High–g (20,000g+) testing of an existing tactical grade gyro design

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Inertial Sensors and Systems 2020
Braunschweig, Germany

978-1-7281-6848-7/20/$31.00©2020 IEEE

Abstract

Since 2009, more than 35,000 of Sensonor's STIM gyro modules and IMUs have been shipped to customers across many applications in defense and commercial markets. The STIM gyro modules and IMUs are based on a proven gyro design that originally came from the automotive safety segment.

There is a growing interest for using the same technology in high-g applications, mostly driven by artillery shells and artillery launched guided ammunitions, often referred to as smart munitions. A common requirement for this is 20,000g survival of the MEMS structure as well as measurement capability up to 10,000°/s. Additionally, the European defense industry has raised concerns regarding the lack of an all-European solution available in the market. Similar concerns have also been voiced by the European Defence Agency (EDA).

In order to investigate whether Sensonor's current gyro could be a candidate for these applications, finite-element modeling (FEM) has been performed with static load of 20,000g. Further, static high-g testing has been performed at 20,000, 25,000 and 30,000g exposing the gyro to high-g forces in all 6 directions. Finally, shock-tests up to 21,300g have been performed, again in all 6 directions. In total 168 gyro dies have been used in the various tests. This paper summarizes the analysis and tests performed and concludes that Sensonor's gyro indeed is a candidate for high-g applications.

1. Short summary of the history of Sensonor

Sensonor was founded in 1985 as a spin-out company of the Norwegian company AME (Aker Mikro Elektronikk). Its MEMS-technology had been specifically developed with high-reliability in mind, and Sensonor's products were well established within the demanding fields of medical, aerospace and military. During the first two decades, Sensonor had its focus on the automotive segment, delivering more than 35 million accelerometers to airbag applications, more than 250 million pressure sensors and accelerometers to tire-pressure applications and more than 2 million gyros to roll-over applications. Sensonor was certified and in compliance with all relevant and required quality standards and gained through this period solid experience and mind-set of high-volume production of products with safety and high-reliability requirements. From 2009, Sensonor changed its focus to high-precision, tactical-grade 3-axis gyro modules (STIM202 and STIM210) and IMUs (STIM300 and STIM318), addressing the segment of high-precision gyros typically covered by fiber-optic gyros. The new products were all based on the technology and know-how established during the previous two decades of high-volume production and deliveries to highly demanding applications.

2. Gyro sensing element

The Sensonor gyro sensing element was originally developed for roll-over detection in cars, an application requiring robustness and reliability. It is simple in its structure, consisting of two proof masses suspended by three springs and 4 sets of electrodes to enable differential drive and detection, as shown in figure 1:

