Novel Capacitive Accelerometers with Beams based on Modified Compliant Crank-Slider Amplifiers

Novedosos Acelerómetros Capacitivos con Brazos Basados en Amplificadores Flexibles de Manivela Deslizante Modificados

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PALABRAS CLAVE:

MEMS, aceleración, ANSYS, parámetros de operación, simulación.

RESUMEN

Los acelerómetros miden las aceleraciones o vibraciones, que experimentan los objetos debido a fuerzas inerciales o excitaciones mecánicas. Los acelerómetros Microelectromecánicos (MEM) tienen diversas aplicaciones en las industrias, aeronáutica, automotriz, petrolera, construcción, manufacturera de equipos de cómputo y electrónica de consumo, entre otras. Estos dispositivos emplean diferentes técnicas para su funcionamiento. El interés en este trabajo, se enfoca en los acelerómetros capacitivos, buscando mejorar su sensibilidad de desplazamiento. Para mejorar este parámetro se ha recurrido generalmente, a la reducción de masa, a la modificación de los brazos de suspensión, o bien, agregando amplificadores de desplazamiento. En este trabajo, después de analizar varias configuraciones, se proponen dos diseños de brazos modificados basados en amplificadores flexibles de manivela deslizante modificados. La mejora en la sensibilidad de desplazamiento, comparada con la obtenida con brazos uniformes, es en uno de los casos, de 72.435% y en el otro de 125%. Los resultados fueron obtenidos usando ANSYS.

KEYWORDS:

MEMS, acceleration, ANSYS, performance parameters, simulation.

ABSTRACT

Accelerometers measure the accelerations or vibrations experienced by objects due to inertial forces or mechanical excitations. The Microelectromechanical (MEM) Accelerometers have various applications, among others, in the industries, aeronautics, automotive, oil, construction, manufacturing of computer equipment and consumer electronics. These devices employ different techniques for their operation. The interest in this work focuses on capacitive accelerometers, seeking to improve their displacement sensitivity. In order to improve this parameter, it has generally been used: proof mass reduction, modification of the suspension beams, or, alternatively, by adding displacement amplifiers. In this work, after analyzing several configurations, two designs of beams based on Modified Compliant Crank-Slider Amplifiers are proposed. The improvement in displacement sensitivity, compared with that obtained with uniform beams, is in one case of 72.435% and in the other, of 125%. Simulations were performed with ANSYS.

Recibido: 3 de Agosto 2019 **Aceptado:** 15 de Mayo 2019 **Publicación en línea:** 28 de junio 2019

1 PROBLEM DESCRIPTION

MEM technology was born from the technology of integrated circuits, which involves small systems with mechanical devices and electrical components [1], working in harmony to achieve the perception and control of the local environment [2]. Among these devices are found sensors, actuators, radiofrequency devices, Micro-Opto-Electro-Mechanical devices (MOEMs), microfluidic devices and BioMEMS.

The interest in this paper focuses on a particular type of sensors, called accelerometers, which measure the acceleration or force applied to the devices. These devices are one of the simplest but also most applicable micro-electromechanical systems. They became indispensable in automobile industry, computer and audio-video technology [3].

Accelerometers can be used to detect the change of position, vibration and impact. They can be of single-axis or multi-axis, the last ones, have the ability to detect accelerations in any direction. Capacitive accelerometers, compared to the other types of MEM accelerometers, have high sensitivity, low power consumption, low noise level, stable direct current (DC) characteristics and lower temperature dependence [4].

Accelerometers to determine the inclination, for vibration and shock, and for seismic and inertial applications are commercialized. Depending on their design, they can be integrated, for example, in seismic recording systems [5]. High g accelerometers are the industry standard way of detecting car crashes and deploying airbags at just the right time. They detect the rapid negative acceleration of the vehicle to determine when a collision has occurred. They also have a built-in self-test feature, where a micro-actuator will simulate the effect of deceleration and allow checking the integrity of the system every time you start up the engine [3]. These devices are also part of smart phones, intelligent sensors and low cost integrated monitoring system [6].

Displacement sensitivity, electrostatic force, operation frequency and quality factor are some of their parameters [7, 2]. In order to improve the displacement sensitivity, several approaches have been implemented, such as the mass reduction or the shape modification of suspension beams, and even, adding complex devices, known as displacement amplifiers [8].

