Computational Analysis and Optimization of a MEMS-Based Piezoresistive Accelerometer for Head Injuries Monitoring

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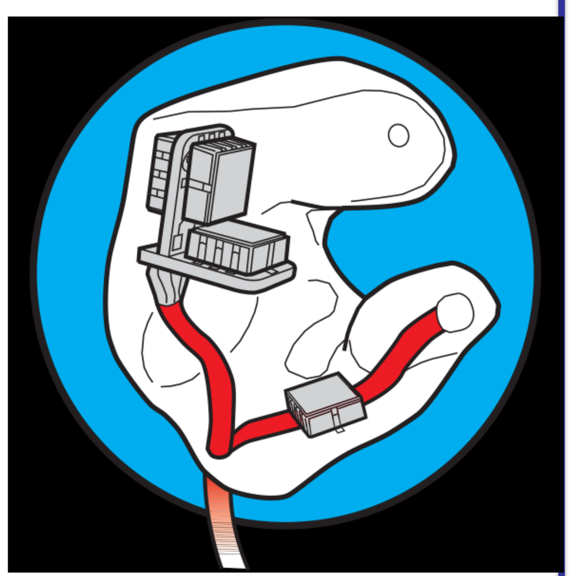
Abstract. This work focuses on the design improvement of a tri-axial piezoresistive accelerometer specifically designed for head injuries monitoring where medium-G impacts are common, for example in sports such as racing cars. The device requires the highest sensitivity achievable with a single proof mass approach, and a very low error as the accuracy for these types of applications is paramount.

The optimization method differs from previous work as it is based on the progressive increment of the sensor mass moment of inertia (MMI) in all three axes. The work numerically demonstrates that an increment of MMI determines an increment of device sensitivity with a simultaneous reduction of cross-talk in the particular axis under study. The final device shows a sensitivity increase of about 80% in the Z-axis and a reduction of cross-talk of 18% respect to state-of-art sensors available in the literature. Sensor design, modelling and optimization are presented, concluding the work with results, discussion and conclusion.

Introduction – Earpiece Accelerometer

- In 2003, Delphi Earpiece Sensor System (DESS)
- In 2006, Begeman et al.
- In 2009, Salzar et al.
- In 2012, ADXL377 from Analog Devices
- In 2013, H3LIS331DL from ST
- In 2014, Messina et al.



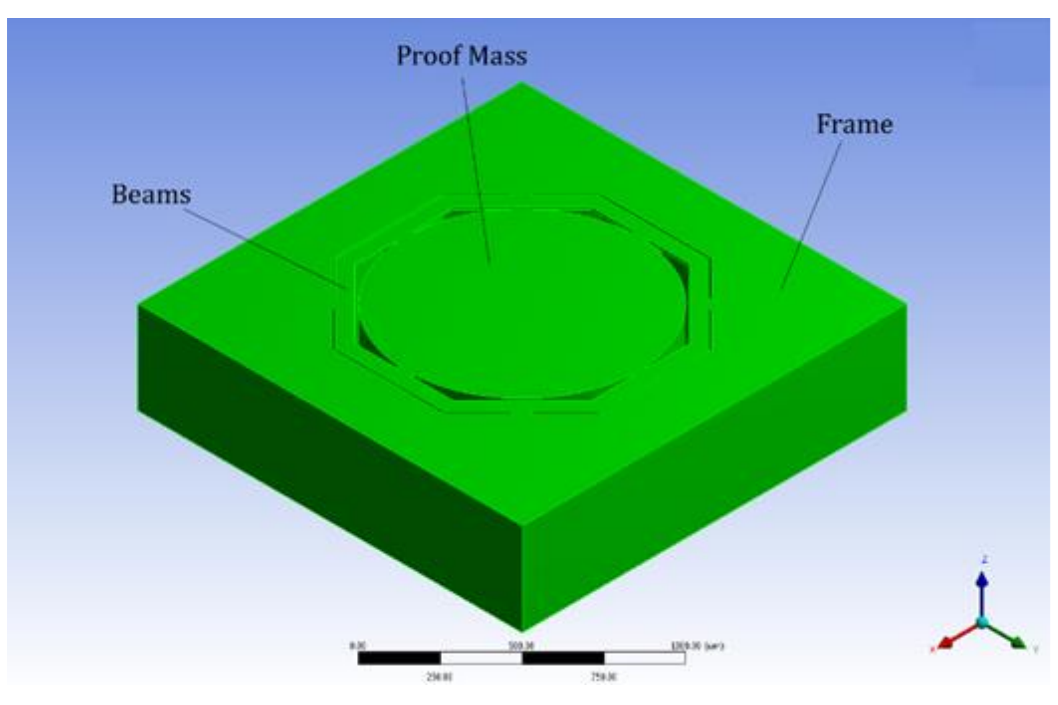
In 2003 a version of these type of earpieces with an integrate acceleration sensor, called the Delphi Earpiece Sensor System (DESS) [1], was introduced for the first time in the Indy Racing League and Championship Auto Race Teams (CART). In 2006, a group of research at the Wayne State University leaded by Begeman [2] reported that these earplugs mounted in post mortem human specimens (PMHS) showed in the output signal a progressive phase lag from 50 to 100 Hz vibration when compared to skull measurement (rigidly mounted head accelerometers). Furthermore, in 2009, Salzar et al. [3] explored a solution in order to try to avoid the issue found by Begeman earlier by developing a smaller tri-axial device meant to be placed inside the ear canal portion of the earpiece. The sensor showed improved coupling to the head over the DESS that was perceived too bulky [4].