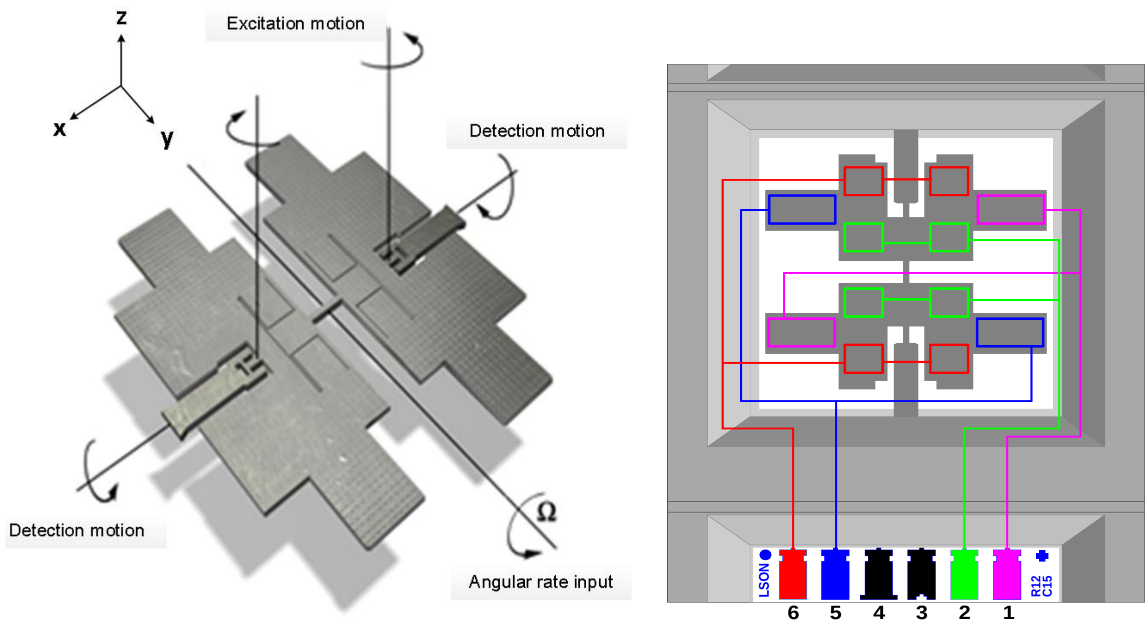


Figure 1: The Sensonor gyro sensing element (left) and capacitor lay-out (right)

The gyro sensing element is made of monocrystalline silicon, a material with no properties of fatigue leading to superior reliability. The balanced design gives high-mechanical common mode rejection, making it suitable for applications with vibrations. Each proof-mass weighs only ~20µgrams. Combined with its simplicity, this makes the Sensonor gyro sensing element very robust towards g-forces and thereby being a potential candidate for high-g applications like gun-hard gyro modules and IMUs.

3. FEM simulations

Finite-element modeling has been performed by applying 20,000g in the different axis-directions of the MEMS gyro. The maximum stress and displacements can be found in table 1.

Table 1: Results from FEM-simulations of 20,000g static load

Direction	Max stress (von Mises)	Displacement
±X	53MPa	0.17µm
±Y	513MPa	0.28µm
±Z	423MPa	4.6µm

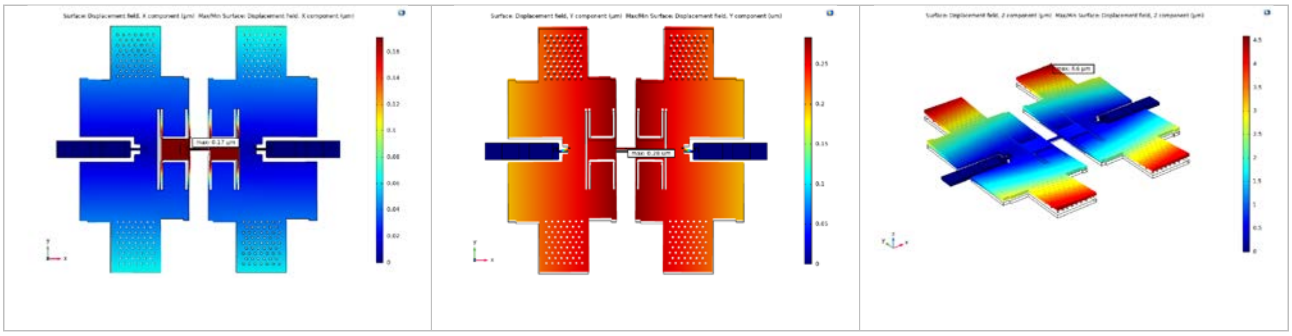


Figure 1. Displacements when applying 20,000g static load in X- (left), Y-(middle) and Z- (right) directions

The displacements of the mass at 20,000g static load were found to be smaller than the available gaps, thereby avoiding any mechanical conflicts, except when the static load is applied in the positive Z-direction. According to the results shown in table 1 and figure 1, this will give a displacement of the tips of the mass of 4.6µm towards the electrodes. As the gap between mass and electrodes is nominally 1µm, this will lead to physical contact.

The maximum stress exceeds the fracture strength of bulk silicon of 200MPa [1]. However, the theoretical fracture strength of monocrystalline silicon at the micrometer scale is much higher than that of bulk silicon, reported in literature up to 6GPa [2] and very much dependent on manufacturing defects.

