Performance and Reliability of MEMS Gyroscopes and Packaging at High Temperatures

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Abstract

Elevated temperatures can significantly affect the performance and reliability of MEMS gyroscope sensors. A MEMS vibrating resonant gyroscope measures angular velocity via a displacement measurement which can be on the order on nanometers. High sensitivity to small changes in displacement causes the MEMS Gyroscope sensor to be strongly affected by changes in temperature which can affect the displacement of the sensor due to thermal expansion and thermomechanical stresses. Analyzing the effect of temperature on MEMS gyroscope sensor measurements is essential in mission critical high temperature applications, such as inertial tracking of the movement of a fire fighter in a smoke filled indoor environment where GPS tracking is not possible. In this paper, we will discuss the development of the high temperature package for the tracking application, including the characterization of the temperature effects on the performance of a MEMS gyroscope. Both stationary and rotary tests were performed at room and at elevated temperatures on 10 individual single axis MEMS gyroscope sensors.

Keywords: MEMS, Sensors, Packaging, Reliability, Tracking

Introduction

Homeland security depends on equipping first responders with the most advanced technology for location and health monitoring. Nowhere is this more true than in fire fighting, where a knowledge of the location of each fire fighter is critical, whether it be to direct them to a survivor who needs assistance, or to a source of fire that needs to be fought. A new system, called the Sentinel Tracking System has been developed to provide real-time 3-D location information on each firefighter to a single command station by means of inertial sensing of status, movement, and location, followed by wireless communication. The system consists of the following three parts: the base station, which is not exposed to the fire; the inertial navigation unit (called the Beacon), which is worn on the firefighter's belt; and the communications unit, which is worn on the firefighter's uniform. Inertial sensing must be used for locating the firefighter instead of the more common GPS technology, because of the high noise levels generated in GPS signals near or inside a building resulting from signal attenuation and reflection. In such environments, MEMS inertial sensors provide the best method for locating the first responder, as they allow for tracking indoors and outdoors.

The environment into which the Beacon is placed, however, is considered harsh for the operation of microelectronics and microsystems. It will include sustained temperatures of 150°F (65°C) with brief (5 -15 minute) periods of temperatures in excess of 400°F (205°C), along with shock, vibration, and the corrosive gases present in smoke. Such a system must therefore be packaged so as to reject unwanted influences (corrosive gases, moisture), tolerate other influences (temperature, vibration) and pass needed information (wireless signals). Current state of the art devices have shown difficulties in meeting this requirement. This paper will focus on the development of packaging for the Sentinel Tracking Beacon that will tolerate the high temperatures present in the use environment. In addition, it will discuss the changes in the performance and reliability of the MEMS gyroscopes used as inertial navigation sensors at elevated temperatures.

The Case

Personal Alert Safety System (PASS) devices for first responders must undergo rigorous testing before they can become certified by the National Fire Protection Agency (NFPA) and be worn by firefighters. These tests are designed to simulate worst case use environments and include high temperature functionality tests at test temperatures of 260°C for 5 minutes and 177°C for 15 minutes. Proper material selection to ensure structural stability at elevated temperatures is critical, as is temperature shielding of the electronic components, so that they can perform within manufacturer's specifications.

In order to design an manufacturable, temperature stable case for the device, injection moldable thermoplastic materials were selected based on their high temperature structural strength and then subjected to high temperature testing at 260°C at the Center for Advanced Life Cycle Engineering (CALCE) laboratory at the University of Maryland to determine their ability to shield the internal electrical components from the heat for the time allotted. The sample polymers were received as 1/8 inch thick plates and were cut to form 2" silicone sealed cube enclosures. A 1/8" hole was drilled into one face of the cube and a thermocouple inserted and sealed with the silicone adhesive. A one-dimensional thermal model was included to ensure that the correct thickness polymer was chosen to provide the necessary thermal capacitance. Testing was performed in both radiative and convective ovens. The materials in table 1 were chosen for evaluation.

Table 1: High temperature, flame retardant polymers

Trade Name	**Material**	**Thickness**
Zenite™ 7130	**LCP**	**0.123"**
Zytel™	**PPA**	**0.122"**
RTP 1400	**PES**	**0.127"**
RTP 4005	**PPA**	**0.123"**
Ultem™1000	**PEI**	**0.125"**
Radel™5000	**PPS**	**0.122"**

The five enclosures were placed on a ceramic dish and once the oven reached the prescribed temperature, the oven test door was opened and the ceramic dish was placed into the oven. The oven was quickly closed to keep the oven ambient temperature as steady as possible. Software was set to record temperature values every 5 seconds, which began as the enclosures were placed in the oven. During heating, the software was monitored to ensure the ambient temperature remained at a constant value. For the $T_{ambient}$ = 260°C, the samples were kept in the oven for an elapsed time of 9-15 minutes and for $T_{ambient}$ = 177°C, the samples were kept in the oven for 20-40 minutes. After testing, the samples were taken out of the oven and cooled at room temperature with $T_{ambient}$ = 33°C. Samples were typically cooled until surface temperatures recovered to 40-45°C.

