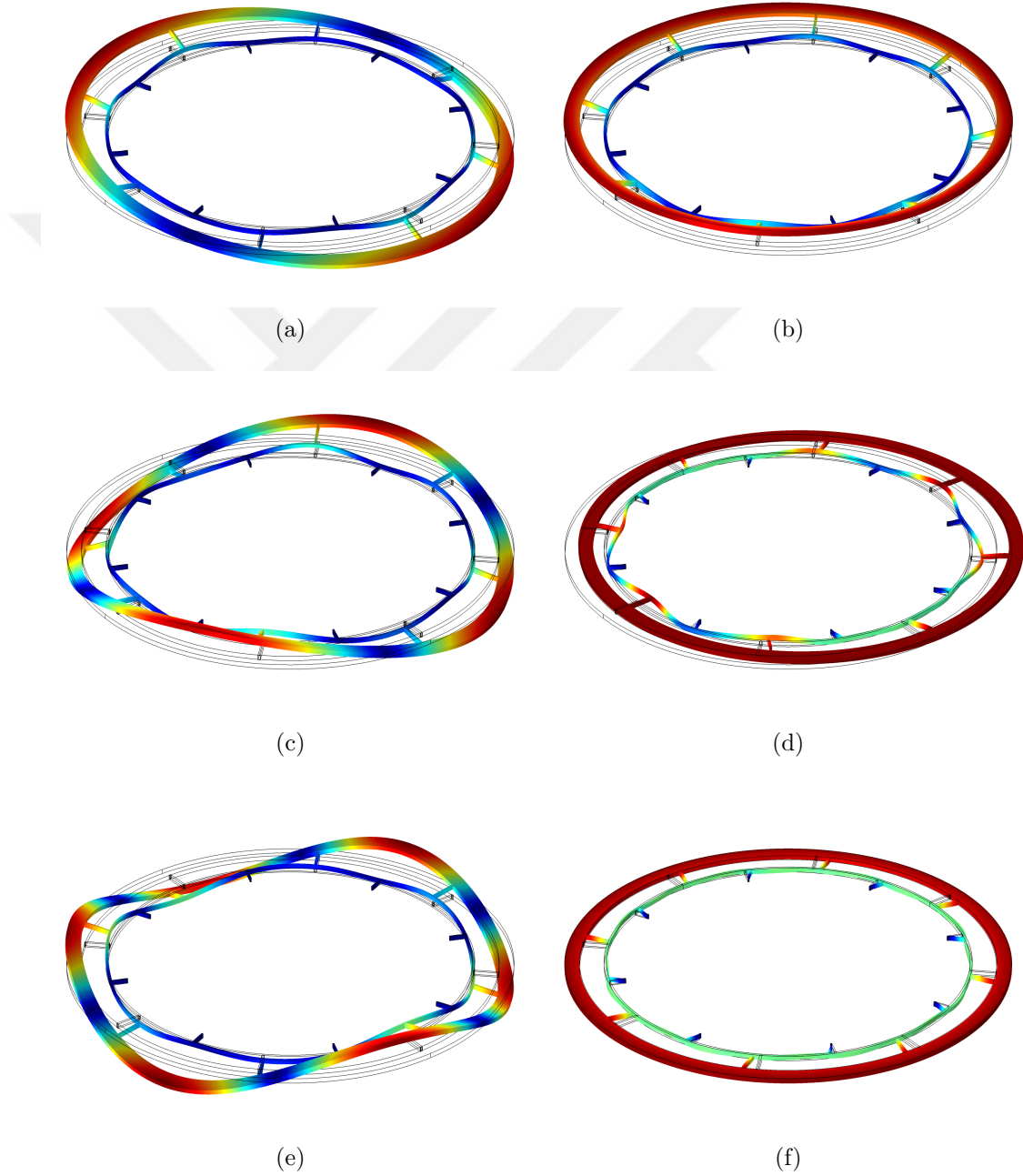


Figure 2.7: The Z-axis Inertial Mode at 31374 Hz (a), the Z-axis Tilting Motion 31395 Hz (b), Z-axis Tilting Motion $n=2$ Mode at 33417 Hz (c), XY-plane Acceleration Mode at 47612 Hz (d), Z-axis Tilting Motion $n=3$ Mode at 50357 Hz (e), XY-plane Torsional Mode at 50647 Hz (f).

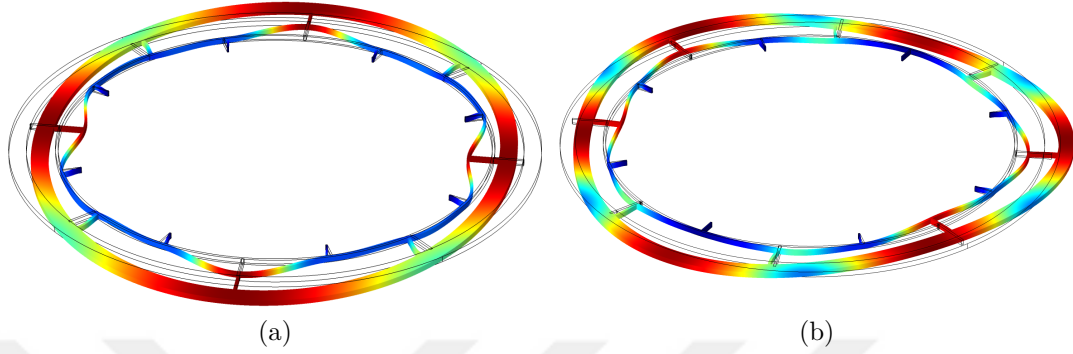


Figure 2.8: The Wineglass Mode $n=2$ at 63345 Hz (a), and the Wineglass Mode $n=3$ at 129286 (b).

The result of the various mode names and their resonance frequency value was given in table 2.3. The modes given in the table are visualized in the figure 2.7 and in figure 2.8. The most dominant mode for a structure is commonly the mode with the lowest resonance frequency. For example, a wineglass's most dominant mode is the $n=2$ mode as it can be seen in the [34]. The mode space of the VRG show that the Z-axis modes have the lowest resonance frequency due to the thinness of the silicon layer that we are required to utilize. However, this doesn't present a major problem since the device won't be subjected to forces in Z-axis. The modes that can interfere with the operation of the VRG are the acceleration sensitive mode in XY-plane and $n=3$ mode. The inertial mode in XY plane will always have a lower resonance frequency value compared to the wineglass($n=2$) mode. As it was stated in 1.6 the resonance frequency is obtained by the modular mass and the spring coefficient of the structure. Since, effective mass of the acceleration mode is larger than the effective mass of the wineglass mode the resonance frequency of these modes will be inversely related. Because of this relation the acceleration mode's resonance frequency must be sufficiently far away from the wineglass mode frequency in the frequency band. The outer ring's width is adjusted so that the frequency difference is arranged to be 16kHz. The addition of the differential drive method we utilize in our system we minimized the possibility of an interference between these two modes.

A careful reader might have recognized that the resonance frequency of the VRG is larger compared to the other circular gyroscopes that were mentioned

earlier. The first reason for us to set the VRG's resonance frequency value high is the compact design. Since the anchor in the middle must be surrounded by stress sensors the silicon space allocated to ring is decreased. The ring's resonance frequency has a inverse relation of $f_{res} \approx 1/R^2$ [31]. As a result, the ring radius is smaller compared to other circular gyroscope designs. Secondly, setting a higher resonance frequency for the wineglass mode also reduces the inertial sensitivity of the gyroscope since the acceleration mode's resonance frequency is also increased.

2.4 Fabrication

The fabrication was outsourced and the devices were fabricated by the METU MEMS. The method of fabrication is a deviated version of the method that can be found in [33]. The fabrication method consist of 2 layer fabrication a silicon layer that house the MEMS structure and a Au metalization layer for connectivity. The fabrication method also provides wafer level vacuum packaging. An SOI wafer is used to encapsulate the device with Au-Si eutic bonding. The fabrication method was one of most detrimental factor in the device design.

The compact design requirement makes the layout design challenging. The VRG's layout requires electrodes in the shape of arcs and the connection anchors create a barriers that prevent passage for the metal traces. The traces can only pass through the space between the electrode anchors. A great attention was given to the output signal traces and their order in the placement. Coupling effect can be observed when a weak signal and a strong signal trace is placed side by side. For example, Clock signal is a strong signal since it's generated by a signal generator. It can couple to the Sense signal due to the parasitic capacitance between the traces when these traces are placed side by side. To prevent this phenomenon a DC signal is placed between a strong and a weak signal and the parasitic capacitance is minimized. Another prevention method is to group the differential output signals together and by placing these traces together the output signal are projected to similar coupling effects. Finally keeping the most important electrode traces short the parasitic capacitance is kept to minimum.

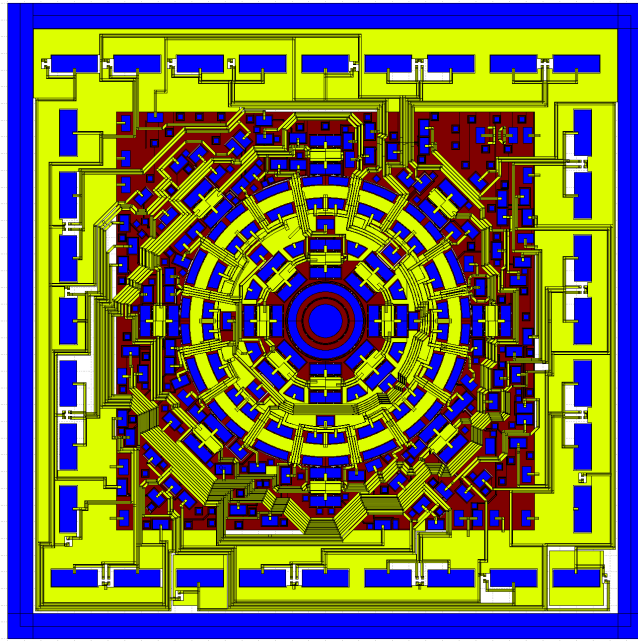


Figure 2.9: The bottom to top view o the VRG's layout



Figure 2.10: SEM image of the VRG

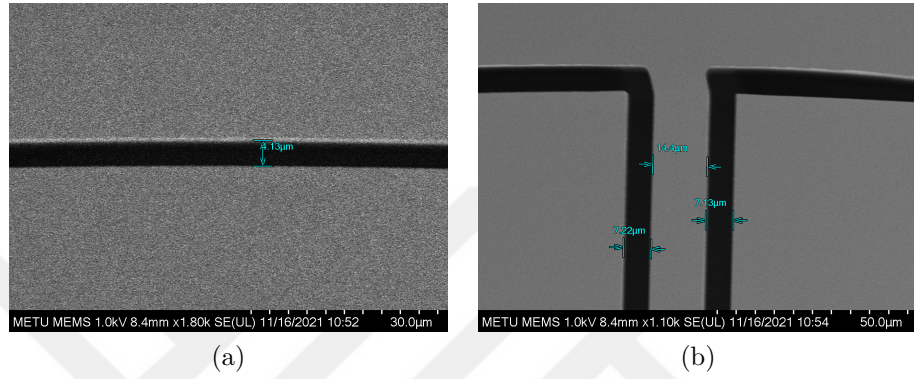


Figure 2.11: The gap between the ring and an outer electrode (a), and the ring spoke width and the gaps between a spoke and the inner electrodes (b).

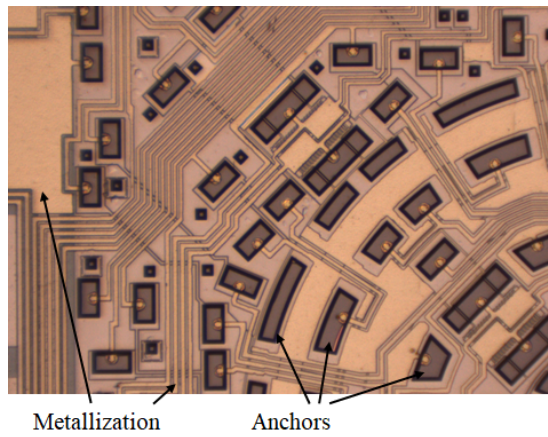


Figure 2.12: The die observed from the bottom with on the probe station

The fabrication results have gone through visual check by a scanning electron microscope(SEM) and a probe station microscope. SEM analysis show the etching in the silicon layer and can be investigated in figure 2.10. the gap distance between the electrodes are measured using the SEM's toolkit. The SEM results shows that the gaps are over etched. As a result, we have anticipated that the VRG's resonance frequency will be decreased since the spring coefficient is decreased compared to the original ring's spring coefficient. The figure 2.11 shows the thinner beams on the supporting and the connecting beams and the larger distance between the ring and the electrodes than anticipated.

During the visual inspection on the probe station the gyroscope can be seen from the bottom to top. The figure 2.12 shows the metallization layer and the silicon layer underneath. The bright yellow colored traces show the metal Au layer. The black bordered rectangles and the arcs show the anchors and the point of contact of the metal and the silicon can be seen in circular shape that is colored in orange. The failure in the visual inspection is investigated in the test results.

Chapter 3

Readout and Control Electronics

The operation of the MEMS gyroscope requires constant regulation of the input signals and the steady recording of the output terminals. In addition to the gyroscope's operation, readout of the stress sensors must be achieved with a minimal amount of interference between each signal chain. This chapter summarizes the electronics and the control loops used to operate the gyroscope.

3.1 Gyroscope Electronics

The purpose of each electrode was explored in the Gyroscope's design chapter. In this chapter, the configuration of each control loop will be explored. The control loops used for this application are entitled as follows:

- Drive Resonance Loop Control
- Force Rebalance Loop Control
- Quadrature Error Loop Control

Resonance control arranges the proof mass's motion for resonance in the drive

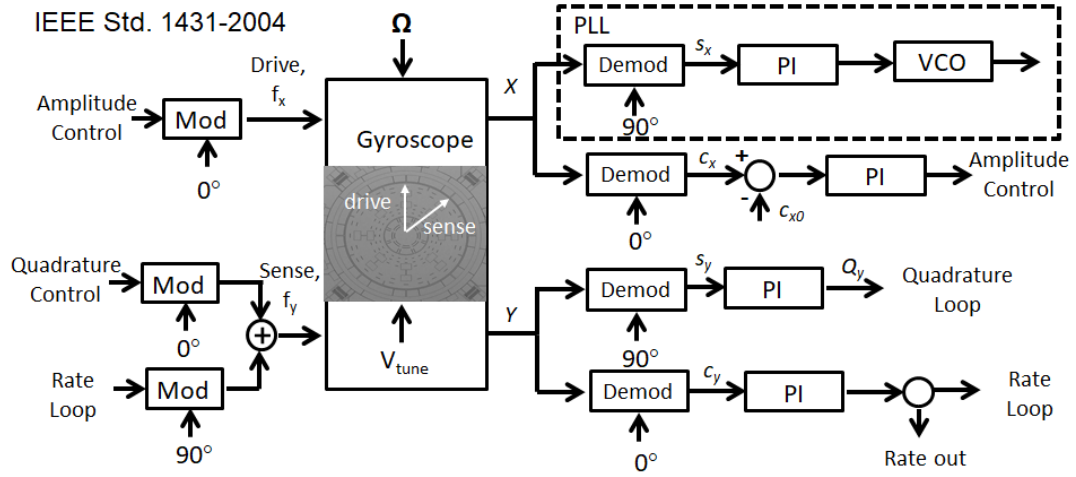


Figure 3.1: Overall Control Schematic of Gyroscope

axis. Achieving this task requires control over two fundamental properties of the drive mode: the frequency of the vibration and the magnitude of the displacement. These values must be kept constant so that the system's response is not altered during operation. With these obligations, the resonance control requires a Phase Locked Loop(PLL) to set the resonance frequency of the displacement and Proportional Integral Derivative(PID) to set the magnitude of the input signal, which is served to the drive electrodes.

The figure 3.1 shows the overall schematic of the signal control chains necessary to operate the MEMS gyroscope. The Drive signal's modulation is controlled by the PID and the PLL sourced by the Drive Pick signal. Initially, the drive signal is introduced to the system with a frequency level close to the drive resonance of the proof mass. The Drive pick signal is demodulated by the Drive and its 90° out of phase signal. The out-of-phase signal is necessary to detect the peak response of the device. After the demodulation, the acquired signal is amplified by a PI and then a Voltage Controlled Oscillator(VCO). VCO generates the frequency component of the Drive signal. The total displacement determines the gyroscope's sensitivity during the operation. The amplitude control of the displacement is necessary to obtain a constant output throughout the operation of the device. The X component of the demodulated drive signal is inserted into a PI controller after subtracted from a set voltage level. The modulation of these

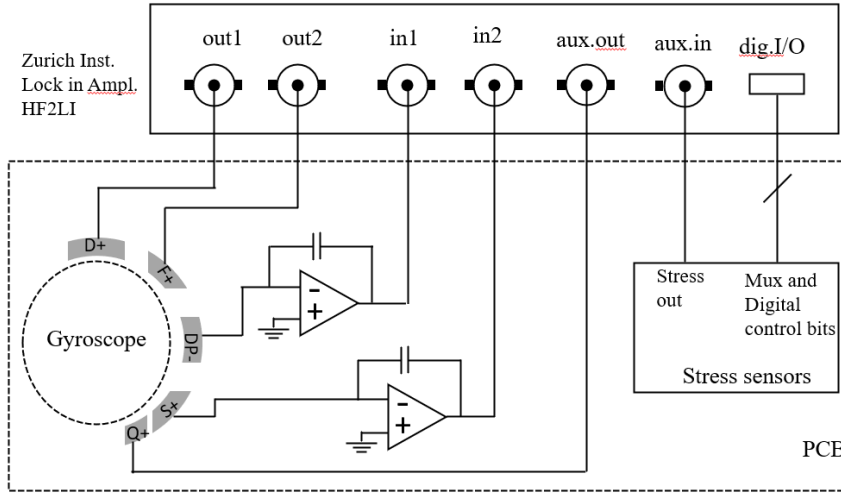


Figure 3.2: Lock-in Amplifier Connections

two components finally generates the Drive Signal, and the feedback loop is kept functional throughout the operation of the device.

The control loops implemented during the testing are set up in a lock-in amplifier Zurich Instruments HF2LI[35]. HF2LI packs the additional modulation, demodulation, PLL, and PID modules which are essential for the system's operation. The lock-in amplifier can be controlled by a PC connected through a USB-B cable using a web browser interface. Figure 3.2 shows the high-level schematic of the link between the gyroscope and HF2LI. HF2LI possess two signal generator outputs which control the Drive and force rebalance electrodes. The two independent lock-in units are connected to Drive Pick and Sense electrodes. The quadrature electrodes are connected to the aux out port of the HF2LI for the required DC voltage to cancel the quadrature error. The lock-in amplifier also controls the readout of the stress sensors. The stress sensor outputs are stored by the aux in port of the HF2LI. The digital I/O pins switch between the stress sensors according to the python code to record each stress sensor output. The readout electronics of the stress sensors will be further explained in the sub-section 3.2. Except for these fundamental features, HF2LI provides additional capabilities depending on the requirements for the test that is run on the MEMS Gyroscope.

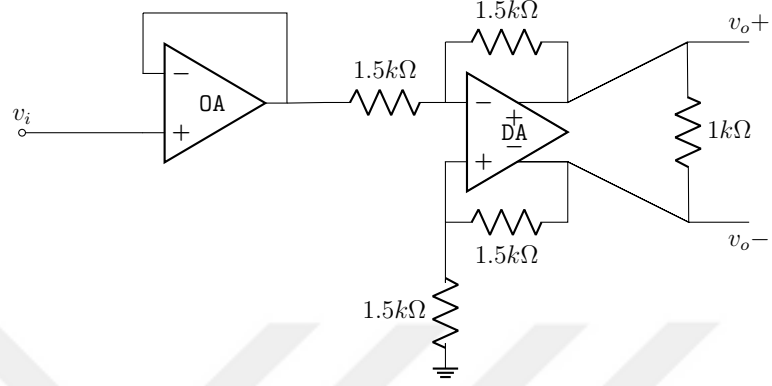


Figure 3.3: Differential Signal Generation Schematic

3.1.1 Gyroscope Drive Stage Electronics

Drive and Force Rebalance signals are generated using the same methodology. A signal is generated by the HF2LI and the generated signal is converted to a differential signal by a fully differential amplifier (THS 4561) after passing through a signal buffer on the main PCB. The buffer was implemented to protect the HF2LI in case of a short circuit that can damage the lock-in amplifier. Figure 3.3 shows the schematic of the differential signal generation where the differential signal is obtained by using standard resistor values of $1.5k\Omega$.

