

Gun Hard Inertial Measurement Unit based on MEMS capacitive accelerometer and rate sensor

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Abstract- Smart munitions and missiles are increasingly incorporating inertial measurement units for guidance of short range weapon systems. In addition to usual high performance of the required sensors, namely, accelerometers and gyros, this application requires high shock survivability and post shock stability of the sensors. Colibrys has successfully developed a gun hard version of its accelerometer product and AIS has integrated these acceleration sensors and rate gyro to a gun hard IMU. The IMU has been extensively tested and characterized over the full temperature range, at Aerobutt and in many live shooting trials. The extreme shock performance of the IMU has been maintained by making the accelerometer shock resistant. This has been achieved by placing a specially designed mechanical stopper over the sensing element to protect the sensor from extreme shock levels by limiting the mechanical displacement of the MEMS element. This approach has resulted in excellent post shock performance of the acceleration sensor. Beyond this a special assembly technology has been developed at AIS to ensure that key shock components are filtered out and their energy is not transferred into the sensing element; and the vibrating elements are not affected by the components of the firing shock.

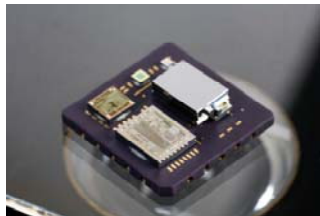


Figure 1. Colibrys extra small LCC20 packaging (8.9mm x 8.9mm)

I. INTRODUCTION

As the MEMS accelerometers and gyros advance in their performances, new application areas emerge that can significantly benefit from these devices. The size, precision, shock performance and not least cost are among benefits that MEMS sensors can offer. An area that requires robust yet small size sensor is the precision munitions and short range missiles guidance systems. To cover all 6 degrees of freedom normally 3 accelerometers and 3 gyros are incorporated to build an IMU.

Typically, these applications involve in shock amplitudes in the range of 20'000g and require a high degree of post shock stability of the accelerometer and gyros inside the IMU. A gun hard shock is generally a combination of a long shock of high amplitude (typ. 20'000g, half sine, >5ms) and some high frequency shocks components (typ. 10'000g to 20'000g, half sine, <0.2ms) as depicted in figure 1.

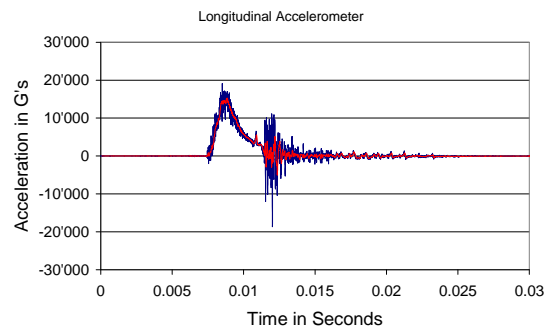


Figure 2. Typical shock profile of a mortar firing.

Usually automotive grade accelerometers have quite a high shock survivability requirement. However, for inertial navigation systems the sensors not only have to survive higher level of shock but also have to perform with a high degree of stability and accuracy after the initial shock. Colibrys accelerometer meets those two requirements.

With its family of proven gun hard Micro Electro Mechanical System (MEMS) Inertial Measurement Units (IMUs), Atlantic Inertial Systems (AIS) (formerly BAE Systems Inertial Products) has a long history of working with its customers on a number of guided projectile programs.

AIS is the only company in the world to take a silicon IMU into full rate production and operational service. Production of all variants has exceeded 500 per month with a current capacity to build 1000 per month. Variants of the second generation digital SiIMU02® are in low rate initial production (LRIP) for a variety of development contracts. Full qualification and certification is now underway.

The SiIMU02® is a digitally-controlled, 6-degree-of-freedom IMU that has already demonstrated gun-hardness to over

20,000g in 155 mm live firing trials. The SiIMU02® was developed to meet the guided projectile market IMU requirements and is the IMU of choice for a number of guided projectile and rocket programs. The latest variant has improved performance, incorporates significant cost-saving features and has enhanced mechanical isolation. It has also demonstrated 100% gun-hardness in all customer trials to date. The modular design of the SiIMU02® means that high commonality between customer programs can bring all our customers benefits of scale.