In the following section, temperature profiles for the different materials are displayed for a 260°C ambient oven temperature. In general, the expected [1 – exp (t/τ)] relationship was observed. In accordance with the NFPA PASS Standards, the exposure time begins once the oven recovers to the desired ambient temperature. In all the tests, the ambient temperature recovers to over 90% of the target temperature value within two minutes. The t=0 exposure time begins when the elapsed time has reached approximately two minutes.

The thermal conductivity, the ability to conduct heat, is a typical parameter to compare between materials when doing a thermal analysis. Two additional parameters to analyze are a material's thermal effusivity and diffusivity. A material's thermal effusivity is a measure of its ability to exchange thermal energy with its surroundings. Thermal diffusivity if a measure of the rate at which a temperature disturbance at one point in a body travels to another point. The materials tested have similar thermal conductivities, but varied effusivity and diffusivity ratings. Their properties can be seen below in Table 2.

Table 2: Thermal Properties of Tested Materials

	Density	Thermal Conductivity	Heat Capacity	Thermal Diffusivity	Thermal Effusivity
	kg/m^3	W/m-K	J/kg·K	m^2/s*10^{-9}	Ws$^{1/2}$/m^{2}K
Zenite 7130	**1600**	**0.32**	**1100**	**181.82**	**750.47**
Zytel	**1440**	**0.26**	**2400**	**75.23**	**947.92**
RTP 1400	**1600**	**0.29**	**1400**	**129.46**	**805.98**
RTP 4005	**1680**	**0.26**	**2400**	**64.48**	**1023.87**
Ultem 1000	**1270**	**0.22**	**2000**	**86.61**	**747.53**
Radel	**1280**	**0.3**	**1130**	**207.41**	**658.73**

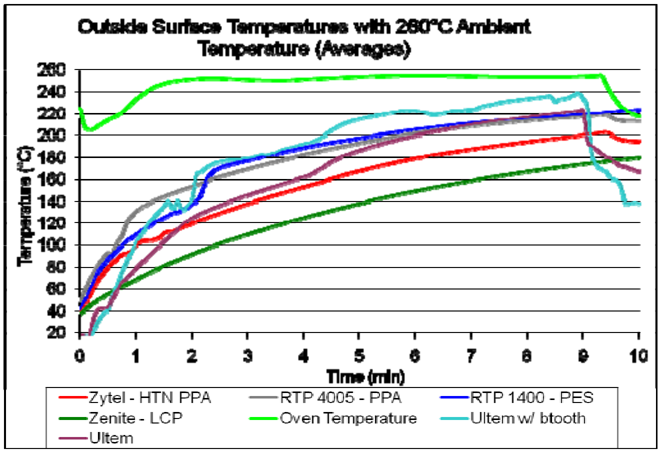

Figure 1: Outside Surface Temperatures

In Figure 1 above, the average temperature values for each material are shown for the thermocouples mounted on the exterior surface of the material. At an elapsed time of 7 minutes (5 minute exposure time) there is up to a 50°C difference between material temperatures. Those values are shown in Table 3 below.

Table 3: Surface temperature after 5 min 260°C exposure

Material	Temperature (°C)	HDT @ 1.80MPa (°C)
Zytel™ - HTN PPA	187	285
RTP 4005 - PPA	208	266
Rtp 1400 - PES	211	218
Zenite™ – LCP	159	310
Ultem 1000	208	201

The surface temperatures of the materials do not exceed the heat deflection temperatures (HDT) of the materials, except for Ultem. However, its Vicat softening point remains above the measured temperature at 216°C. Thus all the materials should remain structurally sound at these extreme temperatures.

While the outer surface temperature is of interest with regard to the material behavior of the polymer, the inside air temperature is important to electronic devices. Electronic devices have a specified operating temperature range where the manufacturer guarantees the correct operation of the component. This temperature is typically the ambient fluid temperature surrounding the device. In Figure 2 below, this ambient air temperature can be seen for inside of the enclosures. The inside air temperature of each of the materials after an exposure time of 5 minutes (t = 7 minutes) is also provided in Table 4 below.