This paper focuses on capacitive accelerometers, where the variable that controls its movement corresponds to the value of g to which it is subjected. To improve its displacement sensitivity, the designs of modified beams based on Compliant Crank-Slider Amplifiers are proposed. These simple amplifiers are made with a distributed mass arrangement, under certain angles. The content of this work is organized as follows. In section 2, the basic concepts of accelerometers and their operation are presented. Section 3 shows the designs of the implemented suspension beams, as well as the results obtained in the corresponding simulations. Finally, in section 4, some concluding remarks are given.

2 INTRODUCTION

2.1. Some basic concepts of accelerometers

All capacitive sensors for detection of mechanical quantities depend on displacement measurements. The movement of a suspended electrode with respect to a fixed electrode establishes a changing capacitance value between the electrodes. If the mechanical quantity controls the mobile electrode, a sensor is made [9], whose capacitance value is obtained from [10]:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \quad (1)$$

where ε0 is the permittivity of the free space (vacuum), of magnitude 8.85 (pf/m), ε is the relative permittivity or dielectric constant of the insulating material, A (m^2) is the overlap area of the plates, referred as effective area, and d (m) corresponds to their separation. In such a way that, any phenomenon that changes the area, the dielectric constant or the separation of the capacitor plates, will cause a change in the value of capacitance C.

Capacitive sensors must be as large as possible, the value of its capacitance is directly related to its size and, a small capacitor means a high susceptibility to noise. Capacitive sensor reveals clear advantages compared to the piezoresistive one: high sensitivity, low energy consumption, better temperature performance, etc. Basically, capacitive silicon sensors measure the displacement of the membrane. They have an extremely high sensitivity and low energy consumption. These characteristics make them especially attractive in biomedical implant devices, or in other telemetry applications. A micro mechanized accelerometer based on the capacitive detection of area variation was developed in [11].

The acceleration is measured by the displacement of the proof or seismic mass. Its unit is g (one g equals 9.81 m/s2). For capacitive sensing type, the displacement is detected by measuring the change in capacitance between the seismic mass and the adjacent fixed electrodes. Accelerometers typically consist of four components: a moving mass, called proof or seismic mass; a suspension formed by one or more elastic supports and springs; a shock absorber; and a mechanism by which the displacement of the moving mass is recorded.

The mass is used to generate a force due to the acceleration or deceleration of the body on which the accelerometer is mounted. The suspension subjects to the moving mass and fulfills functions of rigid support (for example, to prevent the movement of the mass in the directions y and z) and of spring (making that the mass returns to its original position in the x direction, once the acceleration disappears). The damper is generally the volume of air, or controlled environment, captured within the enclosure or cavity that surrounds the device. It is designed to control the behavior of the moving mass in order to obtain favorable characteristics in the frequency response. The displacement of the mass is transformed into an electrical output signal thanks to the registration mechanism. These characteristics make them represented as damping, mass-spring systems. Linear accelerometers are classified as planar (they register on the x or y axis) and out of plane (they register on the z axis). The choice of registration axes is mainly determined by the characteristics of the application. Currently, there are prototypes of accelerometers with registration capacity in the three Cartesian axes within the same encapsulation.

About the shape of the beams, different modifications have been implemented, in order to increase the displacement sensitivity [4]. This fact is based on the movement of the proof mass is determined by the beams that connect this mass to the fixed anchors and dampen the system.

2.2. Parameters and material properties

When an external acceleration is applied, the proof mass tends to move in the opposite direction to the direction of this acceleration, according to Newton's second Law. Equation 2 expresses the relationship between force F, acceleration a, and mass m.

$$\mathbf{F} = \mathrm{m}\mathbf{a} \tag{2}$$

From this equation, it is easy to understand that the acceleration of a body can be determined by measuring the force acting on that body. A body on the surface of the earth experiences an acceleration of 9.81 m/s2 or 1 g, if it is left in free fall. Force and acceleration, as vector quantities, have the same direction and sense.