3.1.2 Gyroscope Readout Stage Electronics

The sense stage is used to amplify the output signals generated by the output signals of the gyroscope, such as Sense and Drive Pick electrodes. The amplification is necessary to obtain an accurate measurement. Figure 3.4 shows the schematic of the readout circuit. A transimpedance amplifier is used for the drive and sense signal chains as the initial gain stage. The current output generated due to changing capacitance is converted to voltage using the transimpedance amplifiers. Transimpedance amplifier provides low input and output impedance values while having a large gain. A high pass filter is placed between the transimpedance and

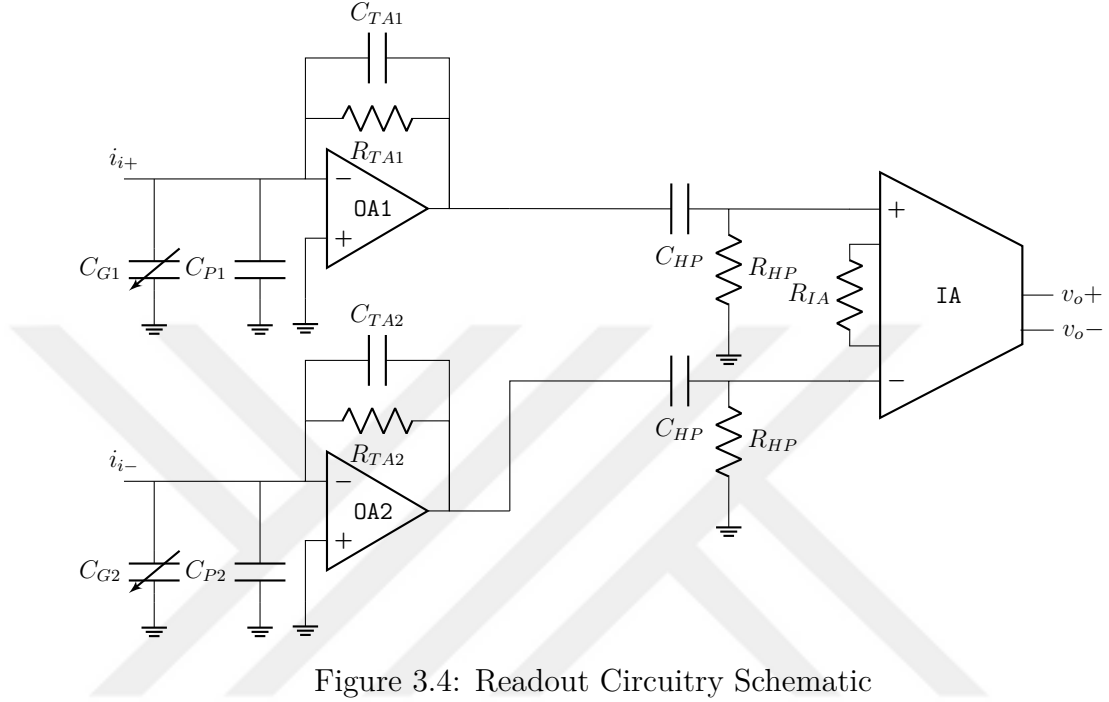


Figure 3.4: Readout Circuitry Schematic

the instrumentation amplifier to eliminate the DC offset. In the second stage of the signal chain, an instrumentation amplifier(AD8295) is deployed. AD8295 possesses a single instrumentation amplifier(IA) and two general-purpose Opamps. An external resistor adjusts the IA's gain. The IA is necessary to introduce pre-determined voltage gain to the signal chain and eliminate the mismatch between the positive and the negative electrodes caused by the inherent design of the circular design. A precise differential signal with minimal noise is generated at the output using the IA and one of the general-purpose opamps. The transimpedance amplifier's gain is obtained by the impedance at the feedback stage and can be written as:

$$\frac{V_{TA}}{i_g} = Z_{TA} \quad (3.1)$$

$$Z_{TA} = R_{TA} // \frac{1}{sC_{TA}} = \frac{R_{TA}}{sC_{TA}R_{TA} + 1} \quad (3.2)$$

The circuit's gain is limited by the HF2LI's input port range which is $\pm 2V$.

Since the displacement is much larger in the drive axis, the Drive pick signal is larger than the sense signal and requires a smaller overall gain. The DP transimpedance capacitance is selected as $C_{TADP} = 2.4pF$ and the IA gain as 1. The overall gain for the drive signal chain is 6.8. The capacitance selected for the transimpedance amplifier for the sense signal is $C_{TAS} = 0.5pF$, and the IA gain is set to 10. The transimpedance resistors are chosen to be very large to $T_{TAS} = 20M\Omega$ which prevents the charge build up at the input of the Opamp.

The initial gain stage is the most detrimental in terms of the electrical noise in the system. These electrical noise sources are the Voltage noise of the opamp, the current noise of the opamp, and the noise dependent on the bias resistor temperature. The parasitic capacitance between the opamp and the sense electrode is the most dominant electrical noise source due to the signal's path. We have calculated the parasitic capacitance within the die to be approximately 20pF. The package adds another 3pF of parasitic capacitance. Additional parasitic capacitance is caused by the electrical circuitry mainly, opamp's input voltage density, and the PCB tracing. We have deployed and tested various solutions to decrease the voltage noise. The OPA2320 offered the best noise performance with the input voltage noise density of $7nV/\sqrt{Hz}$ among other opamps which were tested. We were able to improve the noise performance of the device significantly by relocating the transimpedances' location to the daughter board and bypassing the 2.54mm header pins. The equation 3.6 shows the amount of total electrical noise present in sense signal chain.

$$E_{VN} = e_n(1 + C_P/C_O) = 7 \times 10^{-9}(1 + 30/1) = 217nV/\sqrt{Hz} \quad (3.3)$$

$$E_{IN} = i_n Z_O = 0.6 \times 10^{-15} \times 2.65M\Omega = 1.32nV/\sqrt{Hz} \quad (3.4)$$

$$E_{IR} = \sqrt{\frac{4KT}{Z_O}} Z_O = 19.68nV/\sqrt{Hz} \quad (3.5)$$

$$E_t = \sqrt{E_{VN}^2 + E_{IN}^2 + E_{IR}^2} = 217.9nV/\sqrt{Hz} \quad (3.6)$$

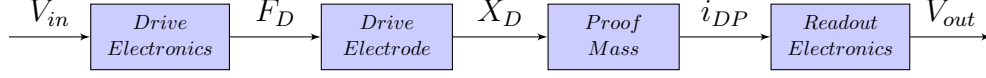


Figure 3.5: Block Diagram of the Drive Resonance

3.1.3 Drive Control Loop

The Drive control loop in 3.5 shows the input, output relation as a block diagram. The amplified input voltage generates an electric field that applies force on the proof mass. This relation is expressed as the change of capacitance vs. the displacement. The exerted force generates displacement on the proof mass. The displacement changes the capacitance of the drive pick electrode and current is generated on this electrode. The current is finally amplified by the transimpedance amplifier and the output voltage is obtained by the readout circuitry.

$$\frac{V_{out}}{V_{in}} = \frac{F_D}{V_{in}} \cdot \frac{X_D}{F_D} \cdot \frac{i_{DP}}{X_D} \cdot \frac{V_{out}}{i_{DP}} \quad (3.7)$$

3.1.4 Quadrature Cancellation

Quadrature cancellation is controlled by the lock-in amplifier as well as it can be seen in figure 3.2. The quadrature error is measured by the demodulated sense output's Y component. Quadrature cancellation is achieved by applying a differential DC voltage to Q+ and Q- electrodes of the VRG. The DC voltage generates a constant electric field on the resonating proof mass and decreases the deviation of the drive axis from the 0° angle. We have used ADA4522 dual opamp to generate the quadrature signals a generic opamp was added for the buffer stage for protection. One of the major issues we have faced with this design was caused by the aux port output of the lock-in amplifier. The aux port changes its output with 0.5mV incremental steps. Since the input voltage wasn't precise the PID loop output couldn't converge the quadrature error to zero. As a result, an irregular resonance was observed at the Y component of the sense

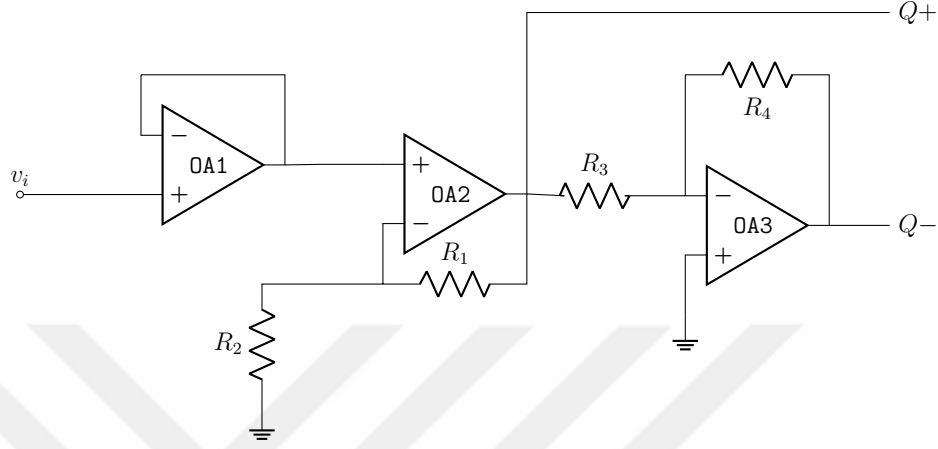


Figure 3.6: Quadrature Signal Amplifier Schematic

signal. We have introduced a voltage divider at the input of the buffer to decrease the overall gain of the quadrature cancellation circuit.

3.2 Stress Sensor Electronics

Demodulation is necessary to obtain measurement from the capacitive sensors. A transimpedance amplifier similar to the sense signal chain was used as the initial gain stage for each stress sensor. Since our setup is limited by a single lock-in amplifier and the lock-in amplifier's input ports are already populated, the demodulation takes part in the main PCB board. Figure 3.8 shows the stress signal chain's schematic. The stress sensor outputs are multiplexed sequentially by two 8x1 multiplexers(AD1208). The two enable pin and the three select bits of the multiplexers, which are connected and are controlled by the digital port of HF2LI. The multiplexer output is high impedance when it is disabled so the output pins of the MUXs can be connected as long as one of them is activated at the same instance. The MUX output can store charge during the switching instances which saturates the output of the instrumentation amplifier. To prevent this phenomena high impedance resistors were connected to the input nodes of the IA which allows a path for the discharging. The gain of the IA is set to 5 and

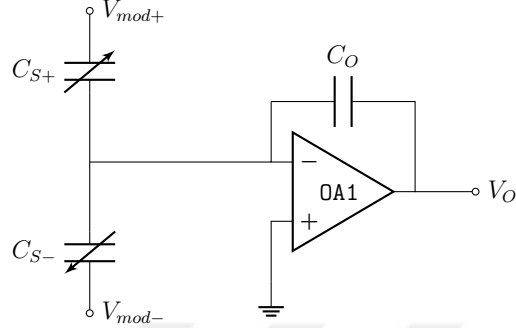


Figure 3.7: Transimpedance amplifier model of the stress sensor

a differential signal is generated for the inputs of the multiplier.

The output of the stress sensor can be measured by excluding the parasitic capacitance as:

$$sC_{S+}V_{mod+} + sC_OV_{O+} = 0 \quad (3.8)$$

$$V_{O+} = \frac{C_{S+}}{C_O}V_{mod+}, \quad V_{O-} = \frac{C_{S-}}{C_O}V_{mod-}, \quad -V_{O+} = V_{O-} \quad (3.9)$$

$$V_O = V_{O+} + V_{O-} = \frac{C_{S-} - C_{S+}}{C_O}V_{mod+} \quad (3.10)$$

$$V_O = \frac{\frac{\epsilon A}{g+x} - \frac{\epsilon A}{g-x}}{C_O}V_{mod+} = \frac{\epsilon A}{C_O} \frac{g-x-g-x}{g^2-x^2}V_{mod+} \quad (3.11)$$

Since x is much smaller than g the equation becomes equivalent to:

$$V_O = \frac{\epsilon A}{C_O} \frac{-2x}{g^2}V_{mod+} \quad (3.12)$$

The polarity of the stress sensor output can be arranged depending on the desired output. For a positive stress sensor output change in compressive stress input the V_{mod+} signal must be connected to the C_{S-} . This way the variable capacitance decreases when the compressive input is applied on the sensor.

The total gain of the stress sensor is obtained by the combination of the product of the mechanical and the electrical gain stages. The output of the transimpedance amplifier's output is measured to be 0.09mV per strain. Since the

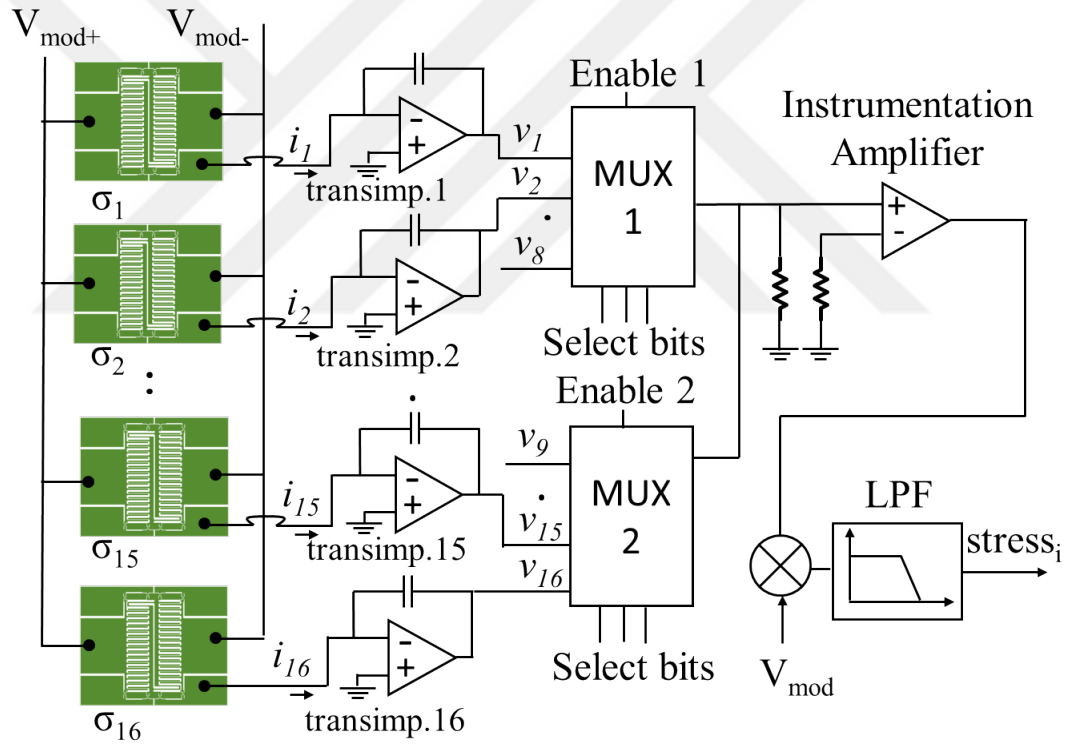


Figure 3.8: The stress sensor signal chain

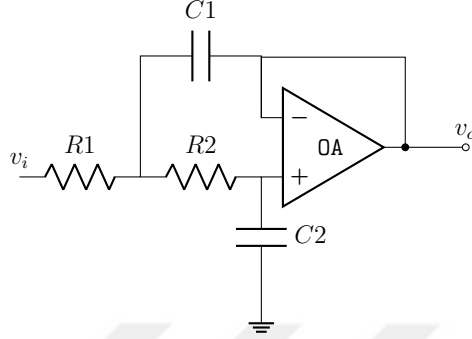


Figure 3.9: 2nd Order Butterworth Low Pass Filter Schematic

test setup is altered the output must be adjusted accordingly. In the tests, V_{mod} magnitude is set to 2V and ZI measures the rms value thus the output is altered to:

$$V_O = 0.09 \cdot \frac{2}{\sqrt{2}} = 0.127mV/170kPa \approx 0.75mV/MPa \quad (3.13)$$

The instrumentation amplifier gain is set to 10. The multiplier's gain is set to 2.66 and differential sensing is utilized thus the overall stress sensitivity is found as:

$$V_{Overall} = 10 \cdot 2.66 \cdot 2 \cdot 0.75 \cdot 10^{-3} = 40mV/MPa \quad (3.14)$$

The output signal is demodulated by a multiplier and a low pass filter. The multiplier(AD633) multiplies the amplified stress output signal with the clock signal. The multiplier's gain is set to 26. The low pass filter is the final stage in this signal chain and has a unity gain with the cut-off point at 100 Hertz. R1 is chosen as 5k Ω R2 is 210k Ω C1 is 220nF and C2 is 100nF. The figure 3.10 shows the spice simulation of the 2nd order low pass filter. Finally the high cutoff frequency derived from the natural frequency of the oscillator can be seen in 3.16.

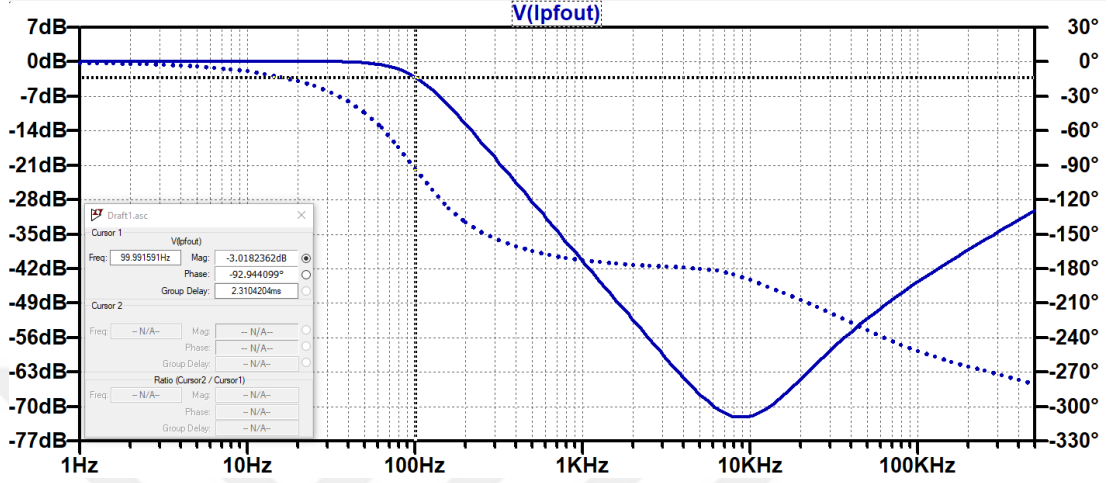


Figure 3.10: Low Pass Filter Spice Simulation

$$V_F = V_O(sC_2R_2 + 1) \quad (3.15)$$

$$\frac{V_O}{V_I} = \frac{C_1C_2R_1R_2}{s^2 + \frac{s}{C_1R_2 + C_1R_1} + \frac{1}{C_1C_2R_1R_2}} \quad (3.16)$$

$$f_h = \frac{1}{2\pi\sqrt{C_1C_2R_1R_2}} \quad (3.17)$$

3.3 Test PCBs

This section will focus on the four different PCB designs during the tests.

3.3.1 Main PCB

The main PCB's 3D virtual image is shown in figure 3.11. Two D-Sub 15 connectors were used as the transmitting the input and output signals. The leftside connector is responsible for the analog signals while the connector at the right side support the digital inputs for the multiplexers and the opamp enable signal. Additionally, the temperature output is connected to the digital connector since all of the pins in the analog connector is paired. The digital dsusb connector is

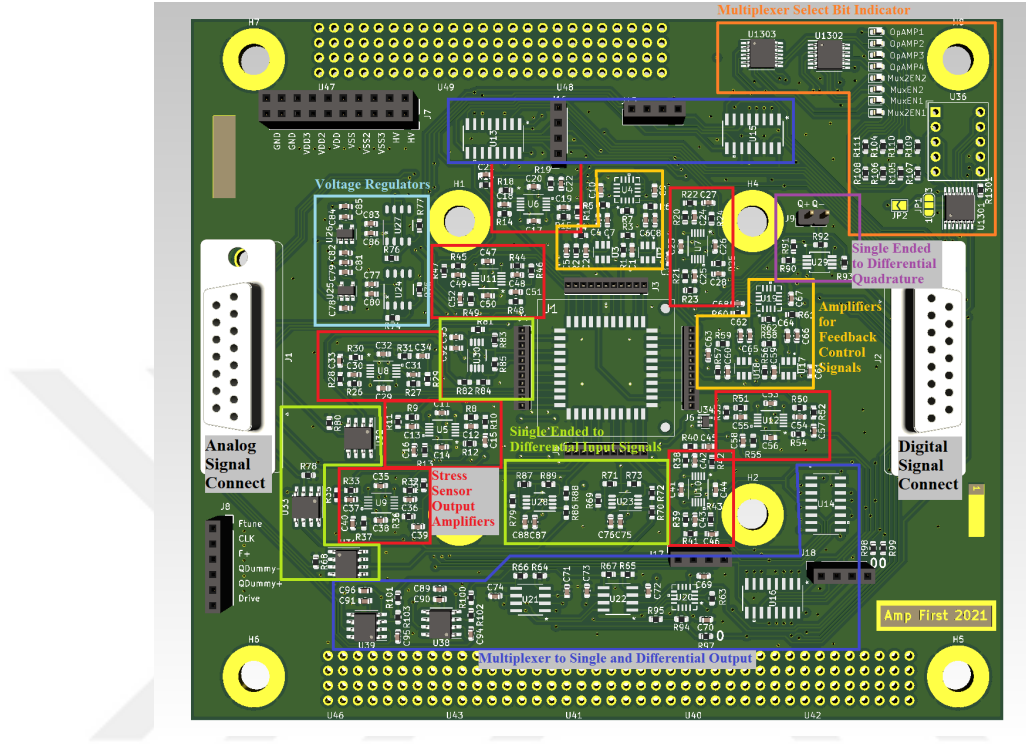


Figure 3.11: Main PCB

connected to a DIO HD 68 bit digital connector's assigned pins with a ribbon cable. The cable assigned to the temperature output is separated and a coaxial connector is soldered on to the stripped cable. This way the temperature output could be read by a multimeter. The pin assignment map of the analog connector is investigated in interface PCB section.

