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# Characterization and testing of a shock absorber embedded sensor

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### Abstract

This article presents the characterization of a shock absorber embedded sensor (SAES) for real-time monitoring of the condition of vehicle shock absorbers in everyday use. A prototype system was built using a custom designed monolithic silicon combined accelerometer, pressure and temperature sensors. The characterization of the SAES was performed and the obtained results meet and even outperform the specification requirements. The SAES was installed in a shock absorber, with adjustable damping properties, and submitted to road tests. Results show that the condition of a shock absorber can be effectively assessed with the presented SAES. Ensuring that shock absorbers are replaced before reach unacceptable condition, this system will increase onboard comfort and vehicle safety.

Keywords: Shock absorber; Embedded sensor; Vehicle safety

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## 1. Introduction

Shock absorbers, as key components in a vehicle suspension system, play an important role in braking performance, dynamic stability and onboard comfort. Common diagnosis on ground suspension platforms gave inaccurate results regarding the shock absorber condition [1]. More accurate testing can be performed on a dedicated dynamometer, but because the shock absorbers must be removed from the vehicle in order to be tested, these analyses are seldom practicable. To address this issue, a monitoring system concept capable of real-time monitoring shock absorbers condition has been proposed [2]. Trials done with an adjustable shock absorber, instrumented with macro sensors, mounted on a vehicle validated the presented assessment methodology to determine the dampers condition with unknown excitation (everyday usage roads) [3]. Later the authors proposed a micro-mechanical monolithic sensor, optimized for the application specifications [4], which measures acceleration, pressure and oil temperature, and enables the integration of the monitoring system in the shock absorbers through miniaturization.

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The presented shock absorber embedded sensor (SAES) prototype, shown in Fig 1(a), was fabricated, using the SensoNor Multi-Project wafer service MultiMEMS. The accelerometer is designed to support up to 2000 g and the geometry of the supporting beams, Fig 1(b), was optimized for improved sensitivity with small variations between samples. The pressure sensor uses a 23.1 µm thickness square membrane to support pressures up to 100 bar. Sensing elements distribution over the membrane is planned for enhanced sensitivity and optimal linearity. The temperature sensor is made up of two buried resistors placed near the pressure membrane. The proof masses, metal connections and sealed glass cavity are visible on the right side of the sensor, Fig 1(b), while on the left side only the top glass cavity (over the pressure diaphragm) is visible.

Fig. 1. (a) SAES dice (dimensions: 6 × 6 mm); (b) Detail of the accelerometer beams shape and proof mass edges (bottom view).

## 2. SAES Characterization

### 2.1. Accelerometer

The accelerometer design was characterized using a vibration exciter and an Analog Devices model ADXL278 accelerometer for reference. A sinusoidal waveform up to 18 Hz was applied to both accelerometers and data was acquired with a NI USB6009 acquisition board connected to a laptop running LabView. Characterization results for six accelerometers, taken randomly from the fabricated samples, are shown in Fig 2. The tested samples were measured to give a sensitivity of 76.8µ V/V/g ± 1.8%. Considering the diversity of factors influencing the measured sensitivity: wet etch inaccurate definition of beams thickness and inertial masses, other fabrication process tolerances (masks alignment), signal acquisition tolerances (a drift of ± 0.7% in sensitivity was verified for successive tests of the same sensor) and accelerometers alignment precision during characterization, the verified small sensitivity variation is an excellent result. Certainly, this is also an outcome of the optimized beams shape, Fig 1(b), which were used to improved reproducibility by controlling the stress distribution with the mask design through using tapered section rather than process variations for the thickness of the beams.

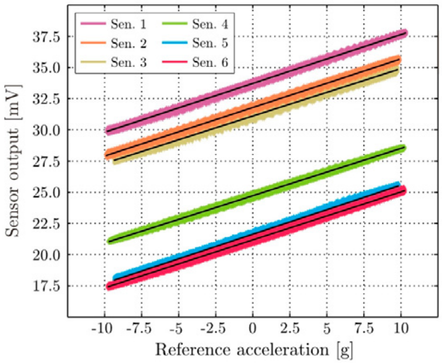

Fig. 2. Accelerometer characterization results (supplied with 5 Volts) using an Analog Devices ADXL278 accelerometer for reference.

The offset measured considering all tested samples is 5.4 ± 1.2mV/V. Ideally the offset should be 5 mV/V, resulting in output of 2.5 V for 0 g (sensor supplied with 5 V and using a gain of 100), perfect for a 5 V single supply operation. Fabrication process tolerances and residual stress formed during wafer processing (glass-silicon-glass bonding) are the main reasons for the offset variation between samples. Nevertheless, the large offset variation verified between samples, it has no influence in the shock absorber assessment methodology [3], where analysis is made in 10-15 Hz frequency range.

### *2.2. Pressure sensor*

To characterize the pressure sensor design, six sensors were used, chosen randomly from the delivered samples. Characterization was done with sensors placed inside a pressure chamber with electrical connection to the outside. Air was used for testing with absolute pressures ranging from 0.1 bar to 11 bar (limits of the testing equipment). Results obtained using an AFRISO DIN 10 pressure gauge for pressure reference are shown in Fig 3(a). The verified high linearity reflects the work done with the positioning of piezoresistors on the sensor membrane, which enables sensing elements, perpendicular and parallel to the membrane edges, to experience similar mean stresses [4].

The tested sensors gave a sensitivity of 3.17 mV/V/bar ± 2.74%. The verified variation in sensitivity is caused mainly by the fabrication tolerances for membrane dimensions (wet etching of silicon), while piezoresistors positioning (mask alignment) also has a small influence. A satisfactory absolute error of 0.0274 bar/bar (measured sensitivity variation) prove that the use of a thick membrane (23.1μm), with poor accuracy since dimensions can not be defined by the mask alignment but necessary due to the required measuring range, is practicable.

