CHARACTERISATION OF A HIGHLY SYMMETRICAL MINIATURE CAPACITIVE TRIAXIAL ACCELEROMETER

J.C. Lötters, W. Olthuis, P.H. Veltink, P. Bergveld

MESA Research Institute, University of Twente

P.O. Box 217, 7500 AE Enschede, The Netherlands

Phone: +31-53-4892755; Fax: +31-53-4892287; e-mail: j.c.lotters@el.utwente.nl

SUMMARY

A highly symmetrical cubic capacitive triaxial accelerometer for biomedical applications has been designed, realised and tested. The sensors are available in two outer dimensions, namely $2 \times 2 \times 2$ and $5 \times 5 \times 5$ mm³. The devices are mounted on a standard IC package for easy testing. Features of the sensor are a highly symmetrical cubic structure, capacitive coupling of the high frequency input voltage to the seismic mass and the use of the polymers polydimethylsiloxane (PDMS) as spring material between the capacitor plates and the mass and polyimide (PI) as flexible interconnection layer between the capacitor plates. The sensor structure and its basic operating principle, its mathematical mass-spring-damper model and the necessary cleanroom technology are described. The measurement results show a sensitivity of ~ 0.15 V/(m/s²) with a corresponding resolution of 0.01 m/s², an off-axis sensitivity of < 5 %, a good linearity in the output voltage for accelerations up to at least 50 m/s² and a bandwidth of DC - 500 Hz.

Keywords: triaxial accelerometer, capacitive sensor, three-dimensional structure

INTRODUCTION

There is a need for very small triaxial accelerometers in the biomedical field. The accelerometers should meet the following specifications: amplitude range ± 50 m/s², resolution 0.01 m/s², bandwidth DC - 50 Hz, off-axis sensitivity < 5 %, dimensions $\sim 2 \times 2 \times 2$ mm³ and power consumption < 1 mW.

Up to now, triaxial accelerometers presented in the literature [1,2,3] have a lack of symmetry and therefore show a large off-axis sensitivity from 5 % up to 21 % [1]. The sensor proposed in this paper has a highly symmetrical configuration, consisting of a central cubic seismic mass surrounded by capacitors, which ideally should not result in any off-axis sensitivity. Furthermore, due to the high degree of symmetry and differential measuring, common mode interferences as introduced by temperature fluctuations, electric and magnetic fields, humidity and other disturbing effects should be rejected. In this paper, the sensor structure and basic operating principle, its theoretical mass-spring-damper model, cleanroom technology and measurement results are described.

THEORY

Sensor Structure And Basic Operating Principle

The basic structure of the sensor consists of a central cubic tungsten seismic mass enclosed by fixed capacitor plates (figure 1a). The mass is suspended to the fixed capacitor plates by springs made of polydimethylsiloxane (PDMS).

Figure 1. Basic structure of the triaxial accelerometer, cross-sectional (a) 3D view, (b) 2D view

Figure 2. (a) Rear view and (b) front view of the two separate fixed capacitor plates confronting each side of the mass; (c) two-dimensional cross-sectional view of a part of the basic structure of the symmetrical cubic triaxial accelerometer

There are two separate fixed capacitor plates confronting each side of the mass (figures 1b, 2b). The inner capacitor C_{couple} [F] is used to capacitively connect the supply voltage V_{in} [V] to the seismic mass and the outer capacitor C_{sense} [F] is used to sense the applied accelerations (figures 1b, 2c). The nominal distance t_{side} [m] between the capacitor plates and the central mass is determined by the thickness of the PDMS structure. When an acceleration is applied, the mass moves a distance Δt [m] with respect to the fixed outer capacitor plates, resulting in a corresponding capacitance change ΔC_{sense} . When the triaxial accelerometer is connected to a differential capacitance to voltage converter (CVC) [4], the output voltage $V_{out,z}$ [V] due to an applied acceleration a_z [m/s²] is [5]

$$V_{out,z} = H_{ina} \hat{V}_{in} \left[\frac{C_{couple,total}}{C_{couple,total} + C_{sense,total}} \frac{C_{sense,z,0}}{C_f} \right] \frac{2ma_z}{k_{total,z} \cdot t_z} \quad (1)$$

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with H_{ina} the gain of the instrumentation amplifier, $\hat{V}_{in}$ [V] the amplitude of the supply voltage, $C_{couple, total} = 6C_{couple}$, $C_{sense, total} = 6C_{sense}$, $C_{sense, z, 0}$ [F] the nominal sense capacitance in the z-direction, C_f [F] the feedback capacitor of the CVC, m [kg] the seismic mass and $k_{total, z}$ [N/m] the spring constant in the z-axis. When C_f is adjusted such that the term between brackets equals 0.5, equation (1) can be simplified:

$$V_{out, z} = H_{ina} \hat{V}_{in} \frac{ma_z}{k_{total, z} \cdot t_z} \quad (2)$$

Corresponding equations can be derived for the output voltage in the x and y-direction.

