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High Precision Accelerometer with Integrated Thermal Sensor †

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Abstract: This paper investigates the design of a Vibrating Beam Accelerometer (VBA) with a resolution of 50 nano-g combined with an integrated thermal sensor. Despite quartz intrinsic thermal stability, the time delay between vibrating beam's temperature and package's temperature gives way to unwanted transient thermal behavior and thus bias instability. The aim of this study is to include a thermal sensor consisting in a torsional resonator directly at the center of the beam. Previous work demonstrated the feasibility of such integration on a tactical class accelerometer but also highlighted limitations like high motional resistance of the torsional resonator. Benefits of the in-situ temperature sensor are investigated thanks to finite element analysis of the accelerometer transient thermal behavior, which shall be compared to measurements on actual cells.

Keywords: VBA; in-situ thermal sensor; transient thermal behavior; finite element analysis

1. Introduction

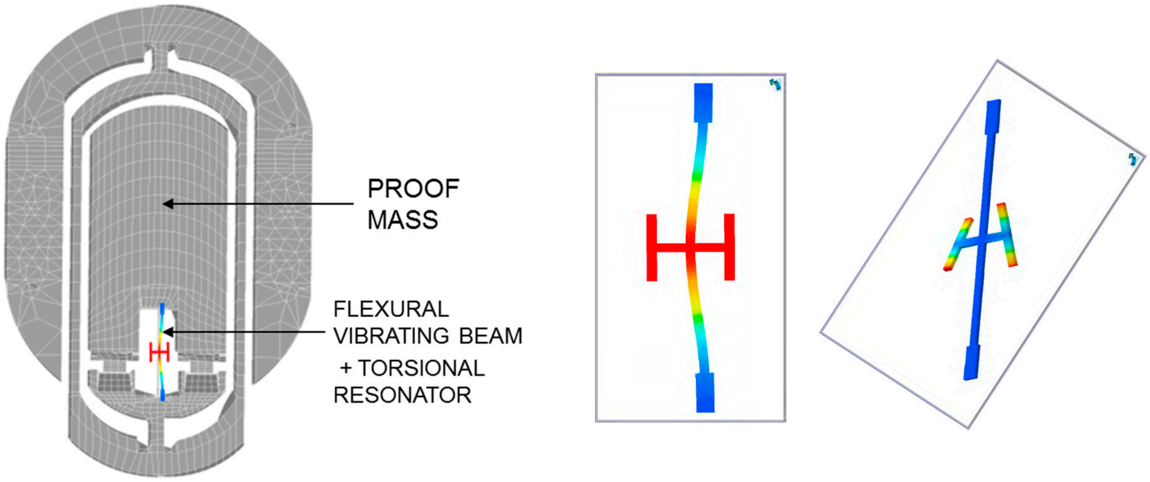
1.1. Inertial Grade MEMS Accelerometer for Emerging Applications

Emerging applications require low bias instability (<10 μg), high resolution (<1 μg), miniature (<1 cm^3) and low power (<1 mW) accelerometers and allow a limited measurement range: wireless sensor network of Precision MEMS accelerometers based inclinometers dedicated to structural health monitoring (buildings, bridges, …) [1,2], wireless sensor networks of MEMS accelerometers based seismometers to detect and identify intruders in a protected area [3,4], inertial measurement units dedicated to micro UAVs. Although Vibrating Beam Accelerometers (VBA) have demonstrated good performances [5,6], actual accelerometers do not fulfill all these requirements, and are mainly limited by bias instability over temperature.

1.2. Bias Drift over Temperature

Bias drift over temperature is of main concern for inertial sensors performances and especially for Vibrating Beam Accelerometers (VBA). The thermal behavior is usually compensated thanks to an external temperature sensor on the package of the accelerometer itself, with polynomial laws of the temperature or even taking into account its time derivative. Despite those numerical compensations it appears that the time delay between the temperature of the vibrating beam and that of the package gives way to unwanted transient thermal behavior peculiarly for very fast thermal solicitations.

In order to overcome such drawbacks, a torsional resonator can be implemented at the center of the vibrating beam to know instantaneously the temperature of the beam itself. This principle was demonstrated on a strategic accelerometer [7] and is now developed on a very highly sensitive accelerometer with a 50 ng resolution.