Measured offset for the tested samples is -2.94 ± 3.1mV/V; the causes for the offset variations being the same as the ones for the accelerometer. However, in the case of the pressure sensor, the offset variation to sensitivity ratio is much smaller, resulting in an error of approximately ±1 bar. As for the accelerometer the pressure sensor offset has no influence in the applied methodology results.

### *2.3. Temperature sensor*

The temperature sensor design was characterized by immersion in temperature controlled shock absorber oil. A precise platinum thin-film temperature sensor, PT100 DIN EN60751 tolerance class, from IST AG, was used as a temperature reference. The oil was slowly warmed up to 100 ºC and then left to cool to room temperature. Data was acquired in 2.5 ºC intervals and the obtained results are depicted in Fig 3(b). The use of two buried resistors in a Wheatstone bridge resulted in a sensitivity of 1.2m V/V/ºC, in line with the theoretical value of 1m V/V/ºC and doubling the sensitivity of a single buried resistor. When a linear output is considered, the tested sensor presented a maximum error of ±2.5 ºC in the 20 ºC to 100 ºC range. A smaller error will occur if we shorten the working range to 20-60 ºC.

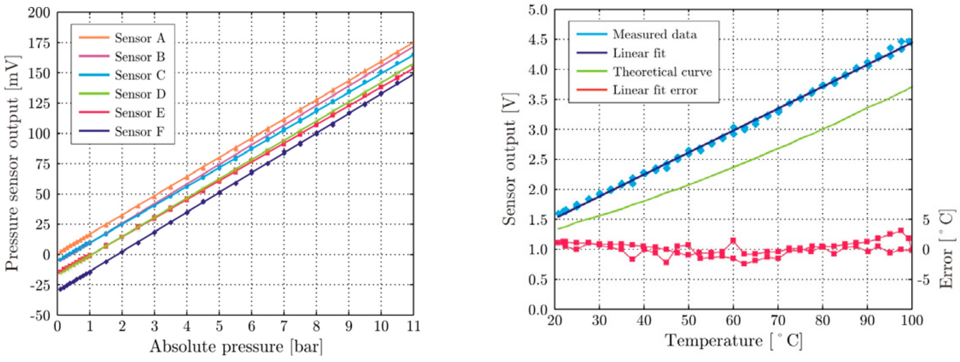

Fig. 3. (a) Pressure sensor characterization results (sensor supplied with 5 V and amplification gain cancelled); (b) Temperature sensor characterization results (supplied with 5 V and amplifier gain of 6.06) using a PT100 DIN EN60751 from IST AG for temperature reference.

## 3. Results with SAES installed into a shock absorber

To test the SAES applicability and feasibility on real-time monitoring of the condition of vehicle shock absorbers, a SAES was fitted in a prototype metal package (without optimized dimensions) to ease its installation into a shock absorber (Fig 4(a)). A KONI dual-tube adjustable shock absorber was modified to enable sensor access to the compression chamber, extension chamber and reservoir. Afterward, a test vehicle was run on a 36 km tour with everything from badly conditioned roads to highways (simulating a typical everyday use). To vary the conditions of the monitored shock absorber, its damping settings were adjusted from maximum to minimum; also, variable amounts of oil were drained from the shock absorber to simulate poor condition shock absorbers. During the tests the SAES outputs were amplified and acquired using a NI USB6009 acquisition board. The results for the shock absorber status in the various tested conditions, applying the methodology formerly presented [3], are depicted in Fig 4(b). As shown, the SAES enables clear identification of the dampers acceptable conditions (Max, Med and Min) and driver alert when shock absorber replacement is required. The SAES was tested for near 1000 km in the vehicle, experiencing extreme working conditions, keeping its characteristics and performance steady.

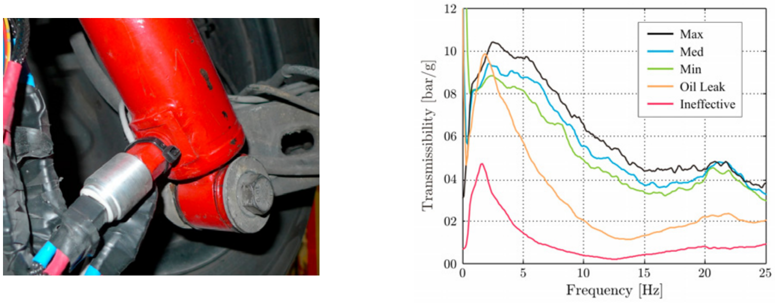

Fig. 4. (a) SAES installed in a rear shock absorber; (b) Results obtained for the testing shock absorber in varied conditions.

## 4. Conclusion

The shock absorber embedded sensor meets and even outperform the specification requirements. Sensitivities for accelerometer, pressure sensor and temperature sensor are in agreement with the theoretical values. It is possible to measure pressures with a thick membrane while keeping the sensitivity drift acceptable. The relatively large offset variation in the samples has no influence in the assessment methodology results, making the MultiMEMS process a successful choice for the prototype fabrication (and also for volume production).

When installed in a shock absorber, The SAES can effectively be used to assess the condition of a shock absorber. Testing can be performed during vehicle operation, exploiting the excitation of everyday use roads, ensuring that shock absorbers are replaced before worn out. The prototype sensor proved to have feasibility enough to be usable in all roads conditions, although further testing must be carried on to prove sensor feasibility over long term utilization. The added functionality of the SAES to the vehicle diagnosis system represents a major contribution to vehicle safety.

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