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Sensors and Actuators A 61 (1997) 303–308

SENSORS AND ACTUATORS A PHYSICAL

Design, realization and characterization of a symmetrical triaxial capacitive accelerometer for medical applications

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Abstract

Small triaxial accelerometers are needed in the medical field for the monitoring of mobility. For this purpose, a new highly symmetrical inherently triaxial capacitive accelerometer has been designed. The basic structure of the device consists of six capacitors surrounding a central mass which is suspended by springs made of the rubber elastic polymer polydimethylsiloxane. The advantages of the design are a low off-axis sensitivity, an equal sensitivity in all axes and a reduction of the sensor's dimensions. In order to show the practical feasibility of the design, a number of manually assembled prototypes of the triaxial accelerometers have been realized with dimensions down to 2 mm × 2 mm × 2 mm. The prototypes are capable of detecting accelerations in three directions with unfortunately unequal sensitivities per axis (e.g., from 0.8 to 1.1 V $(m\ s^{-2})^{-1}$) and a maximum off-axis sensitivity of 3% in the well-assembled devices. Clinical measurements have been carried out with the prototypes. The measurement results indicate that the triaxial accelerometer is sensitive enough to register the kind of movements that occur in healthy persons during normal standing.

Keywords: Capacitive accelerometers; Medical applications; Triaxial accelerometers

1. Introduction

There is a need for small and eventually implantable triaxial accelerometers in the biomedical field. These sensors can, for instance, provide positional information for the control of mobility in paraplegic patients [1] and enable the ambulant monitoring of movement disorders of patients suffering from Parkinson's disease [2]. The most important specifications for medical applications are [3]: amplitude range $\pm 5g$, resolution $10^{-3}g$, bandwidth d.c.–50 Hz, off-axis sensitivity <5%, dimensions <2 mm × 2 mm × 2 mm, low drift and power consumption < 1 mW.

Up to now, triaxial accelerometers presented in the literature [4,5] have a lack of symmetry and therefore show a large off-axis sensitivity from 5 up to 21% [4]. The sensor proposed in this paper has a highly symmetrical configuration which ideally should not have any off-axis sensitivity. Its structure consists of six capacitors surrounding a cubic central mass which is suspended by rubber elastic springs.

The rubber elastic springs are made of polydimethylsiloxane (PDMS), which is a commercially available cleanroom-processible type of silicone rubber [6] with a wide range of applications [7,8]. Important material properties in the triaxial accelerometer application are: the shear modulus G is 250 kPa at room temperature, with a temperature variation of 1.1 kPa °C^{-1} and no variation with frequency [9]. The loss tangent is very low ($\tan\delta \ll 0.001$ [6]). PDMS has a high dielectric strength compared to other polymers (≈ 14 V μm^{-1} [10]), its relative dielectric constant is $\epsilon_r \approx 2.5$ [10]. PDMS shows a high compressibility [6], is usable in a wide temperature range (at least from −100°C up to +100°C [6]) and is essentially non-toxic [6].

The realization of three-dimensional micromachined devices is a developing field with technological challenges. In order not to be limited by technological boundaries and to validate the feasibility of the design, the first prototypes of the triaxial accelerometer are a combination of cleanroom processing, precision mechanics and manual assembly.

In this paper the sensor structure and its mathematical model, its realization procedure, its characterization and some clinical measurement results will be described.

2. Theory

2.1. Sensor structure

The basic structure of the capacitive triaxial accelerometer as shown in Fig. 1 consists of six electrodes surrounding a

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PII S0924-4247(97)01376-9

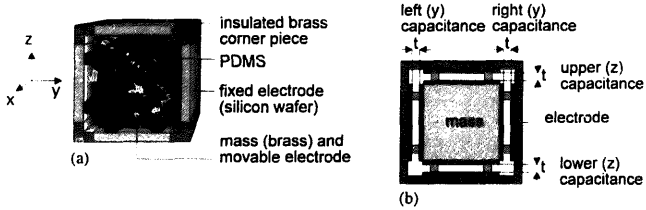

Fig. 1. Cross-sectional (a) 3D and (b) 2D views of the basic structure of the triaxial accelerometer.