The main PCB's main function is to arrange the input and output signal of the Gyroscope and the stress sensors. The differential signals are generated by the block that are circled in green. The differential clock signal and the drive signal are generated here. The drive pick and sense signal amplification is achieved within the block that is surrounded by orange lines. The purple lines highlight the dual opamp that generates the differential quadrature DC signal for $Q+$ and $Q-$ electrodes. The rectangular zones colored in red house the transimpedance amplifiers for each stress sensor. As it can be seen in the figure 3.11 there are 8 dual opamps needed to achieve this goal. These opamps cover a large space on the PCB and increase the power consumption of the board. Due to these

drawbacks another PCB board was also designed in which the stress sensor output are connected to the multiplexer as the first stage and then the signals are passed through a single opamp for amplification. The second design was not employed in our tests due to the higher stress signal noise. The remaining section of the stress sensor signal chain is highlighted within the blue rectangular zones. The multiplexers, multipliers and the low pass filters are located in this zone. 4x1 2.54 mm headers are placed that are connected to the multiplexer input to allow easy reach for oscilloscope probes. The transimpedance amplifiers were tested using these nodes. There are 4 multiplexers in the main PCB. During the design phase the goal was to record the individual stress sensors and the subtracted stress sensor pair values. We have allocated the pairs as the opposite sided stress sensors such as 0SOP and 0SON or 135SIP and 135SIN. The amplified signals are inserted to the 8x2 Multiplexer and the differential pair signal is connected to the input of the instrumentation amplifier. The multiplier and the LPF step at this signal chain is the similar to the single reading. We have decided against employing differential reading method as the output of the paired stress sensor varied wildly due to the initial offset of each stress sensor. In addition to this fact the slow change in stress sensor output meant that we can subtract the pair outputs during the data analysis.

The voltage regulators for the 5V, -5V, 2.5V and -2.5V are located on the upper left side of the main PCB highlighted in teal. The remaining parts of PCB house the miscellaneous components that helps the user during the tests. A seven segmented display is placed on the top right corner that shows the number of the currently selected stress sensor. The discrete LEDs show the enabled components. This part of the circuit is unpopulated after the initial test to reduce power consumption. The perforations were added to the upper and lower side of the PCB for additional through hole component if it is needed. M5 mounting holes are added at the corners of the PCB to elevate the PCB. MOUNTING holes which are located in the middle are used to attach the PCB on the rate table.

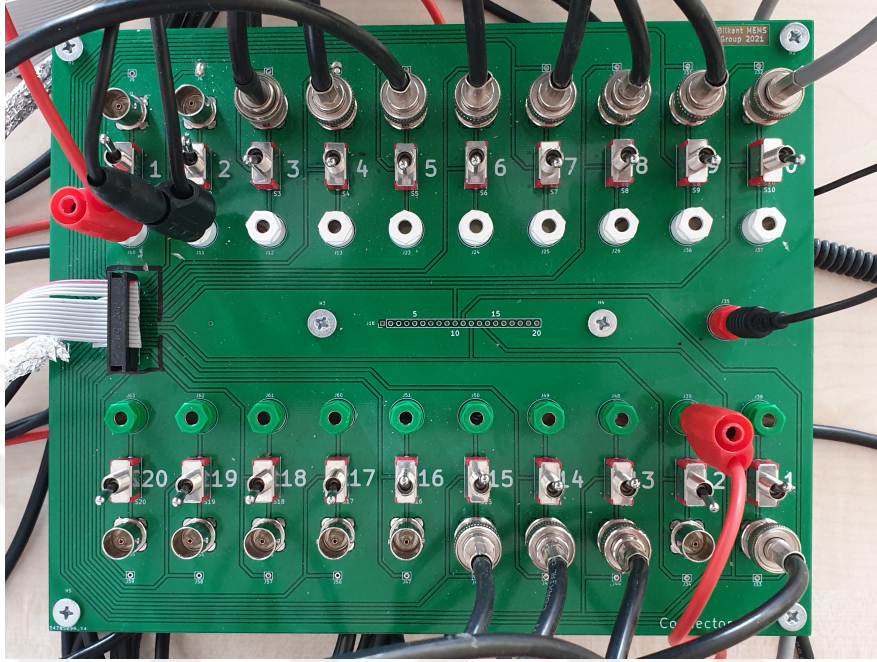


Figure 3.12: Interface PCB

3.3.2 Interface PCB

The interface board houses the connectors of the analog signals on the main PCB. The ground connections of the instruments were achieved on the interface board. Each signal can be transmission line is connected to a mechanical switch that connects to a female BNC connector or a female Banana connector. Either of these connectors can be selected by flicking the switch. The interface board supports 20 transmission lines and these lines are accessible by 2x10 2.54mm male header. The signal map of the interface board can be seen in index B.1

3.3.3 Daughter PCBs

During the PCB design phase we have planned for two different methods to connect the gyroscope package to the PCB. Directly soldering the gyroscope package to the main board would make it difficult to swapping between different gyroscopes and potentially harm the main PCB. One of our solutions was to use a socket

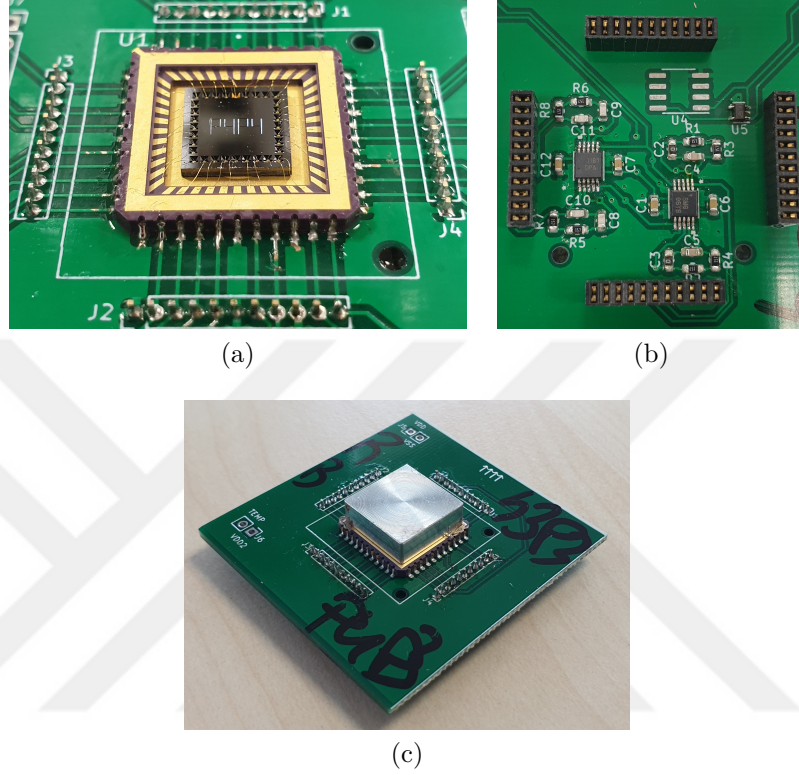


Figure 3.13: The wirebonded Gyroscope (a), the populated bottom layer of the daughter board (b), the daughter board with bonded aluminum cap (c).

for the gyroscope's package(LCC04419). Our second option was to print an additional PCB on which we could solder the PCB and connect the PCB to the main board with 1.27 mm headers. Since the sockets we have purchased weren't compatible with the gyroscope's package the daughter boards were used to connect the PCB to the main board.

The Gyroscope die is glued into the package using an epoxy and after the curing process the gyroscope's contacts are wirebonded to the package. The wirebond map of the gyroscope can be see in the figure 3.14. Since the die is vacuum packaged by bonding two wafers the gyroscope die's height is large for most of the package cavity that can be obtained in the market. Even though we have acquired one of the packages with the largest cavity depth, our die's peak is higher than the package pad height. Since the die's outer shell is connected to the HV an extra caution must be given to the wirebonding. During the bonding process if

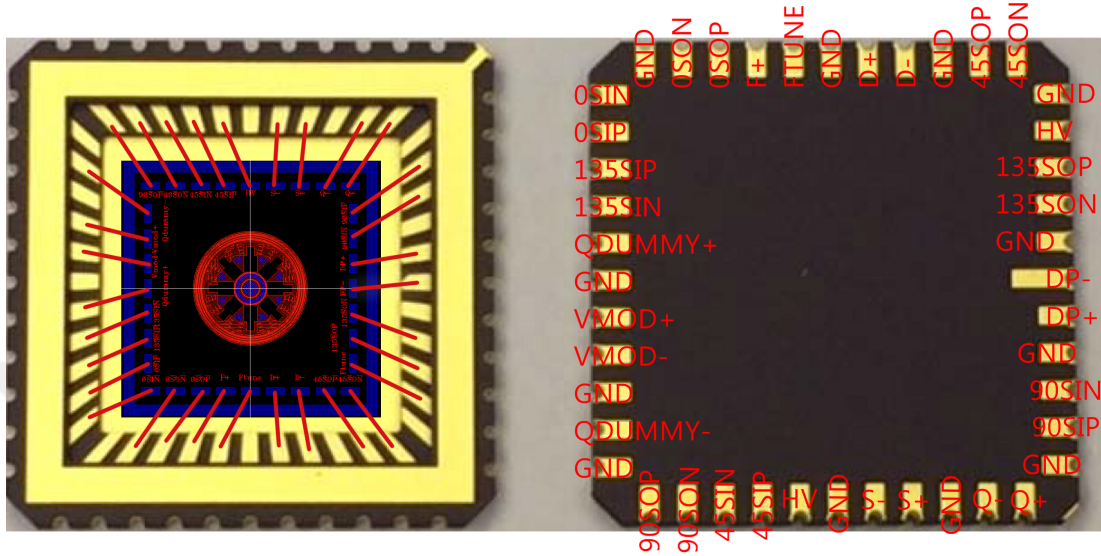


Figure 3.14: The Wirebond Connection Map

the wirebond length is kept short the bond can easily come into contact with the die's outer edge and short the HV to that particular contact pad. As a result, the main PCB or the gyroscope can be damaged. To protect the wirebonded device we have custom fabricated an aluminium cap for the package. A cavity was drilled in to the aluminum block with a CNC machine. The package is glued to the gold metal layer on the edges of the package with a conductive epoxy.

After the initial test the gyroscope ARW was found to be unsatisfactory due to the electrical circuitry noise. The female headers used to connect the daughter PCB to the main board introduced an undesired large parasitic capacitance to our system. To eliminate this parasitic capacitance a second version of a daughter board was designed. In this design we have place two dual opamps on the bottom layer of the PCB. These dual opamps are used for the transimpedance amplifier for the sense and drive pick signals. The supply voltages necessary for these opamps were supplied to the daughter board using two jumper cables that are connected to main board. This change halved the electrical noise.

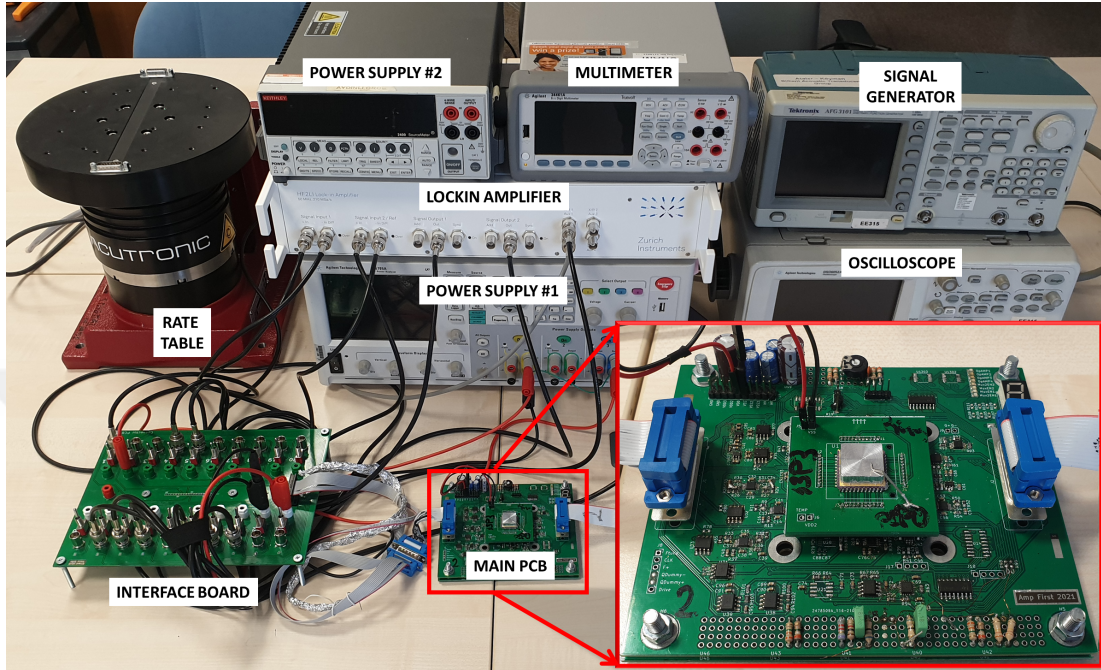


Figure 3.15: The Test Setup

3.4 Test Setup

The figure 3.15 shows the overview of the instruments and the PCBs used during the test. Seven different instruments were used during the tests. The power supplies that are used in the setup supply the proof mass high voltage, Ftune voltage and the $\pm 15V$ necessary to power up the main PCB. Due to component specifications 15V supply voltage is regulated down to $\pm 5V$ and $\pm 2.5V$ on the main board. The lock-in amplifier's functions were investigated in the previous section. The analog ports of the lock-in amplifier is connected to the interface board while the digital port connection is achieved through a ribbon cable and a D-sub 15 connector. The signal generator is used to supply the clock signal and it is connected to the interface board. The multimeter reads and records the temperature sensor located on the main PCB. The rate table is used for the rate measurement of the MEMS gyroscope. Finally an oscilloscope is present for debugging purposes. All of these instruments are connected to nearby PC with GPIB connectors. GPIB interface has allowed us to synchronize and control these instruments simultaneously.

The automation of the setup was achieved by a Python code. When the code is run it asks the user to insert the gyroscope's designated identification. During the initialization, the code subscribes allocated GPIB ports of the instruments and collects the stress sensors are associated by their digital pin port values. Then a .csv file is generated and the recording begins. The current data of the parameters are saved on the csv file which are: time, stress sensor tag, stress sensor output, drive frequency, demodulated sense outputs and temperature. The code converts measured temperature sensor voltage output to degrees according to the manufacturer's specifications. The code takes the mean of the output values for 0.16 seconds and completes a write action. Each stress sensor goes through 8 write action during a single period of the readout. Since there are 16 stress sensors each period of reading takes approximately 20.5 seconds. The complete python code can be viewed at Index C.

Chapter 4

Test Results

In this chapter the test results for the on-chip compensation method will be presented. We have examined the stress sensor and the gyroscope's performances separately. In section 4.1 the Gyroscope's characterization was completed. In section 4.2 stress sensors were measured by applying directional stress on the die. The compensation measurement was done in section 4.3 for various control configurations. Finally the change of the resonance mod frequencies were analyzed in section 4.4

4.1 Characterization of the Gyroscope

The Gyroscope characterization is done by selecting various dies from the fabricated wafer and the dies were place on the probe station for initial testing. Firstly, the selected die is placed on the probe station for visual investigation. The probe station consist of a microscope, a chuck that can be moved precisely on xy plane and the probing equipment which provides connection to die's contact pads that can be moved in vertically on z-axis. The bottom side of the die is an oxide layer and the layers can be seen from below. Unless an issue is detected such as a crack, photo lithography failure in metalization layer or an issue in

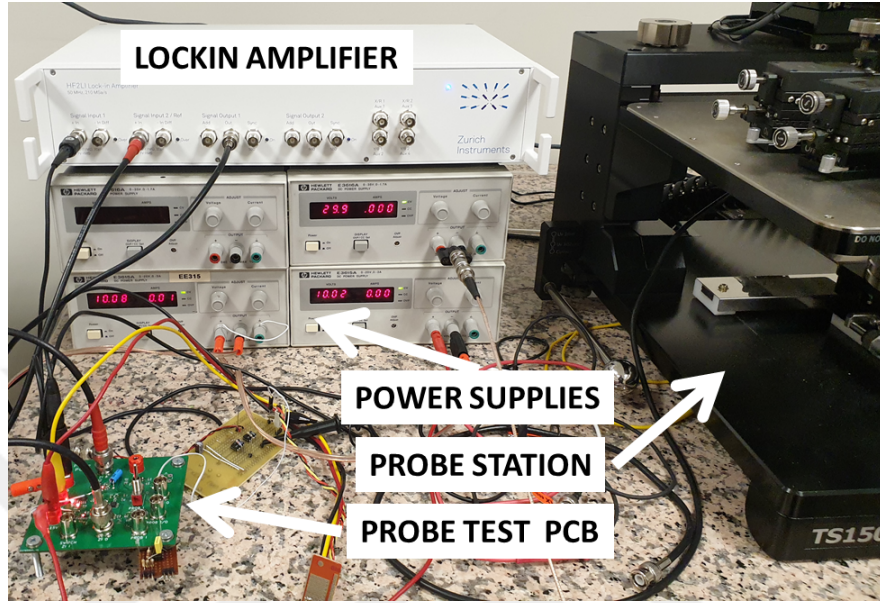


Figure 4.1: Probe Setup

vacuuming, the die is flipped for the probe test. One of the common problems that we have discovered during the visual inspection is a failure in vacuuming. The loss of vacuum is present when a rainbow effect is observable on the oxide layer. In some dies, when the vacuum can not be achieved the water remains in the die and it deflects the incoming light and it is observed as coloring during the inspection. Another common problem has been the failure during the bonding of the silicon and the metal layer. In this case, the silicon acquires a darker color when inspected. These failures can be seen in the index B

During the initial test the fundamental electrodes are chosen for inspection. These are High voltage, Drive, Drive Pick, Force Rebalance and the Sense electrodes. The crucial pads are investigated for possible short in the silicon layer. The short test is crucial to prevent High voltage damage on the testing equipment. The main goal of the probe test is to find out the resonance frequency of the drive and the sense axis modes. To do this, we sweep the drive axis signal with the magnitude of 10-100mV on frequency band 55kHz to 60kHz. The response in the drive pick signal is observed by the HF2LI's sweeping module. The magnitude graph shows valuable information regarding the characteristics of the Gyroscope which are the resonance frequency, Quality factor and the frequency

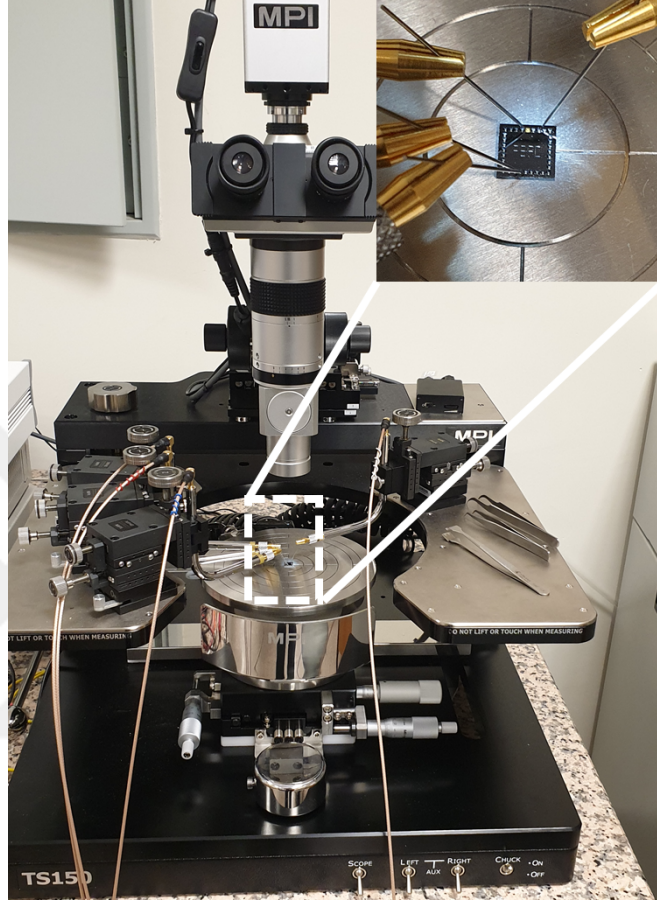


Figure 4.2: Probe Testing

mismatch between the modes.

Figure 4.1 shows the probe test setup. A DC power supply is used to provide high voltage(HV). The probe test PCB is used to provide differential signal to Drive electrodes sourced by the lock-in amplifier. The sensing is also achieved on the probe PCB as well. The probe station consist of only 4 probe needles. For the frequency sweep operation one of the needles is connected to HV. Two of the needles carry the differential drive signal and they are placed on the D+/- for drive axis mod test and Force rebalance and Ftune electrodes for sense axis mod test. The remaining needle is swapped between the positive and the negative electrodes for each respecting sense electrode. Figure 4.2 shows the probing station during the test. The die is placed in the middle of the chuck and kept still by the vacuum's suction.