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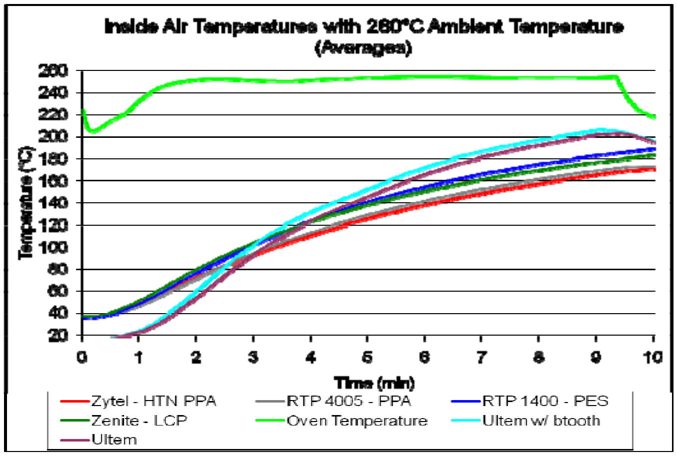

Figure 2: Inside enclosure air temperatures (averages)

Table 4: Inside temperature after 5-minute 260°C exposure

Material	Temperature (°C)
Zytel™ - HTN PPA	148
RTP 4005 - PPA	152
Rtp 1400 - PES	166
Zenite™ – LCP	162
Ultem	182

Figure 2 and Table 4 above reveal that the inside air temperatures exceed the maximum rating for the majority of commercial electronic components, which ranges from 70°C to 125°C. This shows that 1/8” thick case walls provide insufficient thermal capacitance to keep the temperature inside the enclosure below the device manufacturer’s typical specified operating temperature. Thus, either the case wall must be thickened or the electronic components must be uprated, as shown for the MEMS gyroscopes in next section.

Equation 1 can be used to model the inside temperature for different case wall thicknesses.

(Eq. 1) $$T(t) = T_{1,i} - (T_{1,i} - T_{0,i}) \cdot e^{\frac{-R_{th}}{m \cdot c_p} t}$$

where T(t) is the inside temperature at time t, and where T(t) < 125°C for t = 5 minutes.

T_1 is the outside temperature
T_0 is the initial inside temperature
R_{th} is the total thermal resistance
M is the mass of the three layer wall structure
C_p Is the heat capacity of the three layer wall structure

If only one 1/8” layer of Radel is used for the enclosure, as in the original experiment, the temperature after 5 minutes is 180.7°C. This agrees very closely with the result for the measured internal convection temperature for the Radel 5500 enclosure after 5 minutes, shown in figure 3, but is much higher than the 125°C allowable. If, however, a ¼” thick layer of Radel is used for the enclosure, the temperature drops to 115°C which is less than the necessary 125°C.

When performing these experiments, it was expected that the inside temperature would be lowest for the Ultem material since it had the lowest thermal conductivity and highest specific heat. Therefore, it should have the highest resistance to heat diffusion through its walls. The results, however,show the opposite; the inside temperature was highest for the Ultem cubes. Since the oven being used was a radiation oven, there was a potential correlation between the color of the extruded materials and heat transfer. Further testing using a convection oven was thus conducted to compare results.

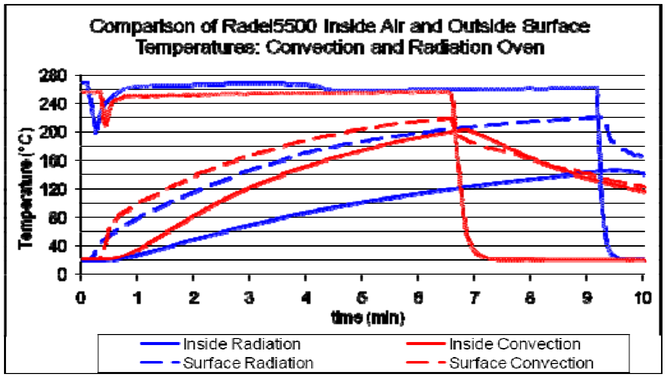

Figure 3: Comparison of Radel 5500 Inside Air and Outside Surface Temperatures for Convective and Radiative Ovens

