

MEMS ACCELEROMETER WITH MULTIAXIAL RESPONSE BY DYNAMIC RECONFIGURATION OF PIEZORESISTIVE BRIDGES

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Abstract: A MEMS accelerometer manufactured in silicon bulk micromachining with piezoresistive detection is presented. The sensor consists of a seismic mass suspended by four flexural beams that integrate two piezoresistors each. The piezoresistors can be externally connected into different Wheatstone bridges, providing acceleration sensitivity along different axes. By means of the dynamic reconfiguration of the piezoresistive bridges a triaxial response is obtained, allowing the measurement of the x , y and z components of acceleration. An electronic interface for the dynamic reconfiguration of the bridges and for the signal conditioning is proposed. Experimental results are reported demonstrating good agreement with theoretical predictions.

Keywords: MEMS accelerometer, piezoresistive detection, resistive bridge, dynamic reconfiguration.

1 SENSOR DESCRIPTION

Micromachined silicon accelerometers are established devices that offer good performance-to-cost ratio. In an increasing number of applications, the measurement of the acceleration along three orthogonal directions is required, demanding for multiaxial accelerometers [1]. Bulk- and surface-micromachining accelerometers present a good linearity and a low level of cross-axis sensitivity. In [2, 3] a triaxial acceleration measurement is obtained by means of multi-mass devices where the measurement is accomplished by combining the acceleration detected by each monoaxial device. In [4, 5] triaxial accelerometers are reported where piezoresistive Wheatstone bridges are implemented for the different measurement axes. In this work a piezoresistive accelerometer capable of multiaxial response was designed, manufactured in silicon bulk micromachining and tested. The device was fabricated in the SensoNor Normic Multimems process offered as a Europractice MPW service for MEMS. Figure 1 shows a schematic diagram of the sensor structure.

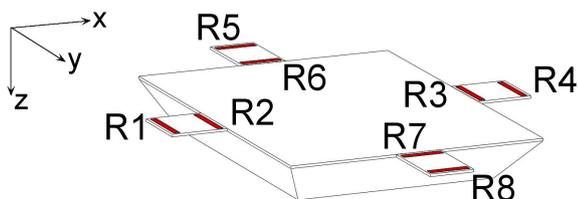


Figure 1. Schematic diagram of the accelerometer structure.

The sensor consists of a seismic mass (2.55 x 2.55 x 0.4 mm) linked to the silicon substrate by means of four suspension beams (0.55 x 0.44 x 0.023 mm) arranged symmetrically at the sides of the mass. Two piezoresistors are

implanted at both ends of each beam. Figure 2 shows a top-view picture of the sensor.

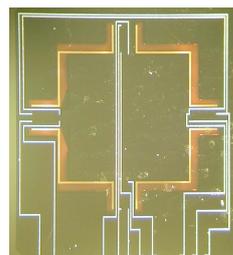


Figure 2. Sensor top-view picture.

The applied acceleration produces the roto-translation of the mass and the deflection of the beams [4, 5]. The eight piezoresistors are only partially connected internally to the sensor, while selected nodes are made accessible through external pads. In this way, the set of piezoresistors can be either configured in two separate Wheatstone bridges for the detection of x and y components of the acceleration, or in a single bridge for the detection of the z component. Figures 3(a) and 3(b) show the displacement of the mass, the corresponding variations of the piezoresistors, and the resulting effects on the bridges for x and z accelerations.

For accelerations along the x axis, the mass tilts around the y axis and only the bridge formed by piezoresistors R1 to R4 produces an unbalance. Similarly, for accelerations along the y axis, the mass tilts around the x axis and only the R5-R8 bridge undergoes an unbalance. For accelerations along the z axis, the mass translates out of plane causing the same deformation in all the beams, and the configuration of the piezoresistors produces an unbalance in the z bridge only.

The symmetry of the structure and the arrangement of the piezoresistors reduce the cross-axis sensitivity.