Problem – too bulky

However, the sensor accuracy and miniaturization is not yet acceptable for this type of in-situ ear measurements. It is perceived acceptable a sensor error below 1% and a miniaturization below 2×2 mm2.
More recently, in 2013, an attempt has been made to improve earplug sensor sensitivity and miniaturization by integrating silicon nanowires as piezoresistors. However, the manufacturing limitations harboured successful fabrication of a proof of concept [5], [6] . Finally, in 2014, a patent was published on a novel optimization method based on variation of the sensor mass moment of inertia [7].

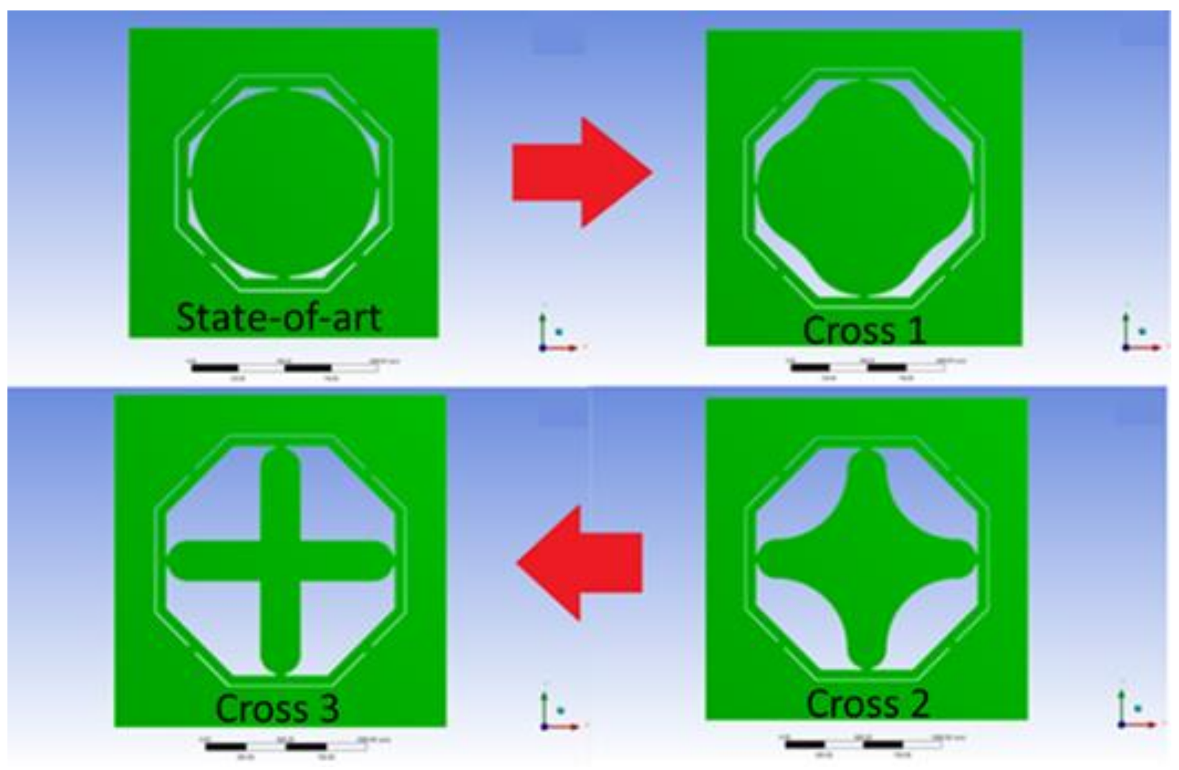
Aim of research

This work attempts a further improvement of the patented work [7] by investigating a way of enhancing sensor performances and miniaturization by specific increments of the sensor mass moment of inertia (MMI), with the objective of achieving the most accurate response in case of medium-G impact crash (<500G) not yet achieved in the state-of-art sensor design.