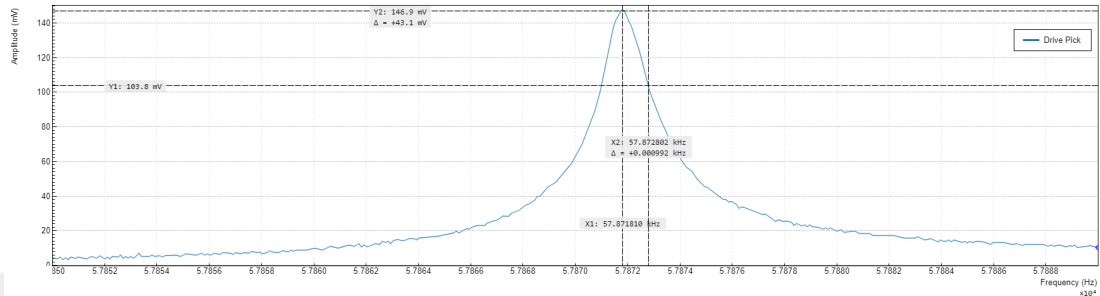


Figure 4.3: Drive Pick Sweep Magnitude Plot

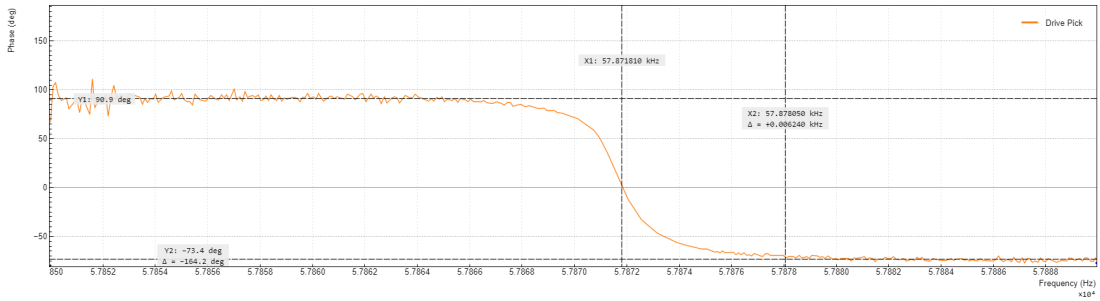


Figure 4.4: Drive Pick Sweep Phase Plot

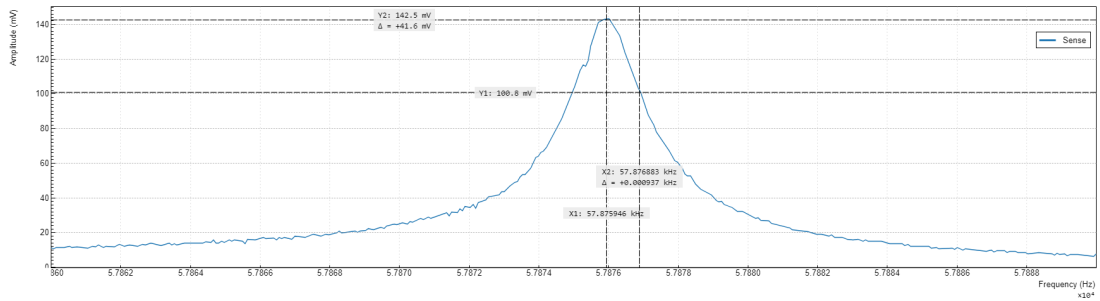


Figure 4.5: Sense Sweep Magnitude Plot

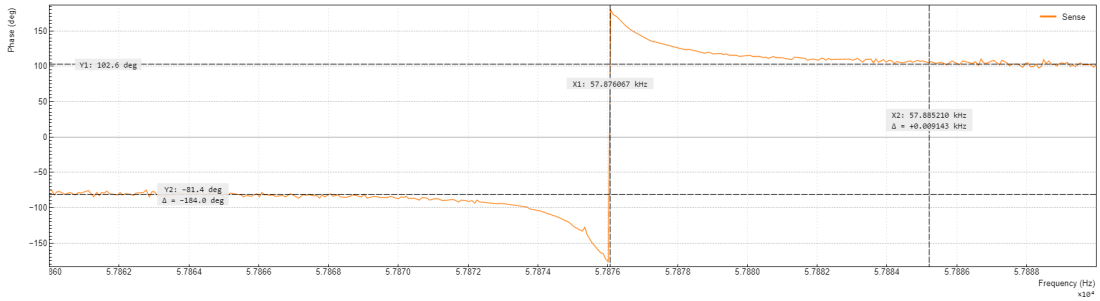


Figure 4.6: Sense Sweep Phase Plot

Table 4.1: Frequency Sweep Results

Gyroscope	Proof Mass	Drive Fres(Hz)	Sense Fres(Hz)	Quality Factor
S3P3-P3P0	30	57877	57875	30207
S3P3-P5P0	30	58022	58016	35164
S3P3-P4N4	30	57812	57850	33438
S3P3-P6P2	30	58077	58121	29959
S3P3-P4P3	30	57865	57887	26302
S3P3-P3P3	30	57813	57858	30451
S3P3-P6P0	30	58124	58105	28623

During the sweep test the Proof mass voltage is set 30V. The input differential signal's magnitude is set to 100mV. The remaining contact pins are floating during this test. The figure 4.3 shows the gain vs frequency of the VRG's the drive mode and the response obtained from the Drive Pick electrode. The sense axis sweep response can be seen in figure 4.5. The frequency sweep results have a similar results for other devices as well and the parameters of these devices are reported in the table 4.1.

We have found several devices fit for further testing. To proceed, these devices are packaged, wirebonded and soldered onto the daughter board. Then the gyroscope can be tested on the rate table to for the sensitivity measurement.

The gyroscope response in mismatch and matched frequency conditions were investigated during these tests. In mismatch condition the rate table is rotated between $100^\circ/\text{s}$ and $-100^\circ/\text{s}$ with $10^\circ/\text{s}$ incremental steps. Each step duration is set to 2 seconds. The time variant output data of the sense signal can be viewed in the figure 4.8a. The figure 4.8b shows the rate of the MEMS gyroscope in mismatched condition vs. the input of rate table. In mismatched condition the response is found to be $0.5\text{mV}/^\circ$ while the gyroscope's response is much higher in matched condition as anticipated. The sensitivity of the gyroscope is measured to be $34.5\text{ mV}/^\circ$ which can be obtained from the figure 4.8b. The linearity of the plot is lost at the peak $50^\circ/\text{s}$ because of saturation. The output reaches the limit of lock-in amplifier's input limit when the rotation vector is increased to $50^\circ/\text{s}$. Due to this reason the rate table input was limited between $50^\circ/\text{s}$ and $-50^\circ/\text{s}$.

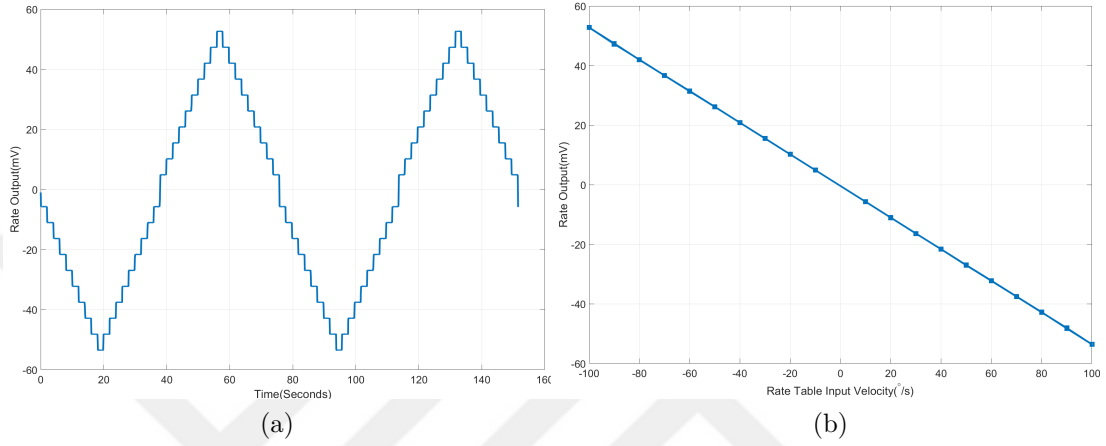


Figure 4.7: Time Variant Data of the Rate Output in Mismatched Frequency Condition(a), Rate Table's Velocity vs. Gyroscope Sensitivity in Mismatched Frequency Condition(b)

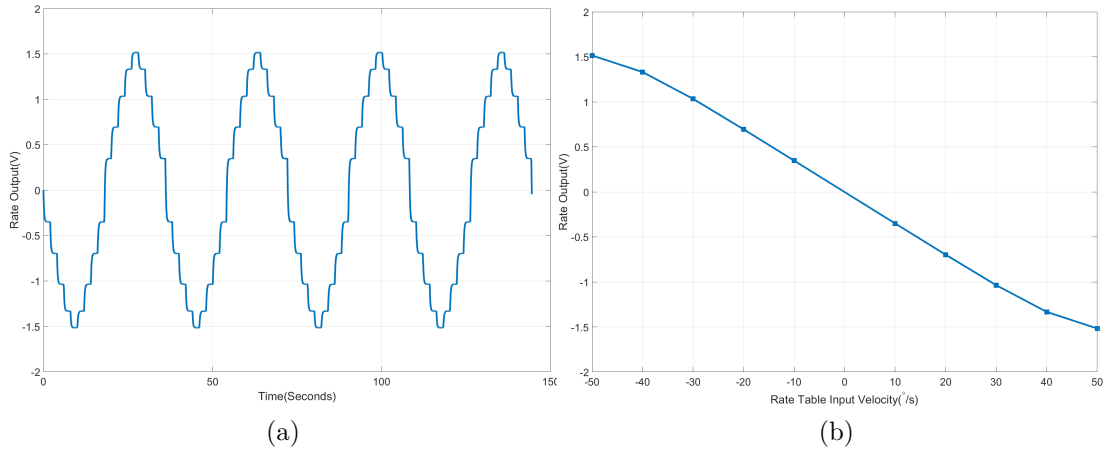


Figure 4.8: Time Variant Data of the Rate Output in Matched Frequency Condition(a), Rate Table's Velocity vs. Gyroscope Sensitivity in Matched Frequency Condition(b)

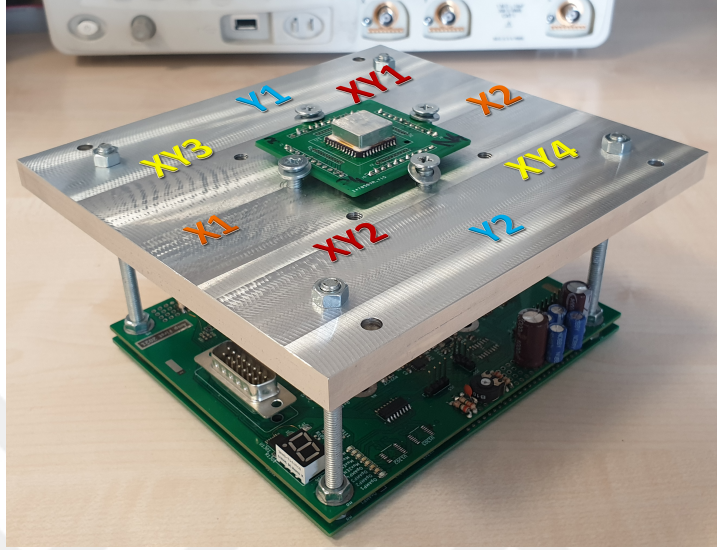


Figure 4.9: Photo of the aluminum stress test-bed

4.2 Characterization of the Stress Sensors

The stress sensor characterization is significant for correctly compensating the long term drift. The device is mounted on layers of different substances and the layout of the daughter board affects the rigidity of the board. Thus the stress measurement is not straightforward. To observe the effect of stress on the board the daughter board must be bent along a certain axis. The direction of the bending force is diverted when the female headers are soldered onto the board. We have created a custom connector by soldering a ribbon cable onto a 1x11 pin 1.27mm header. The ribbon cable is then soldered onto the daughter board to minimize the connector's effect on the structural integrity of the PCB. This way we were able to solve the connectivity issue for the stress test. The second problem we needed to tackle was how to bend the PCB. The solution we have came up with was a stress testbed. The stress testbed is a rectangular aluminium block which has an elevation plane in the center. A smaller aluminum block is fitted into the center which has been previously cutoff. The elevation plane is surrounded by 8 screw holes one for each corner and the edge. The holes are aligned in regards to the daughter boards dimension such that the screws can hold the PCB in place and the tightening the screws would bend the PCB. The

gyroscope placed on the stress test-bed and the test-bed mounted on the main PCB can be seen in the figure 4.9. The custom ribbon cable connector passes through the four rectangular holes to connect the Main PCB which is located underneath the stress testbed. The stress testbed is also elevated by 10 cm long screws that are located at the corners of the testbed. Figure 4.10 shows the cross-sectional view of stress testbed and the layers that the gyroscope sits upon during the screw tightening test.

The goal of the stress test is to bend the PCB along a certain axis to observe the change in the output of the stress sensor and understand the effect of normal and shear stress on the gyroscope's operation. The PCB is bent on a certain axis by tightening the screws present on that particular direction. For example, the screws located on the X1 and X2 slots are tightened and the PCB arcs along the 0° axis(x axis). This way a tensile stress is applied on the stress sensor 0SOP, 0SON, 0SIP, 0SIN. Conversely, a compressive stress is applied on the stress sensors 90SOP, 90SON, 90SIP, 90SIN. We have repeated similar stress test along the 45° , 90° (y axis) and 135° . The stress sensor responses for each test can be seen on the figure 4.12, 4.13, 4.14, 4.15.

Each stress test takes around 20 minutes. The gyroscope is kept operational and for 5-10 minutes and then the responding M5 screws are tightened for approximately $3/4$ of a cycle which responds to a displacement of 0.8mm in the z axis on the edge of the PCB. The response of the sensors are recorded for another five minutes and then the built up stress is released by reversing the screws to their original state. The time domain plot of these test show a step function response as the stress sensor outputs. There has been connectivity issues with the four of the stress sensors which are 0SOP, 0SIN, 90SOP, 135SIN. During the connectivity test to HV port 90SOP was found to be a short. Due to this reason, the pin which was allocated to 90SOP was never connected to the transimpedance amplifier. The other stress sensor had the largest response in the first screw test but the gain of these sensors decreased after the first test. We believe that the force applied on these sensor had stripped the epoxy underneath the die from the die itself. So, the response at these local zones decreased after that point.