Mass-Spring-Damper System

In the frequency domain, the output voltage $V_{out}(j\omega)$ [V] is not only dependent on the applied acceleration but also on the mass m [kg], spring constant k_{total} [N/m] and damping constant b_{total} [Ns/m] of the triaxial accelerometer. In the z-direction, $V_{out, z}(j\omega)$ can be equated with

$$V_{out, z}(j\omega) = V_{out, z} \cdot \frac{1}{\left(\frac{j\omega}{\omega_{0, z}}\right)^2 + \frac{\beta_z j\omega}{\omega_{0, z}} + 1} \quad (3)$$

$$\text{with } \omega_{0, z} = \sqrt{\frac{k_{total, z}}{m}} \quad (4)$$

the resonance frequency [rad/s] of the system

$$\text{and } \beta_z = \frac{1}{Q_z} = \frac{b_{total, z}}{\sqrt{k_{total, z} \cdot m}} \quad (5)$$

the damping coefficient, which is the reciprocal of the quality factor Q_z , of the system.

The mass m [kg] is known by weighing, the total spring constant in e.g. the z-direction can be calculated to be [6]

$$k_{total, z} = 10 \cdot A_{PDMS} G / t_z \quad (6)$$

with A_{PDMS} [m²] the area of the PDMS on one side and G [Pa] the shear elastic modulus of the PDMS.

There are many damping mechanisms. The most important damping factors in this application are:

(I) *air streaming resistance*, also called *squeeze film damping*, due to streaming of air in and out of the capacitor, with damping constant b_{ASR} at the resonance frequency ω_0 derived from equations found in [7,8]

$$b_{ASR} = \frac{12\nu A^2}{\pi^3 t_{side}^3} \quad (7)$$

with $\nu = 17.6 \cdot 10^{-6}$ the viscosity of air [Pa.s] and A the area of the capacitor plates [m²].

(II) *damping of PDMS*, due to its loss tangent, with damping coefficient b_{PDMS} [7]

$$b_{PDMS} = \tan \delta \cdot \sqrt{k_{total} \cdot m} \quad (8)$$

with $\tan \delta$ the loss tangent of the PDMS.

The total damping constant in one direction can now be equated with

$$b_{total, z} = 2b_{ASR, z} + 6b_{PDMS, z} \quad (9)$$

EXPERIMENTAL

Cleanroom technology and assembly procedure

Objective of the cleanroom technology is the realisation of a foldable cross structure, as shown in figure 4. In the assembly procedure, the cross structure is folded around the seismic mass [5]. The process flow of the cleanroom technology is shown in figure 3 and was extensively described in [5]. The only thing that has changed is the protective layer for the PDMS structures. In [5], the PDMS was covered with a chromium layer, but due to cracks in the chromium layer the PDMS structures were removed during RIE etching. At present, the PDMS is covered with a PI layer of 50 μ m thick which is not baked (figure 3f). After the RIE etching, when the foldable crosses are etched free, the unbaked PI was removed by putting the crosses in boiling water in an ultrasonic cleaner. The protective aluminium and chromium layers were removed with aluminium and chromium etchant, respectively, and the structures were ready to be assembled (figures 3h and 4). All dimensions, material properties and CVC data are shown in table I. After assembly, the devices look as is shown in fig. 5.

Table I. Dimensions, material properties and CVC data

sensor size:	5x5x5 mm ³	2x2x2 mm ³
seismic mass	$m = 520$ mg	19 mg
	edge $e = 3$ mm	1 mm
PDMS	$A_{PDMS, sense} = 4.10^{-7}$ m ²	1.10^{-7} m ²
	$A_{PDMS, couple} = 4.10^{-8}$ m ²	-
	$G = 250$ kPa	250 kPa
	$\epsilon_r = 2.5$	2.5
	$\tan \delta < 0.001$	< 0.001
	$t \cong 10$ μ m	$\cong 2.5$ μ m
capacitor/side	outer length $l = 3$ mm	1 mm
	$A_{sense} = 6.75.10^{-6}$ m ²	1.10^{-6} m ²
	$A_{couple} = 2.25.10^{-6}$ m ²	-
	$C_{sense, side, 0} \cong 5$ pF	~ 4 pF
	$C_{couple, side, 0} \cong 1.7$ pF	-
CVC	$C_f = 4..10$ pF	4..10 pF
	$H_{ina} = 100$	100
	$\hat{V}_{in} = 5$ V	10 V
	noise DC-50 Hz: 1.5 mV	1.5 mV

Figure 3. Process steps of the triaxial accelerometer: from silicon wafer to foldable cross structure

Figure 4. (a) Big and (b) small foldable cross structure on a mm-scale

Figure 5. Triaxial accelerometers with a size of (a) $5 \times 5 \times 5 \text{ mm}^3$ and (b) $2 \times 2 \times 2 \text{ mm}^3$ in a tungsten housing on an IC package. Bond wires are attached via slits in the walls of the housing

Measurement protocol

The devices were statically tested by turning their sensitive axes with respect to gravity and dynamically tested by applying known accelerations (reference accelerometer Piezotronics ICP 301A10) with a shaker unit (Gearing and Watson GWV20).