3. High-g static loading

As the finite-element modeling did not conclude that the Sensonor MEMS gyro actually would survive the loads seen in gun-hard applications due to the uncertainty of fracture strength, it was decided to perform tests with high-g static load to investigate this further. A test-matrix was defined to test the MEMS gyro in all 6 axis-directions and with 3 different loads: 20, 25 and 30,000g in order to add some margin to the 20,000g requirement and to see if the fracture strength could be reached.

3.1 Test setup

A special test-fixture was developed to hold the MEMS-gyros during load, to enable testing before and after the load and with a lid to protect the MEMS gyros during transportation and during application of the high-g static load.

Figure 2. Special test-fixture for high-g static load

As the parts were going to be shipped to the test-house by the use of a courier and thereby outside own control, two additional test-fixtures were assembled, to act as references for any incidents that may occur during transportation. They were not exposed to high static g's at the test-house.

The high-g static loading was performed at Golden Altos Corporation located in California. They have a centrifuge capable of applying static loads up to 30,000g. The centrifuge has 6 pockets where the pay-load is placed as shown in figure 3. Symmetric loading is of prime importance. Golden Altos provides a solution where the devices to be tested can be placed inside a sand-filled aluminum holder that fits to the centrifuge. The fine-grained sand ensures that the device under test remains in correct position and orientation during the application of high-g load. The specified g-load was applied for 1 minute.

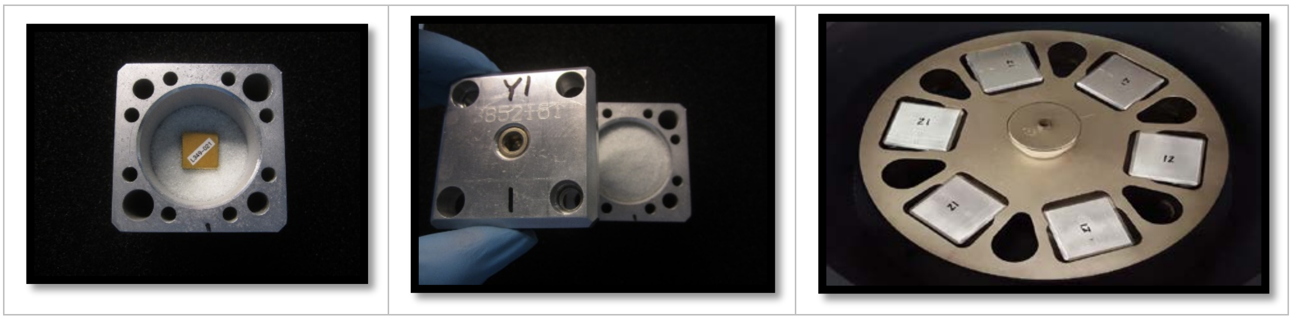


Figure 3. Details of centrifuge (by courtesy of Golden Altos Corporation)

3.2 Results

All MEMS gyros were tested before and after the high-g load using the standard production test performed on all MEMS gyros produced at Sensonor. This test includes measurement of the resonance-frequency of mode 2, the drive mode. In case of damage, for example if one of the springs or masses is broken, this would lead to a change in the resonance-frequency.

Table 2: Results from high-g static loading

Direction / Load	+X	-X	+Y	-Y	+Z	-Z
20,000g	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0
25,000g	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0
30,000g	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0

The difference between the pre and post tests was much less than 1Hz for all MEMS gyros. The shift was systematic and can easily be explained by difference in temperature between the two tests. All gyros passed up to 30,000g static load. These tests did not reveal the fracture strength of the MEMS gyro. The very high fracture strength is a good proof of the high maturity and robustness level of this gyro, being the result of hard and dedicated work over years to avoid manufacturing defects during release-etching of the springs and masses.

4. 20,000g shock testing

The 20,000g shock testing was performed at ISL, a French-German Research Institute located in Saint-Louise in France, very close to the borders of Germany and Switzerland. At this institute they are able to apply shocks up to 25,000g using gun-powder to accelerate the test-vehicle and pressurized gas to decelerate it. The acceleration part will be very close to what is experienced in a gun-hard application. The shock-machine is more than 36 meters long. 27 meters of those are used to as gently as possible decelerate the test-vehicle. The test from start to stand-still takes less than 100ms.

