Development of a Package for a Triaxial High-G Accelerometer Optimized for High Signal Fidelity

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Abstract: In this work a package for a triaxial piezoresistive high-g acceleration sensor is developed. The sensor part consists of three sensor chips placed in a ceramic plate. This sensing element is modeled and simulated within the package including the thin adhesive layers. We examine the behavior at different excitation frequencies. Due to resonance effects the sensitivity of the sensor increases at higher frequencies. The influence of the single Eigen modes is analyzed and the essential modes are identified. Within the experiments the influence of the Eigen frequencies on the sensor signal is investigated and the sensitivity of the sensor is tested for a transient impulse. The experimental results fit quite well with the expected values given by the simulation. So the simulation could be verified with the experiments.

Keywords: high-g, high frequency, accelerometer, piezoresistive, frequency spectrum

1. Introduction

Acceleration is an important quantity to be measured in high-speed dynamics. Many other measurands like velocity, force and pressure can be derived from it. A new piezoresistive sensor chip for the measurement of high-amplitude, short-duration transient accelerations of up to 100000 g has been developed at the Fraunhofer EMI. Its figure of merit (sensitivity times resonance frequency²) is about one order of magnitude higher than that of comparable state-of-the-art sensors [1].

Figure 1 shows the basic design of the sensing element, consisting of a stiff frame, a bending plate and four piezoresistive elements interconnected to a Wheatstone bridge. It is a silicon MEMS that has been fully modeled using COMSOL [2].

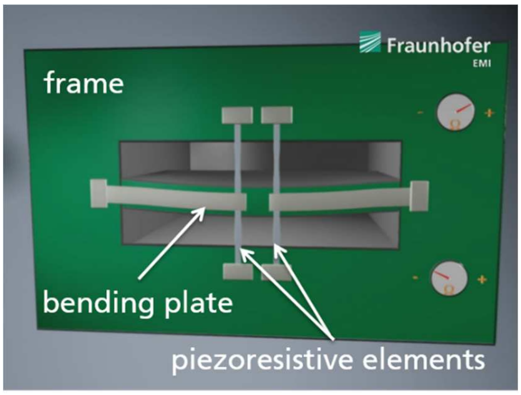

Figure 1: Schematic illustration of the sensor chip. Acceleration deflects the bending plate and the piezoresistive elements are compressed/expanded, resulting in a measurable change of resistivity.

Currently, we develop a triaxial sensor which integrates three uniaxial sensor chips onto a single ceramic substrate (Figure 2).

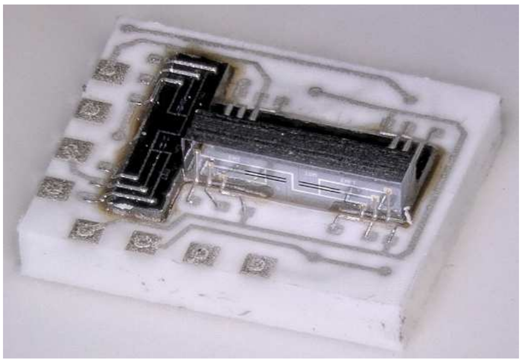

Figure 2: Sensor element: Arrangement of three sensor chips placed in the ceramic plate.

The chips are oriented orthogonal to each other and are sensitive in x,y and z direction. The connection between sensor chip and ceramic is realized as printed aerosol jet connections. This is further called sensor element.

2. Governing equations

There are two governing physical effects that describe the behavior of the sensor chip and the package.

2.1 Mass spring system

The sensor including its package acts like a complex mass spring system. In general the behavior of a harmonic oscillator is defined by the following equation

$$\frac{d^2x}{dt^2} + 2\omega_0\zeta\frac{dx}{dt} + \omega_0{}^2x = a(t)$$

ω_0 = Eigenfrequency of the oscillator
ζ = damping ratio
a(t) = excitation acceleration

When a(t) = a*sin(ωt) the amplitude of the oscillator is dependent on the excitation frequency. This behavior is shown in Figure 3. A detailed analysis is given in [3].