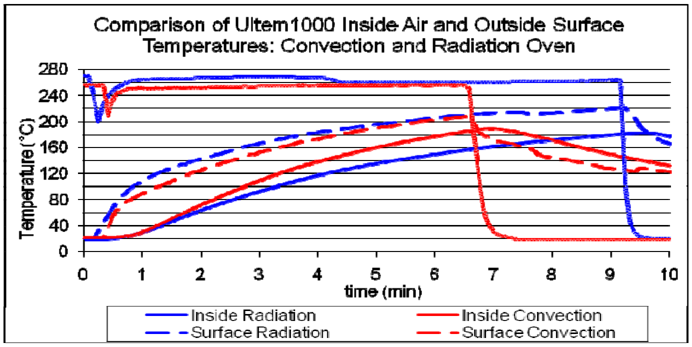

Figure 4: Comparison of Ultem 1000 Inside Air and Outside Surface Temperatures for Convective and Radiative Ovens

In Figure 3 and Figure 4 above, a comparison between convection and radiation ovens can be seen. These results show that a radiation oven will produce temperatures on the surface and inside that are cooler than a convection oven. In the Radel samples (white color), the temperature inside the enclosure is 80°C cooler after a 5 minute exposure with a radiation source vs. a convective source. In comparison, the Ultem enclosure (black color), is cooler by only 30°C. Since a lighter colored body (i.e. Ultem) would reflect more of the radiation, this analysis holds true to heat transfer principles.

MEMS Gyroscope Characterization

MEMS vibrating resonant gyroscopes have the potential to become one of the largest volume MEMS products in the coming years. [2, 4] Because of significant size and cost reduction compared to macro-scale gyroscopes, applications of MEMS gyroscopes are increasing everyday. Currently these devices can be found in consumer electronics, defense, avionics and automotive markets for purposes including camcorder & cell phone stabilization, vehicle stability control and missile guidance. MEMS gyroscopes can also be used for inertial navigation. [2, 4] One such use is in tracking the movement of a fire fighter in a smoke filled indoor environment where GPS tracking is not possible. Here characterizing the performance and reliability of MEMS gyroscope becomes important as they are both affected by elevated temperature operation. [1, 3] This paper investigates the effect of temperature on the performance and reliability of MEMS gyroscope sensors.

Almost all MEMS gyroscope sensors use vibrating mechanical elements to sense rotation. The operating principle of a MEMS gyroscope is a measurement of the transfer of energy between two vibration modes of MEMS comb structures caused by Coriolis acceleration. The vibrating elements are made of silicon and the transfer of energy is measured by capacitive sensing. This allows the devices to have high resolution with low power consumption. [3] Since these devices don't have rotating parts, they can be easily miniaturized and mass-produced using standard MEMS fabrication processes. In addition, the MEMS comb-structure is often connected directly to signal processing circuitry on the silicon chip. In the application of interest in this work, MEMS gyroscopes are used to track safety personnel in harsh environments, so maintaining the accuracy of the MEMS gyroscope is critical. In this study, we examine changes in the noise level and the signal level of the angular velocity measurement as a function of temperature through both rotational and stationary testing in order to ensure device accuracy. The MEMS gyroscope used in our testing is a programmable low power single axis gyroscope in an 11 mm × 11 mm × 5.5 mm, laminate-based land grid array (LGA) package. The device has an integrated thermal sensor, which senses temperature of system during operation, and on-chip signal processing that calibrates the angular velocity measurement output over the temperature range of −40°C to +85°C. Measurement of the angular rotation (°/s), applied voltage (V), applied current (I), temperature (°C), and relative angular position were accomplished using an evaluation system test board specific to the component.

Experimental Set-up and Procedure

In order to determine the effect of temperature on the noise levels and signal levels of a MEMS gyroscope sensor, it is required to observe gyroscope performance under stationary and rotating conditions. In the stationary test, the MEMS Gyroscope sensor was mounted on the evaluation board which was affixed to a stationary table. The evaluation board was connected to the USB port of a Laptop which collected the data. First, testing was performed at room temperature to establish a stationary baseline noise and signal level using the setup shown in figure 5. Each test was conducted until 10,000 data points were acquired, and the tests were repeated on 10 different gyroscope samples. Then the sensor was then subjected to five thermal cycles in air from 25ºC to 85ºC. In order to achieve the thermal cycling conditions, a Temptronic thermostream air system was used. This apparatus has the capability to supply constant temperature flowing air at temperatures ranging from -200ºC to 200ºC. In this case, the gyroscope was placed under and at the center of the glass hood of the Temptronic Thermostream apparatus such that it was directly exposed to hot air flowing from the nozzle at 5 standard cubic feet per minute (SCFM) as shown in figure 6.

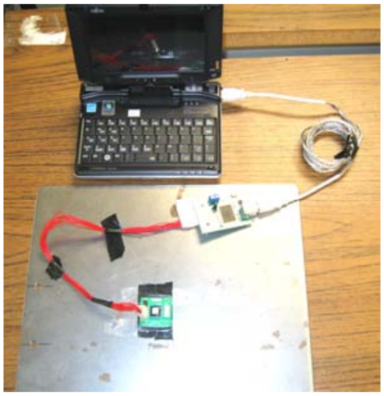

Figure 5: Stationary baseline test setup.