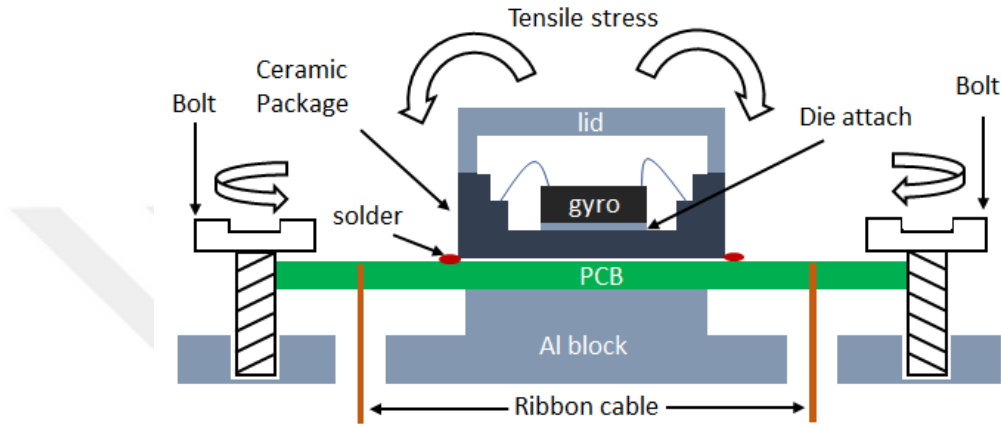


Figure 4.10: The cross sectional diagram of the stress testbed diagram

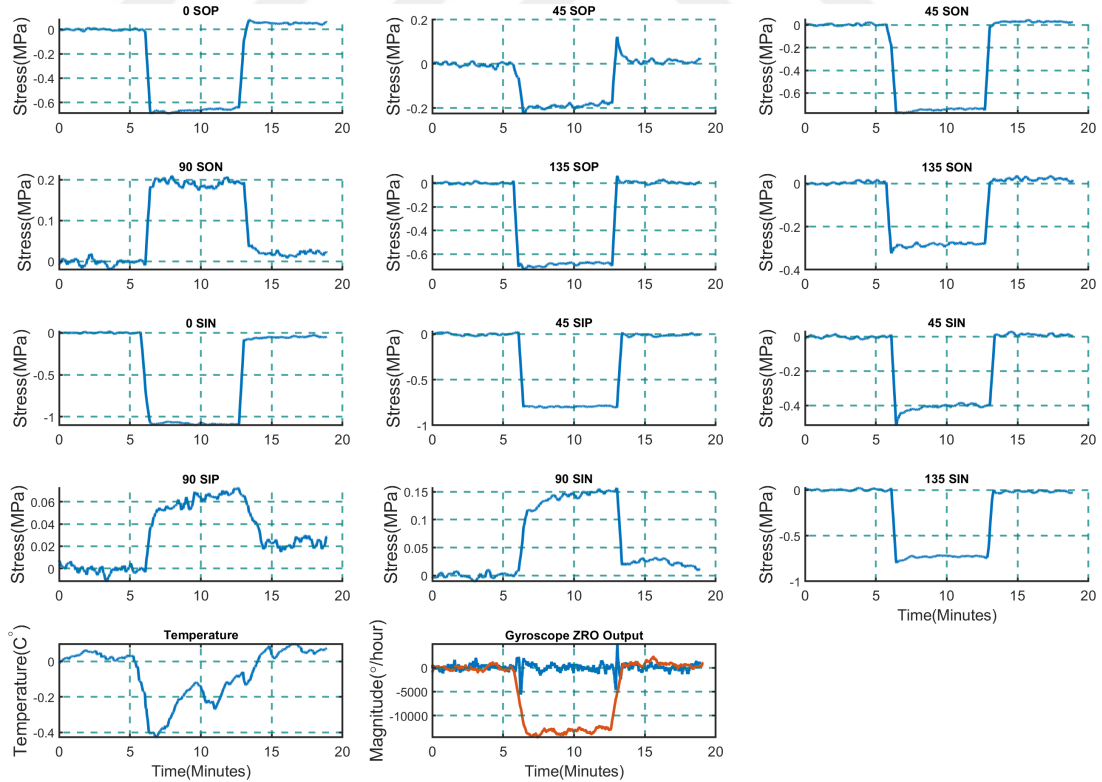


Figure 4.11: Time Variant Data for 0° axis Screw Test

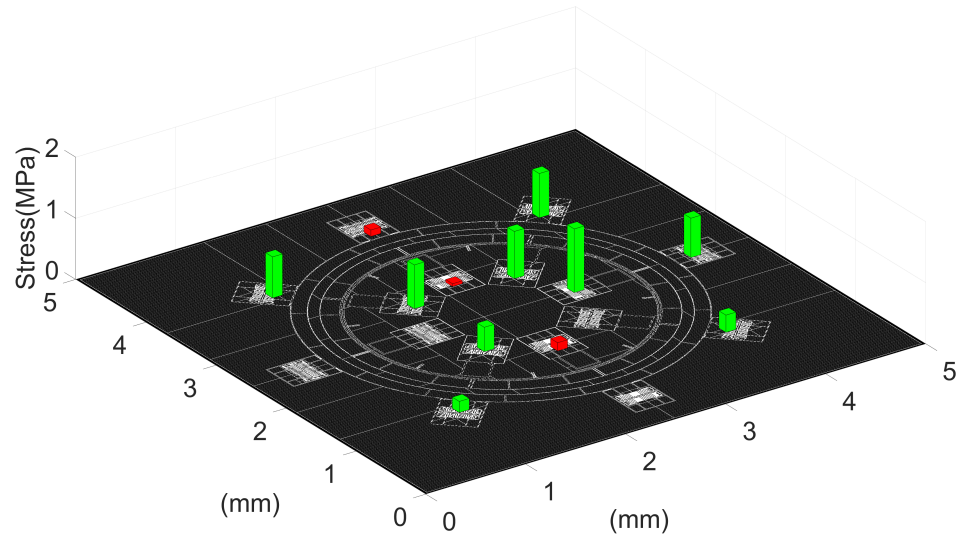


Figure 4.12: 3D Bar Plot for 0° axis Screw Test

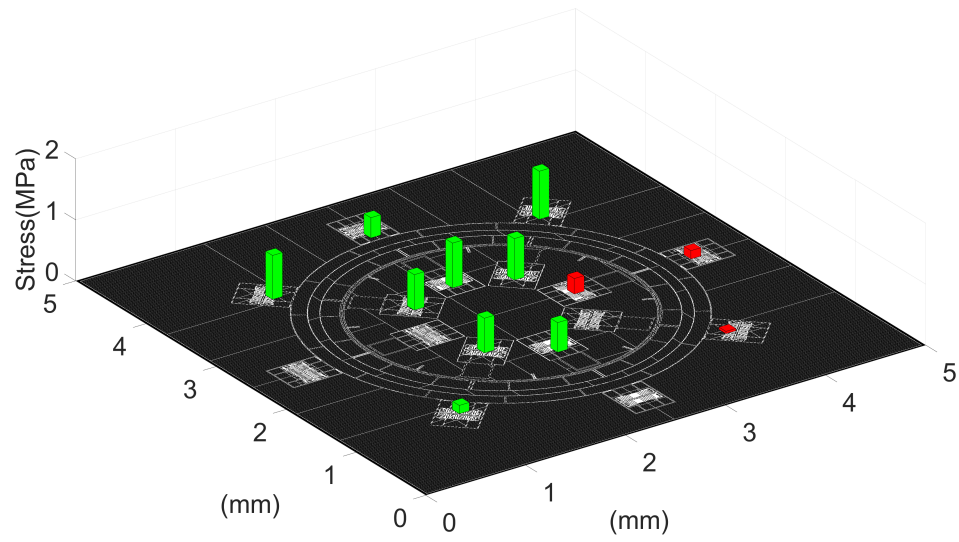


Figure 4.13: 3D Bar Plot for 90° axis Screw Test

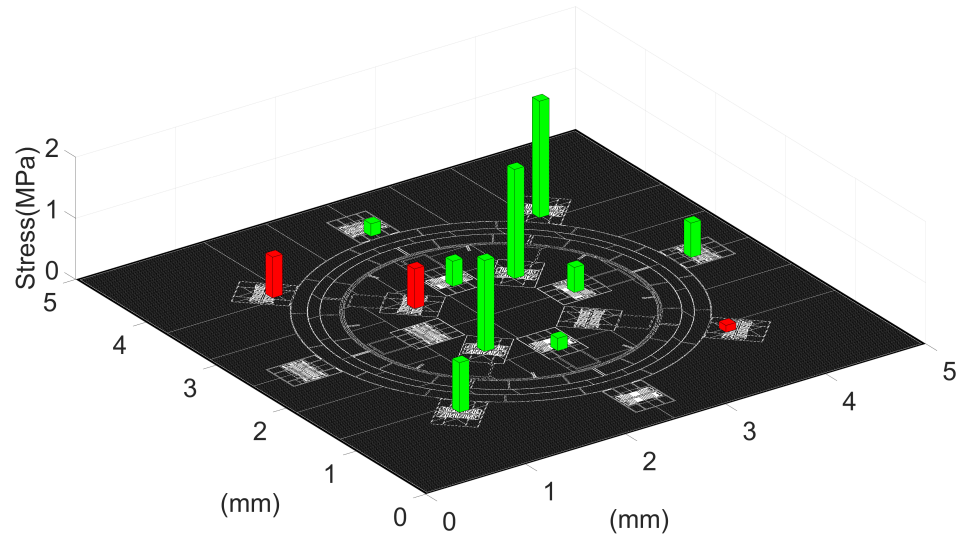


Figure 4.14: 3D Bar Plot for 45° axis Screw Test

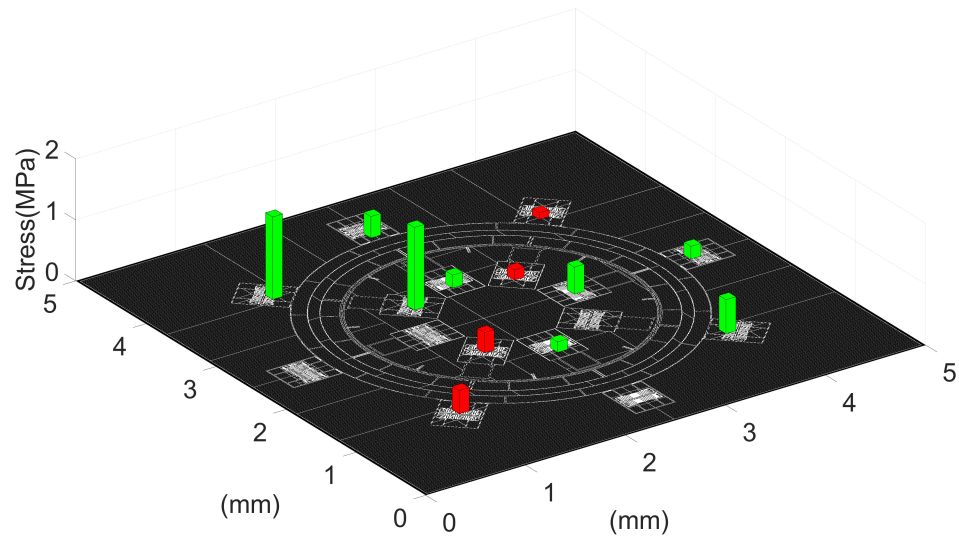


Figure 4.15: 3D Bar Plot for 135° axis Screw Test

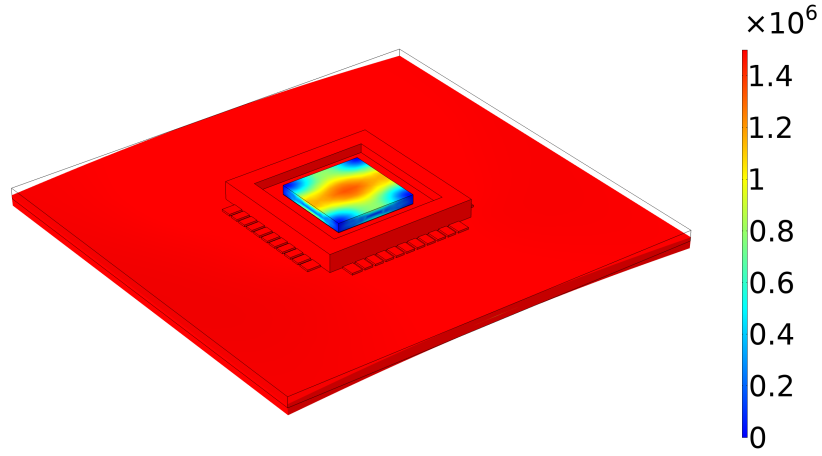


Figure 4.16: Comsol Simulation of the Screw test for 0° axis

The response of the stress sensors are plotted on a 3D bar plot for convenience of the reader 4.12, 4.13, 4.14, 4.15. The green bars show the magnitude of the tensile response while the red bars show the compressive stress applied on the stress sensors. The test results show an expected result when the stress is applied the highest stress is built up on the sensors located on the screw axis. Conversely, the sensors located on the perpendicular axis are subjected to compressive stress. The stress magnitude measured during the test also supported by the FEA simulations. Figure 4.16 shows the simulation results for a daughter board with the same dimensions. The die is placed on an epoxy layer and a ceramic package that sits on soldered joints. The edges of the PCB is displaced in the direction of z- axis for 0.8mm. The highest stress on top of the die is recorded to be around 1.4MPa which is similar to our test results.

Effects of the stress on the Gyroscope is noteworthy. During these test the quadrature error cancellation was not active to observe the effects on the Gyroscope clearly. The gyroscope is driven into resonance and the quadrature is canceled at the initial point. When the stress is applied a sudden spike is observed at the output of the gyroscope. The resonance frequency of the drive mode has also increased. Due to the tensile stress, the gap between the electrode and the ring is widened which decreases the DP signal's magnitude. In response, the drive PID loop has increased the drive signal's magnitude. The higher input voltage increases the displacement of the ring in the drive axis which increases the

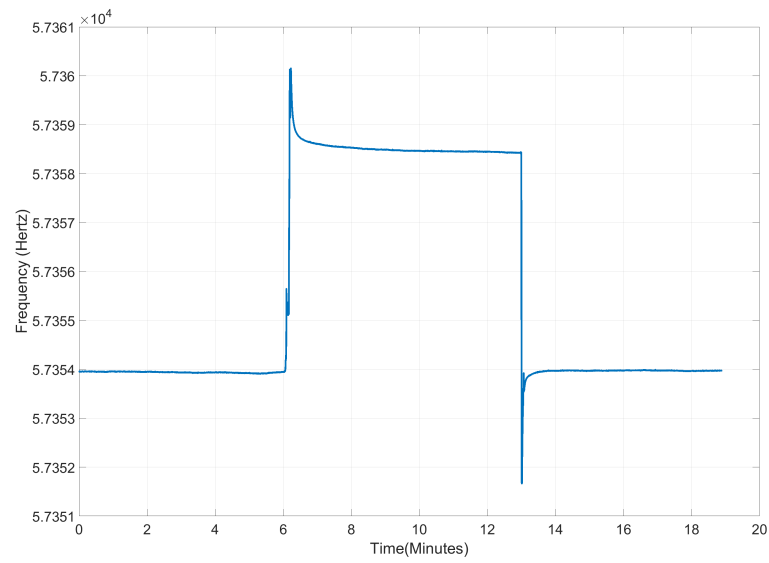


Figure 4.17: Frequency plot for X Axis Screw Test

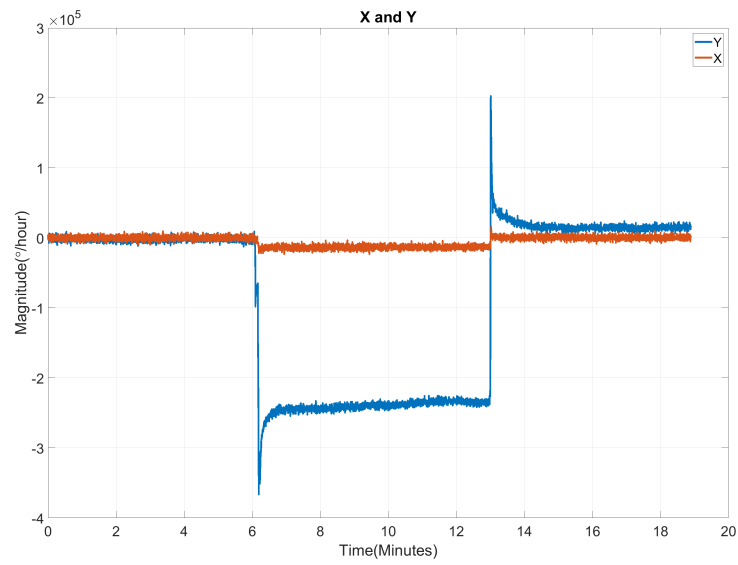


Figure 4.18: Sense Output for X Axis Screw Test

dynamic spring coefficient of the vibrating ring. Since the resonance frequency is the square root of spring coefficient divided by the ring mass, higher resonance frequency is expected under tensile stress. The recorded drive frequency of the ring can be seen in 4.17 and as anticipated the frequency has the shape of a positive square function. It is important to realize that the frequency is level converges back into its original level when the stress is relieved. This phenomenon proves that the gap between the ring and electrodes can presume their original positions.

Figure 4.18 show the demodulated Sense output. From the figure we can see that the quadrature component (Y) of the output has drifted more than the rate component (X) of the gyroscope. The applied stress deviates the drive axis alignment and when the the screws are released the quadrature component does no settle back to its original state. The visible hysteresis effect shows the importance of Quadrature compensation and why it is crucial to increase the performance of the Gyroscope as it was also shown in [36].

4.3 ZRO Tests and the Effectiveness of the Compensation

ZRO test is crucial in determining the performance of the MEMS gyroscope. During ZRO test the gyroscope is in operational mode however the device is isolated to prevent any rotation input to measure its base noise level. In our test we have utilized different control configuration to increase the performance of the gyroscope and to analyze the external effects on the gyroscope for long term operation. The following test are applied on the S3P3-P3P0. The parameters of this particular Gyroscope is listed in table 4.2 after the rate and the sweep tests.

Table 4.2: S3P3-P3P0 Parameters and Values

Parameter	Value
Drive Frequency	57,355 Hertz
As Born Sense Frequency($F_{\text{tune}}=0\text{V}$)	57,361 Hertz
Mismatched Sense Frequency($F_{\text{tuned}}=40\text{V}$)	57,415 Hertz
Proof Mass High Voltage	50V
Quality Factor	30,000
Effective Proof Mass	0.5115 e-07 kg
Angular Gain	0.3898

4.3.1 Quadrature Control Off ZRO Test

Quadrature control is crucial to increase the performance of the gyroscope. However, when the quadrature is cancelled, it is hard to determine the effects of external factors. Due to this reason the first test we apply on our gyroscope only consist of limited control during the operation. The drive resonance was obtained by the Drive PLL and the Drive PID for mismatched condition where the rate was previously acquired as $0.5\text{mV}/^\circ$. The proof mass voltage is assigned to 50V and F_{tune} to 40V. Also, the phase of the sense output is calibrated to minimize the coupling of the quadrature error. The calibration is achieved by inserting a phase offset for the demodulator. To find the exact value of the phase offset the sense output must be monitored. Ideally, the response of the rate output must be unaffected by the quadrature input voltage. Thus, during the calibration the quadrature input is changed by 100mV and the demodulated sense output is observed. The exact value is obtained by iterating the phase value of the phase offset.

The ZRO test took 30 hours to complete and the figure 4.19 shows two different time variant plots. First is the plot that consist of the quadrature and the temperature data. Here it is clearly visible that the quadrature error is linearly dependent to the temperature value. During this test the PCB was left in room temperature and the sudden shifts in temperature is caused by the wind due to an open window or a door. The second plot shows rate output of the gyroscope and the time variant compensated output. The drift is clearly visible during the 30 hour operation of the Gyroscope and our compensation method is successful

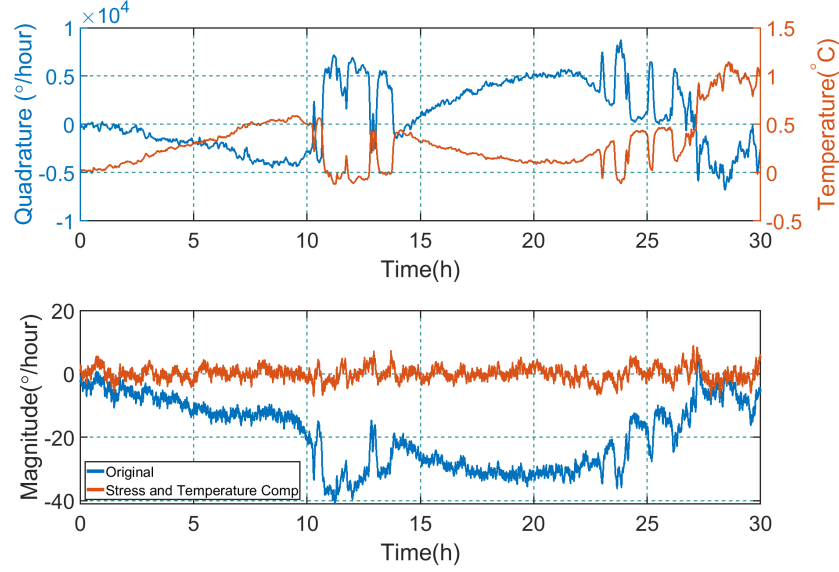


Figure 4.19: The time domain plot of the temperature and ZRO of the gyroscope in open loop quadrature condition for 30 hours.

at eliminating this drift.

The compensation method we have utilized in this study is the least square algorithm. The least square algorithm one of the most commonly used methods for curve fitting and compensation. Three different data sets were used to compensate the gyroscope output which are stress sensor output, temperature and the collection of these two data sets. For this application, it is assumed that the long term drift function can be expressed as linearly dependent function of the stress matrix and/or the temperature vector in adequately short periods of time. The long term drift noise is set to be the output of the regression model and noted as $m \times 1$ y vector. The $m \times n$ X matrix is constructed by the m row of observations while column n represent the variables and $n \times 1$ vector b as the vector for variable constants. The $m \times 1$ vector e contains the residual vector which is the product of the compensation process and the compensated form of the output. The method is applied as follows:

$$y = Xb, \quad b = (X^T X)^{-1} X^T y \quad (4.1)$$

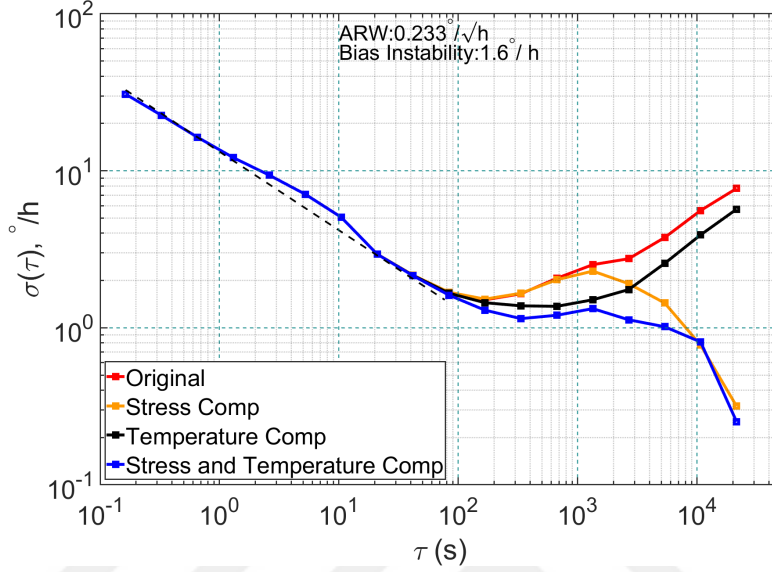


Figure 4.20: The Allan deviation plots in open loop quadrature control configuration for different compensation cases.

$$e = y - Xb = y - X(X^T X)^{-1} X^T y \quad (4.2)$$

Allan deviation plot is used to measure the total noise of the MEMS gyroscopes[37]. Allan variance(AVAR) or Allan deviation(ADEV) measures the stability of a data set in frequency domain. The before mentioned Bias-instability, angular random walk and rate random walk properties of the gyroscope is derived from the ADEV plot. Allan variance is expressed as half of the average of the squared differences of consecutive readings of the frequency deviation over all of the sampling period[38]. ADEV plot without the quadrature cancellation shows 4 different lines in the plot 4.20. First is the original output of the Gyroscope. The original data clearly drifts in time variant figure thus the RRW reaches $7.5^\circ/h$. The ARW is found to be $0.233^\circ/\sqrt{h}$ and the bias instability is measured to be $1.6^\circ/h$. The stress compensated output is depicted in orange, the temperature compensated output is depicted in black and the collective stress and temperature compensated output is depicted in blue.

Compensation is achieved using a MATLAB code. For compensation the raw output data need to be proccessed. Since the output of the stress sensors are

multiplexed the number of points must be matched to the gyroscope and the temperature data. Thus, after a sorting algorithm the stress sensor data points are linearly interpolated. The stress sensor data consist of spikes due to the change in DC voltage at the output of LPF when the the mux are switched. During the sorting phase, these switching points are also removed during the sorting algorithm. The sorting phase is completed by taking a moving average of the stress sensor output. The stress sensor data is noisy since the output is obtained through a single trace. By taking a 2 hour moving average we were able to remove the excessive noise and obtain better noise compensation. In the end, the scaled up stress sensor output matrix is used as the observation matrix for the stress compensated output. The temperature data doesn't require processing since the temperature output is noise free. So, the raw temperature sensor output is used as the observation matrix in temperature compensation.

The compensation results for the Quadrature-OFF test show that the high correlation between the gyroscope output and the temperature offers a major improvement in bias instability while it provides a minor improvement in terms of long term drift compensation. Here, it can be said that the hysteresis effect on long term operations makes the temperature inadequate for linear fitting. However due to the quadrature error and its effect on the output, the temperature and the output can't be linearly correlated in the long term. The stress compensated output on the other hand has an opposite effect for the compensation. By combining these two matrices we were able obtain the best compensation for the linear regression and we obtain x30 improvement for 30 hour operation.

4.3.2 ZRO Test in Mismatched Frequency Operation

In the second ZRO test the quadrature cancellation was turned on. The frequency mismatch between the drive and the sense modes were set to 60Hz. We have increased the duration of this test to 16 days to see the effectiveness of our compensation method. Figure 4.21 shows the time variant plot of the stress

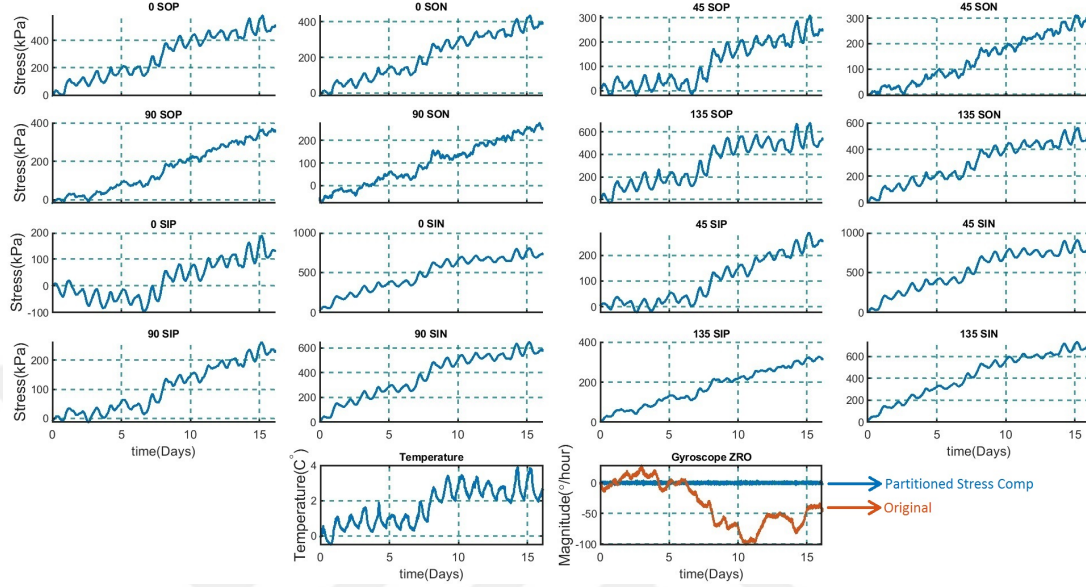


Figure 4.21: The time domain plot of the 16 stress sensors, the temperature sensor and ZRO of the gyroscope in mismatched frequency operation for 16 days. The variations over time are plotted, refer to Figure 3.13.a for stress sensor locations.

sensors output, temperature output and the gyroscope's uncompensated and uncompensated output. Since the stress sensors have inverse polarity as depicted by P and N naming the values for the N tagged stress sensors were multiplied by -1. The overall changes in the stress sensors are as expected. As the temperature of the room had warmed up in the period of 16 days, the output of the sensors has also increased. This effect is caused by the compressive stress applied on the die by the epoxy. We have used the ThermoBond 3508[39] as our die to package attachment. since the expansion rate of the epoxy is larger than Si the bottom edges of the die will be subjected to expansion more than the top of the die. As a result the silicon layer is subjected to the compressive stress due to the increase in temperature.