Accelerometers are devices that determine the necessary force to create a change of speed, maintaining the mass constant and accelerating the body or structure on which they are mounted. The spring, that connects the mass with the structure, is the means of mechanical transmission of acceleration; which, since it is not a rigid body, is affected by the inertia of the mass (it opposes movement) and changes its length. The spring elongates or contracts as a consequence of the direction of acceleration (since the movement of the mass is restricted to the rectilinear type). This deformation measured in units of length is proportional to the force that causes it. The relationship between the displacement of the spring and the force acting directly or indirectly on it is:

$$\mathbf{F} = \mathrm{k}\mathbf{x}$$

(3)

where k is a scalar constant of proportionality between force and displacement and is known as the spring constant. It is obtained by Equation 4, in the case of a uniform guided beam, in which one end is fixed and the other is joined to the proof mass as the guided termination [4].

$$\mathrm{k} = 12\mathrm{EI}/\mathrm{t}^3 = \mathrm{Et}(\mathrm{w_b}/\mathrm{l_b})^3 \tag{4}$$

where E is the Young's modulus of the material, t, wb y lb are the thickness, width and length of the suspension beams, respectively. I is the moment of inertia, which is calculated from: $\mathrm{I} = \frac{\mathrm{tw_b^3}}{12}$.

The displacement sensitivity is defined as the displacement of the moving mass per unit of gravity g along the direction of sensing. This parameter can be calculated by equation 5, based on Hooke's Law:

$$\mathbf{S_x} = \frac{\mathrm{mg}}{\mathrm{k}} = \frac{\rho \mathrm{Vg}}{\mathrm{k}} \tag{5}$$

where, m is the system mass, ρ is the density, V is the volume and g is the gravity acceleration.

Operation frequency in the plane is another of the merit figures and is obtained from [12]:

$$f = \frac{1}{2\pi}\sqrt{\frac{Nk}{m}} = \frac{1}{2\pi}\sqrt{\frac{NEtw_b{}^3}{ml_b{}^3}} \quad (6)$$

The accelerometers will be implemented in Silicon. Its properties are presented in Table 1.

Table 1. Silicon properties**.**

Parameters and units	Silicon [13-15]
Density, ρ, [kg/m3]	2329
Young's modulus, E, [GPa]	130.1
Coefficient of thermal expansion, α, [1/K]	2.568 e-6
Poisson ratio, ν, [Dimensionless]	0.33
Tensile yield strength, [MPa]	250

Suspension beams design

In this work, 3 designs are considered:

Design A: Clamped-clamped flexure or anchored uniform beams [4].

Design B: Beams based on Modified Compliant Crank-Slider Amplifier.

Design C: Beams based on Modified Compliant Crank-Slider Amplifier flexure, with boss.

Design A is very common in the literature, in this case, it is considered as a reference for comparison.

Design B and C are novel proposals. The implementation of these type of geometries in accelerometers were not found in the literature. They were designed on the base of the Description of Compliant Crank-Slider Amplifier [16], where it is presented for the amplification of the input force, as follows:

The ratio between the input and output forces, with equal crank and the coupler lengths is:

$$\frac{\text{Output Force}}{\text{Inout Force}} = \frac{1}{\tan\alpha} \quad (7)$$

As α approaches to 0, its tangent tends to ∞, which causes a small applied input force to cause a large output force. The rigid bodies (coupling masses) are carried to ground and to another rigid body by means of elastic joints that connect both rigid bodies.

On the base of the Compliant Crank-Slider Amplifier, a new arrange of the elements was proposed (Figure 1), replacing the fixed load by a suspended mass.

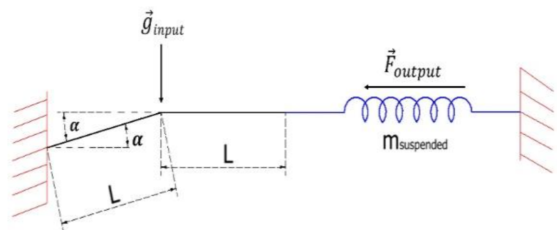
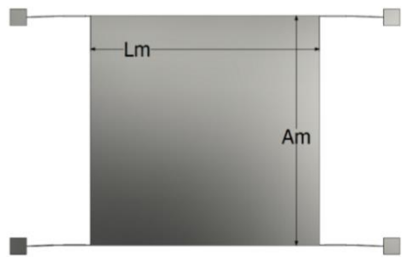
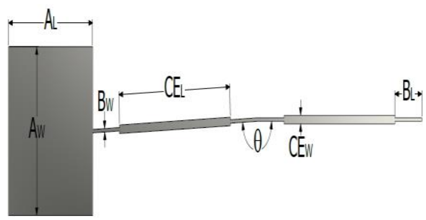


Fig . 1. Modified Compliant Crank-Slider Amplifier.