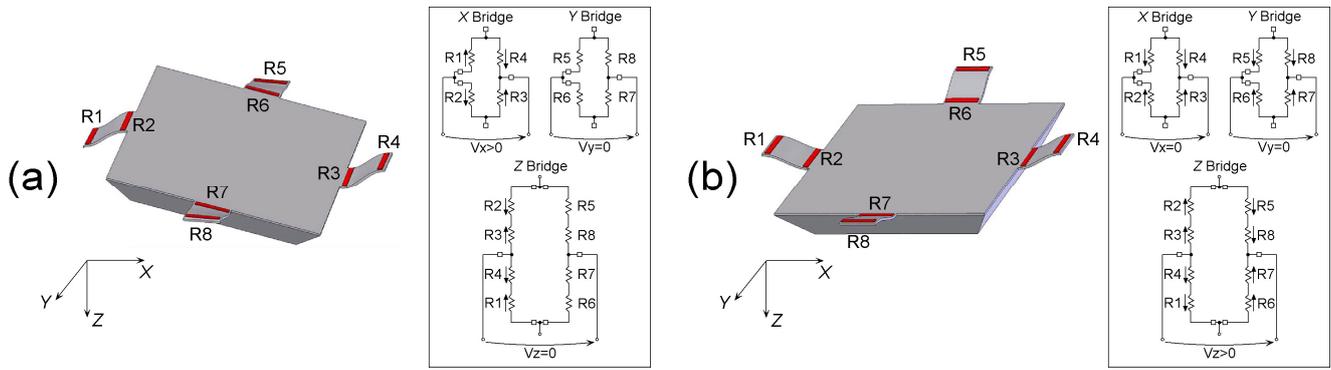


Figure 3. Displacement of the seismic mass and unbalance voltage of the bridges for applied accelerations along the x axis (a) and the z axis (b). The square dots denote the external accessible pads.

Table 1. FEM results for the triaxial accelerometer.

Axis	Measurement range [g]	Sensitivity [(mV/V/g)]	First resonant frequency [kHz]
x, y	± 5000	7.9×10^{-3}	15.5
z	± 1000	4.5×10^{-2}	9.8

By electronically switching the piezoresistors across the different configurations, the sensor response can be changed on the fly. In particular, if the switching frequency is suitably higher than the measurand bandwidth, the sensor provides a sampled-time triaxial response with the capability of measuring the three distinct components of acceleration.

Finite element method (FEM) simulations were performed to predict the natural frequency of the basic vibration modes and therefore the measurement bandwidth of the device. The simulation was used also to determine the stress distribution in the piezoresistor locations for different values of acceleration along the three orthogonal axes. By inserting the piezoresistive response, the sensitivities of the bridges were then calculated. The results of the FEM simulation are shown Table 1.

2 ELECTRONIC INTERFACE CIRCUIT

An electronic circuit to interface with the acceleration sensor was designed. The block diagram is shown in Figure 4. The circuit is based on a network of switches for the dynamic reconfiguration of the sensor piezoresistors into different bridges.

For the measurement of acceleration components a_x , a_y , and a_z in the three orthogonal directions, the switching among the different configurations occur in two phases corresponding to the high level of the signals Φ_{xy} and Φ_z . In the first phase, the x and y measurements are achieved by connecting the corresponding bridges as in Figure 3(a). In the second phase, the z measurement is obtained by connecting the piezoresistors in a single bridge as in Figure 3(b).

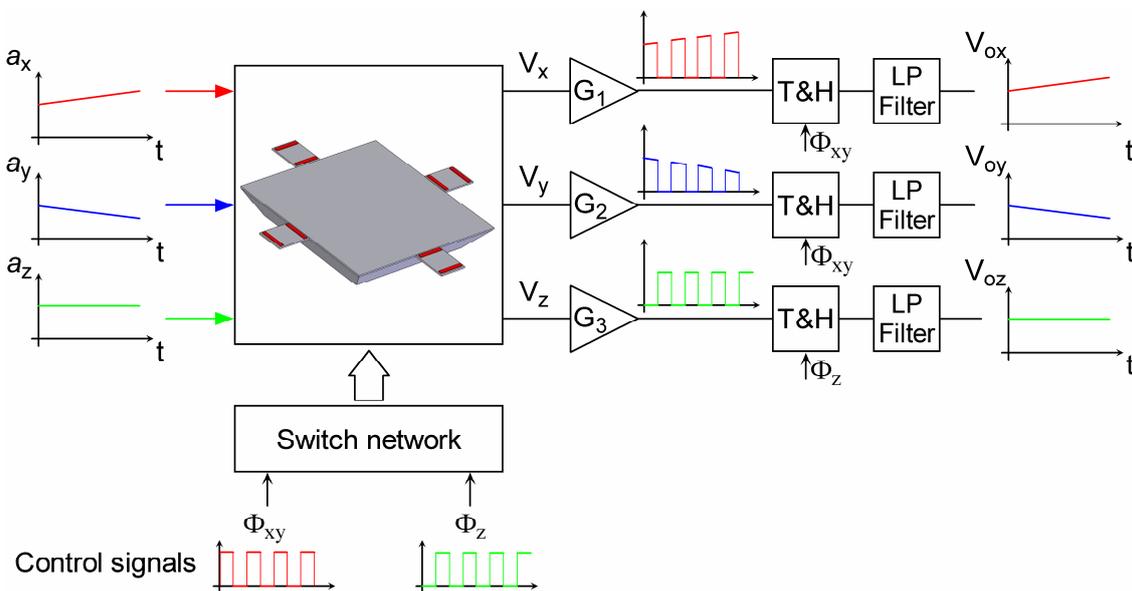


Figure 4. Block diagram of the interface circuit.

