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# PERFORMANCE ENHANCEMENT OF A DUAL-AXIS MICRO-ACCELEROMETER USING COMPLIANT DISPLACEMENT-AMPLIFIERS

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## ABSTRACT

This paper presents a packaged and tested micromachined dual-axis capacitive accelerometer to demonstrate that improved sensitivity can be achieved by using *Displacement-amplifying Compliant Mechanisms (DaCMs)*. Since mechanical noise-floor of an accelerometer can be reduced by increasing the inertia and decreasing structural stiffness, it usually results in a reduction of the bandwidth of the sensor. However, we show here that bandwidth need not be compromised for improved sensitivity even in the open-loop operation by means of DaCMs. The dual-axis accelerometer uses a suspension that combines the features of de-coupling and amplifying the displacements along the two in-plane orthogonal axes. The design was microfabricated, packaged, and tested. The measured axial sensitivity of about 0.58 V/g for both the axes was achieved with a cross-axis sensitivity of less than 1%. The measured natural frequency along the two in-plane axes was 920 Hz. The amplification of displacement by a factor of 6.2 was obtained using the DaCMs in the dual-axis accelerometer.

## KEYWORDS

Compliant-mechanism, DaCM, Dual-axis micromachined accelerometer, Sensitivity-enhancement.

## INTRODUCTION

Micromachined accelerometers are becoming extensively used in many applications because of the emergence of silicon micromachining technology that enables successful miniaturization and batch fabrication of small footprint, cost effective accelerometers. The requirement of high resolution demands low noise of the entire system. The major source of noise present in the micromachined mechanical structures is the mechanical-thermal noise or the Brownian noise [1]. Noise analysis of a micromachined accelerometer shows that the overall system performance becomes dominated by the noise of the signal conditioning electronics as the performance of the mechanical part improves [2]. The best way to improve the mechanical performance of the device is to increase the inertia of the device and decrease the effective structural stiffness [3]. This indicates that the sensitivity of the mechanical structure has to be enhanced in order to achieve high mechanical resolution. Consequently, the bandwidth of the sensor decreases.

In this paper, we aim to enhance the mechanical sensitivity by incorporating a *mechanical displacement amplifier* to the sensor without compromising on the bandwidth of the sensor and increasing the noise significantly. The technical premise for our work is the *mechanical amplification,* which can improve the sensitivity and resolution of the sensor that is beyond the best that could be done with the signal conditioning interface electronics. For mechanical amplification, *Displacement-amplifying Compliant Mechanisms (DaCMs)* [4-5] were used. DaCMs constitute a class of compliant mechanisms that, as suggested by their name, amplify the applied displacement and thus act like levers albeit with some stiffness due to their inherent elasticity. While the stiffness may disturb certain features such as de-coupling of the axes, there is ample freedom in designing a DaCM to achieve amplification beyond what is possible with a simple flexural lever within the same footprint area.

In this paper, development of a dual-axis capacitive accelerometer with an XY de-coupling mechanism and DaCMs is presented. The finite element simulation shows that by design, an improvement of 50% in sensitivity and 25% in bandwidth can be achieved compared to a design without DaCMs but occupying the same chip area. The device was fabricated using Silicon-on-Insulator Multi-user MEMS Processes (SOIMUMPs). Die-level mechanical characterization of the fabricated dual-axis accelerometer using Laser Doppler Vibrometer is presented. The fabricated accelerometer is packaged using a hybrid system-in-package technique and then tested and calibrated by mounting the packaged accelerometer on a vertical turn table. The in-plane modal frequencies were found to be 920 Hz and 918 Hz for X and Y axis respectively. The sensitivity of the packaged accelerometer was measured to be 580 mV/g and 589 mV/g along X and Y axes respectively with a croos-axis sensitivity of less than 1% for both the axes.