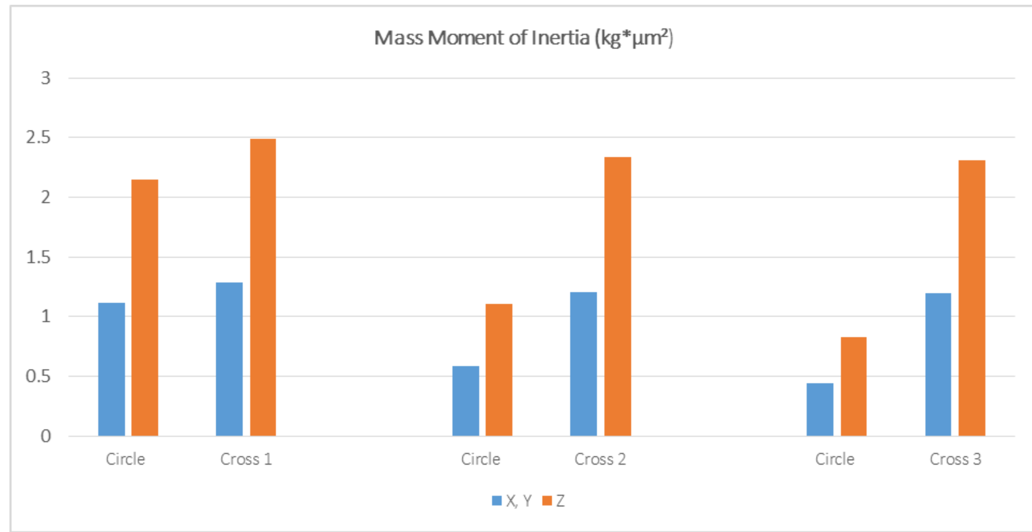


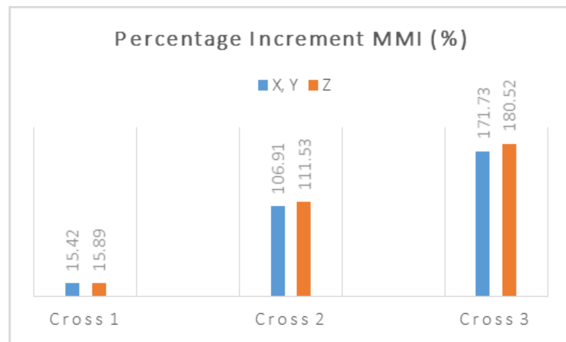
Methodology

Finite Element Model, Optimization Method



Increment of Mass Moment of Inertia



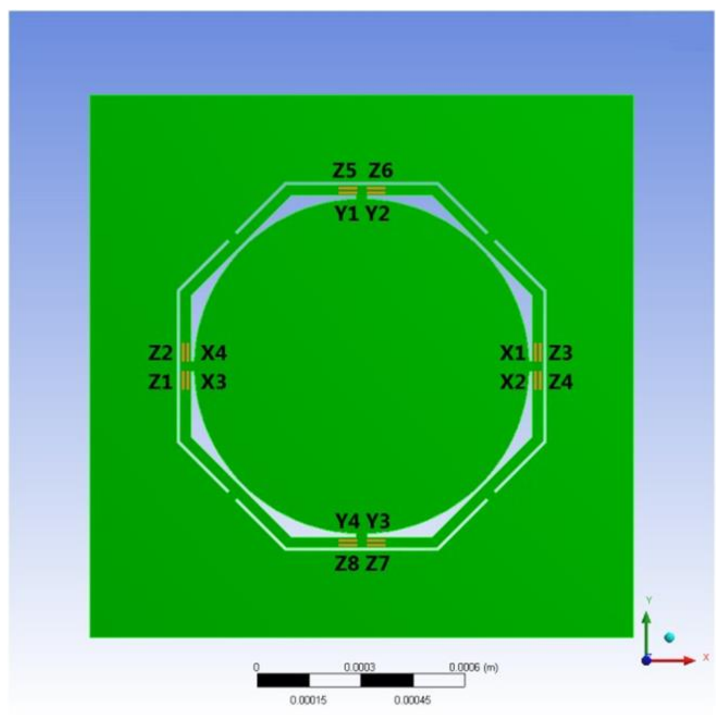


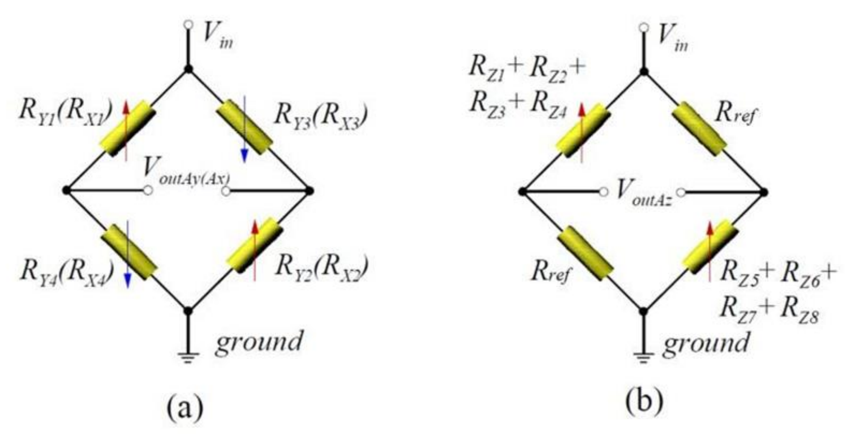
The MMI increases respect to state-of-art shape in all three new shapes. The figure shows better this result by the percentage increment of the MMI respect to the state-of-art circular shape.

Measurement Circuit

Wheatstone Bridge is formed by four resistors connected in a quadrangle. The excitation that could be voltage or current is connected across one diagonal, whereas in the other diagonal there is a voltage detector. Basically the detector measures the voltage output difference of two dividers connected to the excitation. There are different configuration of the bridge circuit, but the best one that minimize the nonlinearities and presents higher sensitivity is the full-bridge configuration which is also adopted in this study. In this configuration the voltage output is simply the excitation voltage times the fractional resistance change.

Vout = Vin*(ΔR/R)