central cubic mass which is suspended by springs made of the rubber elastic polymer polydimethylsiloxane (PDMS). When the sensor structure is fully symmetrical (which is ideally the case), all capacitances between the electrodes and the central mass have an equal nominal capacitance value C_0 [F] of

$$C_0 = \epsilon_0 \epsilon_r A / t \quad (1)$$

with ϵ_0 [F m^{-1}] the dielectric constant of vacuum ($\epsilon_0 = 8.85 \times 10^{-12}$ [F m^{-1}]), ϵ_r the relative dielectric constant of the material between the moving and the fixed electrode (which is a combination of the relative dielectric constants of air and PDMS), A [m^2] the area of the electrodes and t [m] the nominal distance between the electrodes and the mass.

The nominal distance t between the electrodes 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 electrodes, resulting in a corresponding capacitance change ΔC [F].

For instance, when the acceleration is applied in the $+z$-direction, the distance between the mass and the upper electrode increases to $t + \Delta t_z$ and the distance between the mass and the lower electrode decreases to $t - \Delta t_z$. Consequently, the upper capacitance $C_{z,u}$ [F] is decreased and the lower capacitance $C_{z,l}$ [F] is increased:

$$C_{z,u} = \epsilon_0 \epsilon_r A / (t + \Delta t_z) = C_0 t / (t + \Delta t_z) = C_0 - \Delta C_{z,u} \quad (2a)$$

$$C_{z,l} = \epsilon_0 \epsilon_r A / (t - \Delta t_z) = C_0 t / (t - \Delta t_z) = C_0 + \Delta C_{z,l} \quad (2b)$$

When $\Delta t_z < 0.01t$, there is no appreciable difference between the absolute values of $\Delta C_{z,u} = C_0 \Delta t_z / (t + \Delta t_z)$ and $\Delta C_{z,l} = C_0 \Delta t_z / (t - \Delta t_z)$. So, both the upper and the lower capacitance are varied with the same ΔC_z,

$$\Delta C_z = C_0 \Delta t_z / t \quad (3)$$

However, when the sensor is not fully symmetrical, the differences in the thicknesses of the PDMS structures should be taken into account. In that case, the expressions for the change in the upper and lower capacitance $\Delta C_{z,u}$ and $\Delta C_{z,l}$ are, respectively,

$$\Delta C_{z,u} = C_{z,u,0} \Delta t_z / t_{z,u} \quad (4a)$$

$$\Delta C_{z,l} = C_{z,l,0} \Delta t_z / t_{z,l} \quad (4b)$$

where the upper thickness and nominal capacitance are $t_{z,u}$ and $C_{z,u,0}$ and the lower thickness and nominal capacitance are $t_{z,l}$ and $C_{z,l,0}$, respectively.

In order to know the relation between Δt_z and the applied acceleration a_z, the two system forces $F_{\text{acceleration},z} = m a_z$ and $F_{\text{spring},z} = -k_z \Delta t_z$ have to be equated:

$$F_{\text{acceleration},z} = -F_{\text{spring},z} \rightarrow m a_z = k_z \Delta t_z \rightarrow \Delta t_z = m a_z / k_z \quad (5)$$

with $F_{\text{acceleration},z}$ [N] the force in the z-direction on the mass m [kg] due to the applied acceleration in the z-direction a_z [m s^{-2}], $F_{\text{spring},z}$ [N] the force in the z-direction on the spring with spring constant in the z-direction k_z [N m^{-1}] due to the deflection of the spring in the z-direction Δt_z [m]. The indices in the above-mentioned equations should be subsequently changed for the x- and y-directions.

Now, all parameters but the spring constant k are known. The relation between the dimensions of a PDMS structure, the combination of these structures in the triaxial accelerometer and the resulting spring constant will be derived in the next section.