II. DEVICE FEATURES

A. MEMS accelerometer

Colibrys has developed new Gun-hard MEMS accelerometer based on its MS8000 product family. The focus has been on maintaining the same level of bias and scale factor stability post firing shock levels.

The new accelerometer is a further development of the MS8000 product family. It consists of a MEMS capacitive sensor, an interface ASIC, a μ -controller and a temperature sensor.

The principle of operation of this differential capacitance device is based on a mass-spring mechanical system. At zero acceleration the mass is centred between two parallel plates of silicon. The mass moves to one side changing the value of the upper and lower capacitance proportionally to the applied acceleration. Large capacitance of 2×35 pF ensures large basic signal for low noise and stable electronic and robust signal processing. The structure is made of single crystal silicon having very low residual stress which could bend structures and therefore affect performance. This highly symmetrical structure is specially designed to get very low offset and accordingly, very high stability performances.

The MEMS bulk micromachining accelerometer design and technology was a real breakthrough when published in the early 80's [1]. Building on this knowledge, Colibrys has constantly improved this accelerometer over the years and it now benefits from more than ten years of production expertise.

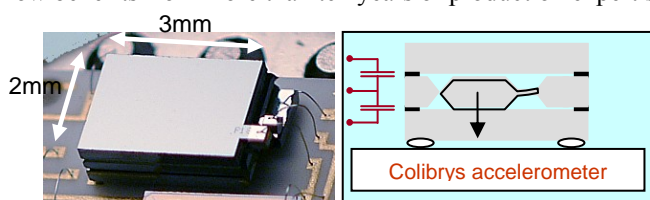


Figure 3. The MEMS sensor element and schematic principle of operation.

The gas damping of the MEMS element is a key performance feature, which requires to be precisely controlled, not only to have a controlled bandwidth, but also to have a low rectification error. This value is representative of the even order non-linearity and results in a bias when the device is

subject to sinusoidal or random vibration. This value is of course especially critical for inertial navigation applications.

The readout electronic is a proprietary solution, self balanced capacitive readout. It is a highly stable low power ASIC with a power consumption lower than 390nA at 5V. The electronic has a power-on reset and a brown out protection to insure a reliable output in the most severe conditions. The sensor contains a PIC microcontroller that is used during the start-up and brown-out reset sequences. It's software has recently been certified with respect to the EN 50128 railway application standard for safety critical applications, like magnetic trains electronic has a power-on reset and a brown out protection to insure a reliable output in the most severe voltage conditions.

A major feature of MS8000 is the die-attach technology, which reduces the stress levels on the MEMS die to extremely small levels. Any stress on the MEMS die will cause an imbalance of the lower and upper capacitance and hence create an intrinsic bias shift. To ensure that this initial offset is minimised, Colibrys has developed a proprietary die attach technology that minimises the stress level to the sensing die.

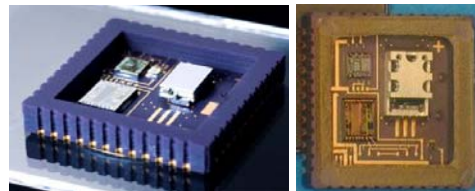


Figure 4. Interior of the MS8000 and the high shock HS8000 products.

To improve the shock performance of this device, critical attention has been paid on the die attach technology. It has been demonstrated that as a result of high shock the MEMS sensor die is normally severed from its underlying ceramic position. Using hard glue increases the stress field and hence increases the initial bias stability of the device. Knowing this, Colibrys has developed and patented [2] an innovative assembly technology to ensure solid assembly without constraints. This solves the well known compromise between shock resistance and bias stability. This new technology is applied to create the high shock HS8000 product family. Figure 4 shows the interior of MS8000 and HS8000.