## DESIGN

### Mechanisms in Accelerometer

A dual-axis accelerometer is designed to sense acceleration in any arbitrary direction in a plane. This uses a compliant mechanism called a compliant XY stage for decoupling the input excitation into its X and Y components. Figure 1a shows the schematic of the sensing element with 12 folded-beam suspensions [6] and two DaCMs. This special configuration retains decoupling of the two axes even after appending DaCMs as opposed to de-coupling layout of the XY stage proposed in [7]. It may be noted that there is a direct correspondence between the configuration of the schematic in Figure 1a and that of the designed device layout in Figure 1b. Figure 1b also shows electrostatic comb-drives attached to the output of DaCMs appended at the sensing side of either axis. This increases the sensitivity by amplifying the displacement of the comb-fingers and hence the capacitive sensitivity. De-coupling ensures low cross-axis sensitivity.

In addition to achieving de-coupling of the two axes with the special configuration of Figure 1a and large amplification, the DaCM was designed to have low stiffness along the intended axis and high stiffness along the cross axes. A stiffness-matched inverting DaCM was obtained using topology, shape and size optimization [4-5] and further modifications were made to account for practical constraints of fabrication.

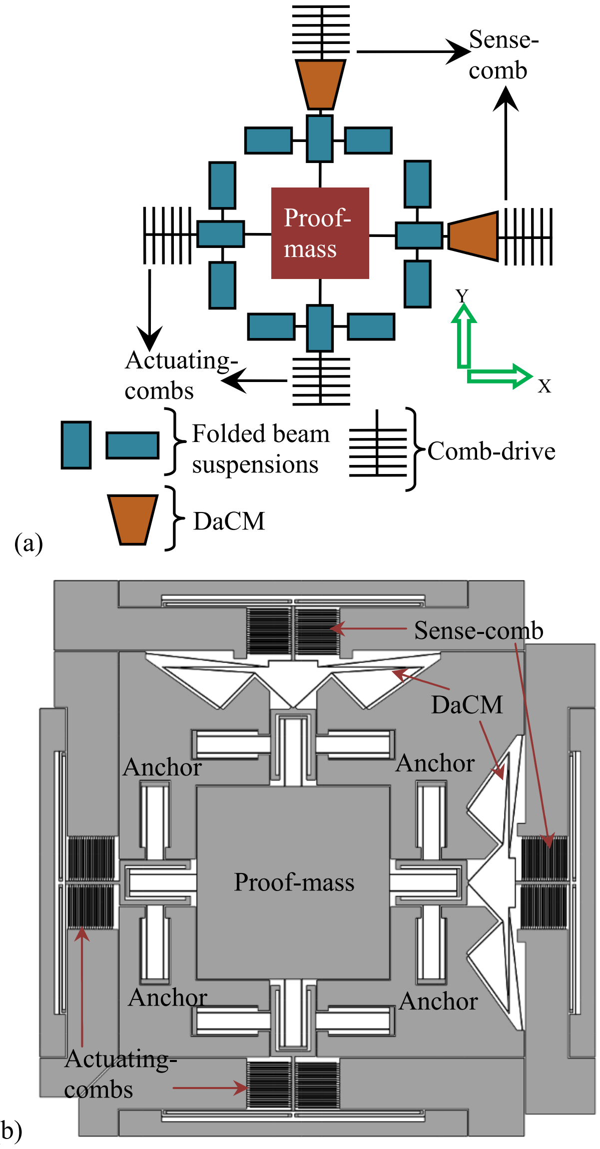


*Figure 1: a) The schematic and (b) the layout of a dual-axis capacitive lateral accelerometer with a decoupling mechanism and two inverting DaCMs.*

The design is symmetric along both the X and Y axes. The thickness of the device of the entire device was kept at 25 μm. The minimum feature size is kept at 6 μm and the sensegaps at 4 μm. The total size of the designed accelerometer is 8.5 mm × 8.5 mm along with a proof-mass that is as big as 3 mm × 3 mm.