The allan deviation plot in 4.22 shows the different compensation sets' and the original gyro output's stability. The performance of the VRG is measured to be $0.233^\circ/\sqrt{h}$ for ARW and the bias instability is improved to $1.6^\circ/h$ compared to the quadrature cancellation off test. The quadrature loop improved the bias instability by reducing the effects of the temperature change on the gyroscope's output. Naturally the gyroscope is prone to drift after an hour mark. Due to this

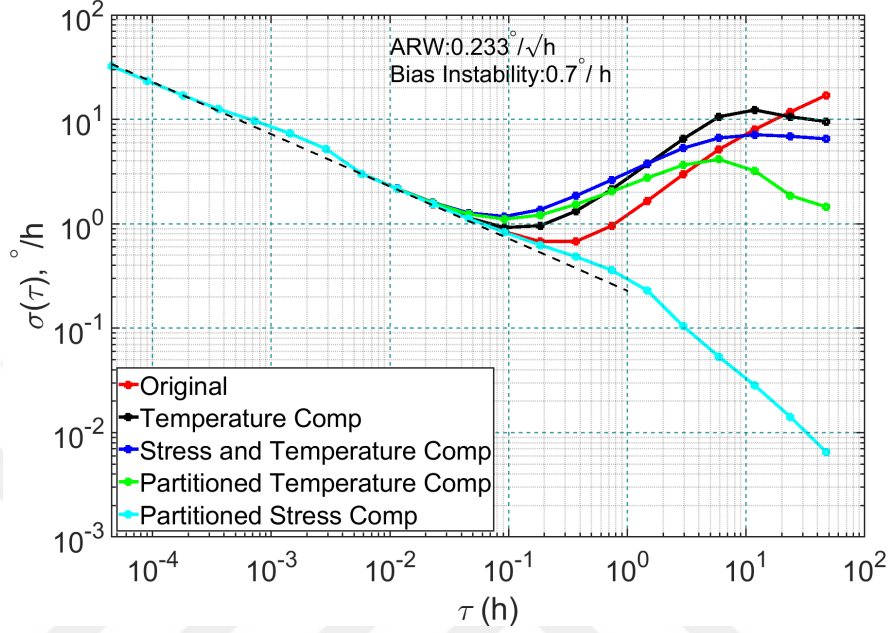


Figure 4.22: The Allan deviation plots of the gyroscope in mismatched operation for 16 days for various compensation cases.

reason the bias instability region is found to be around half an hour to hour mark of the test. By activating the quadrature control the sense output is stabilized to changes in relatively short periods of time of an hour. In allan deviation plot a bump in ARW slope around 2-10 seconds band. This was caused by the MUX switching. During the switch the change in voltage generates a spike that couples to the transimpedance amplifier in the sense readout signal chain. We weren't able to overcome this problem in the current main board. We aim to overcome this problem by isolating the stress and the sense signal chain and by separating their supply voltages.

The long term operation has shown us the deficiency of the least squares method. When the temperature and the combined stress sensor and temperature data are used as the observation matrix it is clearly visible that the compensation is under performing. Especially in bias instability region of the uncompensated gyro the least square compensation offers worse performance. To overcome this problem we have partitioned the data to 12 hour slots to separate the rising and the decreasing order of the temperature cycle. This way, we were hoping to increase the first order correlation between the temperature and the ZRO of

gyroscope by reducing the hysteresis effect. However, the compensation with partitioned temperature data improves the long term compensation minimally. The long term drift is present even after the compensation. We have obtained true success by partitioning the stress and temperature combined observation matrix with our method. As it can be seen in the figure 4.22 the partitioned compensation removes the rate random walk and bias instability regions. The stability is improved by x2500 compared to the original output.

4.3.3 ZRO Test in Matched Frequency Operation

In the final ZRO test we have implemented we have configured the gyroscope to operate in frequency matched condition. The Ftune was set to 0V and the frequency mismatch between each mode was decreased to ≈ 1 Hz. A closed loop for the force rebalance system was not added in this test. Due to the time limitations, necessary circuitry for closed loop sense signal couldn't be implemented. The test took 8 days to complete. Figure 4.23 shows the time variant data of the sensor outputs. The temperature variation over 8 days was smaller compared to the change of temperature in 16 days Mismatched test. The small variation in the temperature and the matched condition resulted with the smaller drift in the gyroscope output as it can be seen in the uncompensated gyroscope plot. The maximum stress built has been less than 400kPa which is smaller compared to the mismatch test as well. Thus, the gyroscope drift has been limited to $20^\circ/\text{hour}$.

Allan deviation plot in 4.24 shows the stability of the original data and the various compensated data. ARW of the matched gyroscope has improved compared to mismatch test. As it was shown previously the rate response is higher for the gyroscope which increases the SNR of the system. ARW was measured to be $0.0583^\circ/\sqrt{h}$ and the bias instability is found to be $0.3^\circ/h$. The drawback of the open loop configuration is early drift. The drift start after 10 minutes compared to the 30 minutes in mismatch condition. The compensation methods show a similar result except a better performance in temperature compensation in mid to long term duration. The long term stabilization reaches $0.0025^\circ/h$

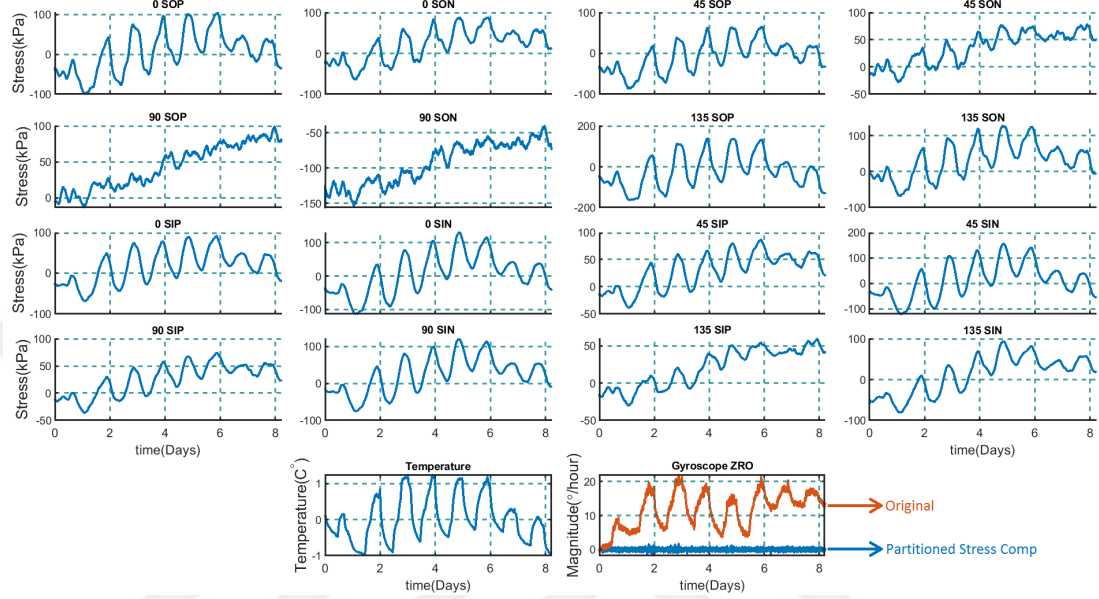


Figure 4.23: The time domain plot of the 16 stress sensors, the temperature sensor and ZRO of the gyroscope in matched frequency operation for 8 days. The variations over time are plotted, refer to 3.13.a for stress sensor locations.

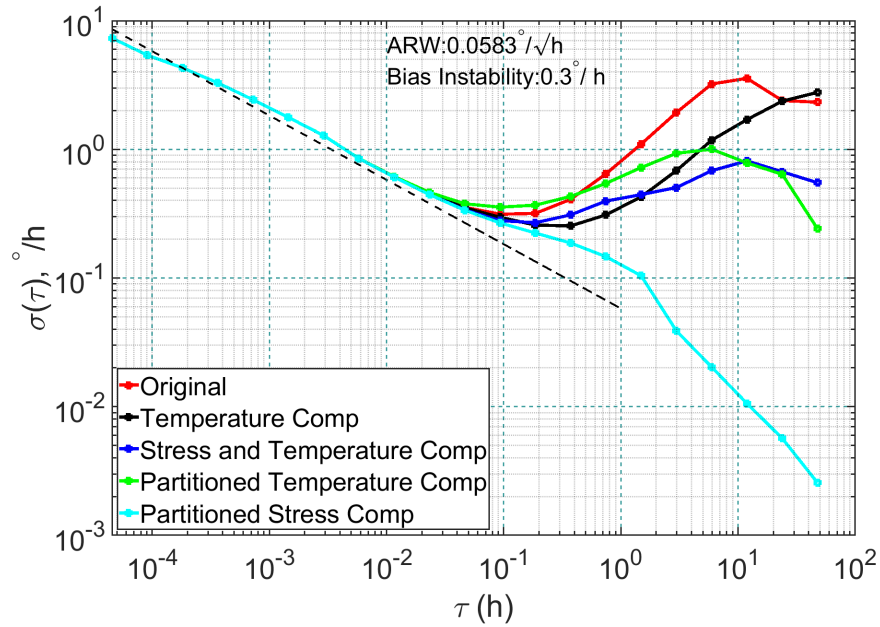


Figure 4.24: The Allan deviation plots of the gyroscope in matched frequency operation for 8 days for various compensation cases.

with partitioned stress compensation with no signs of increase of the long term noise level. With this performance level our gyroscope perform on par or even better compared to state of the art MEMS gyroscopes found in the industry or previously reported [4]-[6] in long term drift.

4.3.4 Post Investigation of ZRO Tests

ZRO test has shown that linear fitting using the temperature data is insufficient. The stress compensation has proven itself to be better in compensation. Compared to temperature compensation, stress compensation provided 20x in quadrature off test, 100x in mismatch test, 80x in matched ZRO test better compensation. We believe that the stress sensor data is able to track the frequency drift mismatches which are present in the absence of an actively frequency matching loop.

In this study we have implemented the least squares algorithm. As the results suggest, there is strong correlation between the stress sensor data and the gyroscope output. By applying least squares algorithm we are presenting the optimum pairing of the stress sensor and the gyroscope output. The coefficients that are found for each test differ from one another. Even in the partitioned compensation the coefficient value can change wildly for each consecutive period. Currently, the algorithm is underdeveloped for eliminating the long term drift on an operating gyroscope.

It is important to realize the utilization of stress sensors in compensation and the minimum number of sensors required to successfully compensate. Thus, we have tested our algorithm by using the different sets of sensor data which are allocated as:

Inner Comp: 8 stress sensors located inside of the ring.

Outer Comp: 8 stress sensors located outside of the ring.

Normal Stress Comp: Stress Sensors located on the x and y axis.

Shear Stress Comp: Stress Sensors located on the 45° and 135° axis.

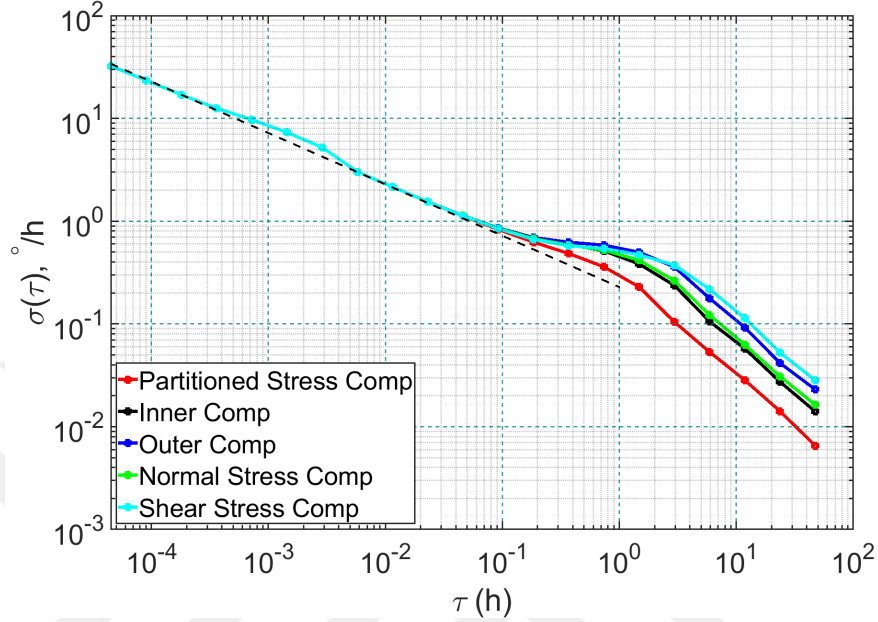


Figure 4.25: The Allan deviation plots for the mismatched operation compensated with various stress sensor sets.

These sets were used to compensate the 16 days mismatched gyroscope's operation since this was the longest test that we have completed. By halving the number of stress sensors the compensation was worsened by a magnitude of 2x. The localization of stress on the die and the stress change over time has caused slight changes in the compensation performance. One can argue that only inner stress sensor can be used to achieve a more compact device design. This finding shows that the accurate assessment of stress is necessary for the compensation performance and the using 16 stress sensors offers the best compensation.

The partition was the most substantial improvement in our method. In the figure 4.26 the compensation with different partition period lengths can be seen. The periods were arranged from 12 hours to 1 day and to 2 days length. As anticipated the increase in the duration of the periods have worsened our results. The linear relation between the stress and the gyroscope's output is lost when the period is increased to two days. On the other hand, the two days period was able to remove the long term drift of the Gyroscope and continuous to decrease in

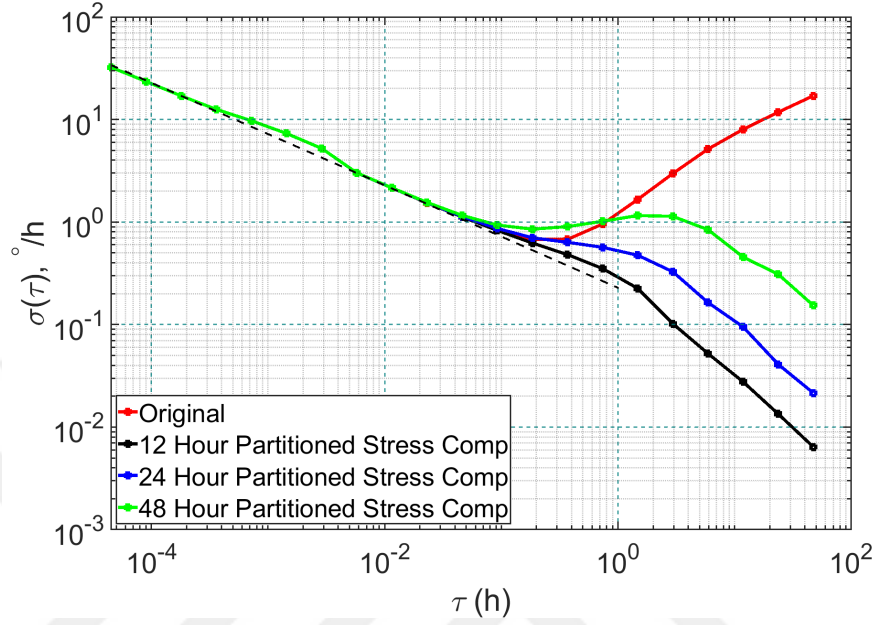


Figure 4.26: The Allan deviation plots for the mismatched operation compensated with different partition periods.

order. This is another finding that suggest that the stress sensor and the output relation is not linear and further development of a nonlinear based algorithm is required.

4.4 Resonance Lock Tests

The test that have been reported in the previous chapters are focused on the amplitude modulated(AM) output of the gyroscope. However, the frequency of the modes requires analysis to complete our analysis. In resonance lock test, the gyroscope is driven into resonance in both the sense and the drive axis. For a duration of 3 minutes the gyroscope is driven from the drive axis and then the control loop is shut down. The force rebalance electrode is activated to resonate the gyroscope along the sense axis for 3 minutes and the cycle is repeated. The sequential locking was controlled by the python code which can be found in the index C. The displacement of the ring is the same for the each mode. The amount of displacement has been decreased to keep the sense signal within the limits of

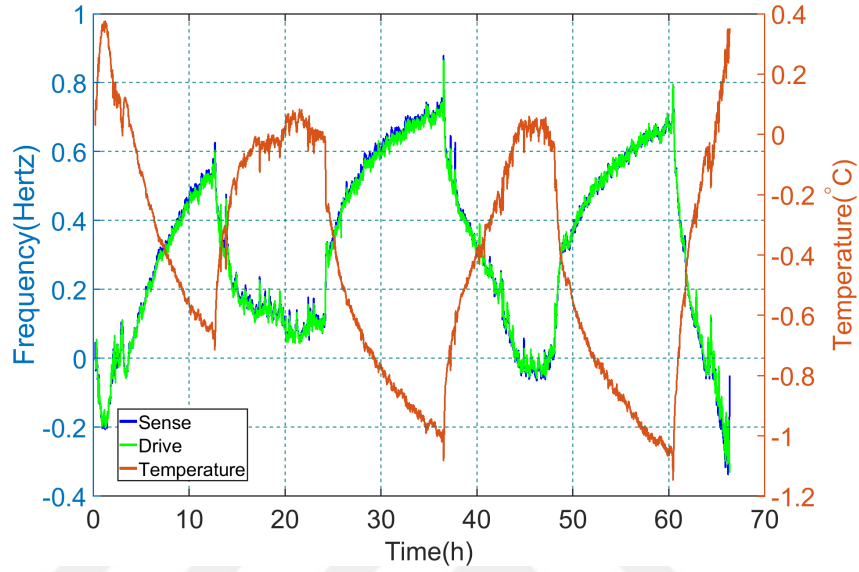


Figure 4.27: The time domain plots for the drive and sense frequency shifts and temperature changes for 65 hours.

the lock-in amplifier's input range. The gyroscope is operated in quadrature cancellation off configuration and in mismatch frequency conditions. The test was completed in 65 hours in room temperature.

Figure 4.27 shows the time domain data for the sense and the drive signal's frequency in relation to the temperature data. The temperature and the frequency values are highly correlated and have an inverse proportion. The frequency change of the modes are almost identical. The inherit property of the circular topology is a change in the resonance frequency of the sense and the drive mode shifts each for the same amount thanks to circular symmetry. This way the frequency band between each mode is kept the same. As a result, the sensitivity of the gyroscope is kept constant throughout the operation.

The frequency to temperature plot in 4.28 shows the existing hysteresis of the frequency change clearly. The plot is color coded for each passing day. The linear relation of the temperature and the frequency change can be observed for the short duration but the linear relation is lost with the progression of the test. The increasing temperature changes the Young's Modulus of the silicon. Silicon's Young's Modulus temperature dependence is reported to be -60ppm/K [40] and

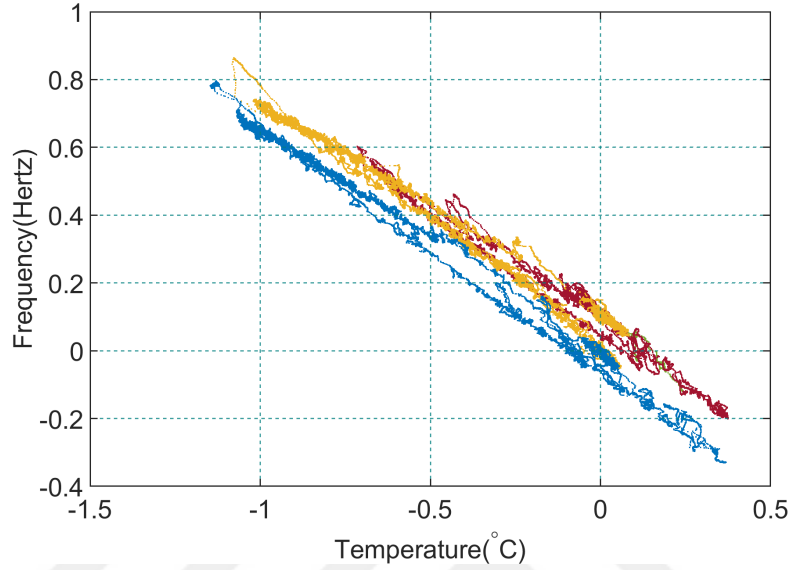


Figure 4.28: The change of drive frequency vs the change of temperature, hysteresis is visible. The plot is colored with progressing time.

the expected change in resonance frequency is -30ppm/K . However, in figure 4.28 we report -11.6ppm/K change for an initial resonance frequency at 57.355kHz . The temperature increase widens the gap between the electrodes as well which reduce the electrostatic softening effect. In addition to this effect, the induced stress on the electrodes change the width of the gaps. The decrease in the electrostatic softening in combination with the stress induced upon the electrodes reduce the linearity between temperature and the resonance frequency.