Figure 6: Stationary thermal test setup.

Next, rotary tests was performed in which a MEMS gyroscope was mounted on an evaluation board affixed to the center of a rotating platform that turned at calibrated values of 10, 20 and 40 rotations per minute (rpm). Again baseline noise and signal levels were established for each rotational velocity at room temperature. In this case the evaluation board was connected to a Palmtop computer for data collection as shown in figure 7. The Palmtop computer was mounted onto the rotary table as well using a vertical brace. Care was exercised in placing and mounting the laptop to avoid vibration during table rotation. The test was conducted until 10,000 data points were acquired and again the test was repeated on 10 different samples. After this the gyroscope sensor was subjected to thermal cycling in air at 10, 20 and 40 rpm. Each velocity was tested for a number of thermal cycles, directly exposing the MEMS sensors to Class I and II+ temperatures recommended by NIST and the National Fire Protection Agency (NFPA). [5] This included five thermal cycles each from 25ºC to 85ºC, from 25ºC to 125ºC , from 25ºC to 150ºC and from 25ºC to 175ºC. The test setup for rotary thermal test was identical to that for rotary baseline test, except that the entire rotating platform was placed under the glass hood of the Temptronic Thermostream apparatus such that the gyroscope was centered directly under the hot air flowing from the nozzle at 5 SCFM as shown in figure 8.

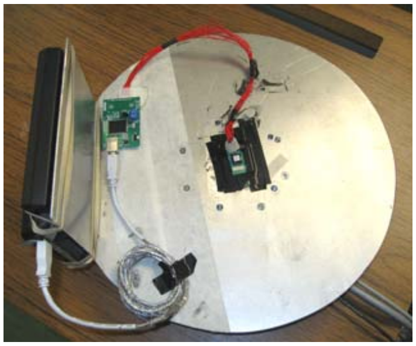

Figure 7: Rotary baseline test setup.

Figure 8: Rotary thermal test setup.

Results and Analysis

All MEMS Gyroscope sensors were analyzed separately for stationary and rotary tests conditions. In both sets of tests, an initial baseline test was conducted, followed by thermal exposure. The same pattern was followed for all stationary and rotary tests. The primary purpose of conducting the baseline test was to observe device characteristics before elevated temperature exposure to allow for comparison. [3]

Stationary test result:

Figure 9 (top) shows the first 10,000 angular velocity values measured by the MEMS Gyroscope sensor at baseline conditions. The scattering of data was easily analyzed by averaging every 500 data points into single point and plotting that reduced output as shown in bottom plot of figure 9. After the first baseline test, the sensor was subjected to five thermal cycles in air from 25ºC to 85ºC. Figure 10 includes three different plots representing the raw angular velocity data (at the top), the reduced angular velocity data in sets of 500 points (in the middle) and the temperature cycle (at the bottom). The top plot indicates that the noise level increases with temperature and this is verified in the averaged plot in the middle. This effect appears only when temperature reaches its peak value with the noise level returning to its normal value when the temperature returns to room temperature, with no apparent decrease in durability.

The sensor was then subjected to five air cycles from 25ºC to 125ºC. Here, the noise level again increased with temperature, and again returned to its normal value as the temperature dropped below 85ºC. An angular velocity drift was also observed at this temperature condition as shown in figure 11. This drift made it look as if the device was subjected to angular velocity increases that were not actually occurring. This drift must be compensated for when using the device at temperatures exceeding 85°C. Finally, a baseline test was again performed which showed no long term durability damage to the baseline parameters as shown in figure 12.

