INGENIERÍA MECANICA

Diseño y simulación de un acelerómetro con respuesta de sensibilidad mejorada

MECHANICAL ENGINEERING

Design and simulation of an accelerometer with improved sensitivity response

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Abstract

The capacitive accelerometers based on microelectromechanical systems (MEMS), are widely used in the automotive industry, in seismic detection, and in military applications. The sensitivity is one of their main characteristics, which widely benefit their use in front of small acceleration changes. In this work, the elements considered in the analyses of these systems are mass and suspension beams, which constitute a mass-spring system. The mathematical modelling establish its mechanical response. Based on the equations of sensitivity and frequency of displacement response sets out the criteria to determine the geometry of the mass and the length of suspension beams are obtained in order to improve the sensitivity response. The importance of the stiffness constant is also considered as part of the design. In this case, the changes in the mass produces irregular geometries that, at the same time, allows to increase the beam's length. The improvement in the sensitivity value permits the actuation at lower levels of acceleration. In addition, the simulation of the vibration mode, corresponding to the in-plane displacement, is carried out with the purpose of determining the appropriate frequency for the system operation. Material used for the actuator implementation is silicon. ANSYS is the software used to carry out simulations and characterization of the analyzed systems.

Keywords: *Accelerometer, MEMS, sensitivity, operating frequency.*

Resumen

Los acelerómetros capacitivos basados en sistemas microelectromecánicos (MEMS), son ampliamente utilizados en la industria automotriz, en detección sísmica y en aplicaciones militares. La sensibilidad es una de sus características principales, la cual beneficia ampliamente su uso frente a pequeños cambios de aceleración. En este trabajo, los elementos considerados en el análisis de estos sistemas son masa y brazos de suspensión, los cuales constituyen un sistema masa-resorte. Su modelado matemático muestra la respuesta mecánica del sistema. Con base en las ecuaciones para calcular la respuesta del desplazamiento de la masa y de la frecuencia de desplazamiento, se establecen los criterios para determinar la geometría de la masa y la longitud de los brazos de suspensión, con la finalidad de mejorar su respuesta en sensibilidad de desplazamiento. La importancia de la constante de rigidez es también considerada. En este caso, los cambios en la masa producen geometrías irregulares que al mismo tiempo permiten el incremento en la longitud de los brazos. La mejora en la sensibilidad permite la actuación a bajos niveles de aceleración. Además, la simulación del modo de vibración de desplazamiento en el plano es llevada a cabo con el propósito de determinar la frecuencia apropiada para la operación del sistema. El material utilizado para la implementación de los acelerómetros es silicio. Ansys es el software utilizado para llevar a cabo las simulaciones y caracterización de los sistemas analizados.

Palabras clave: *Acelerómetro, frecuencia de operación, MEMS, sensibilidad.*

1. Introduction

Microelectromechanical systems (MEMS) are integrated devices that combine both electrical and mechanical components. Their size ranges from micrometers to a few millimeters (MEMS Research Center, 1999). Their most common applications include: accelerometers, sensors of pressure, chemical sensors, flow sensors, as well as optical scanners and pumps of flow.

The MEMS are widely used for measurement of inertia in the automotive market, using many principles of signal transduction for their operation; among them, the capacitive detection, (Comi, 2016).
The microaccelerometers are devices that stand out due to their high sensitivity of displacement and operation frequency (Jing, 2015). Among of their applications, they can be used in touch screens, where with the processing of an input touch, for the selection of the desired object, information is received indicating the orientation or movement of the screen. (Patent US2016041755, 2016). Accelerometers are also used for systems of monitoring, which can include also optical fibers (Antunes, 2012). In order to perform ultra-sensitive MEM systems, all the elements are integrated in a single chip, also to reduce the 1/f noise, as shown in (US Patent, 2003).

On the other hand, it is important to mention that in the bibliography there are works in which modifications are made in the geometry of the accelerometers, both in their mass (US Patent, 2011) and in the form of suspension beams. In (Patent US2016041199, 2016), E-shaped beams are presented.

The sensitivity of displacement is defined as the displacement of the moving mass per unit of gravitational acceleration g (Benmessaoud & Danskin-Nasreddine, 2013). For such sensitivity, it is necessary to starting from Newton's second law that establishes that the acceleration of an object is directly proportional to the net force, that acts on it and inversely proportional to its mass, and it is represented by Eq. (1).

$$F = ma \tag{1}$$

Where $\boldsymbol{F}$ is the net force, m is the mass of the system and $\boldsymbol{a}$ is the acceleration.

Suspension beams, connected to the mobile mass, are affected by the inertia of the mass, when they are opposed to the movement, so their length is changed. Beams become deformed as a result of the sense of acceleration. This deformation is proportional to the force that causes it. Thus, the relationship between the movement of beams and the force acting directly or indirectly on them according to Hooke's law, is expressed by Eq. (2).

$$F = kx \tag{2}$$

Where $\boldsymbol{x}$ is the displacement and k is the stiffness constant or constant of the spring, which is obtained by Eq. (3):

$$k = Et\left(\frac{w_b}{l_b}\right)^3 \tag{3}$$

E is theYoung's modulus of the material, t, w_b and l_b are the thickness, width and length of the suspension beams, respectively.