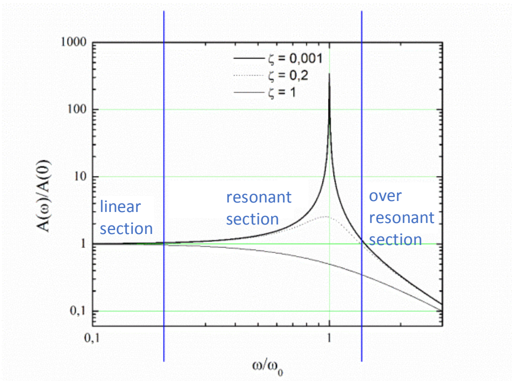

Figure 3: Normalized Bode plot of a spring mass system. Displayed is the normalized amplitude over the normalized excitation frequency for three different damping ratios.

The linear section shows nearly no difference (max 5%) to the static behavior of a spring mass system up to about 20% of ω_0. At higher frequencies the amplitude reaches its maximum at about $\omega = \omega_0$. For even higher frequencies the amplitude will decrease again.

For measuring it is crucial to stay in the linear section to get accurate values. Thereof a rule of thumb is established that the usable bandwidth is 1/5 of the relevant lowest Eigenfrequency of the sensor system.

2.2 Piezo-resistive effect

Due to the movement of the bending plate at acceleration loadings the piezoresistive elements are stretched respectively compressed. This results in a change in electrical resistance and is called the piezoresistive effect. For silicon this effect is anisotropic and can be described by the following formula:

$$\frac{1}{\rho_0}\begin{pmatrix}\Delta\rho_{xx}\\ \Delta\rho_{yy}\\ \Delta\rho_{zz}\\ \Delta\rho_{yz}\\ \Delta\rho_{xz}\\ \Delta\rho_{xy}\end{pmatrix} = \begin{pmatrix}\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0\\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & \pi_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & \pi_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & \pi_{44}\end{pmatrix} \cdot \begin{pmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{pmatrix}$$

$\Delta\rho_{xx}$ = change of the specific resistance
π_{ij} = piezo-resistive coefficient
σ_{xx} = stress in the specified plane

For given piezo-resistive coefficients and known stress the change of the relative resistance can be computed for each plane. The values of the silicon used for the sensor chips are specified in [3] based on [4].

3. Simulation with COMSOL Multiphysics® Software

As part of this development we simulate the sensor with different package concepts with COMSOL Multiphysics. One example for a package concept is shown in Figure 4. The goal of the simulation is to examine and understand the oscillation behavior of the sensor and package for high excitation frequencies. The geometry is modeled with the CAD software Autodesk Inventor and imported via "LiveLink for Inventor".

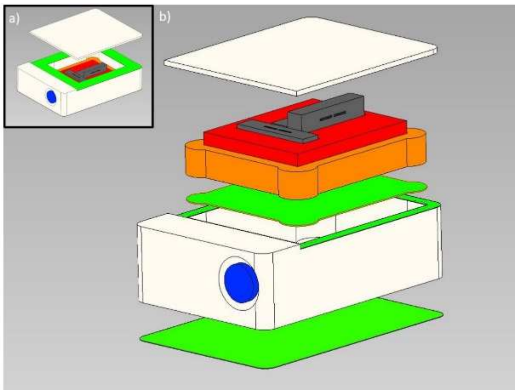

Figure 4: Example package design a) with lifted cap and b) shown as exploded view. The parts are color-coded: white/transparent: package box + cap, red: ceramic substrate, grey: sensor chips, orange: grouting, green: adhesive layers, blue: cable dummy.

To examine the behavior of the sensor over the relevant frequency range we made two approaches. One is a modal analysis of the system which gives us the value and shape of the resonance frequencies. For the second approach we simulated the sensor with an oscillating volume acceleration load that is applied to the system and swept over a frequency range from 0 to 250 kHz. The outcomes of the simulation contains the stress and displacement of all components within the package. With this information the relative resistance of the piezoresistive bridges can be derived and the output signals of the sensor chips have been computed.