A similar compensation method was applied on the resonance test as well. The least squares algorithm was implemented using the temperature and the stress sensor output. In figure 4.29 the residue of the Hysterisis can be seen in the temperature compensated frequency. The frequency compensation was also implemented on the 16 Days mismatch test. The best stability can be observed with the partitioned stress and temperature compensation in figure 4.30. In mismatch test only the drive mod could be recorded. Since we have established the frequency of each mode trace each other we can infer that the sense mode frequency would have a similar compensation result. Our findings show that the one of the most detrimental metric of the gyroscope, resonance frequency, is primarily

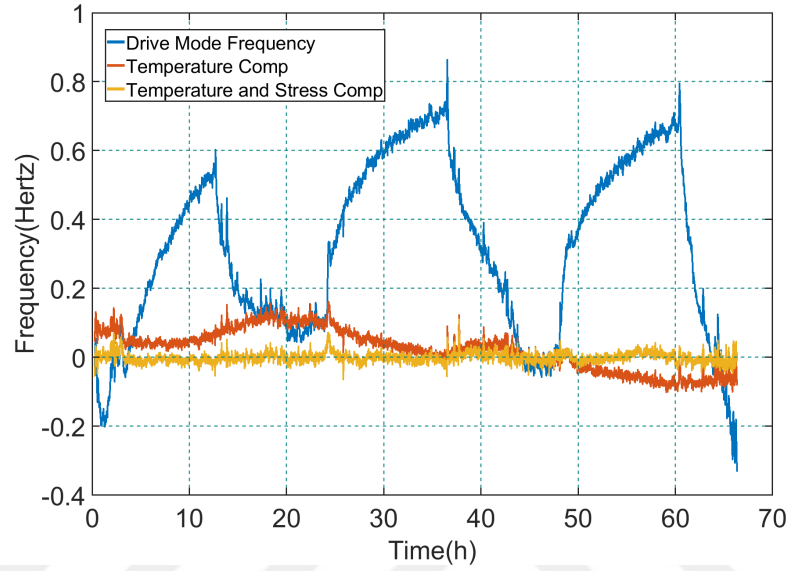


Figure 4.29: Original and compensated drive frequency with temperature and stress.

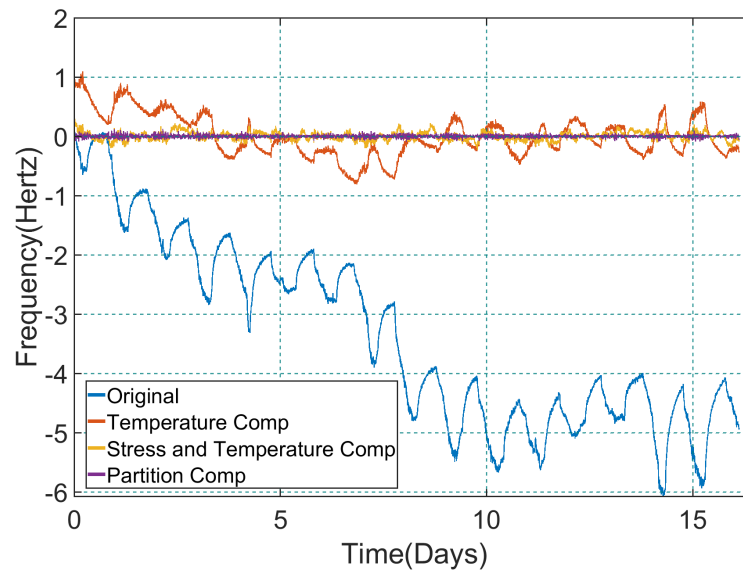


Figure 4.30: Drive frequency compensation in mismatched frequency ZRO test with temperature and stress.

distorted by not just the temperature change but with the combination of temperature change and the induced stress. The stress compensation is better suited to capture the change in frequency which is one of the reason the effectiveness of the drift suppression with stress compensation.



Chapter 5

Conclusion and Future Work

5.1 Conclusion

Previously, the temperature change has been used to compensate the long term drift of a MEMS gyroscope. With the new approach shown in [29] it was observed that the on-chip stress sensing is a great addition to observe external effects on the gyroscope and compensate for long term drift. A suitable design for accurate stress reading on the gyroscope's proof mass was achieved with a circular vibrating ring topology. The compact nature of the bridge type capacitive stress sensors was suited for this study. Thus, bridge type capacitive stress sensors were chosen over a piezoresistive stress sensor design. 8 stress sensors are placed inner part of the ring surrounding the main anchor, 8 stress sensors are placed in outer region surrounding the electrodes of the VRG. In total 16 stress sensors were employed to measure the change in stress. The distribution of these stress sensors makes it possible to observe the gap changes between the rings and the electrodes by measuring the displacement vector present on the anchors. The gyroscope design was simulated in Comsol Multiphysics tool and the drive resonance frequency was found to be 63,345 Hz. The fabricated ring was over-etched resulting with a lower spring coefficient thus a lower resonance frequency of 57,872 Hz.

The readout circuitry was complicated by the abundance of the stress sensors. Due to the slow change in stress over time the stress sensors were recorded through a multiplexer. The recording process during the tests were controlled by a python code which synchronized the signal generator and lock-in amplifier(HF2LI) clocks. The Gyroscope was soldered onto a daughter board with transimpedance for improved noise performance and mounted to the main PCB using 4 female headers. The analog and digital signals were ere separated and provided to the main PCB through two different dsub-15 connectors.

The gyroscope was put through a set of test to determine its performance values. Sweeping tests show that our design is capable of reaching higher than 30,000 in terms of its Quality factor and the frequency mismatch between the drive and sense modes can vary between 3 to 120 Hz depending on the fabrication mismatches. An aluminum custom testbed was manufactured with a CNC machine to test the response of the ob-chip stress sensors. The daughter board was compressed using the screws at the opposite sides and the axis of these screw were changed to test the normal and shear stress components both on the gyroscope and the stress sensors. Tensile stress response was observed on the stress sensors that are located close to the tightened screws. The magnitude of the applied stress was observed to reach up to 1.2 MPa. The gyroscope's response was also recorded during this process and our algorithm manage to compensate the gyroscope output using the change of stress which showed us the direct correlation between the stress and the gyroscope output. Two ZRO tests were completed in which the long term drift was observed thoroughly and compensated by the stress sensor outputs. In the first one the VRG was operated in open loop frequency mismatch configuration for 16 days. The ARW of the gyroscope was recorded to be $0.233^\circ/\sqrt{h}$ while the bias instability was measured to be $0.7^\circ/h$. The Allan deviation plot has shown us that the relation between the stress and the gyroscope's output to be linear in for short periods of time. Thus, the data was partitioned to 12 hour sets and then the least squares method was applied for compensation. The long term stability of the gyroscope was increased by x4000 compared to the uncompensated output. A similar method was also examined for the temperature data. The results show that linear correlation between the

temperature and the gyroscope output is minimal compared to the change of stress in the die. The long term stability of the partitioned stress compensated output reaches $0.008^\circ/h$ in a period of 48 hours with no signs of increasing. The gyroscope was configured for an open loop frequency matched operation for the second ZRO test. The ARW of the gyroscope was recorded to be $0.0583^\circ/\sqrt{h}$ while the bias instability was measured to be $0.3^\circ/h$. The matched frequency increased the sensitivity of the gyroscope and the SNR of the sense output was improved by this change as well. The long term stability of the partitioned stress compensated output reaches $0.003^\circ/h$ in a period of 48 hours with no signs of increasing.

Mismatched ZRO test was further investigated in terms of understanding the importance of stress sensors and the period of the time set for the partition duration. 16 stress sensors were separated to the groups of 4 both of which were allocated as inner, outer, normal and shear set groups that are formed of 8 stress sensors. The gyroscope output was compensated using these test and the compensation result show that even though there was a difference between the compensation results, all of the were approximately halved. We believe that these results are inadequate to determine the superiority of a specific stress sensor's capability to realize the change in the output of the gyroscope over another stress sensor. The straightforward result one can argue is that as the number of the stress sensor used for compensation the accuracy of the compensation increases. The period durations were altered to test the linearity of the stress sensor and the gyroscope output. The durations are set to be 12, 24 and 48. As it was anticipated the compensation performance decreased when the period spans were increased. The 12 hours span was set as the minimum limit to catch the daily changes in temperature due to day and night cycle. The compensation can be further enhanced by decreasing the span of the period. These results show that the on-chip stress compensation is the best method to improve the long term stability of a MEMS gyroscope as of today. We were able to eliminate the long term drift noise of the gyroscope and able to reach a similar noise level compared to the state of the art MEMS vibratory gyroscopes in long term operations. The currently utilized compensation method presents an optimum solution yet it can

not manage a real time compensation for the gyroscope. This study was focused on showing an optimum solution for the long term drift compensation problem with the induced stress sensing upon the die. Thus, the stress sensor coefficients that provide an optimal solution found for each period vary with each period. We believe that this work can be further developed for real time compensation of the long term drift.

5.2 Future Work

The real time drift compensation is naturally the next step to take to further develop this work. A machine learning algorithm can be developed to compensate the long term drift which can be trained by the current data sets we possess. The gyroscope performance can be increased by redesigning the main PCB. Closed loop configuration must be implemented to increase the stability and the performance of the gyroscope. A dither signal can be added during the modulation to guide the force rebalance electrode during demodulation and eliminate the displacement in the sense axis. We have observed a bump in the Allan deviation plot due to the interference between the stress sensor demodulation and the sense signal chain amplification. In the new design special care must be given to eliminate this periodic noise. Gyroscopes can also be redesigned for another fabrication process so that a thicker silicon layer is used. This way the undesired modes can be eliminated and the effective mass of the gyroscope is increased.

Bibliography

- [1] D. M. Rozelle, “The hemispherical resonator gyro: From wineglass to the planets,” *Advances in the Astronautical Sciences*, vol. 134, pp. 1157–1178, 2009.
- [2] C. Boone, M. Galloway, and M. J. Ruiz, “Fun with singing wine glasses,” *Physics Education*, vol. 53, p. 35025, 3 2018.
- [3] S. Finkbeiner, “MEMS for automotive and consumer electronics,” in *2013 Proceedings of the ESSCIRC (ESSCIRC)*, pp. 9–14, 2013.
- [4] A. D. Challoner, H. H. Ge, and J. Y. Liu, “Boeing disc resonator gyroscope,” *Record - IEEE PLANS, Position Location and Navigation Symposium*, pp. 504–514, 2014.
- [5] Y. Xu, Q. Li, P. Wang, Y. Zhang, X. Zhou, L. Yu, X. Wu, and D. Xiao, “0.015 Degree-Per-Hour Honeycomb Disk Resonator Gyroscope,” *IEEE Sensors Journal*, vol. 21, pp. 7326–7338, 3 2021.
- [6] Silicon Sensing, “High Performance MEMS Gyroscope CRS39A Series Technical Datasheet,” 2021.
- [7] S. Koenig, S. Rombach, W. Gutmann, A. Jaeckle, C. Weber, M. Ruf, D. Grolle, and J. Rende, “Towards a navigation grade Si-MEMS gyroscope,” *2019 DGON Inertial Sensors and Systems, ISS 2019 - Proceedings*, 9 2019.

- [8] D. Endean, K. Christ, P. Duffy, E. Freeman, M. Glenn, M. Gnerlich, B. Johnson, and J. Weinmann, “Near-Navigation Grade Tuning Fork MEMS Gyroscope,” in *2019 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, pp. 1–4, IEEE, 4 2019.
- [9] M. Gadola, A. Buffoli, M. Sansa, A. Berthelot, P. Robert, and G. Langfelder, “1.3 mm²Nav-Grade NEMS-Based Gyroscope,” *Journal of Microelectromechanical Systems*, vol. 30, pp. 513–520, 8 2021.
- [10] J. Y. Cho, S. Singh, J. K. Woo, G. He, and K. Najafi, “0.00016 deg/sqrt(hr) Angle Random Walk (ARW) and 0.0014 deg/hr Bias Instability (BI) from a 5.2M-Q and 1-cm Precision Shell Integrating (PSI) Gyroscope,” in *Proc. 2020 IEEE International Symposium on Inertial Sensors and Systems - INERTIAL 2020*, (Hiroshima, Japan), pp. 1–4, 3 2020.
- [11] E. Tatar, “On-Chip Compensation of Stress, Temperature, and Nonlinearity in a MEMS Gyroscope,” 2 2016.
- [12] S. Chong, S. Rui, L. Jie, Z. Xiaoming, T. Jun, S. Yunbo, L. Jun, and C. Huiliang, “Temperature drift modeling of MEMS gyroscope based on genetic-Elman neural network,” *Mechanical Systems and Signal Processing*, vol. 72-73, pp. 897–905, 5 2016.
- [13] Y. H. Tu and C. C. Peng, “An ARMA-Based Digital Twin for MEMS Gyroscope Drift Dynamics Modeling and Real-Time Compensation,” *IEEE Sensors Journal*, vol. 21, pp. 2712–2724, 2 2021.
- [14] R. L. Kubena, R. J. Joyce, and A. D. Challoner, “Correlation of frequency, temperature, and bias stability of a Si ring gyro,” in *Proc. 2016 IEEE International Symposium on Inertial Sensors and Systems - INERTIAL 2016*, (Laguna Beach, CA, USA), pp. 21–24, 3 2016.
- [15] H. Ge and R. M’Closkey, “Simultaneous Angular Rate Estimates Extracted from a Single Axisymmetric Resonator,” *IEEE Sensors Journal*, vol. 17, pp. 7460–7469, 11 2017.

- [16] E. Tatar, T. Mukherjee, and G. K. Fedder, "Simulation of stress effects on mode-matched MEMS gyroscope bias and scale factor," *Record - IEEE PLANS, Position Location and Navigation Symposium*, pp. 16–20, 2014.
- [17] X. Zhang, S. Park, and M. W. Judy, "Accurate assessment of packaging stress effects on MEMS sensors by measurement and sensor-package interaction simulations," *Journal of Microelectromechanical Systems*, vol. 16, pp. 639–649, 6 2007.
- [18] J. Lau, *Thermal stress and strain in microelectronics packaging*. Springer Science & Business Media, 2012.
- [19] E. Tatar, T. Mukherjee, and G. K. Fedder, "Stress Effects and Compensation of Bias Drift in a MEMS Vibratory-Rate Gyroscope," *Journal of Microelectromechanical Systems*, vol. 26, pp. 569–579, 6 2017.
- [20] J. C. Suhling and R. C. Jaeger, "Silicon piezoresistive stress sensors and their application in electronic packaging," *IEEE Sensors Journal*, vol. 1, no. 1, pp. 14–30, 2001.
- [21] S. S. Kumar and B. D. Pant, "Design principles and considerations for the 'ideal' silicon piezoresistive pressure sensor: A focused review," *Microsystem Technologies*, vol. 20, pp. 1213–1247, 5 2014.
- [22] R. C. Jaeger, J. C. Suhling, and R. Ramani, "Errors Associated With the Design, Calibration and Application of Piezoresistive Stress Sensors in (100) Silicon," *IEEE Transactions on Components Packaging and Manufacturing Technology Part B*, vol. 17, no. 1, pp. 97–107, 1994.
- [23] L. L. Chu, L. Que, and Y. B. Gianchandani, "Measurements of material properties using differential capacitive strain sensors," *Journal of Microelectromechanical Systems*, vol. 11, pp. 489–498, 10 2002.
- [24] M. Suster, J. Guo, N. Chaimanonart, W. H. Ko, and D. J. Young, "A high-performance MEMS capacitive strain sensing system," *Journal of Microelectromechanical Systems*, vol. 15, pp. 1069–1077, 10 2006.

- [25] H. W. Ma, S. M. Yao, L. Q. Wang, and Z. Zhong, “Analysis of the displacement amplification ratio of bridge-type flexure hinge,” *Sensors and Actuators A: Physical*, vol. 132, pp. 730–736, 11 2006.
- [26] “A Piezoelectric Rate Gyroscope,” in *Microsystem Design*, pp. 561–604, Boston, MA: Springer US, 2001.
- [27] “Fundamentals of Micromachined Gyroscopes,” in *MEMS Vibratory Gyroscopes: Structural Approaches to Improve Robustness*, pp. 1–26, Boston, MA: Springer US, 2009.
- [28] I. S. . (2019), “IEEE Standard for Inertial Sensor Terminology,” *IEEE Std 528-2019 (Revision of IEEE Std 528-2001)*, 2019.
- [29] E. Tatar, T. Mukherjee, and G. K. Fedder, “On-chip stress compensation on the ZRO of a mode-matched MEMS gyroscope,” in *Proc. 2016 IEEE International Symposium on Inertial Sensors and Systems - INERTIAL 2016*, (Laguna Beach, CA, USA), pp. 128–131, 3 2016.
- [30] R. Eley, C. H. J. Fox, and S. Mcwilliam, “Anisotropy effects on the vibration of circular rings made from crystalline silicon,” *Journal of Sound and Vibration*, vol. 228, no. 1, pp. 11–35, 1999.
- [31] J. Kirkhope, “In-plane vibration of a thick circular ring,” *Journal of Sound and Vibration*, vol. 50, pp. 219–227, 1 1977.
- [32] M. Hosseini-Pishrobat and E. Tatar, “Modeling and Analysis of a MEMS Vibrating Ring Gyroscope Subject to Imperfections,” *Journal of Microelectromechanical Systems*, pp. 1–15, 2022.
- [33] M. M. Torunbalci, S. E. Alper, and T. Akin, “Advanced MEMS process for wafer level hermetic encapsulation of MEMS devices using SOI cap wafers with vertical feedthroughs,” *Journal of Microelectromechanical Systems*, vol. 24, pp. 556–564, 6 2015.
- [34] G. Jundt, A. Radu, E. Fort, J. Duda, H. Vach, and N. Fletcher, “Vibrational modes of partly filled wine glasses,” *The Journal of the Acoustical Society of America*, vol. 119, pp. 3793–3798, 6 2006.

- [35] Zurich Instruments, “HF2LI 50 MHz Lock-in Amplifier.”
- [36] E. Tatar, S. E. Alper, and T. Akin, “Quadrature-error compensation and corresponding effects on the performance of fully decoupled MEMS gyroscopes,” *Journal of Microelectromechanical Systems*, vol. 21, no. 3, pp. 656–667, 2012.
- [37] H. Hou, *Modeling Inertial Sensors Errors Using Allan Variance*. PhD thesis, University of Calgary, Calgary, CA.
- [38] D. W. Allan, “Statistics of Atomic Frequency Standards,” *Proceedings of the IEEE*, vol. 54, no. 2, pp. 221–230, 1966.
- [39] U. A. Inc., “Thermally Conductive Adhesives.”
- [40] M. A. Hopcroft, W. D. Nix, and T. W. Kenny, “What is the Young’s modulus of silicon?,” *Journal of Microelectromechanical Systems*, vol. 19, pp. 229–238, 4 2010.

