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Standard MEMS capacitive accelerometers for harsh environment

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Abstract
Many markets have already successfully introduced MEMS based products in a very large panel of applications. When looking carefully at the market implantation, it is very interesting to see that benefits of this technology go well beyond the obvious size advantage. Size and weight but also performance, power consumption, parallel manufacturing capability and cost or reliability are common arguments in favour of this family of products.
Nowadays, standard MEMS technologies give access to a broad range of unexpected new applications opportunities by always pushing the products at their limits, mainly in term of environmental constraints. Great potentials have been demonstrated and have engendered development alliance to improve the performances of the products in so called harsh environments: Imagine the utilization of an accelerometer in oil and gas prospecting applications. They must provide precise measurements in a very high or cold temperature environment, in a world of extreme vibrations and must potentially endure very high shocks.
The objective of this presentation is to review actual results and current limitations when using MEMS sensors in harsh environments (temperature, shock, vibration, environment, security). The conjunction of material and technologies (standard Si, SiC or SOI), advanced micromachining techniques and advanced assembly techniques are the key to provide robust sensors. Within a large portfolio of examples, the following applications will be presented and developed in more details:

- Accelerometers surviving shock levels up to 20’000g with minimum impact on specification
- Very robust MEMS sensors used between -120°C and +180°C

MEMS sensors in harsh environment are already a reality and various products are already available off the shelf and supplied with high volume opportunities.

I. Introduction

MEMS accelerometers impose themselves thanks to numerous advantages even if they are not yet able to achieve the same level of specifications as traditional micro-mechanical products (i.e. quartz vibrating structures). Size, weight or advantageous cost versus specifications are generally the key highlights of the MEMS technology. Furthermore, MEMS sensors impose themselves in a growing number of applications thanks to their ability to perform in very aggressive environments. “Harsh environment” is the recognized acronym to describe the markets and applications that behave under extreme conditions in term of temperature, shock, vibration, atmosphere (ESD, radiation, chemistry…) or security.

II. Harsh Environment Market Characteristic

There is not one unique and specific market that fit with harsh environments but many examples can be found where precision measurements in difficult environments are required.
Typical examples of applications are: Down hole drilling where accelerometers must behave under high

temperature and extreme vibration conditions, space missions where the product must behave under high radiations and in some cases extreme temperature, smart ammunition where sensors (i.e. accelerometers and gyro) must survive extreme gun hard shock with a minimum impact on specification or extreme shock monitoring for industrial or military applications (> 10'000g)… These few examples with many other applications can be classified in the following domains: aerospace & defence, energy (oil & gaz), industrial markets and of course automotive, which is the most demanding sector for robust sensors.
It is interesting to see how standard MEMS accelerometers, that present intrinsic good harsh environment capabilities, have facilitated the emergence of these new applications, which were simply difficult or even impossible to imagine with standard technologies.
The figure 1 shows the North American MEMS sensors market trend specific to harsh environment products.

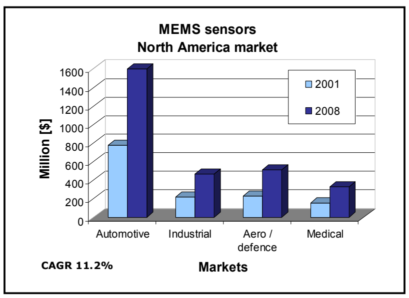


Figure 1: North American market perspectives (2001 to 2008)

In term of number of sensors, the business evolution, largely driven by automotive, is expected to grow from 190 mio. sensors (ASP 7$) in 2001 to 640 mio. sensors (ASP 4.5$) in 2008.

III. Products Development For Harsh Environment

Harsh environment requirements have initially been fulfilled by pushing existing products at their limits. Lately, major investments have been invested to improve the environmental resistance of these products and many specific developments made to push the limit of the technology itself. Developments of new materials, new designs or new assembly schemes have also been done, allowing the emergence of new specific products. A large part of these investments have also been allocated to the test and qualification required for these new products. Indeed, test conditions are not obvious: as for example, consider the setup required to qualify a sensor for 20'000g, 10ms shocks, over the full temperature range (i.e. -55°C to 85°C).
The figure 2 shows a typical aerobut equipment required to generate shock profiles as close as possible from the real application.