2.2. Spring constant of the rubber elastic elastomer

For simple extension and uniaxial compression (see Fig. 2(a)) the rubber elastic stress–strain relation can be expressed as [11]

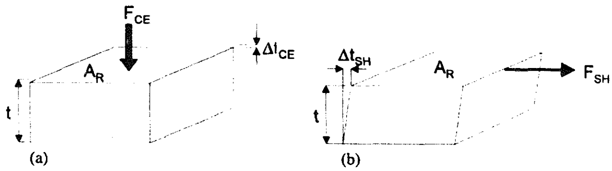

Fig. 2. Piece of rubber elastic material on which (a) a compressive or extensive force or (b) a shear force is applied.

$$F_{CE} = A_R G(\lambda - 1/\lambda^2) \quad (6)$$

with F_{CE} [N] the applied compressive or extensive force, A_R [m^2] the area of the rubber on which the force is applied, G [Pa] the shear modulus of the rubber, λ the rubber's extension ratio: $\lambda = 1 + \Delta t_{CE}/t$, t [m] the thickness of the rubber and Δt_{CE} [m] the change in thickness of the rubber due to F_{CE}. When this expression is linearized around $\Delta t_{CE}/t < 0.01$, Hooke's equation $F_{CE} = k_{CE}\Delta t_{CE}$ can be used such that the spring constant for small compression and extension k_{CE} [N m^{-1}] can be expressed as

$$k_{CE} = F_{CE}/\Delta t_{CE} = 3A_R G/t \quad (7)$$

Simple shear is a type of strain which may be represented by the sliding of a plane with area A_R [m^2] which is parallel to a ground plane through a distance Δt_{SH} [m] proportional to the distance t [m] between the planes (Fig. 2(b)). The stress–strain relation is given by $F_{SH} = A_R G \Delta t_{SH}/t$ [11], so the shear spring constant k_{SH} [N m^{-1}] is

$$k_{SH} = A_R G/t \quad (8)$$

When the symmetrical accelerometer of Fig. 1 is accelerated along one axis, the PDMS structures which sense the acceleration in this direction will be extended or compressed whereas the other four PDMS structures will be subjected to a shear stress. The resulting total spring constant k_{tot} in one direction is therefore

$$k_{tot} = 2k_{CE} + 4k_{SH} = 10A_R G/t \quad (9)$$

Eq. (9) can be used for all axes (x, y and z) of the triaxial accelerometer. However, when the sensor is not fully symmetrical, the differences in the layer thicknesses should be taken into account, for instance in the z-direction:

$$k_{tot,z} = 3A_R G/t_{z,u} + 3A_R G/t_{z,l} + A_R G/t_{x,l} + A_R G/t_{x,r} + A_R G/t_{y,l} + A_R G/t_{y,r} \quad (10)$$

where $t_{x,l}$, $t_{x,r}$, $t_{y,l}$ and $t_{y,r}$ are the thicknesses of the PDMS structures in the left and right x- and y-direction, respectively. The indices in Eq. (10) should be subsequently changed for $k_{tot,x}$ and $k_{tot,y}$ to obtain the total spring constant in the x- and y-directions, respectively.

2.3. Capacitance to voltage converter

The capacitance variations ΔC are measured with a differential capacitance to voltage converter (CVC) [12] (Fig. 3) resulting in an output voltage V_{out} due to an applied acceleration a [m s^{-2}] in a fully symmetrical device, e.g., in the z-direction

$$V_{out,z} = H2\Delta C_z/C_0 = H2\Delta t_z/t = H2ma_z/(k_{tot,z}t) \quad (11)$$

where H is the amplification factor of the CVC. If the structure is not symmetrical, the CVC will produce an output voltage V_{out} [V], e.g., in the z-direction:

$$V_{out,z} = H(\Delta C_{z,u}/C_{z,u,0} + \Delta C_{z,l}/C_{z,l,0}) = H(\Delta t_z/t_{z,u} + \Delta t_z/t_{z,l}) = H(ma_z/k_{tot,z})(1/t_{z,u} + 1/t_{z,l}) \quad (12)$$

3. Experimental

3.1. Device preparation

The PDMS was spin-coated (Fig. 4(b)) on a silicon wafer with annealed aluminium on both sides (Fig. 4(a)). After the spin-coating, the PDMS was processed photolithographically in order to obtain the specified dimensions, as given in Table 1. Three cleanroom runs were done. Sensors constructed of wafer pieces from the first, second and third run are labelled A, B and C, respectively.