### Modeling

The 2D finite element structural analysis of the designed device, shown in Fig. 2, using COMSOL Multiphysics [8] shows that the displacement sensitivity, i.e., the displacement of the sense-comb per unit gravitational load, is 0.586 μm/g for both the axes. This corresponds to a capacitance sensitivity of 0.166 pF/g with a base capacitance of 0.66 pF. The off-axis sensitivity was simulated to be 0.7% of the axial sensitivity for both the axes. The inherent geometric amplification achieved using the DaCM was 6.12. The Net Amplification (NA), defined as the ratio of the maximum displacement at the sensing port of the sensor with a DaCM to the maximum displacement of the sensor without a DaCM but occupying the same chip area, achieved for the design of the accelerometer by using a DaCM was 0.586/0.382 = 1.53. Thus, the improvement of sensitivity was calculated by {(0.586-0.382) / 0.382} × 100% = 53%. The simulated two fundamental in-plane modal frequencies, which are identical due to structural symmetry, were found to be around 1031 Hz. This is approximately 25 % more than the model without DaCMs but occupying the same footprint area.

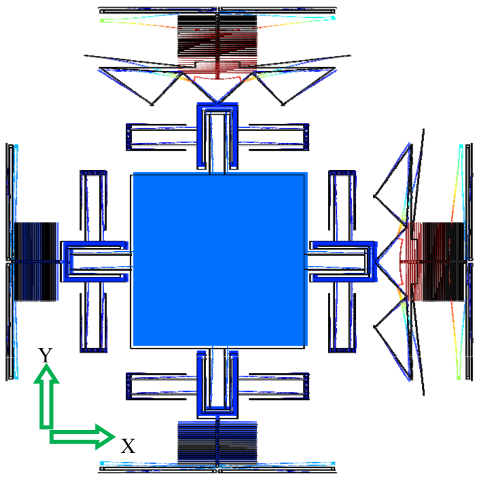


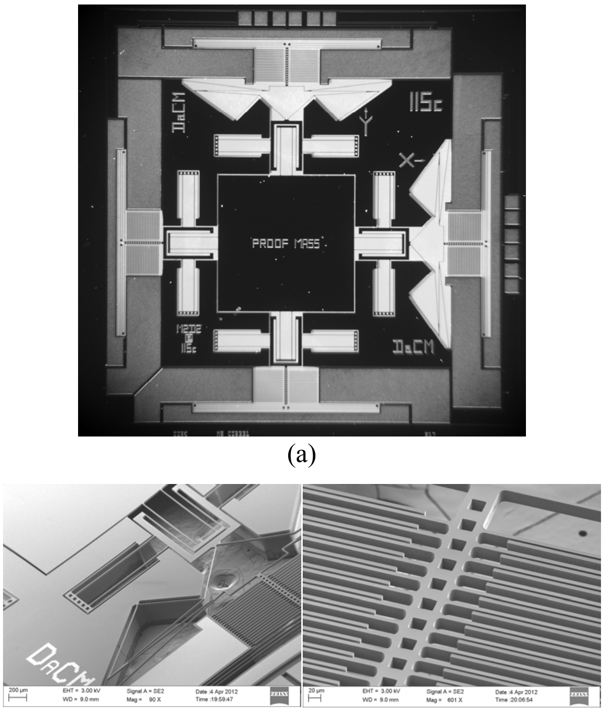
*Figure. 2: Simulated image of the device under 1 g body-load along both the axes. The decoupling mechanism decouples the applied acceleration into its corresponding axial components and the two DaCMs amplify the displacement of the proof-mass along both the axes.*

## MICROFABRICATION

The dual-axis accelerometer was fabricated using the SOIMUMPs [9] process. This process uses Silicon-on-Insulator (SOI) wafer with 25 μm thick structural layer, 2 μm buried oxide layer and 400 μm substrate layer. The device was fabricated by patterning the 25 μm structural layer of the SOI wafer. The 400 μm-thick substrate layer is removed from the backside using DRIE and then a wet oxide etch process is used to remove the oxide layer. An optical micrograph of the fabricated device is shown in the Fig. 3a and two scanning electron microscope (SEM) images showing different parts of the device are given in Figs. 3(b-c).