In each phase, the circuit configures the corresponding bridges by turning on and off suitable switches whose arrangement improves the symmetry of the bridges. The piezoresistors are connected in Wheatstone bridge configurations excited by a DC current by means of a voltage-to-current converter. The current excitation reduces the effect of the voltage drop across the switches and improves the thermal stability and the transient response in switching between phases. The bridge unbalance voltages V_x , V_y and V_z are amplified by means of instrumentation amplifiers followed by non-inverting stages, with overall gains G_1 , G_2 , and G_3 of about 1000. The stages are based on devices that have been chosen to maximize the bandwidth and reduce the settling time of the outputs. Each amplification channel includes a circuit for the offset correction. The amplified signals are synchronously sampled by means of track and hold (T&H) devices and the outputs are low-pass filtered (LP Filter). Tailored nonlinear filters were used in order to preserve signal fast transients and, at the same time, attenuate residual wideband noise aliased due to sampling. The circuit then provides three different output voltages V_{ox} , V_{oy} and V_{oz} proportional to the x , y and z components of acceleration.

The nominal sensitivities result of about 48 mV/g for the x and y axes, and 210 mV/g for the z axis.

3 EXPERIMENTAL RESULTS

The sensor was connected to the electronic interface for the characterization. The bridge reconfiguration frequency was set to 10 kHz, therefore a conservative estimation of the measurement bandwidth is the 0÷1 kHz range. The static sensitivity of each accelerometer axis was measured by mounting the sensor on a rotating fixture and turning it to variable inclination between -90° and 90° , i.e. static acceleration between $-g$ and g . In Figure 5 the schematic diagram of the measurement system is shown.

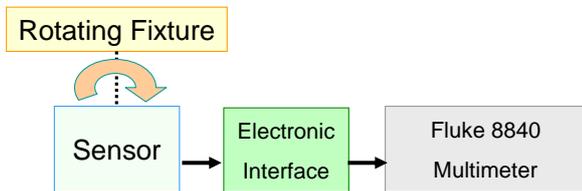


Figure 5. Schematic diagram of the measurement system used for static inclination tests.

For each axis x , y , z the voltages V_{ox} , V_{oy} and V_{oz} were respectively measured as a function of the inclination angle. The zero angle was chosen at the inclination where the axis response is null.

Measurements were made both with the dynamic reconfiguration active and disabled, i.e. with the bridges always on. Figures 6, 7, 8 show the output voltages V_{ox} , V_{oy} and V_{oz} as a function of the inclination of the corresponding axis with respect to the horizontal. The results show the expected sinusoidal behavior in good agreement with the theoretical prediction. The sensitivities, expressed as the output voltage versus the component of acceleration along the measurement axis, are about 51 mV/g for x and y axes, and about 206 mV/g for z axis.

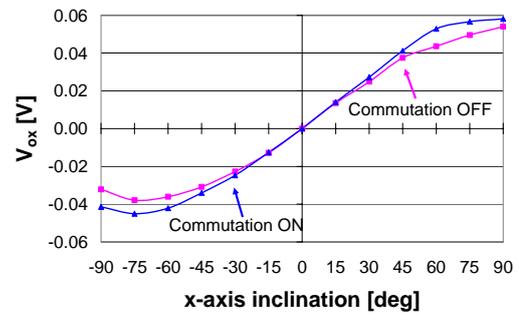


Figure 6. V_{ox} circuit output versus x -axis static inclination.

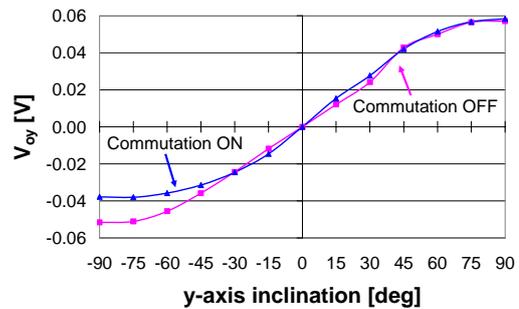


Figure 7. V_{oy} circuit output versus y -axis static inclination.

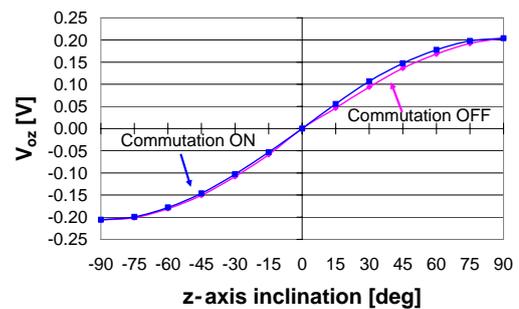


Figure 8. V_{oz} circuit output versus z -axis static inclination.