4.1 Test set-up

For the 20,000g shock test a cube was designed onto which MEMS gyros could be assembled on all 6 faces, thereby enabling the high-g shock to be applied to all directions during one single shock. The design also supported pre and post testing of the MEMS gyros using the standard production test. End caps were mounted to the cube in order to hold it in place inside the cylindrical space provided by the test-vehicle as shown in figure 4.

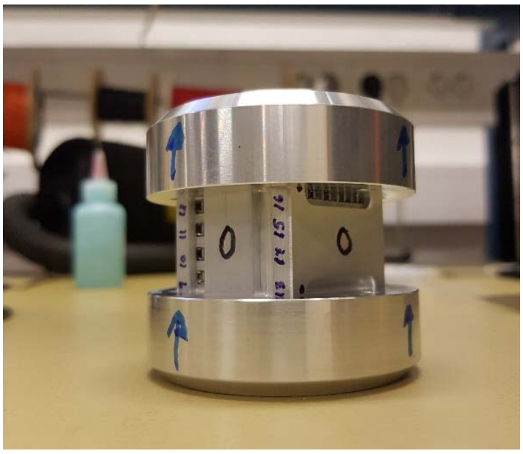
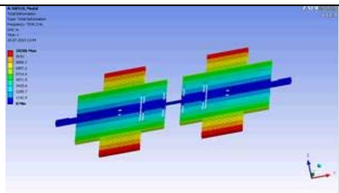
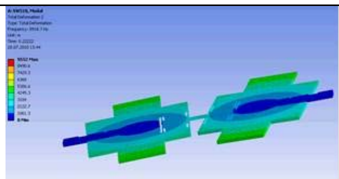
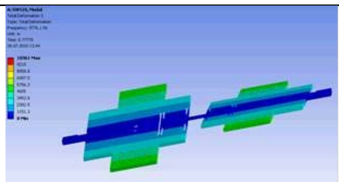
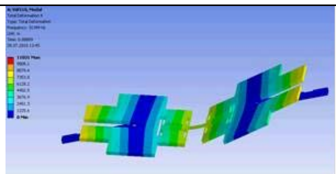


Figure 4. Test cube for 20,000g shocking

Each face of the cube has space for 8 MEMS gyros. It was decided to assemble half of the gyros with the same assembly process as is used in the standard assembly of Sensonor's gyro modules and IMUs and half with an alternative configuration. Prior to assembling the MEMS gyros on to the cube, shear-testing of both assembly methods was performed to verify that they would have sufficient strength to hold the MEMS gyros during the 20,000g shock. Three cubes were prepared: one partially populated with MEMS gyros on three sides for running an initial test-shock and two cubes fully populated.

An initial test-shock was required by ISL in order to fine-tune and verify the parameters for the shocking. The parameters for the initial test-shock were good and the amplitude very close to 20,000g. When visually inspecting the MEMS gyros after the initial test-shock, it turned out that all MEMS gyros were broken. One major difference in the static g-load performed on the centrifuge and the shock performed at ISL is the frequency content in the load. One plausible explanation was therefore that the high-frequency vibrations would cause the excitation of one or more modes in the MEMS gyro. Reviewing Q-factors and mode-shapes, ref. table 3, it was concluded that the main suspect would be mode 2 at 9kHz and possibly mode 4 at 30kHz.

Table 3: Characteristics of first four modes of the MEMS gyro

Mode	Frequency	Q factor	Mode shape
1	7kHz	150	
2	9kHz Drive mode	50,000	
3	10kHz Detection mode	300	
4	30kHz	1500	

4.2 High-frequency vibration damping

It was clear that damping of high-frequency vibrations would be required for the MEMS gyro to survive the 20,000g shock test. Neoprene rubber and steel-wire cushions were both investigated for high-frequency vibration damping in the direction of travel. Frequency-response, though limited to 2kHz, was measured using both materials before and after simulating the 20,000g shock by compressing them with a force of 8 tons. The steel-wire cushion gave the best results and were chosen. In addition, O-rings were added to the end-caps to avoid metal-to-metal collision between the end-caps and the test-cylinder during shock. The complete assembly is shown in figure 5.