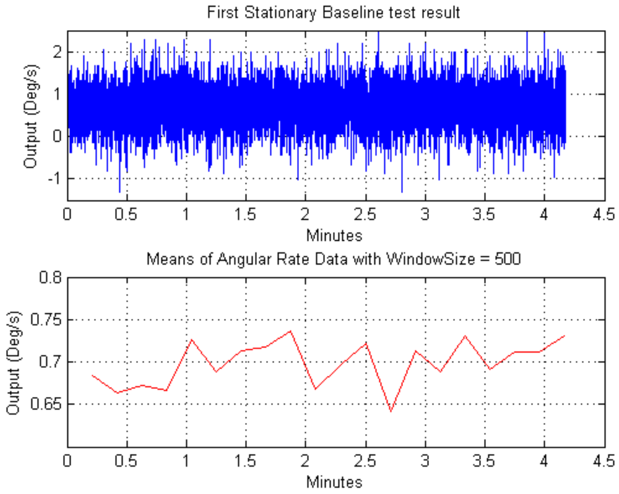

Figure 9: First stationary baseline test

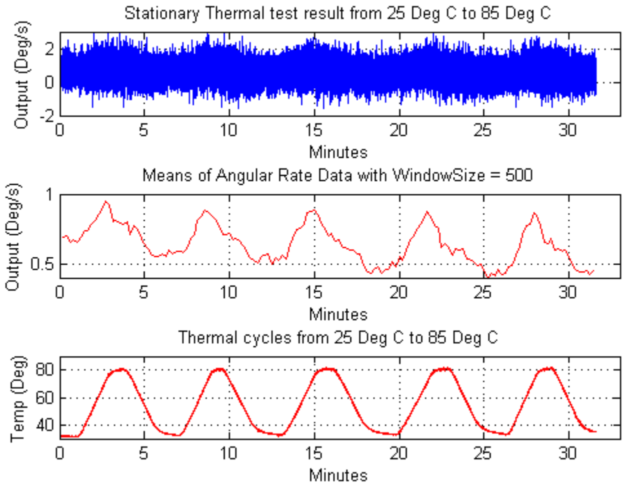

Figure 10: Stationary thermal test from 25°C to 85°C.

Table 5: Stationary baseline test summary

Tests	Mean (°/s)	Std. Dev. (°/s)
Baseline test 1	0.69	0.44
Baseline test 2	0.55	0.45
Baseline test 3	0.43	0.44

The statistical values for stationary baseline tests are given in Table 5 above.

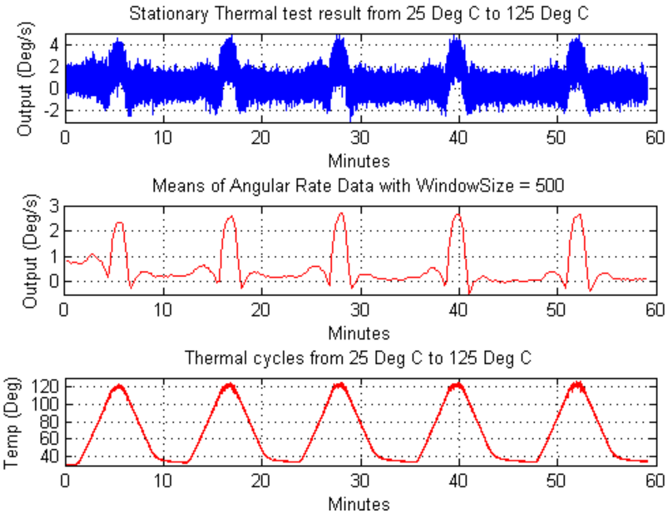

Figure 11: Stationary thermal test from 25°C to 125°C.

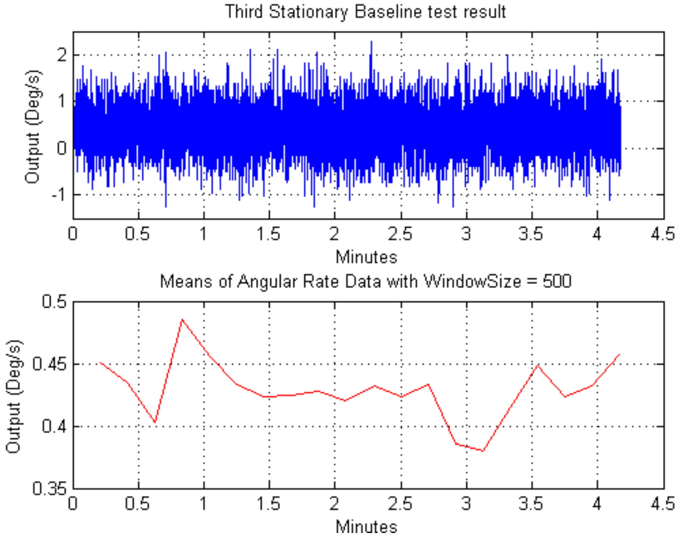

Figure 12: Third stationary baseline test

Rotary test result:

The rotary test protocol is similar to the stationary test protocol, except the sensor was exposed to two further temperature cycles from 25ºC to 150ºC and from 25ºC to 175ºC. All 10 MEMS Gyroscope sensors were tested at 10, 20 and 40 rpm for each of the 5 different thermal cycles, but for simplicity only sensor performance at 10 rpm at the 5 different thermal cycles is discussed.