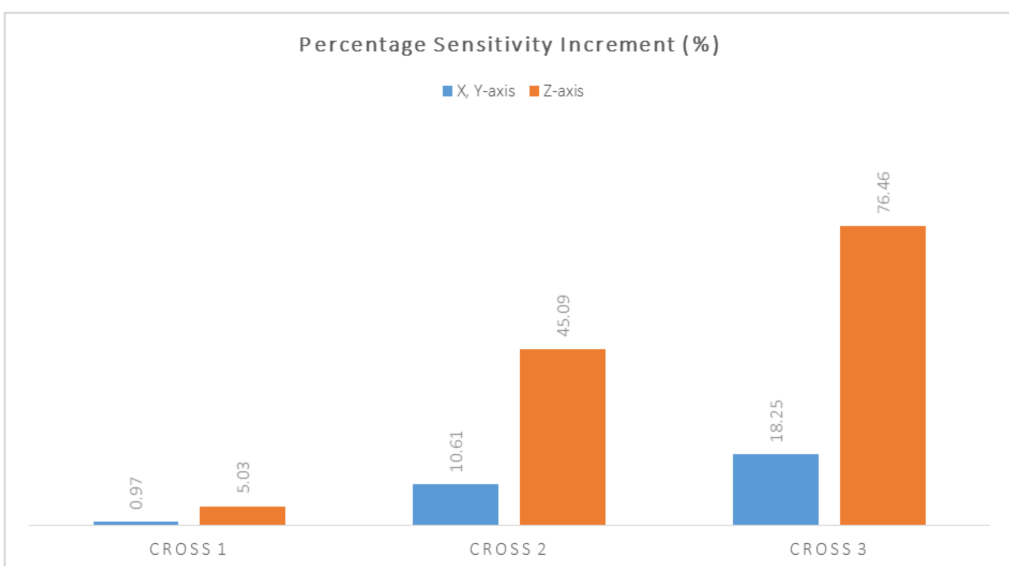




In this work four piezoresistors are used for the full-bridge for the X- or Y-axis and eight piezoresistors are used for the Z-axis, therefore a total of 16 piezoresistors are used and placed in strategic locations on the top surface of the device mechanical structure. In particular these piezoresistors are placed where the highest stress is located by the stress simulation analysis in order to maximize sensor sensitivity. These regions are identified by Finite Element stress distribution analysis.