4. Numerical results

The results will be shown for a defined example package with following parameter settings:

Wall thickness: 1 mm
Cap thickness: 200 µm
Package material: Titanium
Adhesive Young's modulus: 2.5 GPa
Adhesive layer thickness: 20 µm
Sensor chip: type M (0.65 µV/V/g)

Figure 5a shows the complete spectrum of the output signal of the sensor at the given excitation frequencies. The signal is computed for 100000 g and a supply voltage of 1 Volt. We have defined a maximal change of sensitivity of 5% as limit for our sensor.

At first glance the curve seems to show a flat behavior until ~130 kHz where the high resonance peak appears. However as seen in Figure 5b the sensitivity change appears also at lower frequencies. With a maximum of 5% change of sensitivity the package has a possible bandwidth of 47 kHz.

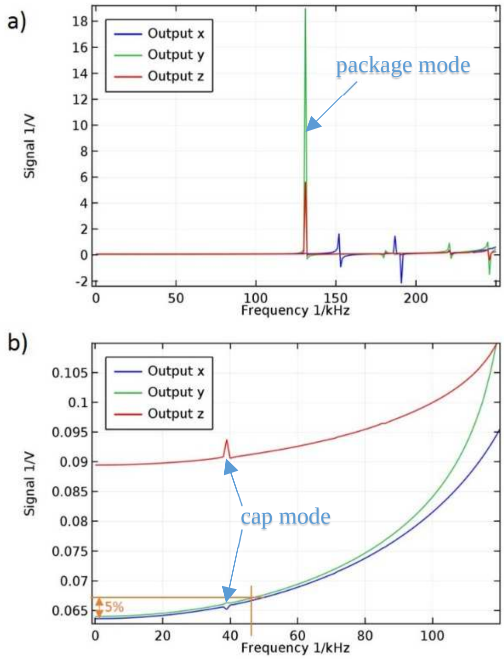

Figure 5: Results of the frequency spectrum analysis for all three sensor axes. Output signal over the excitation frequency. a) Whole frequency spectrum from 0 to 250 kHz. b) Zoomed in to frequencies from 0 to 100 kHz.

Besides the examination regarding the bandwidth we looked at the modes of the package and could identify the relevant modes that are seen as peaks in the spectrum.

The first mode is a "cap mode" at 39 kHz (Figure 6). It has very little influence on the sensor sensitivity and can be seen as the first small peak in the spectrum. The influence is below the 5%-limit.

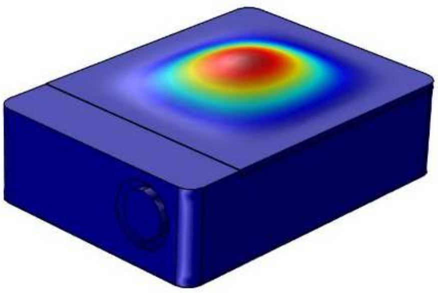

Figure 6: Example of results of the modal analysis. First "cap mode": cap deflects in z-direction at 39 kHz.

The high peak is located at 128 kHz and its mode is displayed in Figure 7. It is the first mode besides the cap oscillations and is further called "package mode". In the simulation the influence of this mode on the sensor signal is very high.

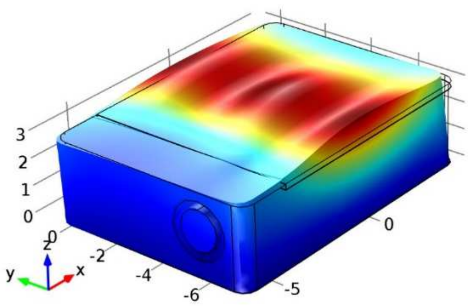

Figure 7: First "package mode" with oscillations in y-direction at 128 kHz.

The modal analysis shows another oscillation at 287 kHz (Figure 8) in which we expect a huge influence on the signal. It is the main oscillation of the sensor element. This frequency is not shown in Figure 5.