B. Modular IMU Design

The generic SiIMU02® package has been designed around a $3\frac{1}{4}$ cubic inch pod. This steel pod can be packaged in a variety of housings, with bespoke housings available for backward-compatibility with older IMU designs. With all the sensors and electronics contained within such a small form factor, the pod may be housed in a variety of ways without affecting the performance or gun-hardness of the overall design. The sensors are housed within the IMU pod. Initially, the individual sensor boards are assembled into a cube, this

sensor assembly is then inserted into the pod and assembled with the cover (see Figure 5).

A potting compound is then injected to fill the void. The potting supports both the sensors and ancillary electronics during the gun launch, helping to maintain performance before and after shock.

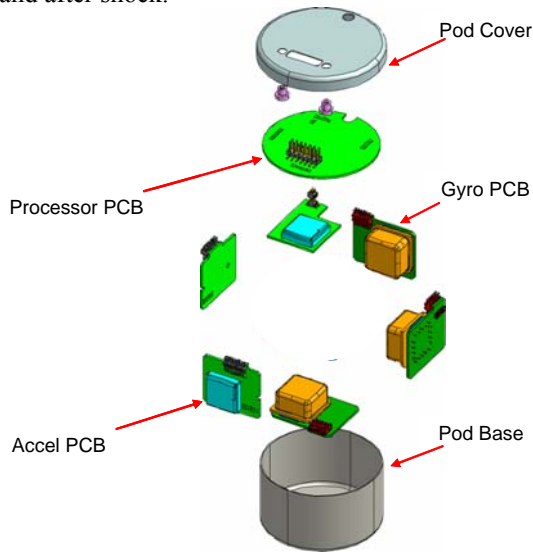


Figure 5. SiIMU02® Pod.

The SiIMU02® pod is then mounted within a two part external housing using an anti-vibration isolator between the pod and the housing (see Figure 6). The use of an isolator prevents the balloting shock during gun launch and any high levels of vibration from exciting potentially harmful resonances within the structure of the gyros. This isolation system has been proven to survive and perform following launch shock levels of over 20,000g and extreme rocket motor-induced vibration.

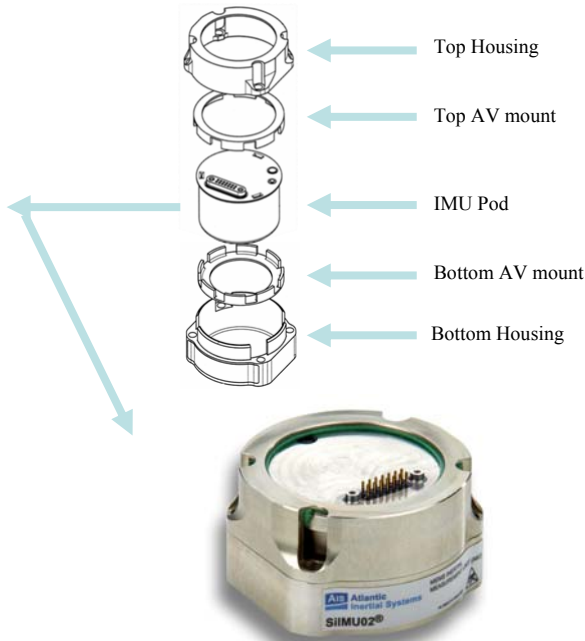


Figure 6. SiIMU02®

C. Gun Hard rate sensor

AIS produces over 2 million inductive rate sensors per year for use in the automotive, commercial and military markets. This volume of product means that rate sensors can be selected from the production line that provide the best performance for the gun-hard military market, without incurring the high cost of producing bespoke military sensors.

The inductive rate sensors used on SiIMU02® are naturally gun hard by design. Prior to use in the IMU build process, additional screening to 20,000g is performed on all sensors in order to detect potential manufacturing defects. These sensors have been proven gun-hard over a number of years testing in both the SiIMU01® and SiIMU02® designs, with SiIMU02® tested to over 20,000g launch shock in Aerobutt mortar and full caliber 155 mm firings.

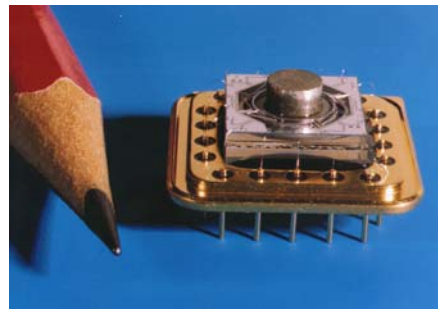


Figure 7. AIS Inductive Rate Sensor.