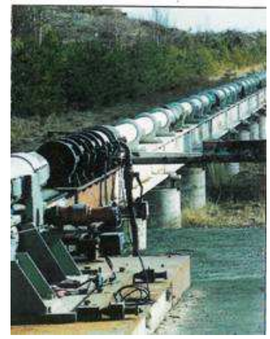


Figure 2: Aerobut testing equipment

First harsh environment sensors have been obtained relatively rapidly by adaptation or small improvements of existing manufacturing techniques. Thanks to a precise analysis of failure mechanisms, it was quite obvious that in many cases, the assembly technique was the real weak point of the products.
The figure 3 tends to show how these adaptations combined with simple design improvements have allowed covering a relative wide range of harsh environment requirements.

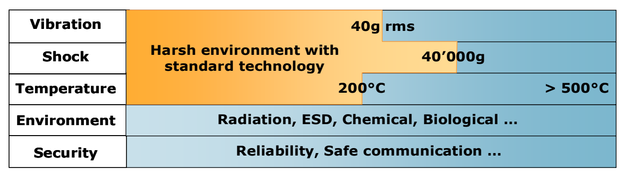


Figure 3: Standard MEMS response to harsh environment requirements.

Note that at that stage of development, we do not consider the radiation, ESD, chemical or biological aspects neither the security aspect, which is probably not applicable at the sensor level and certainly largely related to security or jamming protection of communication.

IV. Concrete Examples Of Sensors Improvements

Some concrete examples will be discussed hereafter to illustrate the harsh environment capability of standard MEMS technology. As accelerometers developer and manufacturer, Colibrys had mainly to face three requirements for improvements, which were the shock resistance, the ability to perform at extreme temperatures and in a smaller extent, the capability to survive higher levels of vibration.

A. High Shock Resistance

This is probably the best example to demonstrate how standard MEMS have been upgraded to fulfil this harsh environment requirement.
A rapid comparison of datasheets shows that MEMS technology has a much larger intrinsic potential in term

of shock resistance compared to traditional micro-mechanical products (typ. 6000g for standard MEMS compared to 300g for micro-mechanical). Even if this specification was not meeting the shock requirements (>20’000g, 10ms, half sine), preliminary aerobut tests have been anyway conducted to determine the real potential of this technology and surprisingly enough, 50% of the products have survived under such extreme conditions.

These results were encouraging enough to initiate a custom development. Note at that point that, it is important to distinguish between the survivability and the resistance to the shock. Considering the requirements of the application, a good resistance to the shock with minimum and controlled impact on all specifications and especially on the stability is required (bias and scale factor stability, misalignment stability, vibration rectification error...) and survivability only without considerations on specifications is clearly not enough.

After analysis of defective parts and few short loops to confirm some basic ideas, we have been able to demonstrate that the MEMS sensor die was compatible to the requirements (sensors die have been successfully tested on centrifuge up to 40’000g without degradation) and that we had mainly to focus on a more robust assembly scheme. Indeed, die attach is one of the key factor to ensure the advanced specifications of the Colibrys accelerometers and it was not obvious to consolidate this bonding technique without impacting the inherent specifications of the product. Finally, thanks to our local experience in the watch industry and using various existing patents, a cost effective and smart solution has been found and implemented by Colibrys to meet the objective. The schematic of the solution is presented in the figure 4.

The main idea was to combine the existing patented stress isolation technique (required for the good level of specification) with stoppers and combine them in an hybrid shock protection solution. After simulations and a short design phase, initial samples have been tested and results were impressive.

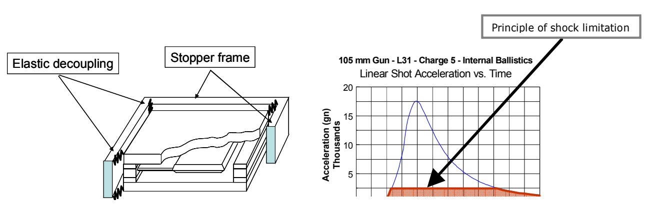
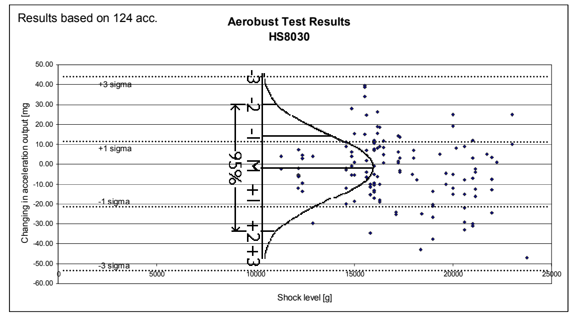