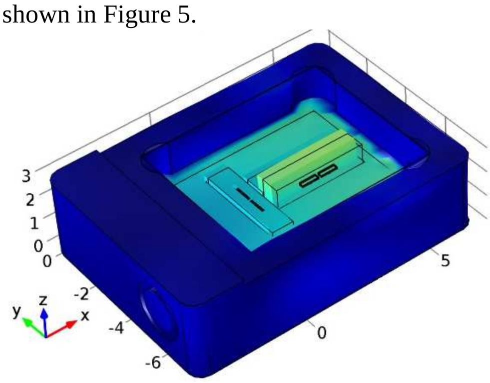

Figure 8: Mode of the main displacement within the sensor element. The green and yellow color show the displacement of the sensor element.

With the bandwidth of 47 kHz the main oscillation is expected at ~235 kHz. Due to the superposition of all influences of the modes the mode at 287 kHz seems to be the main influence on the signal output for vibration and shock events. This assumption shall be tested with experiments.

5. Experimental results

The experimental parameters of the package differ due to practical issues from the shown example. The following package parameters were used:

Wall thickness: 1 mm
Cap thickness: 200 µm
Material: Titanium
Adhesive Young's modulus: 0.56 GPa
Adhesive layer thickness: 20 - 70 µm
Sensor chip: type L (1.3 µV/V/g ± 30%)

Due to the uncertainty of the adhesive thickness an adapted simulation with these parameters was executed. It predetermines in following ranges for the expected frequencies:

5%-limit: 16-30 kHz
Package mode: 67-98 kHz
Sensor element mode: 129-200 kHz

We have tested for two characteristics of the sensor. Its relevant and measurable Eigen frequencies and its sensitivity for each axis.

5.1 Eigenfrequencies

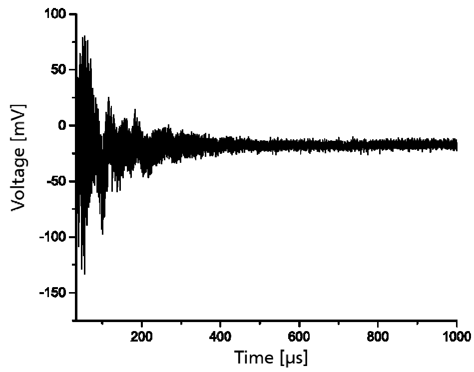

Figure 9: Example of an impulse answer of the packaged sensor attached to a ceramic plate.

To measure the Eigen frequencies the sensor oscillation was stimulated with a transient impulse. The impulse was induced by a small glass hammer. The sensor signal of this impulse is recorded (example in Figure 9) with a sampling rate of 10 MHz.

To examine the signal for the relevant frequencies the signal was converted into the frequency domain via FFT. The relevant Eigen frequencies should appear as peaks. To get a better signal to noise ratio we averaged over the FFT of 10 measurements of one sensor. The result is shown in Figure 10.

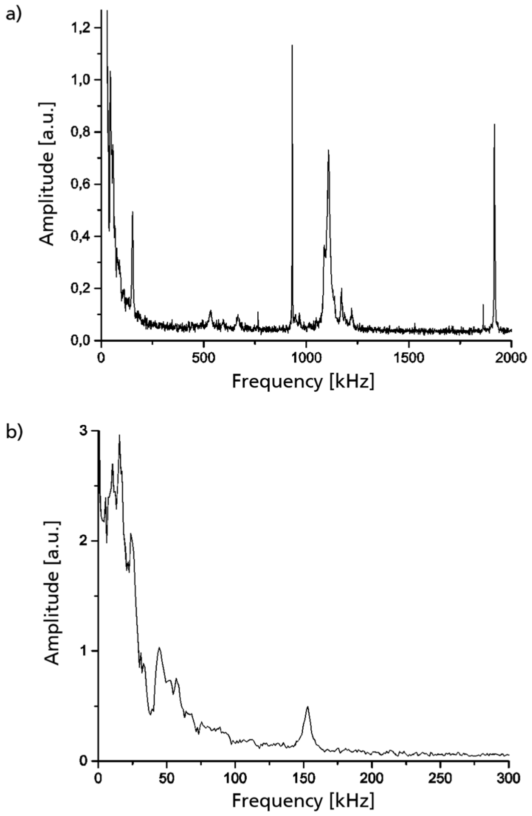

Figure 10: Averaged frequency spectrum of the impulse answer. a) Displayed from 0 to 2 MHz. b) Displayed from 0 to 350 kHz.