The gun-hard nature of the rate sensors and accelerometers used on SiIMU02® has also been demonstrated during several trials performed by AIS, its customers and end users.

III. TEST & CHARACTERIZATION

The accelerometer has been intensively qualified. The resistance to environmental elements is qualified with respect to the recognized standard MIL-STD-883-E, the reliability is based on MIL-HDBK-217 and all performances are qualified using IEEE standard 1293 – 1998 definitions and test procedures. Key features are essentially, the bias stability due to extreme environmental conditions like extensive power on/off, storage and operating temperatures, vibrations, shocks and constant accelerations.

The accelerometer has not only been rigorously tested both as stand alone device, but also integrated in an IMU and higher in the manufacturing chain.

In Figure 8, we see the bias over temperature of ten HS8030 accelerometers. These data are obtained without any temperature correction and are raw accelerometer data. The temperature calibration is preferably performed at the IMU level. To facilitate this, a temperature sensor is placed inside the LCC ceramic package and its output is available for the

system integrator. When the accelerometer is uncompensated, the IMU manufacturer can get better results with a lower polynomial fitting order.

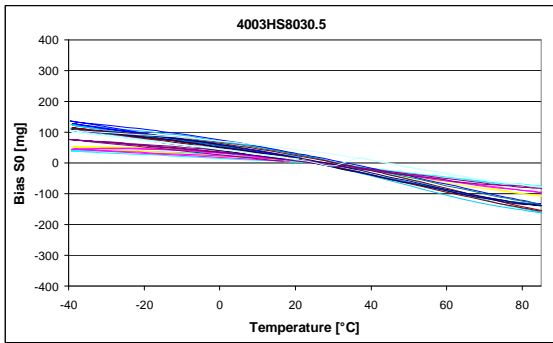


Figure 8. Offset measurements over temperature on a 30g sensor

Another key feature is the bias stability. The term “bias stability” is quite vague and depends very much on the measurements conditions and on the way of synthesising the results. In this article, we represent the raw accelerometer bias data:

- When the sensor is continuously powered at 20°C (Figure 9)
- When the sensor go through different environments (Figure 10), like power on/off, when the sensor is stored at -55°C or 85°C during several days, when the sensor is cycled with different temperature slopes and when the sensor is vibrated at 20grms from 20Hz to 2kHz. These conditions are quite aggressive and this is how Colibrys usually measure the bias stability.
- When the accelerometer is stored at 85°C (Figure 11). Reliability model derived from the semiconductor industry evaluate the ageing factor. We can thus deduce an equivalent number of years. In our case, it typically corresponds to about 10 years of ageing.

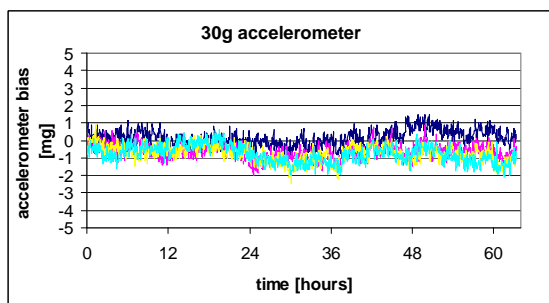


Figure 9. Short term bias stability on 4 sensors

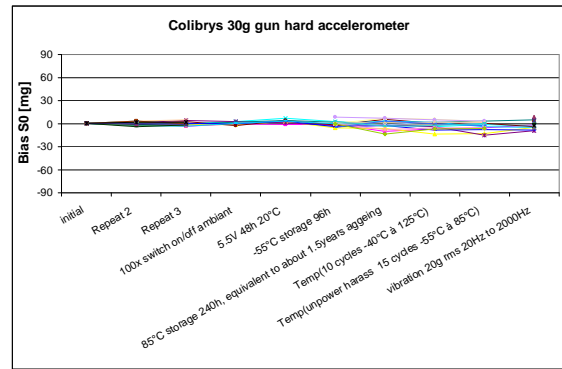


Figure 10. Bias stability due to voltage, temperature and vibrations.