Figure 4: Gun hard assembly schematic with elastic decoupling and stoppers

Products have been gradually ‘’aerobut tested’’ from 12’000g up to 24’000g with very good results. During the last campaign of tests, products have even been successively shocked up to three consecutive times without further degradation of the specifications. Today, more than 700 products have been tested with success and thousands of parts have been produced in a well established manufacturing process. The graphic 1 presents a typical distribution of bias change due to shock on 30g sensors (HS8030.C)



Graphic 1: Bias shift distribution due to high shock

Complementary tests have been conducted to determine the validity of the solution over temperature. Cold and hot rail gun firings have been successfully conducted and all parts remained within required specification.

Finally, the same assembly scheme has been successfully qualified for repetitive shock requirements. The goal was to demonstrate the resistance of the HS8000 series when submitting them to 10’000 successive shocks of ~1000g (accelerometer mounted on a M16 gun). Here again, we have been able to prove the reliability of this product under such harsh environment conditions.

B. Extreme Temperature Operation

Standard MS8000 accelerometers from Colibrys have also been tested for various applications requesting unusual temperatures. Inclinometers for extra-terrestrial applications have been tested down to -120°C as continuous measurements up to 180°C have been successfully demonstrated on inclinometers for directional down hole drilling.

As well as for the high shock program, the MEMS sensor die is not generating any problem and improvements have mainly to be made on the die-attach process and of course on the electronic side, which was not specifically designed for such temperatures.

Intrinsic performances of the MEMS technology allow some of our customers to use our standard product in an intermittent mode at extreme temperatures without extra development. Continuous improvements allow us to know more and more about the limit of this technology

V. Harsh Environment And New Materials

When consulting the literature, harsh environment is systematically associated to new materials like Silicon Carbide (SiC) or Silicon on Insulator (SOi). This is partially true as MEMS for harsh environment, as presented before, are already a reality in a certain extent even with a traditional Silicon material. Anyway, these new techniques are clearly required for devices that must operate at very high temperature (i.e. above 400°C) for extended periods of time while experiencing very high loads for instance. So, in some cases, these new materials are clearly a must and literature already presents very interesting and positive results.

Anyway, if these new materials clearly offer the opportunity to improve the resistance of the sensor dies, major questions remain concerning the assembly of the sensor, the packaging and the electronic. If the material used for the sensor is extremely robust, the assembly scheme could become the weak point of the product and limit the overall specifications. Many aspects like sensor mounting, wire bonding, electrical interconnect, material degassing, delaminating of metallisation layers or lid sealing have to be carefully considered in such aggressive environment and in some extent specifically developed.

This is also especially true for the electronic as motivations for harsh environment sensors are also characterized by the location of the electronic in the final application:

- Electronics placed closer to the ultimate point of use (often in high temperature environments) to reduce weight, decrease connection complexity and improve reliability.
- Electronics placed in chemically corrosive or erosive environments to improve sensing capabilities and/or improve control (in chemical process plant or in marine environments).
- Electronics placed in extremely low (cryogenic) temperatures (in superconducting systems or space environments).

Extreme temperature electronics have certainly to be specifically developed for these kinds of applications and specific investments are required.

VI. Conclusion

MEMS for harsh environment are already a reality. Thanks to minor design adaptation and the implementation of an adequate assembly scheme, quasi standard products can resist to shocks higher than 20’000g with minimum impacts on performance or behave in an intermittent mode at extreme temperatures. These developments allow covering a partial area of the global harsh environment market.

To complete the harsh environment domain, new materials impose themselves. SiC or SOi seems to be the ideal candidates and demonstrators already exist to verify the capability of these technologies at least at the sensor level. Anyway, further developments are certainly required to qualify the complete system. Assembly techniques as well as electronics must become compliant to these extreme conditions and are certainly today the weak part of these new harsh environment sensors.