After the PDMS was processed, the wafer was cut into separate pieces, each containing a PDMS structure and acting as an electrode in the assembled device (Fig. 4(c)). Wafer pieces of run A were covered with another piece of silicon wafer with negative photoresist (Fig. 4(d)) (to obtain a good adhesion) and subsequently attached to each side of a cubic brass seismic mass (Fig. 4(e)). Wafer pieces of runs B and

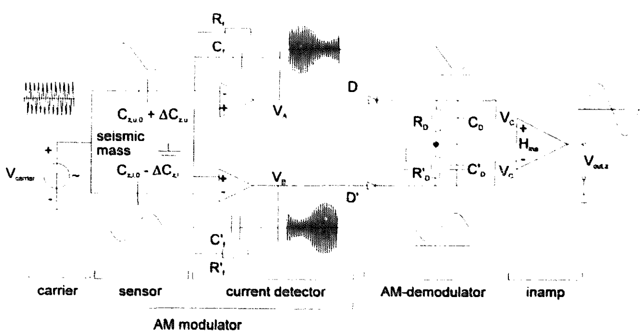

Fig. 3. Differential capacitance to voltage converter [12].

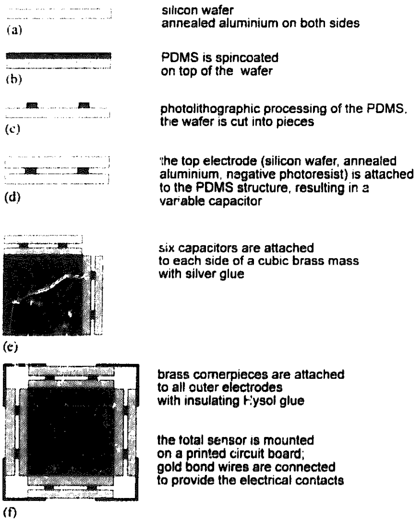

Fig. 4. Technology and assembly procedure necessary to realize the triaxial accelerometer.

C were directly connected to each side of a cubic tungsten seismic mass (this way a good adhesion was obtained). The outer electrodes were mechanically interconnected such that a rigid cubic construction was formed, using insulated brass corner pieces (Fig. 4(f)). The total device was mounted on a small printed circuit board (PCB). All electrodes, including the seismic mass, were electrically connected to corresponding copper tracks on the PCB with gold bond wires.

3.2. *Accelerometer test set-up and 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: PCB Piezotronics ICP 301A10) with different amplitudes and frequencies with a shaker unit (Gearing and Watson GWV20) and measuring the output voltage of the accelerometer system with an HP35670A dynamic signal analyser.

4. Results

A number of prototypes of the capacitive triaxial accelerometers have been realized with outer dimensions 5 mm × 5 mm × 5 mm (A and C) and 2 mm × 2 mm × 2 mm (B). The resulting thicknesses of the PDMS structures as calculated from the measured capacitances are shown in Table 2. The theoretical spring constants are calculated using Eq. (10) and the theoretical sensitivities V_{out}/a using Eq. (12). All devices were connected to the capacitance to voltage converter with $H = 1000$. The results of Eq. (12) as well as the obtained measurement results (sensitivity and off-axis sensitivity) are shown in Table 2. Fig. 5 shows the measured linearity of all axes and Fig. 6 shows the measured frequency response of the x-axis of sensor C.