Based on this proposed modified amplifier, the beams of the accelerometer shown in Figure 2 were designed. The size of the test mass is 7x7 mm2, the total length of the arm is 2mm. The thickness of the beams and proof mass is 0.025 mm.



(a)



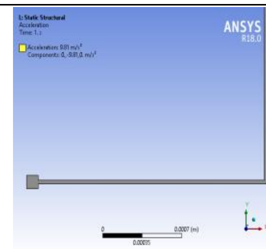
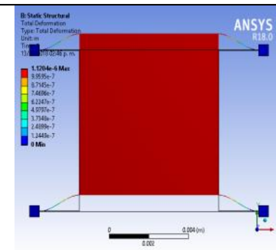
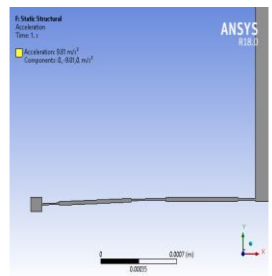
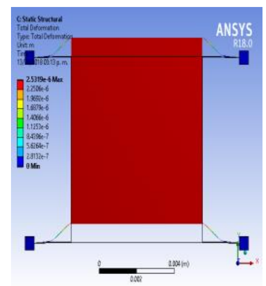
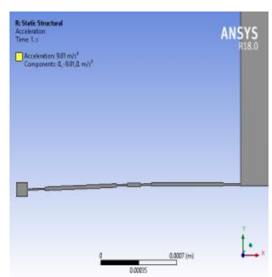
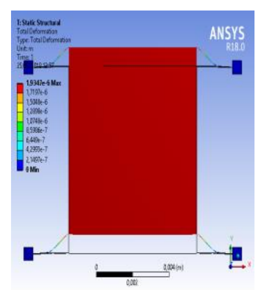
(b)

Fig. 2. (a) Accelerometer with beams based on Modified Compliant Crank-Slider Amplifiers and (b) One of the left beams.

For design C, a boss element was implemented in the central part of the beam, according to [17]. In this reference, the inclusion of a boss in each beam of a chevron structure produces a reduction of rigidity of 35.5%, compared to uniform beams case, when the width of bosses were 40 times the beam width. An increment in operation frequency and in the displacement of the arrow was also obtained.

In Table 2, beams geometries and displacement sensitivity of accelerometers A-C, when 1g is applied, are given. Parameters values are provided in Table 3.

Table 2. Beams geometries and displacement sensitivity of accelerometers A-C.

Design	Beam geometry	Displacement sensitivity
A		
B		
C		

The proof mass in all cases is of 2,853 mg.

Table 3. Simulation results. % of increment (Inc. %) and decrement (Decr. %) are calculated considering as reference the values of Design A.

Param eter	Des ign A	Des ign B	In c. %	Dec r. %	Des ign C	Inc. %	Dec r. %
Stiffne	25.	11.	-	55.	14.	-	42.

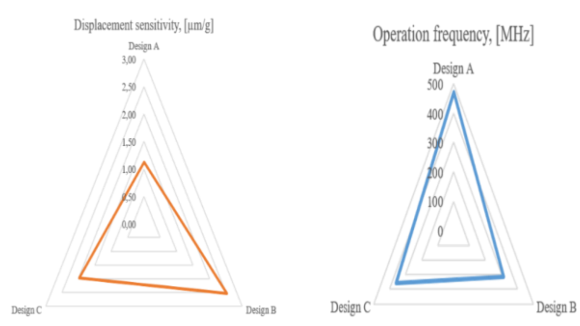
ss [N/m]	054	077		787	504		109
Total Mass, [mg]	2.867	2.865	-	0.070	2.865	-	0.070
Operation frequency, Hz	470.48	312.94	-	33.485	358.1	-	23.886
Displacement sensitivity, [µm/g]	1.121	2.528	125.513	-	1.933	72.435	-
Normal stress [MPa]	2.681	11.8	340.134	95.599	9.794	265.311	-

From Table 3, it can be seen that the rigidity of Design B is lower (11.077%) than that of the conventional accelerometer (Design A). The highest displacement sensitivity value was obtained with the same accelerometer (125%), although the decrease in frequency has a high value (33.485%).

