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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.**

Keywords—Piezoresistive Accelerometer; Sensor Design; Mechanical Sensor Optimization; Biomechanical Device; Head Injuries Monitoring; TBI.

I. INTRODUCTION

In the past decade considerable research effort has been made in order to prevent and monitor the severity of head injuries, especially in motorsport and American football. For an accurate detection of head acceleration it is crucial to have the coupling between head and sensor. Consequently, the instrumented helmet solution has been soon replaced in the new century by an accelerometer attached to an earpiece.

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]. However, the sensor accuracy and miniaturization ($<2\times2mm^{2}$) is not yet acceptable for this type of in-situ ear measurements.

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]. Finally, in 2014, a patent was published on a novel optimization method based on variation of the sensor mass moment of inertia is proposed [6].

This work attempts a further improvement of the patented work [6] by investigating a way of enhancing sensor performances and miniaturization by specific increments of the sensor ass 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.

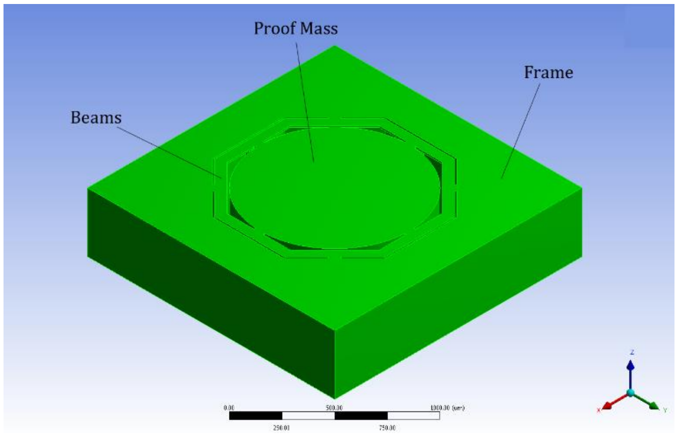

Fig. 1. State-of-art mechanical structure of a three-axial accelerometer available in the literature [6,7].

II. DESIGN MODELLING AND OPTIMIZATION

This section aims at the design, modelling and optimization of a 3-axial single square millimeter bio-mechanic piezoresistive accelerometer available from the literature as state-of-art device [6], [7] and presents mass moment of inertia results. This chosen device as starting point of the optimization process is a three-axial accelerometer with one single mass available for all axes of measurement and it is characterized by a cylindrical proof mass suspended by four octagonal beams fixed to an external frame (Fig. 1) [6], [7]. Main application requirements are miniaturization (<2×2mm^2) and medium-G measurement range (<500G) to allow the accelerometer incorporation into an earpiece.

The optimization methodology adopted in order to increase sensor sensitivity and minimize cross-sensitivity is based on the hypothesis that an increment of sensor MMI will positively affect the sensor sensitivity and negatively influence the sensor cross-axis sensitivity, therefore, overall improving sensor performance. The state-of-art sensor has been obtained from a different optimization method based on MMI changes as well. In this study the MMI will be increased progressively passing from a circular proof mass shape (Fig. 1) to a cross shape, that, at each step of optimization, increases the angle of curvature of the proof mass corners, until it becomes a complete cross as shown on Fig.2.

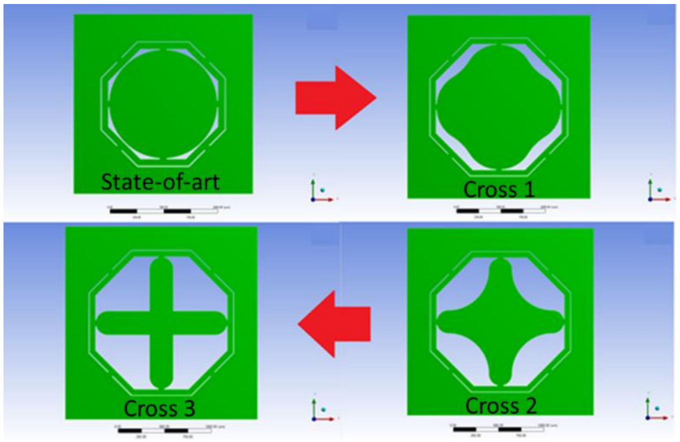

Fig. 2. Mechanical structures top views. Optimization process that increases the MMI at each step of evolution and therefore hypothetically there would be an increase in the sensitivity and a reduction in cross sensitivity.