There are several peaks at higher frequencies. The highest at 930 kHz displays the first Eigen frequency of the sensor chip itself. The lower frequencies up to ~70 kHz are part of the excitation impulse.

The interesting peak is at 153 kHz as it represents the oscillation of the sensor element that is expected between 129 and 200 kHz. This result supports the theory that this oscillation is the main influence on the sensing elements.

5.2 Sensitivity

All axes were tested with a setup which is designed to induce the same acceleration of 8600 g on each axis. To generate the shock load a titanium Hopkinson bar [5] was used. To distribute the load equally on each sensor axis the sensor must be attached with an angle of 54.7%. This is achieved with an attachment at the end of the Hopkinson bar (Figure 11).

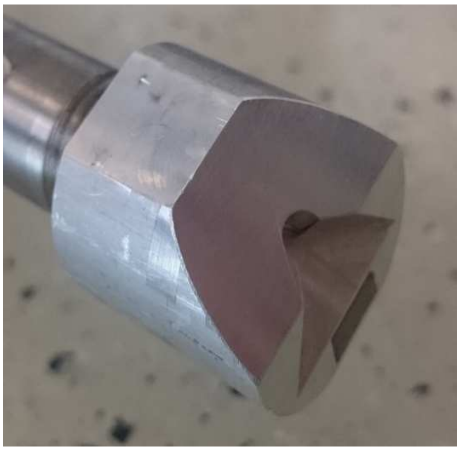

Figure 11: Attachment for the Hopkinson bar to get equally distributed triaxial loads.

The measured output signals are displayed in Figure 12.

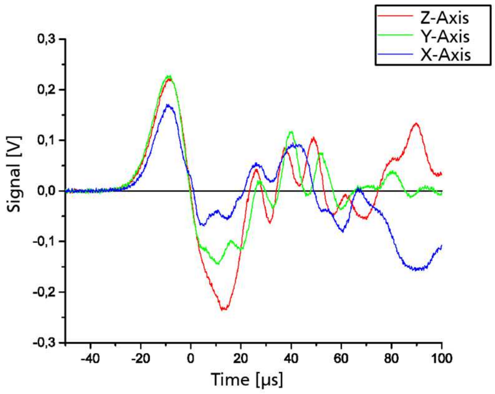

Figure 12: Triaxial sensor signal under triaxial transient loads of 8600 g.

From this data the sensitivities for the axes were computed

X: 1.00 µV/V/g

Y: 1.33 µV/V/g

Z: 1.30 µV/V/g

The expected sensitivity is 1.3 µV/V/g with a deviation of up to 30%. The highest deviation occurs at the X-axis sensitivity with about 23 %. The deviation of the other axis is much lower. All sensor chips are within the 30 %-deviation range. We do not expect an influence of the package on the sensitivity of the sensor.

With this experiment the suitability of the sensor including its package could be verified.

6. Conclusion

The frequency spectrum simulation revealed a bandwidth of 47 kHz for the package. This exceeds the performance of commercial products which have a much lower bandwidths of 10-20 kHz. The main influence and thus the most relevant Eigen frequency for the performance of the sensor including package is the oscillation of the sensor element inside the package. This is shown by both simulation and experiments.

With the known behavior of the sensor it is possible to optimize the package furthermore to get an even higher bandwidth for the sensor.

The experiments have shown the general suitability of the sensor and confirmed the results of the simulation as far as possible.

The next step is to achieve a higher Eigen frequency for the sensor element mode and further experimental characterization of the developed sensor.

7. References

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8. Acknowledgements

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