Appendix A

Additional Figures

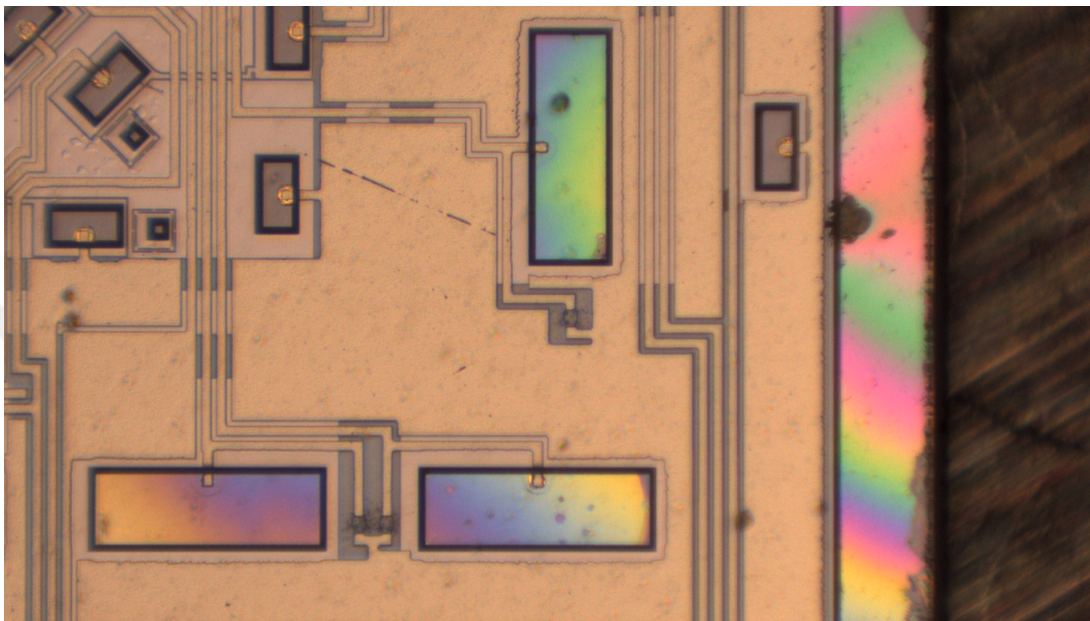


Figure A.1: Failure in the vacuuming process

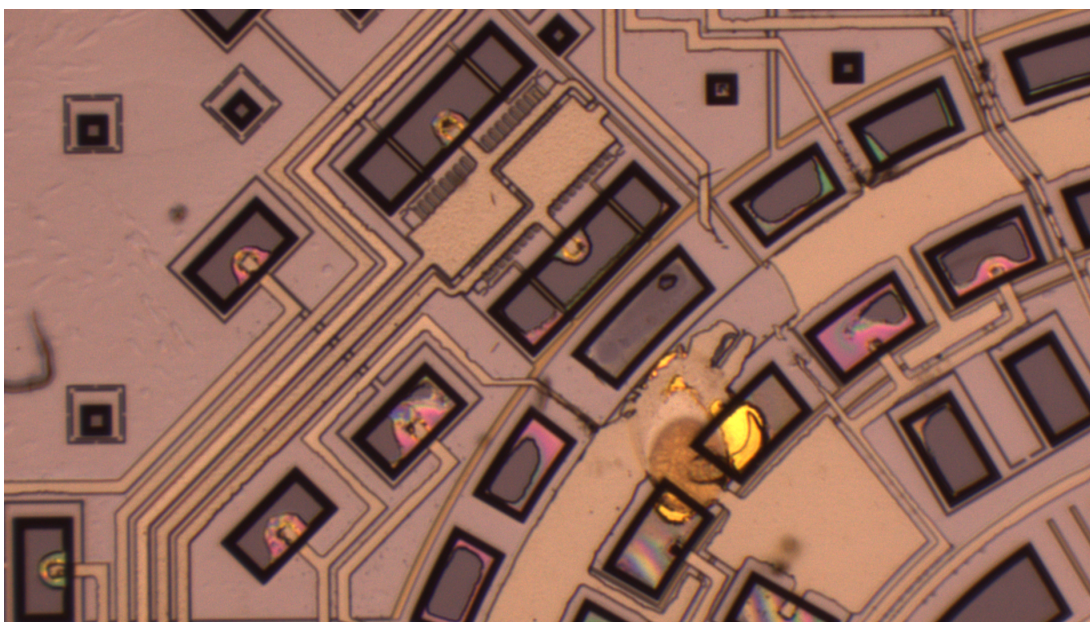


Figure A.2: Failure in the metal lithography

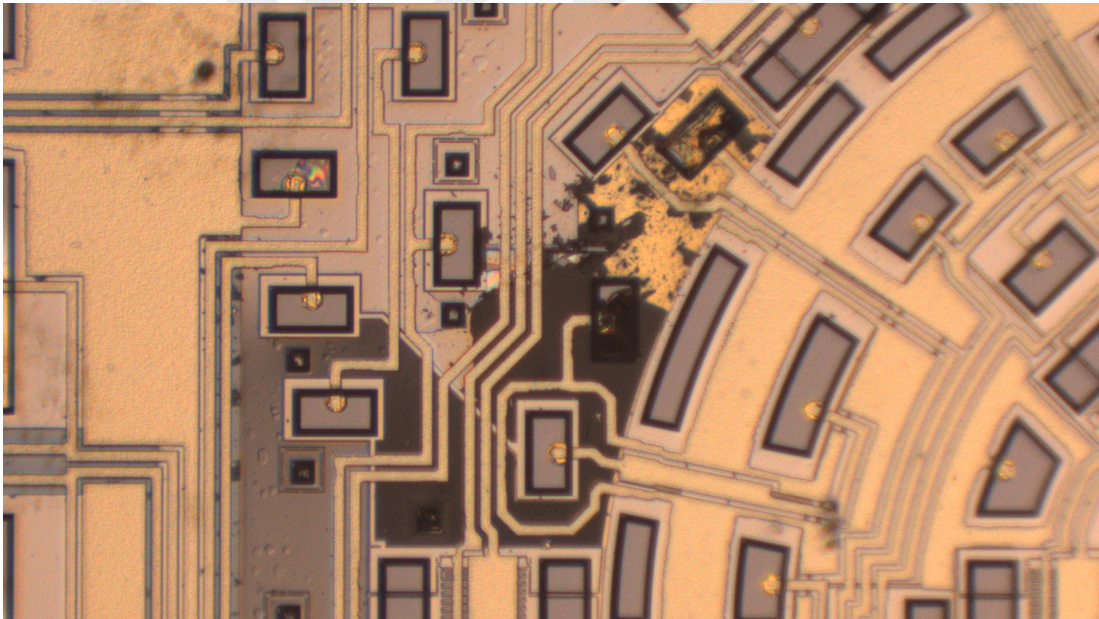


Figure A.3: Failure in the silicon bonding

Appendix B

Additional Tables

Table B.1: Interface Board Pin Map

Pin Number	Assigned Signal
1	VDD (15V)
2	GND
3	Ftune
4	Force Rebalance
5	Clock Signal
6	Drive Signal
7	Drive Pick + Signal
8	Differential Stress Output
9	Drive Pick - Signal
10	Stress Output
11	Input Quadrature Signal
12	VSS (-15V)
13	HV (Proof Mass)
14	Sense + Output
15	Sense - Output

Appendix C

Code

C.1 Digital Pin Definitions

```
class AMPFIRST:
    #Raw bit definitions
    MUX_A0 = 0b000_0000_0001
    MUX_A1 = 0b000_0000_0010
    MUX_A2 = 0b000_0000_0100
    MUX_EN1 = 0b000_0000_1000
    MUX2_EN1 = 0b000_0001_0000
    OPAMP_EN2 = 0b000_0010_0000
    OPAMP_EN3 = 0b000_0100_0000
    OPAMP_EN1 = 0b000_1000_0000
    OPAMP_EN4 = 0b001_0000_0000
    OPAMP_EN = 0b001_1110_0000 #Including this enables all opamps
        ↪ at once
    MUX2_EN2 = 0b010_0000_0000
    MUX_EN2 = 0b100_0000_0000
    #Stress sensor definitions using req'd bits (last number
        ↪ selects A2, A1, A0 together)
```

```

S_OIP = OPAMP_EN1 | MUX_EN2 | 2 | OPAMP_EN2
S_OIN = OPAMP_EN1 | MUX_EN2 | 6 | OPAMP_EN2
S_45IP = OPAMP_EN2 | MUX_EN1 | 4 | OPAMP_EN2
S_45IN = OPAMP_EN2 | MUX_EN1 | 0 | OPAMP_EN2
S_90IP = OPAMP_EN2 | MUX_EN1 | 5 | OPAMP_EN2
S_90IN = OPAMP_EN2 | MUX_EN1 | 1 | OPAMP_EN2
S_135IP = OPAMP_EN3 | MUX_EN1 | 2 | OPAMP_EN2
S_135IN = OPAMP_EN3 | MUX_EN1 | 6 | OPAMP_EN2
S_OOP = OPAMP_EN1 | MUX_EN2 | 3 | OPAMP_EN2
S_OON = OPAMP_EN1 | MUX_EN2 | 7 | OPAMP_EN2
S_45OP = OPAMP_EN4 | MUX_EN2 | 4 | OPAMP_EN2
S_45ON = OPAMP_EN4 | MUX_EN2 | 0 | OPAMP_EN2
S_90OP = OPAMP_EN3 | MUX_EN1 | 3 | OPAMP_EN2
S_90ON = OPAMP_EN3 | MUX_EN1 | 7 | OPAMP_EN2
S_135OP = OPAMP_EN4 | MUX_EN2 | 5 | OPAMP_EN2
S_135ON = OPAMP_EN4 | MUX_EN2 | 1 | OPAMP_EN2

#Differential stress sensor definitions
S_OI = OPAMP_EN1 | MUX2_EN2 | 2 | OPAMP_EN
S_45I = OPAMP_EN2 | MUX2_EN1 | 0 | OPAMP_EN
S_90I = OPAMP_EN2 | MUX2_EN1 | 1 | OPAMP_EN
S_135I = OPAMP_EN3 | MUX2_EN1 | 2 | OPAMP_EN
S_OO = OPAMP_EN1 | MUX2_EN2 | 3 | OPAMP_EN
S_45O = OPAMP_EN4 | MUX2_EN2 | 0 | OPAMP_EN
S_90O = OPAMP_EN3 | MUX2_EN1 | 3 | OPAMP_EN
S_135O = OPAMP_EN4 | MUX2_EN2 | 1 | OPAMP_EN

#helper dicts to iterate over
#SINGLE = {"O_S_I_P":S_OIP,"O_S_I_N":S_OIN,"45_S_I_P":S_45IP
    ↪ ,"45_S_I_N":S_45IN,"90_S_I_N":S_90IN,"90_S_I_P":S_90IP
    ↪ ,"135_S_I_P":S_135IP,"135_S_I_N":S_135IN,"O_S_O_P":
    ↪ S_OOP,"O_S_O_N":S_OON,
# "45_S_O_P":S_45OP,"45_S_O_N":S_45ON,"90_S_O_P":S_90OP,"90
    ↪ _S_O_N":S_90ON,"135_S_O_P":S_135OP,"135_S_O_N":S_135ON}

```

```

SINGLE = {"90_S_O_P":S_900P,"90_S_O_N":S_900N, "45_S_I_P":
    ↪ S_45IP,"45_S_I_N":S_45IN,"90_S_I_N":S_90IN,"90_S_I_P":
    ↪ S_90IP,"135_S_I_P":S_135IP,"135_S_I_N":S_135IN,"0_S_O_P"
    ↪ :S_00P,"0_S_O_N":S_00N,
    "45_S_O_P":S_450P,"45_S_O_N":S_450N,"0_S_I_P":S_0IP,"0
    ↪ _S_I_N":S_0IN,"135_S_O_P":S_1350P,"135_S_O_N":S_1350N
    ↪ }

SINGLE_INNERS = {"0_S_I_P":S_0IP,"0_S_I_N":S_0IN,"45_S_I_P":
    ↪ S_45IP,"45_S_I_N":S_45IN,"90_S_I_P":S_90IN,"90_S_I_P":
    ↪ S_90IP,"135_S_I_P":S_135IP,"135_S_I_N":S_135IN}

SINGLE_OUTERS = {"0_S_O_P":S_00P,"0_S_O_N":S_00N,"45_S_O_P":
    ↪ S_450P,"45_S_O_N":S_450N,"90_S_O_P":S_900P,"90_S_O_N":
    ↪ S_900N,"135_S_O_P":S_1350P,"135_S_O_N":S_1350N}

DIFF = {"0_S_I":S_0I,"45_S_I":S_45I,"90_S_I":S_90I,"135_S_I":
    ↪ S_135I,"0_S_O":S_00,"45_S_O":S_450,"90_S_O":S_900,"135
    ↪ _S_O":S_1350}

DIFF_INNERS = {"0_S_I":S_0I,"45_S_I":S_45I,"90_S_I":S_90I,"135
    ↪ _S_I":S_135I}

DIFF_OUTERS = {"0_S_O":S_00,"45_S_O":S_450,"90_S_O":S_900,"135
    ↪ _S_O":S_1350}

```

C.2 Multiplexing and Recording

```

import zhinst.ziPython as zp
import time
from datetime import datetime
import asyncio
import statistics
import pyvisa
import sys
import math

```

```

import csv
import os
from gyrodefs import AMPFIRST
import threading

#HOSTNAME = "EE315-ZURICH2" #Hostname of the machine where Zurich
    ↳ data server is hosted
HOSTNAME = "localhost"
DEV = "dev1658" #S/N of our HF2LI

#resource manager for GPIB
rm = pyvisa.ResourceManager()

#sensor_dict = AMPFIRST.SINGLE_OUTERS #Dict of sensors we need to
    ↳ read and their corresponding DIO values
sensor_dict = AMPFIRST.SINGLE
stresses = dict()
temp = None

threadAlive = True

lastTemp = None

agilent = rm.open_resource("USB0::0x0957::0x1A07::MY53202857::0::
    ↳ INSTR") #34461A 6.5 Digit Multimeter
scope = rm.open_resource("GPIB0::3::INSTR") #DS06000 Oscilloscope
smu = rm.open_resource("GPIB0::5::INSTR") #Keithley 2400 SMU
awg = rm.open_resource("GPIB0::2::INSTR") #Tek AFG3101 Arbitrary
    ↳ Function Generator
psu = rm.open_resource("GPIB0::6::INSTR") #N6705A DC Power
    ↳ Analyzer
#Clear errors in the DC Power Analyzer
err = ""

```

```

while err != '+0, "No error"\n':
    err = psu.query("syst:err?")

#convert sensor voltage to a temperature
def voltToTemp(volt):
    #Calibration constants for linear approximation as per LMT87
    ↪ datasheet
    return (13.582 - math.sqrt(13.582**2 + (4*0.00433*(2230.8 -
    ↪ volt*1000))))/(2*(-0.00433)) + 30 #quadratic
    ↪ approximation
    #return (volt - 2.637)/-13.6e-3 #linear approximation

def readGyroStress(filename):
    global HOSTNAME
    global DEV
    global sensor_dict
    global threadAlive
    global lastTemp
    global agilent
    global psu

    api = zp.ziDAQServer(HOSTNAME,8005) #Open a connection to the
    ↪ LabOne server
    api.connectDevice(DEV,"USB") #Connect to the HF2LI

    api.subscribe("/{}/demods/1/sample".format(DEV)) #Subscribe to
    ↪ source for samples
    api.setInt("/{}/dios/0/drive".format(DEV),0b11) #both 8 bit
    ↪ banks are driven
    api.setInt("/{}/dios/0/output".format(DEV),0) #initialize
    ↪ outputs at 0 to avoid any collisions with mux

    sensors = list(sensor_dict)

```

```

dios = list(sensor_dict.values())

current_sensor = 0 #which sensor is selected?
current_sensor_name = "" #ditto
sample_count = 7 #how many times have we sampled this sensor?

print("Started_gyro_reader")
with open(filename,"w",newline='') as csvfile:
    writer = csv.writer(csvfile)
    #Timestamp System time (s) Sensor Value F+ Output(V)
    ↪ Temperature F+ Raw St. Dev Resonance Frequency
    writer.writerow(["System_time", "Perf_time", "Sensor_name", "
    ↪ Raw_sensor_data", "F+ Output", "Temperature", "Filtered_
    ↪ sensor_data", "Drive_Frequency", "Sample_X", "Sample_Y
    ↪ ", "VDD_Current", "VSS_Current"])
    first_time = True #stress sensors haven't been assigned
    ↪ yet so don't drop any value
    while threadAlive:
        try:
            sample = api.poll(0.1,1000,flat=True) #collect 0.1
            ↪ seconds of data from the subscribed node

            if sample_count > 7: #we have taken enough samples,
            ↪ on to the next sensor
                current_sensor = (current_sensor + 1) % len(
                    ↪ sensors)
                current_sensor_name = sensors[current_sensor]
                api.setInt("/{}/dios/0/output".format(DEV),dios[
                    ↪ current_sensor]) #select the device
                sample_count = 0
                print("At_{sensor_is}_{(DIO={0x{:4x}})".
                    ↪ format(time.strftime("%H_%M"),
                    ↪ current_sensor_name,dios[current_sensor]))

```

```

print("VDD={:6.5f}_VSS={:6.5f}".format(
    ↪ vdd_current, vss_current))

timestamps = sample["/{}/demods/1/sample".format(DEV
    ↪ )]["timestamp"] #if we aren't subscribed to
    ↪ the node correctly it will raise a KeyError
    ↪ here
samplex = sample["/{}/demods/1/sample".format(DEV)][
    ↪ "x"]
sampley = sample["/{}/demods/1/sample".format(DEV)][
    ↪ "y"]
if sample_count != 0 or first_time or True: #drop
    ↪ the first value for each sensor unless it is
    ↪ the first data collected
    stressval = sample["/{}/demods/1/sample".format(
        ↪ DEV)]["auxin0"]
    first_time = False
fplusvolt = sample["/{}/demods/1/sample".format(DEV
    ↪ )]["auxin1"]
drivefrequency = sample["/{}/demods/1/sample".format
    ↪ (DEV)]["frequency"]

if current_sensor_name in stresses: #Save the data
    ↪ from stress sensor on auxin0 to the dict
    stresses[current_sensor_name] = 0.875 * stresses
        ↪ [current_sensor_name] + 0.125 * statistics
        ↪ .mean(stressval) #AR filter, 3 dB around 1
        ↪ Hz
else:
    stresses[current_sensor_name] = statistics.mean(
        ↪ stressval)

```

```

(vss_current, vdd_current) = [float(i) for i in psu.
    ↪ query("meas:curr?_(@1,3)").split(",")]
#if vdd_current > 0.045 or vss_current > 0.055:
    #agilent.write("syst:beep:imm")
    #scope.write(":stop")

writer.writerow([time.time(), time.perf_counter(),
    ↪ current_sensor_name, statistics.mean(stressval
    ↪ ), statistics.mean(fplusvolt), lastTemp,
    ↪ stresses[current_sensor_name], statistics.mean
    ↪ (drivefrequency),
    statistics.mean(samplex), statistics.mean(sampley
    ↪ ), vdd_current, vss_current])

sample_count = sample_count + 1

csvfile.flush() #Flush the csv file to disk so we
    ↪ can peek the file while it is still being
    ↪ written to
except (RuntimeError, KeyError) as err: #Connection to
    ↪ the Zurich timed out or something else broke, so
    ↪ we reinitialize everything
    api = zp.ziDAQServer(HOSTNAME, 8005) #Open a
        ↪ connection to the LabOne server again
    api.connectDevice(DEV, "USB") #Connect to the
        ↪ HF2LI
    api.subscribe("/{}/demods/1/sample".format(DEV))
        ↪ #Subscribe to source for samples
    with open("log_stress.txt", "a") as log:
        log.write("{}:_LabOne_timed_out\n".format(
            ↪ datetime.now().isoformat()))

```



```

        log.write("Actual_error_text_is: {}\n".format
            ↪ (str(err)))
    except pyvisa.errors.VisaIOError as err:
        with open("log_stress.txt","a") as log:
            log.write("{}: VISA_error\nError_text: {}\n".
                ↪ format(datetime.now().isoformat(),str(err))
                ↪ ))
        print("{}: VISA_error\nError_text: {}\n".format(
            ↪ datetime.now().isoformat(),str(err)))

def readMultimeter(filename): #open a CSV file at the given
    ↪ filename and start reading the multimeter
    global agilent
    global threadAlive
    global lastTemp

    #time.sleep(1)
    print(agilent.query("*IDN?"))
    agilent.write("MEAS:VOLT") #Configure meter for DC voltage
    ↪ reading
    err = ""
    while err != '+0,"No_error"\n':
        err = agilent.query("syst:err?")
        print(err)

    print("Multimeter_connection_opened")
    with open(filename,"w",newline='') as csvfile:
        writer = csv.writer(csvfile)
        writer.writerow(["System_time(s)","Raw_voltage",
            ↪ Temperature"])

    while threadAlive:
        try:

```

```

    volt = float(agilent.query("READ?"))
    agilent.write("DISP:TEXT\\\"Temp:_{:5.2f}_C\\\"".format
        ↪ (voltToTemp(volt)))
    temp = voltToTemp(volt)
    writer.writerow([time.perf_counter(),volt,temp])
    print("temperature_{:}".format(temp))
    if lastTemp is not None:
        lastTemp = 0.875*lastTemp + 0.125 * temp
    else:
        lastTemp = temp
    csvfile.flush() #flush file to disk so we can peek
        ↪ it while it is being written to
except pyvisa.errors.VisaIOError as e:
    print("multimeter_error_at_{:}_{:}".format(time.
        ↪ strftime("%c"),str(e)))
except KeyboardInterrupt:
    print("Received_KeyboardInterrupt")
    raise SystemExit #End the thread or hopefully the
        ↪ whole program

if not threadAlive:
    raise SystemExit

def infoText(foldername): #Generates an info.txt file in the
    ↪ folder
    #Stuff we want to save: HV, Ftune, Zurich state: PLL on? PID
        ↪ on? PID setpoint?
    global HOSTNAME
    global DEV

    path = os.path.join(foldername,"info.txt")
    api = zp.ziDAQServer(HOSTNAME,8005) #Open a connection to the
        ↪ LabOne server

```

```

api.connectDevice(DEV,"USB") #Connect to the HF2LI

with open(path,mode="w") as infofile:
    infofile.write("Ftune={}\n".format(round(float(psu.query("
        ↪ meas:volt?_(@4)")))))
    infofile.write("HV={}\n".format(round(float(smu.query("sour
        ↪ :volt?")))))
    pll_state = api.getInt("{} /PLLS/0/ENABLE".format(DEV))
    infofile.write("PLL={}\n".format(pll_state))
    pid_state = api.getInt("{} /PIDS/0/ENABLE".format(DEV))
    infofile.write("PID1={}\n".format(pid_state))
    pid_state = api.getInt("{} /PIDS/1/ENABLE".format(DEV))
    infofile.write("PID2={}\n".format(pid_state))
    pid_state = api.getInt("{} /PIDS/2/ENABLE".format(DEV))
    infofile.write("PID3={}\n".format(pid_state))
    pid_state = api.getInt("{} /PIDS/3/ENABLE".format(DEV))
    infofile.write("PID4={}\n".format(pid_state))
    pid_setpoint = api.getDouble("{} /PIDS/0/setpoint".format(
        ↪ DEV))
    infofile.write("PID1_Setpoint={}\n".format(pid_setpoint))

def main():
    global threadAlive
    #print(psu.query("*idn?"))
    #hv = round(float(psu.query("meas:volt? (@4)")))
    wafer = input("Wafer_name?_(leave_blank_for_S3R0)") or "S3R0"
    die = input("Die_name?_(leave_blank_for_P5P0)") or "P5P0"
    nick = input("File_name?") or "data"
    foldername = "{}_{}_{}_{}".format(time.strftime("%Y_%m_%d_%H_%
        ↪ M_%S"), wafer, die, nick)
    #foldername = "{}_HV{}_{}".format(name,hv,time.strftime("%Y_%
        ↪ m_%d_%H_%M_%S"))
    os.mkdir(foldername)

```

```

infoText(foldername)

meter = os.path.join(foldername,"multimeter.csv")
multimeter_thread = threading.Thread(target=readMultimeter,
    ↪ args=(meter,))
multimeter_thread.start()

gyrostress = os.path.join(foldername,"gyrostress.csv")
try:
    readGyroStress(gyrostress)
except Exception as e:
    threadAlive = False #if the previous function exited, then
    ↪ the program should stop so instruct the meter
    ↪ thread to kill itself
    print("bittik_{}".format(str(e)))
    raise e
except KeyboardInterrupt:
    threadAlive = False
    print("keyboardinterrupt_geldi")

main()
threadAlive = False

```