5. Discussion

The measurement results show that the highly symmetrical triaxial accelerometer is functioning well because the devices

Table 1
Designed dimensions of the PDMS structures. Electrode area: A and C, 3 mm × 3 mm; B, 1 mm × 1 mm. Mass: A, 220 mg; B, 21 mg; C, 520 mg

Sensor number and PDMS structure per side	Area A_R [m²]	t [m]	C_0 [pF]
(A) 4 square layers of 120 μm × 120 μm	5.8×10^{-8}	10×10^{-6}	10.0
(B) circle, outer radius 0.5 mm, width 35 μm	1×10^{-7}	5×10^{-6}	2.0
(C) circle, inner radius 0.94 mm, width 60 μm	4×10^{-7}	10×10^{-6}	8.0

Table 2
Measurement results of the triaxial accelerometer; the calculated sensitivity is according to Eq. (12)

Sensor axis	Thickness [μm] of the PDMS	Sensitivity [V (m s⁻²)⁻¹]		Off-axis sensitivity [%]
		calculated	measured	
A_x	13.1, 6.3	2.5	6.0	2
A_y	3.3, 4.8	3.5	3.6	6
A_z	6.9, 6.1	2.8	2.6	3
B_x	2.9, 2.3	0.16	0.15	3
B_y	2.6, 2.6	0.16	0.02	3
B_z	2.8, 3.0	0.15	0.19	2
C_x	15.9, 15.6	1.1	0.8	2
C_y	16.6, 16.6	1.0	1.0	2
C_z	15.3, 17.3	1.1	0.9	3

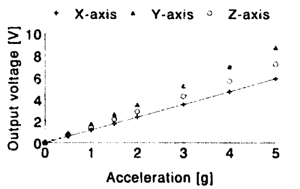

Fig. 5. Linearity of all axes of triaxial accelerometer C.

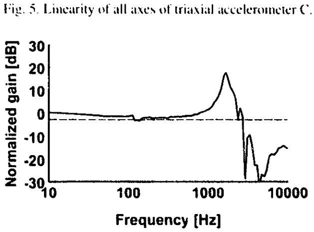

Fig. 6. Bode plot of the x-axis of triaxial accelerometer C.

are able to detect accelerations in three directions with an off-axis sensitivity of less than 3% in the devices B and C. As can be seen in Table 2, there is a fairly good correspondence between the measured and the calculated sensitivities in A_y, A_z, B_x, B_z and C_x, C_y and C_z. The sensitivity in A_x is higher than expected, possibly due the inactivity of the shear springs in the x-direction of device A, which may be caused by a bad adhesion of the PDMS structures to the electrodes. When the shear springs are not considered in the calculation (Eq. (10)), the spring constant in the x-direction is reduced such that the theoretical and measured values correspond. The sensitivity in B_y is much lower than expected, possibly due to the PDMS structures being pre-compressed in the assembly process, which causes them to be stiffer, according to Eq. (6).

Summarizing, the deviations in the sensor parameters are due to sometimes severe variations in height of the PDMS structures and pre-stressing of some of the PDMS structures due to experimental cleanroom processing, preparation variances and manual assembly. Furthermore, due to the manual mounting, non-reproducible sensors were introduced. In order to reduce errors due to manual mounting, a micromachined sensor realized by automated mounting of a self-aligning structure has to be made. Further research will concentrate on this.

6. Clinical results

Several measurements have been performed, with healthy subjects, in order to show the usability of the triaxial accelerometer in the registration of the stability of standing. Triaxial accelerometer A was mounted on a motor cyclist belt which was placed around the waist of the subject. The device

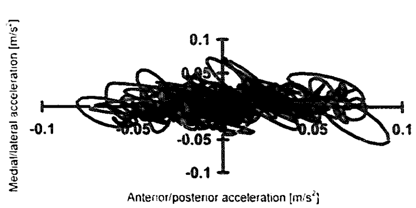

Fig. 7. Measurement result obtained during a standing stability test using triaxial accelerometer A. A healthy subject stood as quietly as possible for 30 s with eyes open and feet apart.

was levelled such that the z-axis was in parallel with the earth's gravitational force. The subjects were asked to stand as quietly as possible for 30 s, with, e.g., eyes open, eyes closed, feet apart and feet together. Fig. 7 shows a typical measurement result of a subject who stood as still as possible for 30 s with eyes open and feet apart. The measurement results indicated that, using the triaxial accelerometer, it is possible to register the kind of movements which occur in healthy persons during normal standing and that it is possible to discriminate between very similar situations like standing with the feet apart and standing with the feet together [13]. The accelerometer measurement system is currently being implemented for routine clinical use.