The resolution of the system was evaluated by measuring the output voltages at constant applied acceleration and by calculating the standard deviation over a 30-sample population. For each axis the sensitivity, the output standard deviation, the corresponding nominal RMS resolution, calculated taking in account the measured sensitivities, and the nominal measurement range are shown in Table 2.

Table 2. Main specifications of the system.

Axis	Sensitivity [mV/g]	Output standard deviation [mV _{rms}]	Resolution [g]	Measurement range [g]
$x - y$	51	3.3	0.06	190
z	206	6.5	0.03	48

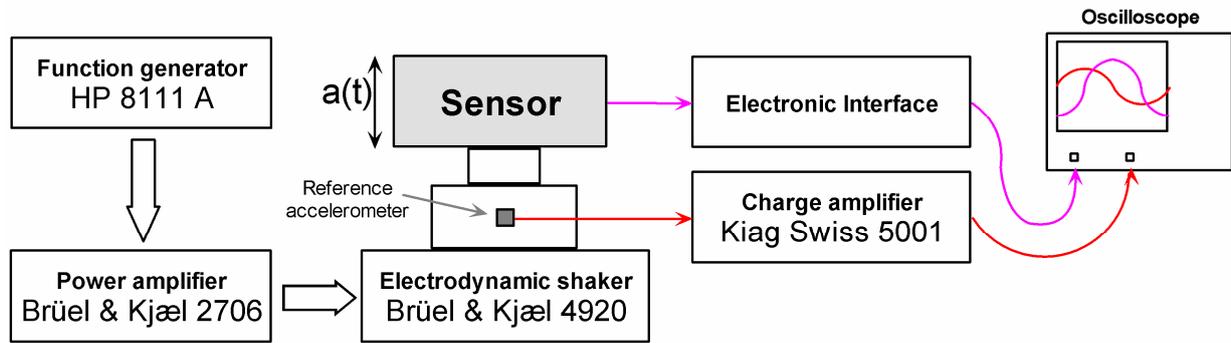


Figure 9. Experimental setup for the dynamic characterization.

The sensor was then tested under AC acceleration. In Figure 9 the experimental setup used for the dynamic measurements is shown. A sinusoidal acceleration was applied to the sensor by means of a calibration exciter Brüel & Kjæl 4920 having a built-in reference accelerometer with a sensitivity of 1 V/g. A function generator provides a signal to a power amplifier that feeds the electrodynamic shaker. A constant-amplitude acceleration was applied to the sensor at various frequencies for each axis direction. The outputs of the circuit interface were acquired by means of a digital storage oscilloscope LeCroy LT374M. Figure 10 and 11 show the obtained results for acceleration applied to the x and z axis respectively, for a peak acceleration of 2 g at 600 Hz.

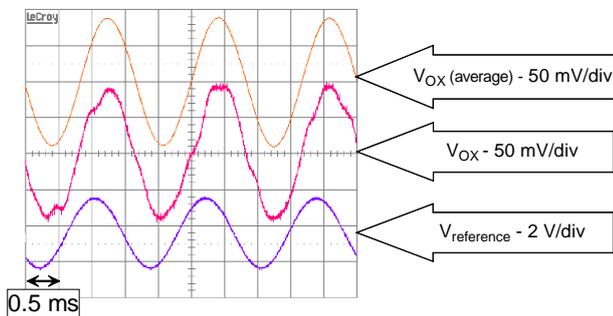


Figure 10. V_{ox} circuit output for sinusoidal acceleration along x-axis.

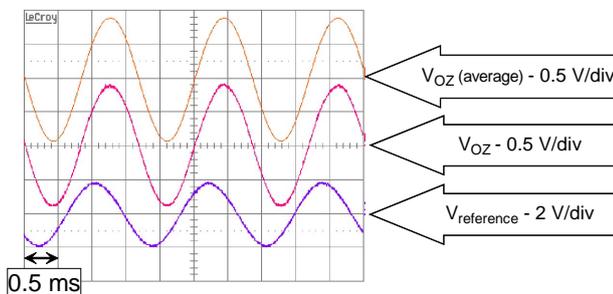


Figure 11. V_{oz} circuit output for sinusoidal acceleration along z-axis.

The slight phase shift is due to the mechanical mounting of the packaged sensor on the exciter. Similar results were obtained for the y axis, confirming a good reproduction of the applied acceleration.

4 CONCLUSIONS

A MEMS triaxial accelerometer with piezoresistive detection has been designed, manufactured in bulk-micromachining technology and characterized with a tailored electronic interface. The interface circuit implements the dynamic reconfiguration of the sensor piezoresistors into different bridges and the processing of the unbalance signals, thereby allowing the measurement of the three components of acceleration. Results have shown a behavior in agreement with expectations. The system has a sensitivity of about 51 mV/g for x and y axes, and about 206 mV/g for z axis and a resolution of 0.06 g and 0.03 g respectively.

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