Fig. 3 shows the percentage increment of the MMI respect to the circular shape. It is obvious that the MMI increases in respect to the state-of-art shape in all three new shapes.

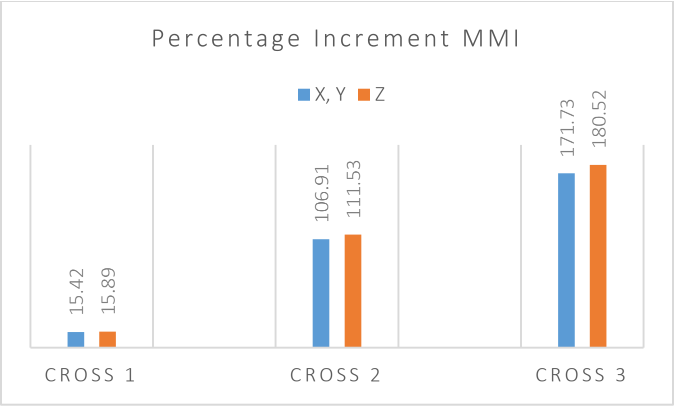

Fig. 3. Percentage increment of MMI respect to circle one. The shape cross 3 offers the highest percentage increment of MMI.

III. RESULTS

Sensitivity and cross-axis sensitivity have been calculated for the new shapes under study by an extensive FEM stress analysis, and results compared to the circle device shape. In Fig. 4 the sensitivity results are presented.

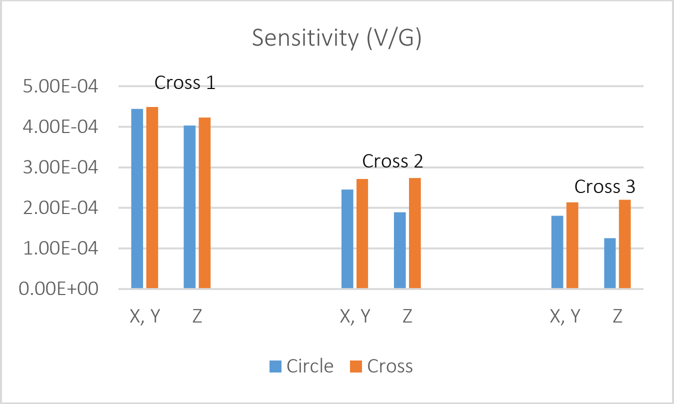

Fig. 4. Sensitivity comparison results of new shapes Cross 1, 2, and 3 to Circle. As it can be seen the new shapes are always offering a higher sensitivity compared to circle shape.

As expected from the study all the new shapes show higher sensitivity than the circle one coming from the literature. Notice that Fig. 4 shows that shape Cross 1 has the highest absolute sensitivity because of its slightly higher proof mass size respect to Cross 2 and 3. In order to estimate the progressive sensitivity increment from shape Cross 1 to Cross 3, a percentage increment graph is presented. Fig. 5 shows the percentage sensitivity increment for each new shape compared to the circle one. Cross 3 shape has the optimal performance compared to the other shapes.