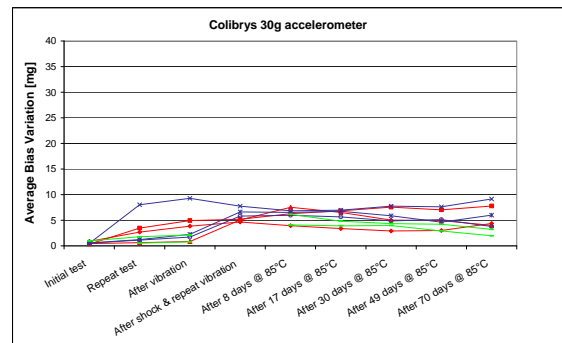


Figure 11. Bias stability when aged during 70 days at 85°.

At the end of these ageing processes, the stability is estimated by taking the 1 sigma value over all sensors during the last measurement. This gives the following values:

	Stability [mg]
Short term stability (Figure 9)	0.5
Voltage, temperature, vibration (Figure 10)	9.4
70 days at 85°C (Figure 11)	5.3

Table 1 : 1-sigma stability value on a 30g accelerometer.

So we see that under the “term bias stability” we can already have more than an order of magnitude difference depending on the way of defining it.

Another key feature is the rectification error. This value is important when the accelerometer is operating in an environment containing vibrations. This is the apparent shift in accelerometer bias when subjected to sinusoidal or random vibration. Rectification error depends on the accelerometers even order non-linearity and on the accelerometer transfer function.

The rectification error is measured according norm IEEE std 1293-1998 test procedure 12.3.17.4. A sine signal of half the full scale amplitude is applied on the accelerometer along its sensitive axis. The accelerometer is dwelled at different frequencies varying from 20 to 2000Hz. The bias is measured with and without vibrations. This bias shift is then converted into mg/g^2 , by normalizing with the applied vibration amplitude squared.

Figure 12 shows the rectification error distribution over one batch. The average rectification error is $0.1mg/g^2$ for a 30g accelerometer. This value is very low and allows getting very low bias shift even in applications with a high level of vibrations.

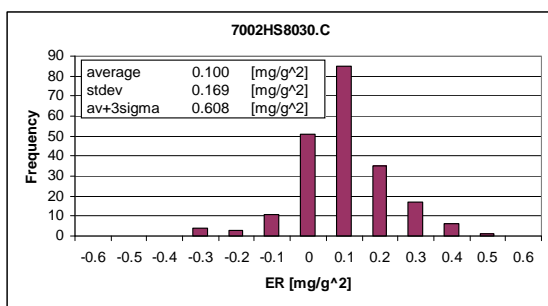


Figure 12. Vibration rectification error measurements.

After stability and rectification error, the last very important feature is the shock resistance. Special care has been taken to test the IMU with respect to shock. Tests have been performed at sensor level to get the confidence about survivability and determine the performance change due to shock. Typically the high frequency component of the shock has been studied using an impact hammer. To study the low frequency components of the shock, a centrifuge has been used. When sensor design was ready, several shock campaign has been made using a high g Aerobutt test equipment (see Figure 13) at BAE Systems' in Ridsdale, Northumberland, U.K. This equipment allows recovering the IMU just a few minutes after the gun-shock. Altogether about 150 accelerometers have been shocked.



Figure 13. Photo of a high g Aerobutt test equipment.

Aerobutt results

Colibrys accelerometers have been extensively tested on Aerobutt high-g test equipment. HS8030 have regularly demonstrated a bias stability within 15 mg and a scale factor within 1200 ppm (see Figure 13).