RESULTS AND DISCUSSION

When the data of table I is substituted in the equations (1) through (9), the behaviour of the sensor can be theoretically predicted. The results of both the calculations and the measurements are shown in table II. It should be noted that the small sensor B3 was realised using a more complicated assembly procedure in which a gold bond wire, instead of the six couple capacitors in parallel, was used to connect the supply voltage to the seismic mass [9]. However, small sensors constructed as described in this paper will be available in due time.

The static sensitivity of the devices as shown in figure 5 was determined by turning their sensitive axes with respect to gravity. As can be seen in table II, the measured and calculated sensitivity show a reasonably good correspondence. Differences in calculated sensitivity between the axes in one sensor can be explained by unequal height of the PDMS structures due to compression of the PDMS structures during assembly. When the sensitivity in a certain direction is less than calculated, as in B3_y and D2_z, this is probably caused by compression of the PDMS layers in that direction. When the sensitivity in a certain direction is higher than calculated, as in D2_x and D3_z, the higher sensitivity is probably due to a bad mechanical connection between some of the PDMS structures and the seismic mass [6].

The resolution of the sensor is dependent on the rms noise level of the CVC which was found to be 1.5 mV in the frequency range DC - 50 Hz [4]. So, given the sensitivity and the noise level of the CVC, the resolution can be calculated. The result is shown in table II.

The linearity of the devices B3 and D3 is shown in figure 6. The output voltage of all axes increases linearly with the applied acceleration, up to at least 50 m/s^2 .

Figure 6. Linearity of sensors B3 and D3: measured output voltage per axis versus the applied acceleration

As can be seen in table II there is a large mismatch between the calculated and measured bandwidth. This mismatch can be explained in two ways [10]: the first explanation is a bad adhesion between some of the PDMS layers and the seismic mass; the second explanation is a local deformation of some of the PDMS structures due to compressive stress causing them to be much stiffer than in the uncompressed case. Both phenomena cause a much larger damping and therefore a smaller bandwidth than expected.

CONCLUSIONS

A highly symmetrical miniature cubic capacitive triaxial accelerometer has been designed, realised and tested. The outer dimensions of the sensor are $2 \times 2 \times 2 \text{ mm}^3$ and $5 \times 5 \times 5 \text{ mm}^3$. The device is put upon a standard IC package for easy testing. The mathematical mass-spring-damper model, technology and measurements results of the sensor were described. The measurement results show a sensitivity of $\sim 0.15 \text{ V/(m/s}^2\text{)}$ with a corresponding resolution of 0.01 m/s^2 , an off-axis sensitivity of $< 5 \%$, a good linearity in the output voltage for accelerations up to at least 50 m/s^2 and a bandwidth of DC - 500 Hz, thus meeting all specifications. A bandwidth lower than expected can be explained by both a bad mechanical connection and a high compressive stress between some of the PDMS structures and the tungsten seismic mass.

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Table II. Measured and calculated values of important parameters of three triaxial accelerometers

Device _axis	Dimens. [mm ³]	Sensitivity [V/(m/s ²)]		Resolution [m/s ²]	Linearity range [m/s ²]	Off-axis sens. [%]	Bandwidth [kHz]	
		Calc.	Meas.				Calc.	Meas.
B3_x	2x2x2	0.16	0.15	0.01	$> \pm 50$	3	10	3
B3_y		0.16	0.02	0.08	$> \pm 50$	3	10	3
B3_z		0.16	0.19	< 0.01	$> \pm 50$	2	10	3
D2_x	5x5x5	0.18	0.35	< 0.01	$> \pm 50$	2	2	0.5
D2_y		0.28	0.27	< 0.01	$> \pm 50$	1	2	0.5
D2_z		0.23	0.15	< 0.01	$> \pm 50$	3	2	0.5
D3_x	5x5x5	0.24	0.22	< 0.01	$> \pm 50$	5	3	0.5
D3_y		0.24	0.24	< 0.01	$> \pm 50$	3	3	0.5
D3_z		0.24	0.36	< 0.01	$> \pm 50$	4	3	0.5