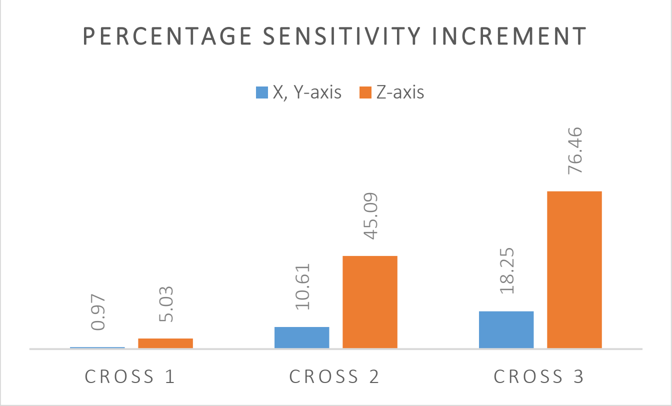

Fig. 5. Sensitivity increment of new shapes in percentage. Highest increment is for the Z-axis sensitivity of shape Cross 3 (≈80%), overall the sensitivity increases progressively from shape Cross 1 to Cross 3, demonstrating the effect of MMI.

The progressive increment of sensitivity from shape Cross 1 to Cross 3 respect to state-of-art circle shape is down to the progressive increment of the MMI, therefore the study hypothesis is here confirmed.

Fig. 6 presents the results of cross sensitivity of each new shape compared to circle one.

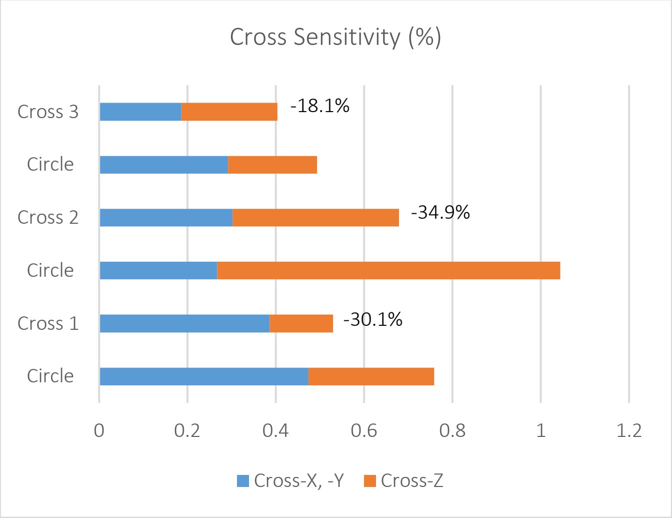

Fig. 6. Cross-axis sensitivity reduction comparison of each new shape.

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.

IV. DISCUSSION AND CONCLUSION

Comparing the optimized device performance to commercial ones, the only available three-axis medium-G accelerometer in the market, at the time of writing, are the analog 3×3mm^2 ADXL377 from Analog Devices specifically designed for concussion and head trauma detection with a range of ±200G and the digital 3×3mm^2 H3LIS331DL from ST with a maximum range of ±400G. The performance comparison is presented in the Table I.

TABLE I. PERFORMANCE COMPARISON WITH COMMERCIAL DEVICES.

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 (mm^2)	2×2	3×3	3×3

The Cross 3 shape developed in this study is a 2×2mm^2 device, therefore the sensitivity results reduced compared to the Analog Devices accelerometer that is 3×3mm^2. For a proper ear-plug device a 2×2mm^2 size is desirable as a bigger device would slip off the ear [3]. Moreover, the sensitivity of the ADXL377 is much higher of the device of this work because the signal output is amplified by internal circuitry, while the device developed in this work is not amplified at all.

Furthermore, the Cross 3 presents a higher measurement range because race car crash can reach impacts of more than 300G forces. Finally, Cross 3 shape presents the lowest cross-sensitivity of all three accelerometers, therefore, it is the most suitable device for biomechanical measurements. Notice that ST device sensitivity is not comparable as the device is digital. For this device the cross-sensitivity is ±2% for a range of ±70G, therefore for impacts of ±200G the error could reach peaks three times higher (≈ ±6%).

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.

The increment of sensitivity of cross shapes in respect to state-of-art circular shape reaches 76% in the Z-axis and 18% in the X- or Y-axis, moreover the optimization method used allows for a simultaneously reduction of cross-axis sensitivity for the same shape of 18.1%. These remarkable results allow for measurements of advanced accuracy where high sensitivity and low error are paramount such as in the head injuries monitoring. Future work would be to manufacture the optimal shape and test the performance under specified loading condition.

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