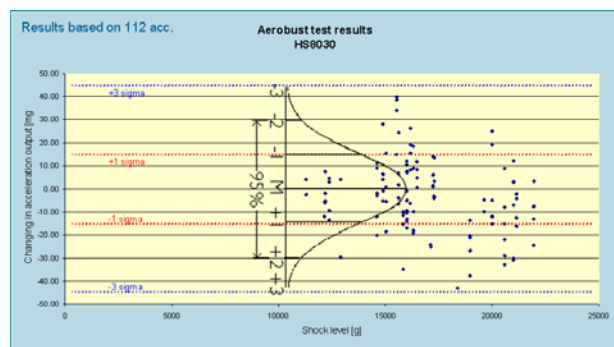


Figure 14. Bias shift due to Aerobutt firing test, ranging from 11'000 g to 22'000 g's along 3 axis. It demonstrates a 5×10^{-5} offset stability/ working range.

Howitzer results

IMU have also been tested when fired with a 155mm G5 Howitzer using soft recovery in sand. Units have survived up to 20'000g and no failures have been observed.

Three IMU have been shocked with amplitude ranging from 11'800 to 19'500 g's. On the units fired with the highest shock, the accelerometers have shown very little bias shift from 7 to 28 mg.



Figure 15. Photo of a 155mm G5 howitzer.

The accelerometer proved to be mechanically very robust and has survived acceleration up to 40'000 g with a bias shift of only 14mg. We have limited our testing to 40'000g's because it's the maximum safe operating range of our centrifuge. A typical accelerometer bias curve measured before and after shock is represented in Figure 16.

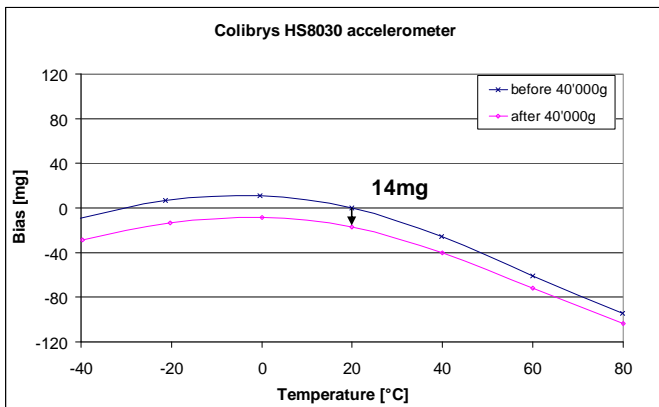


Figure 16. Accelerometer bias before (black) and after (pink) 40'000g acceleration.

After having estimated the accelerometers in “normal operating conditions”, we have also tried to find the survivability limits in operation. Three accelerometers have been measured at 1g when heated up to 180°C (

Figure 17). All sensors still give an output at these extreme temperatures.

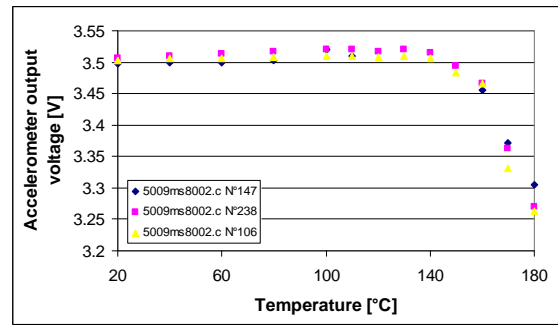


Figure 17. Measurements of the accelerometer signal have been made up to 180°C.

IV. CONCLUSIONS

Colibrys has successfully developed a gun hard accelerometer, which has been proved to survive the shocks and perform satisfactorily post gun shot.

AIS has integrated this accelerometer with its rate sensor into the first commercially available silicon IMU. This product has been extensively tested both in an IMU formation and as stand alone accelerometer. The obtained results confirm the mechanical ruggedness and high sensitivity of the sensor and indeed the IMU under such harsh environment as gun shot.

This accelerometer is now commercially available as part of Colibrys extensive acceleration product portfolio.

V. REFERENCES

- [1] F. Rudolf, "A Micromechanical Capacitive Accelerometer with a Two-Point Inertial-Mass Suspension," *Sensors and Actuators*, 4 (1983), pp. 191-198.
- [2] US Patent Issued on January 30, 2007 « Microelectromechanical system », B. Dutoit & al., Colibrys SA.