(**a**) (**b**) (**c**)

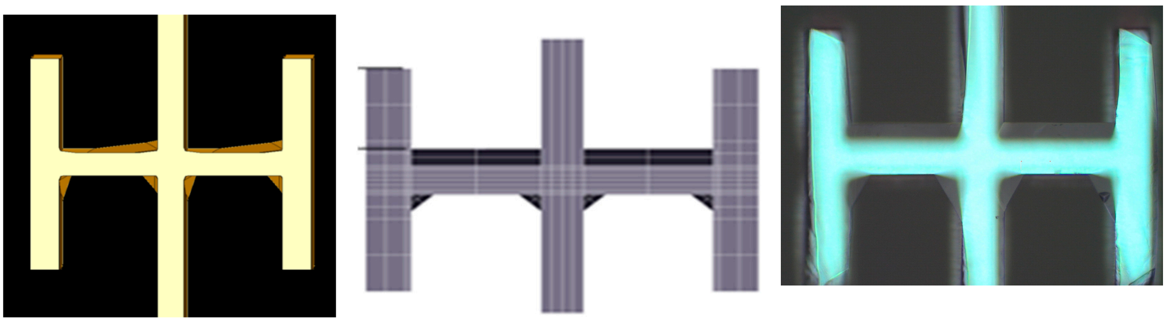
Figure 1. Vibrating beam accelerometer MEMS (**a**), flexural mode of the beam which eigen frequency is proportional to axial load induced by acceleration (**b**), torsional mode which eigen frequency is proportional to the beam temperature (**c**).

The new design, presented in Figure 1 was first elaborated thanks to finite element analysis and some realizations were achieved. In a second phase, the benefits of the use of the in-situ sensor are investigated thanks to finite Element Analysis (FEA) and measurements on actual cells.

2. MEMS Detailed Design

Torsional Mode Design

To integrate the torsional resonator on the vibrating beam, the complete structure was simulated, including the facets due to chemical etching. Figure 2, shows the results of etching facets predicted thanks to MicroCAD® software, the finite element model used and the actual cell with its etching facets.



(**a**) (**b**) (**c**)

Figure 2. Predicted etching facets (**a**), finite element model taking into account etching facets (**b**), actual etching facets on the quartz cell (**c**).

The frequency shift of the torsional resonator with the dimensions of the etching facets was investigated and showed 0.1% evolution of the frequency for 1 µm evolution which highlights that realization dispersions are very critical for such design. Thus eigen frequencies where thoroughly studied thanks to modal finite element analysis for both the flexural mode of the VBA and the torsional mode to isolate them from other potential parasitic modes.

3. Results

In order to improve the performances of the thermal sensor the frequency of the torsional resonator was increased in the design "Candidate B" compared with former version "Candidate A" leading to a lower motional resistance Rm. This frequency increase is also aimed at reducing electrical coupling of the two modes enabling a more efficient signal filtering. The two versions characteristics are described in Table 1 and Candidate B is presented on Figure 3.

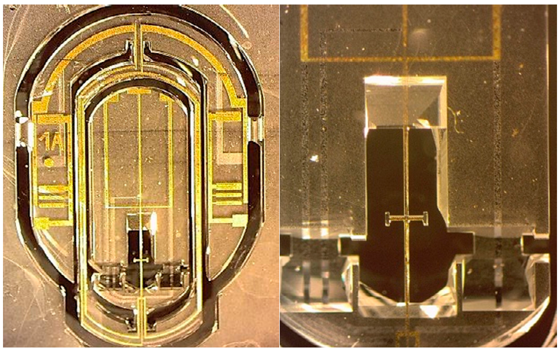


Figure 3. The new accelerometer design and an enlargement of the area with the vibrating beam with the torsional resonator at its centre on the right.

Table 1. Characteristics of the two versions of accelerometers "Candidate A" and "Candidate B".

	Flexural Frequency (Hz)	Torsional Frequency (Hz)	Torsional Rm	Scale Factor
Candidate A	35,020	207,210	22 MΩ	211 Hz/g
Candidate B	34,970	737,850	5 MΩ	247 Hz/g

Thermal Transient Behavior

The thermal transient behavior of both candidates was studied thanks to the finite element analysis software OOFELIE::Multiphysics©. The finite element analysis includes the thermal transient behavior of the structure chained with static thermomechanical and a prestressed modal analysis. The transient evolution of the vibrating beam frequency is caused by the time delay between the temperature evolution outside and inside the packaging and the thermal gradient which appears in the quartz cell itself.

Usually, the thermal sensitivity of a resonator is modelled thanks to a polynomial law. As an example the evaluation of the temperature behavior was made on an actual cell without torsional sensor on Figure 4.

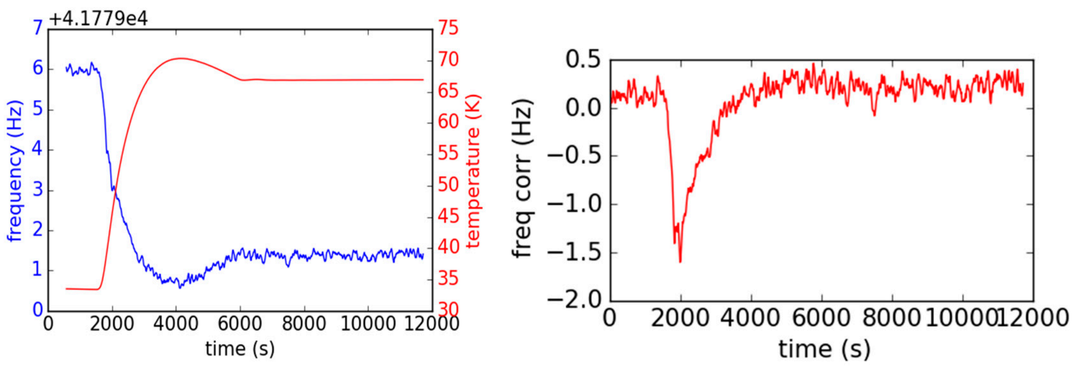


Figure 4. Transient behavior measured on an actual cell and residual frequency shift after polynomial correction.