On the other hand, with respect to Design C, there is a lower improvement in displacement sensitivity, but also considerable (125.513%). It also present a lower reduction in operating frequency (23.886%).

In Figure 3, graphical comparison of displacement sensitivity and operation frequency is provided. In both cases, the three designs under analysis are considered. From Figure 3a, it is possible to observe that the highest response for displacement sensitivity is given by Design B, while operation frequency (Figure 3b) is largest for Design A.

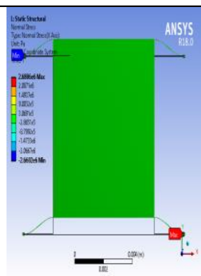
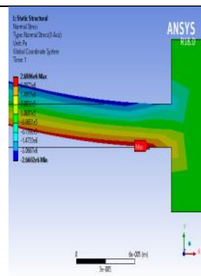
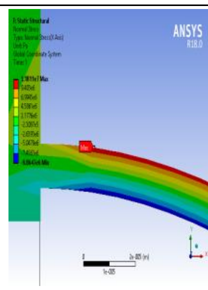
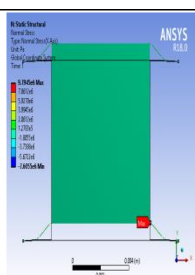
Table 4 shows the location of normal stress in the accelerometers A-C, and in the corresponding beams. As it can be seen, in all analyzed cases, location of maximum values of normal stress are in one side of the right beams, for Design A, closed to anchor, and for Designs B and C, closed to proof mass, on the same side. The bigger value correspond to Design C, but it is considerable lower than the tensile yield strength, which is convenient to guarantee the device integrity.



(a) (b)

Fig. 3. a) Comparison of displacement sensitivity and b) operation frequency.

Table 4. Location of normal stress (a) in the accelerometers A-C, and (b) in the corresponding beams.

Design	Location of Normal Stress in the accelerometer structure	Zoom in location of Normal Stress in the corresponding beam
A		
B		
C		

CONCLUSIONS

The proposed Modified Compliant Crank-Slider Amplifiers have a simple geometry, which had been successfully applied as suspension beams in capacitive accelerometers. Their implementation allow to obtain improvements in the displacement sensitivity, compared with the accelerometer of uniform beams, achieving the objective of this work. Beams of Designs B and C have geometries of masses distributed under a non-uniform fashion, based on the proposed amplifiers.

The highest displacement sensitivity value corresponds to Design B, providing an improvement of 125.513%, with respect to the conventional uniform beams accelerometer when 1g is applied. Its frequency, however, is reduced by 33.485%, according to the relationships established in equations 5 and 6 that involve the mass value under a direct and inverse proportionality, respectively. In future work, a compliant displacement amplifier will be added in order to increase both parameters simultaneously.

On the other hand, the results obtained with Design C, improvements in the displacement sensitivity (72.435%) and a lower decrease in operation frequency (23.886%), with respect to the uniform beams accelerometer. Addition of a compliant displacement amplifier is also suggested for future works.

In all analyzed cases, the location of maximum values of normal stress are in the same side of the right beams of these accelerometers. For Design A, location is closed to anchor and, for Designs B and C, closed to proof mass. The bigger value correspond to Design C, but it is considerable lower than the tensile yield strength, which is necessary for the structure integrity.

ACKNOWLEDGEMENTS

Pedro Vargas-Chable is grateful for the support of CONACYT, for his doctoral studies scholarship, under grant 484392/273928. M. Tecpoyotl-Torres and R. Vargas-Bernal also thank to CONACyT for its support, through the National System of Researchers, SNI, with references 20650 and 37831, respectively

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