Figure 5. Complete assembly with shock absorbers

4.3 Results

The two cubes were shocked carrying 48 MEMS gyros each. The estimated g-load shows a peak at around 20,000g during acceleration and a peak at around -8,000g when decelerating.

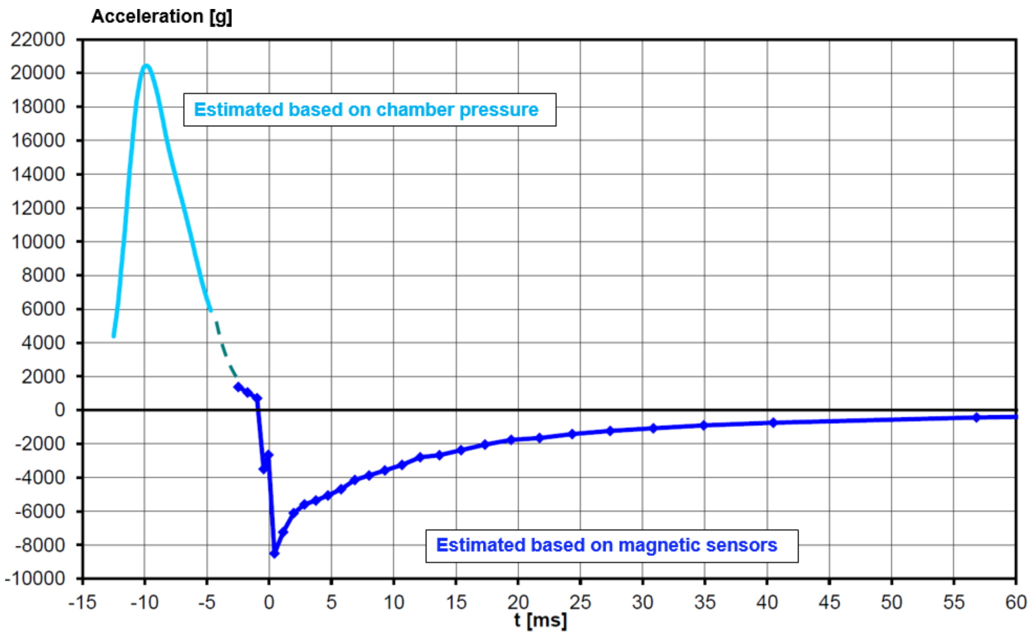


Figure 6. Estimated g-load from 20,000g shock

The MEMS gyros were tested before and after the application of the high-g shock. In addition, all gyros were visually inspected after the shock. Not all MEMS gyros survived the shocks with the added high-frequency vibration damping as can be seen in table 4. However, a significant difference emerged when looking at parts with standard and alternative assembly. All gyros assembled with standard assembly passed the test. Without going into details related to the two different assembly methods, the conclusion is that the difference in results also lies in improved high-frequency vibration damping when using the standard assembly.

Table 4: Results from 20,000g shock testing

Shock	Assembly	+X	-X	+Y	-Y	+Z	-Z
19,800g peak	Standard	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0
	Alternative	Pass: 4 Fail: 0	Pass: 1 Fail: 3	Pass: 1 Fail: 3	Pass: 3 Fail: 1	Pass: 3 Fail: 1	Pass: 4 Fail: 0
21,300g peak	Standard	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0	Pass: 4 Fail: 0
	Alternative	Pass: 4 Fail: 0	Pass: 2 Fail: 2	Pass: 1 Fail: 3	Pass: 0 Fail: 4	Pass: 2 Fail: 2	Pass: 1 Fail: 3

6 Conclusion and further work

The results obtained in the static and dynamic high-g tests performed, confirms that the Sensonor MEMS gyro indeed is a candidate for gun-hard applications. However, damping of high-frequency vibrations is required.

Based on these encouraging results, a gun-hard demonstrator will be built in order to be able to study the remaining electronics with respect to high-g shocks, study the possible effects on gyro performance after being exposed to high-g shocks and finally study size and weight-efficient solutions for damping of high-frequency vibrations.

6 References

[1] GoodFellow Supplier Handbook Data. https://www.goodfellow.com/

[2] Johansson, Stefan. Micromechanical Properties of Silicon. Uppsala : s.n., 1988.