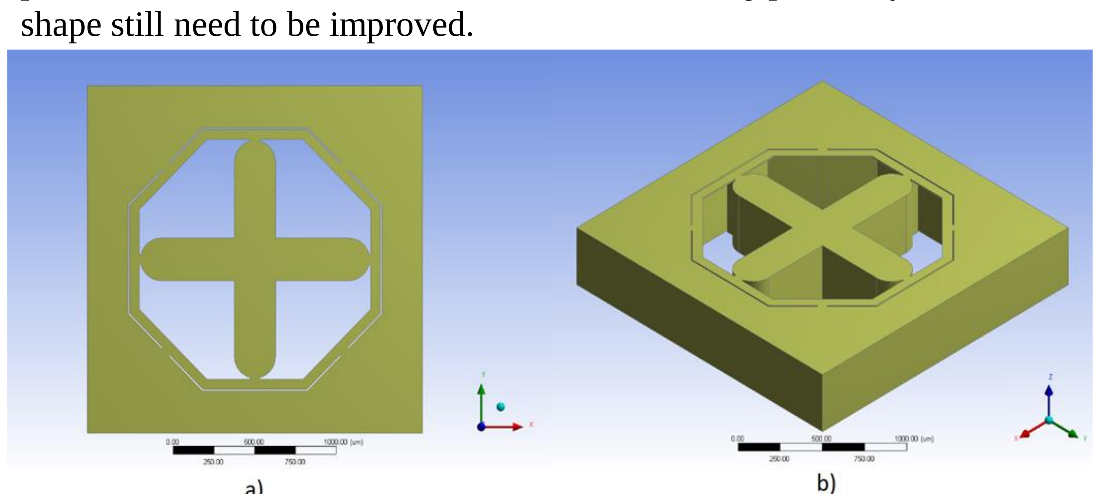
Results

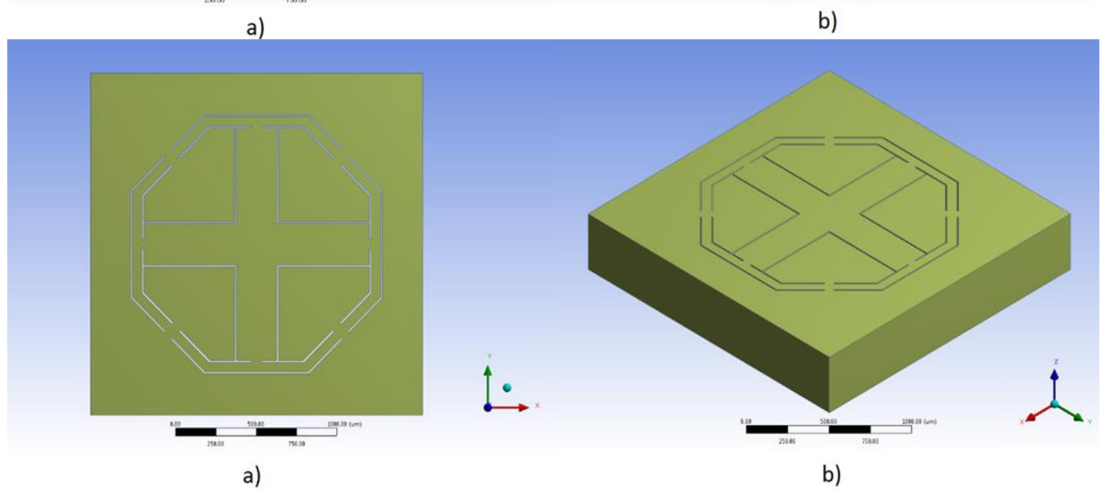
Sensitivity Comparison



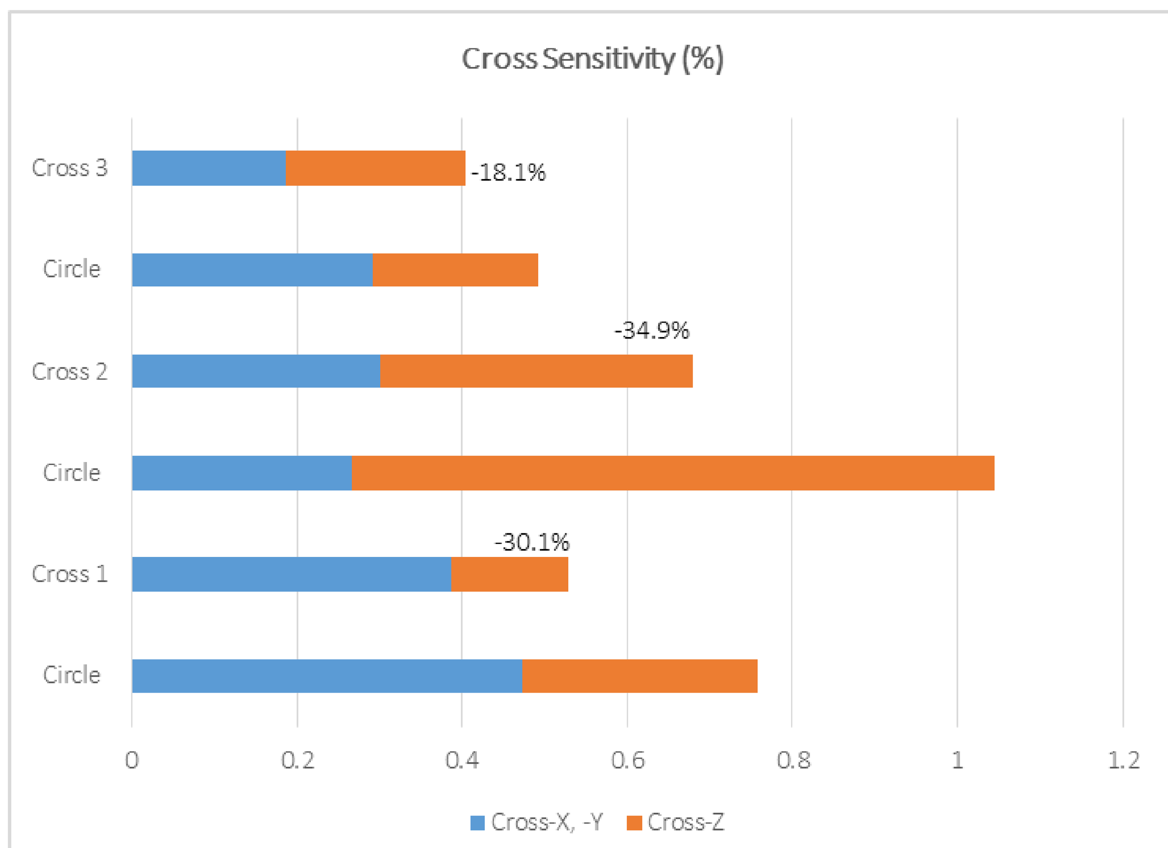
Design for Manufacturing

The Cross 3 shape is the optimal shape obtained from the optimization process, but it seems obvious from a manufacturing point of you that the shape still need to be improved.





Cross-Axis Sensitivity Comparison



Lowest value of cross sensitivity as expected is of the new shape Cross 3, where the combined cross-X, or -Y, and -Z is of just 0.4%, well below the target of 1% for each axis.

Conclusion

Parameter	This work	ADXL377	H3LIS331DL
Measurement Range (G)	±500	±200	±400
Sensitivity (mV/G)	0.22	6.50	-
Cross-sensitivity (%FS)	<±1	±1.4	±2
Size (mm²)	2×2	3×3	3×3

This work numerically demonstrates that an increment of the MMI is a viable optimization strategy for a single mass mechanical structure of a piezoresistive accelerometer where high performance is a must, such as in biomechanical or biomedical applications.

References

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