## DYNAMIC CHARACTERIZATION

The die-level dynamic measurements were performed using MSA 500 Micro System Analyzer, a Scanning Laser Doppler Vibrometer [10]. The device was actuated electrostatically using an alternating voltage of 5 V above a DC bias of 5 V applied on the actuating-combs. The frequency of the applied voltage was swept from 10 Hz to 1.2 KHz. The in-plane frequency response along both the X and Y axes of the device is shown in the Fig. 4. The experimentally obtained in-plane modal frequency was 920 Hz for X axis and 918 Hz for Y axis. It was observed that the average geometric amplification achieved using the DaCMs is 6.22 along X axis and 6.28 along Y axis. The 3 dB bandwidth of the sensor was measured to be approximately 580 Hz for both the axes.



(a)

(b) (c)

*Figure 3: a) The optical micrograph of the entire fabricated dual-axis accelerometer and (b-c) two scanning electron microscope (SEM) images showing parts of the fabricated device.*

## PACKAGING

The fabricated accelerometer was packaged along with commercially available universal capacitance readout ASIC die MS3110D [11]. A hybrid die-to-die System-in-Package (SiP) technique was adopted to package the device inside a 30-pin flat hybrid ceramic package. A custom designed Low Temperature Co-fired Ceramic (LTCC) substrate was used as the base for both the micromachined device and the interface electronic ASIC dies. Electrical connections are routed by screen printing of silver paste on the LTCC substrate. Conductive silver epoxy was used to perform die-to-substrate attachments and non-conductive epoxy was used to attach the ceramic substrate to the package. All the electrical connections between the accelerometer die to capacitance extraction ASIC dies and between the ASIC dies to the contact pads on the LTCC substrate were established by performing thermosonic ball-to-wedge gold wire bonding. Figure 5a shows an optical image of the accelerometer wire-bonded to the capacitance extraction ASIC dies placed inside the hybrid ceramic package. An evaluation board was designed and fabricated for testing the packaged accelerometer.

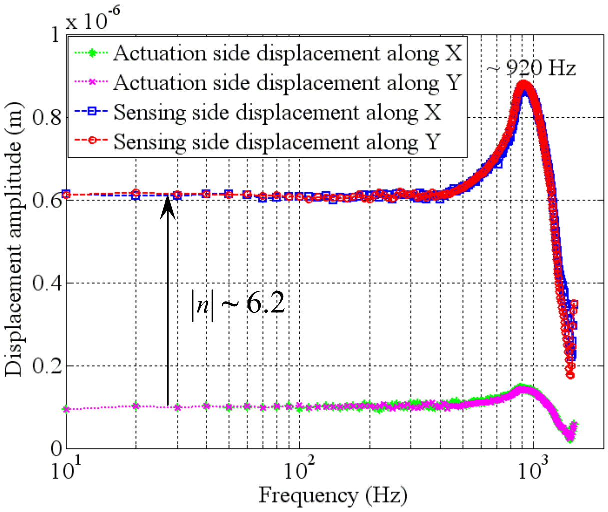
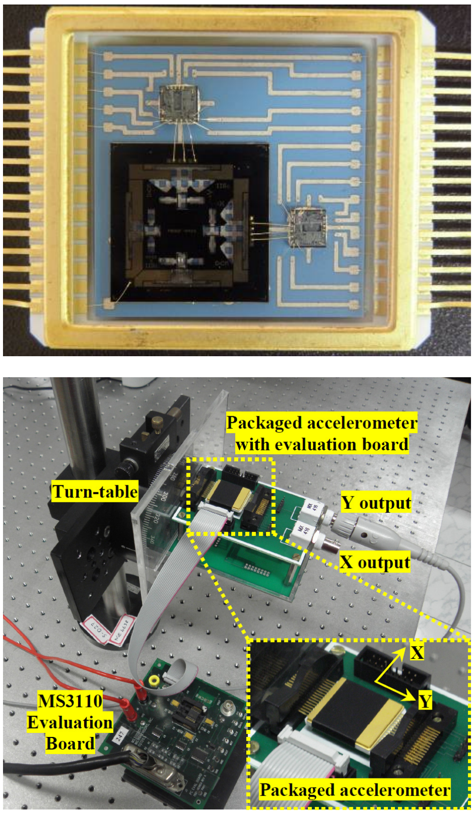