In the rotary test, a baseline test was conducted to characterize the initial gyroscope sensor output at room temperature as shown in figure 13. After the first baseline test, the sensor was subjected to five thermal cycles in air from 25ºC to 85ºC. The noise level was slightly increased with temperature as before as shown in figure 14. This was followed by a second baseline test and then a thermal cycle from 25ºC to 125ºC. Here, the angular velocity as shown in the middle graph increased monotonically with temperature without any corresponding change in the actual angular velocity of the turntable as shown in figure 15. After another baseline test, the sensor was thermal cycled from 25ºC to 150ºC, with an even more pronounced shift, as shown in figure 16. Finally, a fourth baseline test was conducted before exposing the sensor to thermal cycling from 25ºC to 175ºC. Figure 17 shows that in this case the gyroscope ceased to operate as soon as the internal temperature exceeded 150°C. Finally, fifth baseline test, shown in figure 18, was conducted to show no permanent change in the device parameters had occurred. Statistical values for all the above rotary baseline tests are listed in Table 6.

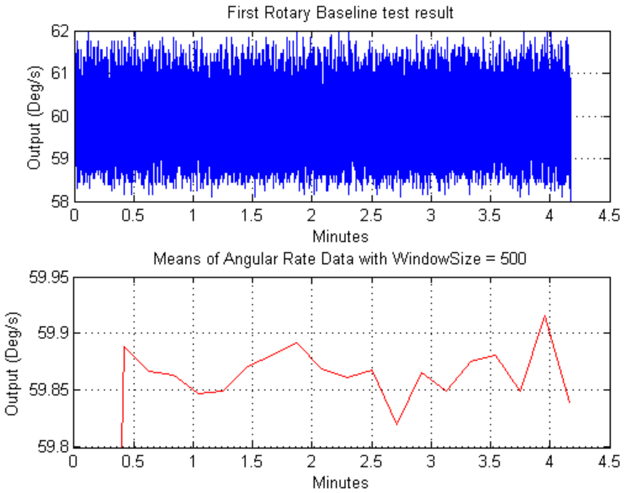

Figure 13: First rotary baseline test result.

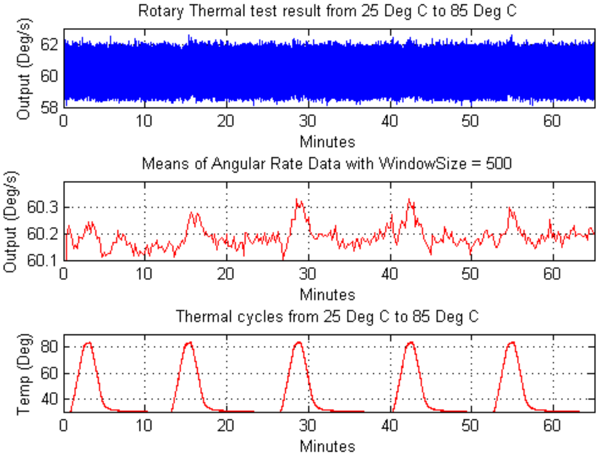

Figure 14: Rotary thermal test from 25°C to 85°C.