The Eq. (4) shows the equality of Eq. (1) and Eq. (2).

$$ma = kx \tag{4}$$

In order to obtain the sensitivity of displacement, it is necessary to use $\boldsymbol{x}$ from Eq. (4), as it can be appreciated in Eq. (5).

$$x = \frac{m \cdot a}{k} \tag{5}$$

It should be noted that the mechanical sensitivity has a similar expression (Cruz-Acero, 2010), being only $s_m = \frac{m}{k}$. The expression for the sensitivity of displacement calculation, here developed, considers the effect of acceleration and allows us to get very close values to those obtained through simulation.

Displacement sensitivity will remain constant within a frequency range before any resonance frequency (Khan, 2013). This happens since, as it is widely known, before the resonance frequency, the device will operate according to the design conditions, under those it is was developed. So, it is recommended to design at high operation frequencies.

For these reasons, in this work an improvement on the sensitivity of displacement is presented. However, the frequency of operation is low. This determine the future work, where amplifiers of displacement will be implemented that favor the sensitivity, minimizing the effect exerted by the operation frequency on it.

To obtain the operation frequency of an accelerometer, Eq. (6) is used (Jianbing, 2013).

$$f = \frac{1}{2\pi}\sqrt{\frac{Etw_b^{\,3}}{ml_b^{\,3}}} \tag{6}$$

2. Theoretical analysis of a capacitive accelerometer

Accelerometers are devices used to measure acceleration and vibration. These devices transform the acceleration of gravity or movement into an electrical analogue signal, proportional to the force applied to the system (Manzanares, 2008). Figure 1 shows the main elements of a conventional rectangular accelerometer.

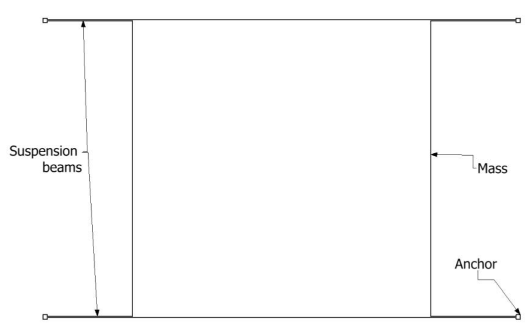


Figure 1. *Main elements of an accelerometer.*

The purpose of this work, additional to the proposal of a geometry that enhances the sensitivity of a capacitive accelerometer, is to validate the theoretical results way with those obtained by the use of Ansys software, which makes modeling by finite element method.

Figure 2 shows the dimensions of the used capacitive accelerometer and Table 1 shows the properties of Silicon.

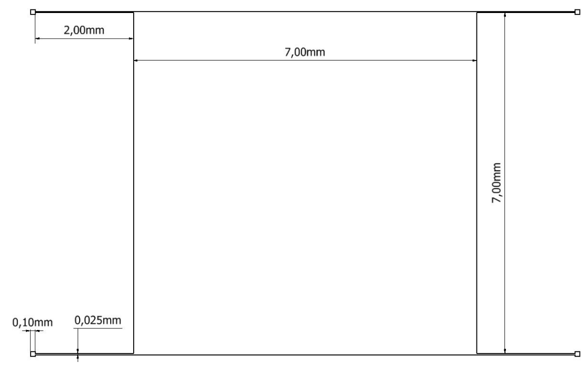


Figure 2. *Sizes of the capacitive accelerometer.*

Table 1. *Properties of Silicon, (Ansys, 2015).*

Property	Value
Density (ρ), in Kg/m^3	2330
Thermal Expansion coefficient (α), 1 / ° C	2.6x10^{-6}
Young´s modulus (E), in GPa	131
Poisson ratio, dimensionless	0.33

For the calculation of sensitivity of displacement and frequency, Eqs. (5) and (6) were employed, respectively. The calculated values are shown in Table 2.

Table 2. *Values of calculated parameters of conventional accelerometer.*

Parameter	Value
Sensitivity of displacement, $\boldsymbol{x}$	1.09 µm/g
Frequency, f	475.35 Hz

3. Simulation and results of a capacitive accelerometer

In simulations, 1 g (9.81 m/s2) is applied, in order to validate the values calculated in section 1 (Table 2). Figures 3 and 4 show the sensitivity of the in plane displacement, as well as the frequency that corresponds to this vibration mode, respectively.