4. Conclusions

The thermal transient behavior described above evolution produces a bias instability which is partially compensated by the static polynomial model. A residual evolution remains due to transient behavior of 1.5 Hz i.e., 4 mg with the scale factor of Candidate B. Taking into account the time delay between the beam temperature and the packaging presented in Figure 5 should drastically reduce bias instability presented in Figure 4. This is complementary with a correction of the temperature time derivative effects. Experimental measurements on actual cells shall confirm this point soon.

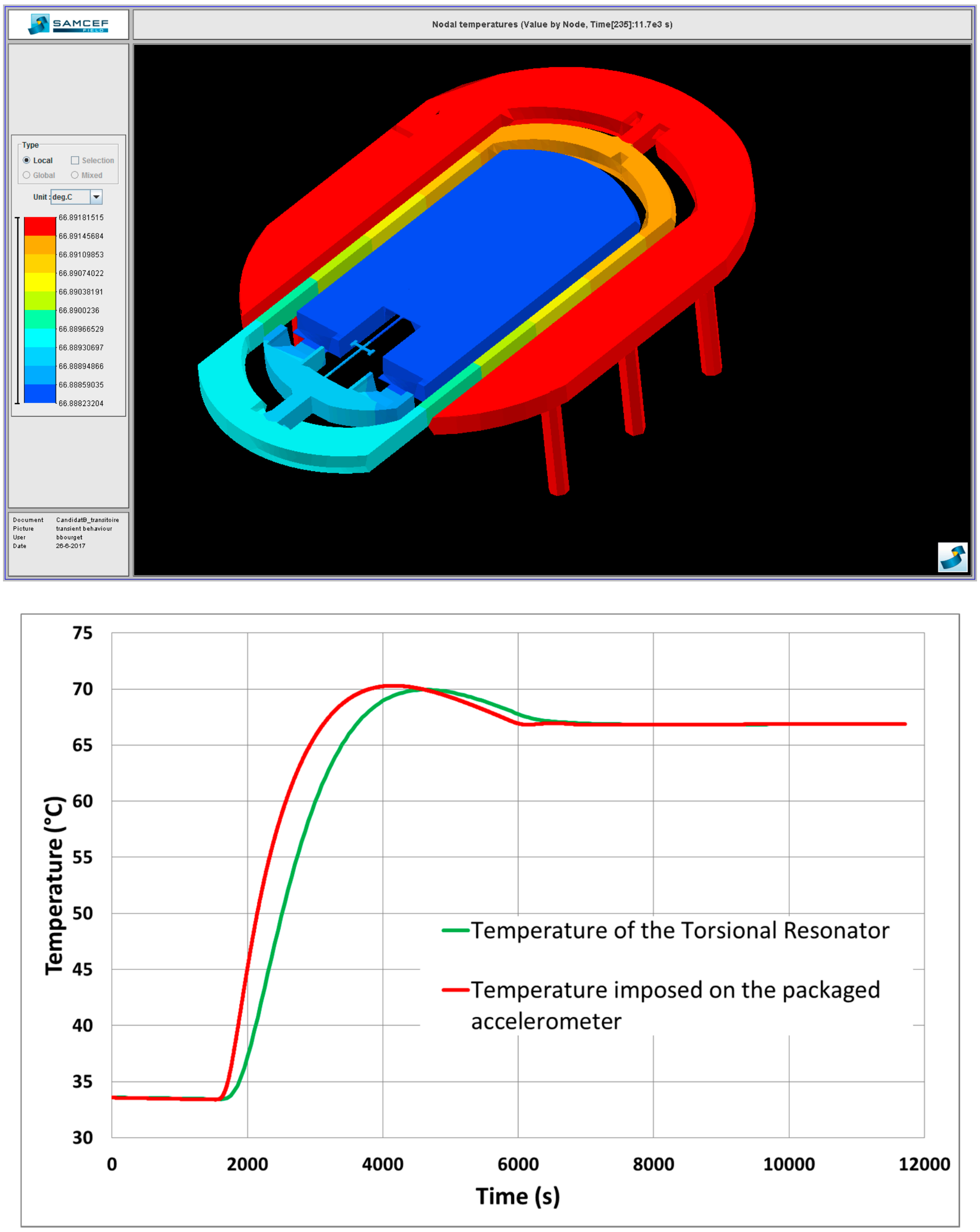


Figure 5. Thermal transient behavior of the accelerometer (FEA).

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