7. Conclusions

A number of prototypes of the symmetrical triaxial accelerometer with outer dimensions of 5 mm × 5 mm × 5 mm and 2 mm × 2 mm × 2 mm have been designed and realized. The highly symmetrical structure is advantageous with respect to the reduction of off-axis sensitivity: a maximum of 3% was measured in the well-assembled devices B and C. The sensitivity of all axes in one device should have been equal due to the symmetrical structure of the sensor. Unfortunately, variations in sensitivity within one device appeared. They are caused by unequal height of the PDMS layers due to experimental cleanroom processing and the presence of stress in the PDMS layers due to the manual mounting of the devices. All devices showed a good linearity up to accelerations of at least 50 m s^{-2} and their frequency response was flat up to 1 kHz.

The measurement results showed the practical feasibility of the design. Further research will concentrate on the realization of a more reproducible manufacturing process, thus facilitating the assembly procedure and reducing the variation in performance.

Acknowledgements

The authors would like to thank Mr J.G. Bomer, Mr A.J. Verloop and Mr Ed A. Droog for their assistance in technology and electronics and the Dutch Technology Foundation (STW) for its financial support.

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Biographies

Joost C. Lötters was born in Doetinchem, The Netherlands, on July 20, 1967. He received in 1990 the B.Sc. degree in electrical engineering from the Technical Institute Arnhem, Arnhem, The Netherlands and in 1993 the M.Sc. degree in electrical engineering from the University of Twente, Enschede, The Netherlands. Since 1993 he has been working as a Ph.D. student at the biosensors group of the Department of Electrical Engineering of the MESA Research Institute of the University of Twente, Enschede, The Netherlands. The aim of his Ph.D. project is the realization of a miniaturized and eventually implantable triaxial accelerometer for biomedical purposes, such as the control of mobility in paraplegic patients and the monitoring of movement disorders of patients suffering from Parkinson's disease.

Wouter Olthuis was born in Apeldoorn, The Netherlands, on October 23, 1960. He received the M.Sc. degree in electrical engineering from the University of Twente, Enschede, The Netherlands in 1986, and the Ph.D. degree from the Biomedical Engineering Division of the Faculty of Electrical Engineering, University of Twente, in 1990. The subject of his dissertation was the use of iridium oxide in ISFET-based coulometric sensor–actuator devices. Currently he is working as an assistant professor in the biosensor technology group, part of the MESA Research Institute, of the University of Twente.

Peter H. Veltink studied electrical engineering at the University of Twente, The Netherlands, where he received the M.Sc. degree and the Ph.D. degree in 1988 (dissertation: recruitment of myelinated nerve fibres during artificial nerve stimulation). Currently, he is a member of the Biomedical Engineering Division of the Department of Electrical Engineering, University of Twente, and is engaged in the research of neuromuscular stimulation for rehabilitation of spinal cord injured patients, which is carried out in cooperation with the Roessingh rehabilitation centre in Enschede. His research interests are nerve stimulation and control systems for functional electrical stimulation.

Piet Bergveld was born in Oosterwolde, The Netherlands, on January 26, 1940. He received the M.Sc. degree in electrical engineering from the University of Eindhoven, The Netherlands, in 1965 and the Ph.D. degree from the University of Twente, The Netherlands, in 1973. The subject of his dissertation was the development of ISFETs and related devices, the actual invention of the ISFET, since then also investigated by many international research groups of universities as well as industry.

Since 1965 he has been a member of the Biomedical Engineering Division of the Faculty of Electrical Engineering (University of Twente) and was in 1984 appointed as full professor in biosensor technology. He is one of the project leaders in the MESA Research Institute. His research subjects still concern the further development of ISFETs and biosensors based on ISFET technology as well as physical sensors for biomedical and environmental applications, resulting up to now in more than 250 papers.