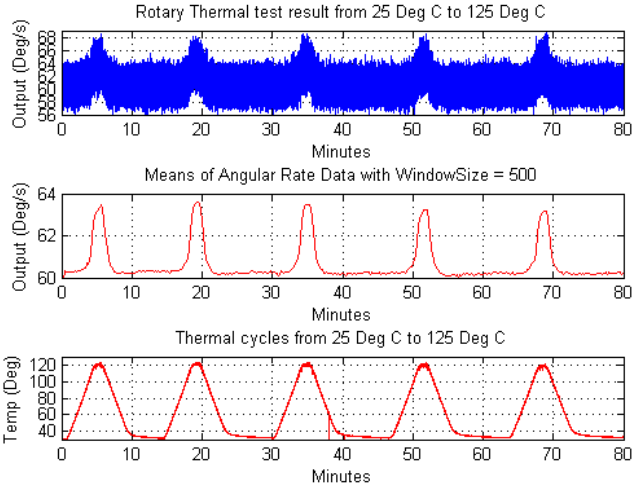

Figure 15: Rotary thermal test from 25°C to 125°C

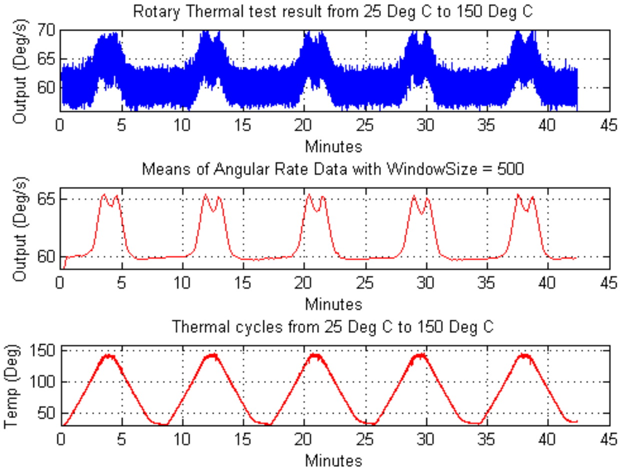

Figure 16: Rotary thermal test from 25°C to 150°C

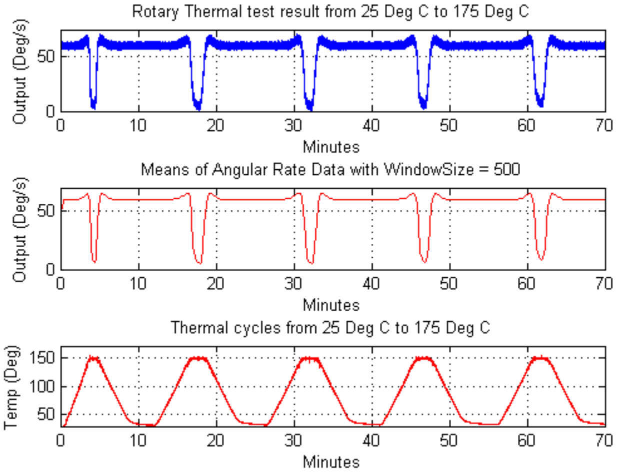

Figure 17: Rotary thermal test from 25°C to 175°C

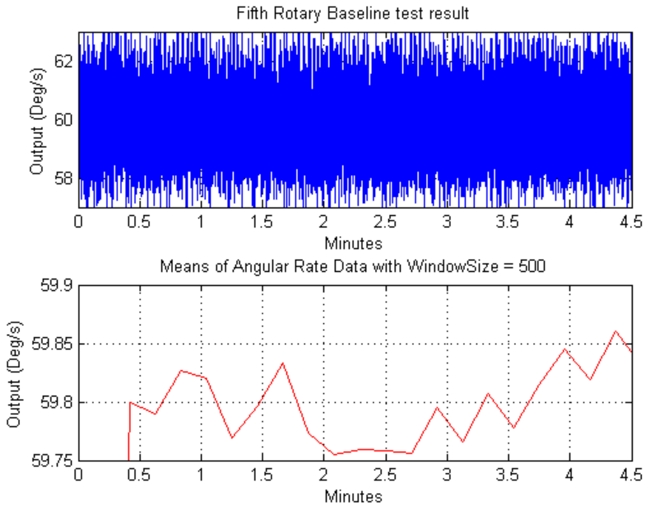

Figure 18: Fifth rotary baseline test

Table 6: Rotary baseline test summary.

Tests	Mean (°/s)	Std. Dev. (°/s)
First Rotary baseline test	59.87	0.84
Second Rotary baseline test	59.98	1.49
Third Rotary baseline test	59.68	0.82
Fourth Rotary baseline test	59.99	1.27
Fifth Rotary baseline test	59.79	1.28

Summary and Conclusions

1.Initial thermal studies of the case materials showed that none of the injection molded thermoplastic materials could keep the internal temperature of the case below 125C for 1/8" thick case walls. Zytel PPA produced the lowest internal temperature of 148°C. Ultem 1000 produced the highest internal temperature of 182°C.

2. Simulations indicated that Ultem 1000 was able to keep the internal temperature of the case at 115°C, if the case wall thickness was increased to ¼."

3. A test procedure has been developed for evaluating the effects of temperature on MEMS gyroscopes operated beyond the manufacturer's recommended temperature range.

4. There was a monotonic increase in the angular velocity measured by the gyroscope with temperature when the gyroscope was operated above 85°C that did not correspond to any actual change in the angular velocity of the table. This increase was a temperature related drift in performance which must be accounted for in using the angular velocity measurements for tracking. This was true for both rotary and stationary tests.

5. There was an increase in the noise levels when the gyroscope was operated at temperatures above 85°C during temperature cycling. The noise level returned to normal when the temperature dropped below 85°C with no apparent decrease in durability as a result of the effect. This was true for both rotary and stationary tests.

6. When the MEMS gyroscope was subjected to 175°C, the noise level increased drastically. The device ceased to function when the internal temperature exceeded 150°C, most likely due to an internal over-temperature protection.

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