*Figure 4: Experimentally obtained Bode plot of the accelerometer showing the frequency response of the device at both the input and output of the DaCMs.*


(a)

(b)

*Figure 5: (a) Hybrid die-to-die packaging of a dual-axis accelerometer die along with two MS3110 dies, (b) experimental setup showing the packaged accelerometer along with the evaluation board mounted on a vertical turn-table.*

## TESTING AND CALIBRATION

The packaged dual-axis accelerometer was tested and calibrated by mounting the packaged accelerometer along with the evaluation board on a vertical turn-table. The experimental setup showing the packaged device on the turn-table is shown in Figure 5.b. The turn-table was rotated precisely to vary the applied acceleration on the device. The open-loop static response of the packaged device is shown in Figure 6. The measured sensitivity was 580 mV/g and 589 mV/g for X and Y axes respectively. The cross-axis sensitivity of the packaged accelerometer was also measured by mounting the packaged accelerometer such that the acceleration due to gravity acts perpendicularly to the measuring axis. The cross-axis sensitivity of the packaged dual-axis accelerometer was measured to be less than 1% for both the axes.

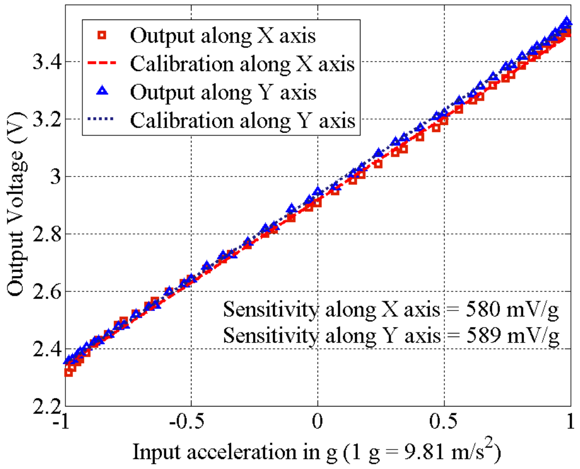


*Figure 6: static calibration curve for the dual-axis accelerometer along both the axes.*

## DISCUSSION AND CLOSURE

In this paper, we demonstrated a dual-axis capacitive in-plane micromachined accelerometer with Displacement-amplifying Compliant Mechanisms (DaCMs). The accelerometer contains an XY stage mechanism that acts as a decoupling mechanism as well as the proof-mass of the accelerometer. The decoupling mechanism was designed by arranging 12 folded-beam suspensions in a specific way to achieve a high cross-axial and rotational stiffness. The input sides of the DaCMs were appended to the decoupling mechanism and the output sides were attached to differential capacitive comb-drives. The comb-drive measures the amplified displacement of the proof-mass in both the X and Y axes. Thus, 50% improvement of sensitivity along with 25% improvement in bandwidth was achieved. The static displacement sensitivity was simulated to be 0.586 µm/g which corresponds to a static capacitance sensitivity of 0.166 pF/g.

A Silicon-on-Insulator Multi User MEMS Processes (SOIMUMPs) was used to fabricate the device. The in-plane dynamic characterization on the fabricated device was performed using Laser Doppler Vibrometer. The in-plane natural frequency of the fabricated device was found to be 920 Hz and 918 Hz for X and Y axes respectively. Finally, the fabricated device was packaged using hybrid System-in-Package technique. The testing and calibration of the packaged dual-axis accelerometer was performed by mounting the packaged accelerometer on a vertical turn-table and then applying acceleration on the device by rotating the turn-table precisely. The open-loop static sensitivity of the packaged dual-axis accelerometer was found to be 580 mV/g and 589 mV/g for X and Y axes respectively with a cross-axis sensitivity of less than 1%.

## ACKNOWLEDGEMENTS

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