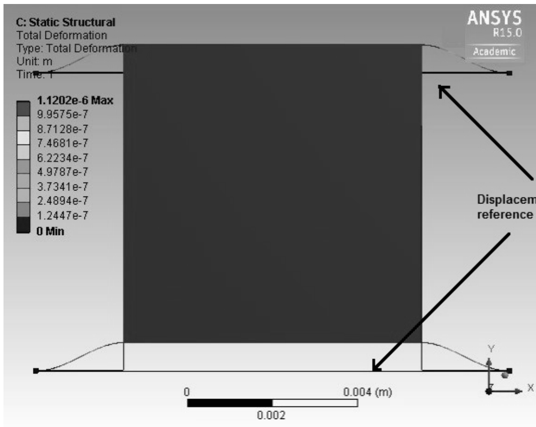


Figure 3. *Sensitivity of the in plane displacement response of conventional accelerometer.*

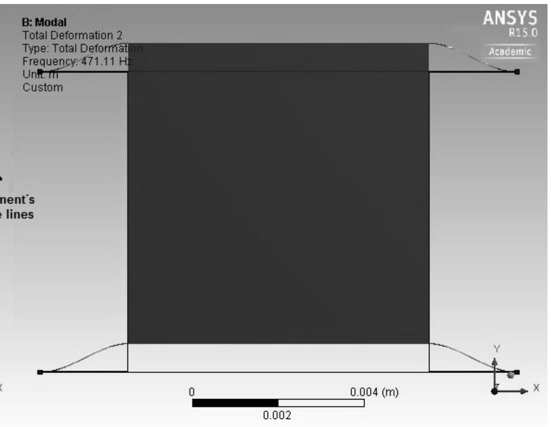


Figure 4. *Frequency corresponding to the in plane displacement of the conventional accelerometer*

Table 3. *Comparison of results obtained for the conventional accelerometer.*

Sensitivity of in plane displacement (calculated)	Sensitivity of in plane displacement (simulated)	Frequency of in plane displacement (calculated)	Frequency of in plane displacement (simulated)
1.09 µm/g	1.12 µm/g	475.35 Hz	471.11 Hz

Table 3 shows a comparison of theoretical and simulated results, corresponding to the in plane movement.

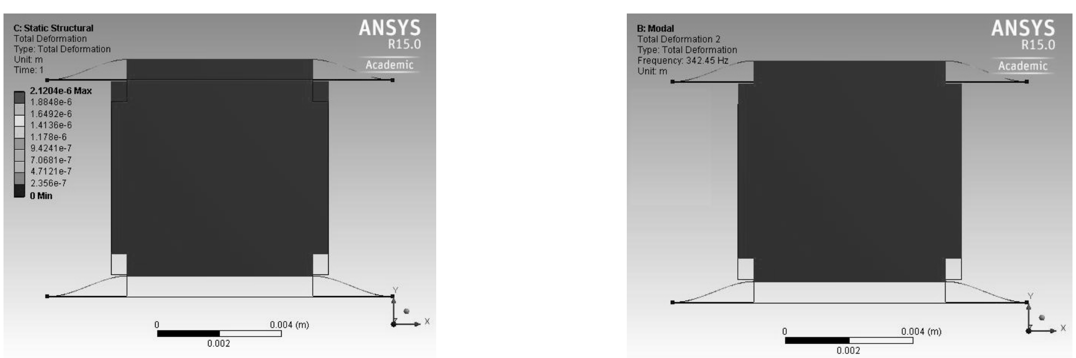
From the results obtained through simulation, the sensitivity of in plane displacement has a percentage error of 2.7 and in the case of the frequency, the percentage error is 0.9, with respect to the analytical results.

4. Geometry proposal for the sensitivity improvement

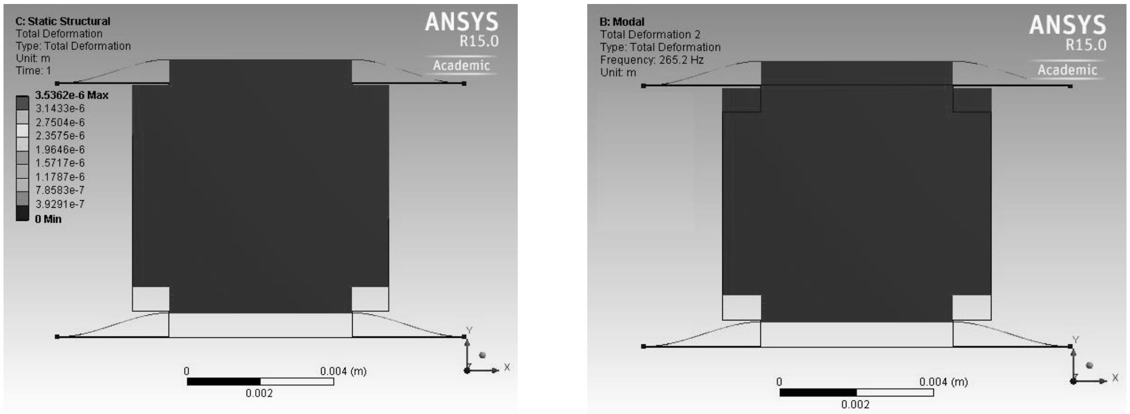
4.1 Theoretical analysis of the accelerometer extended beams

After the comparison of the analytical and simulated results of the conventional capacitive accelerometer, some modifications to its geometry, are proposed in order to improve the sensitivity of in plane displacement, based on a lengthening of the beams which at the same time, causes modifications in the form of the mass.

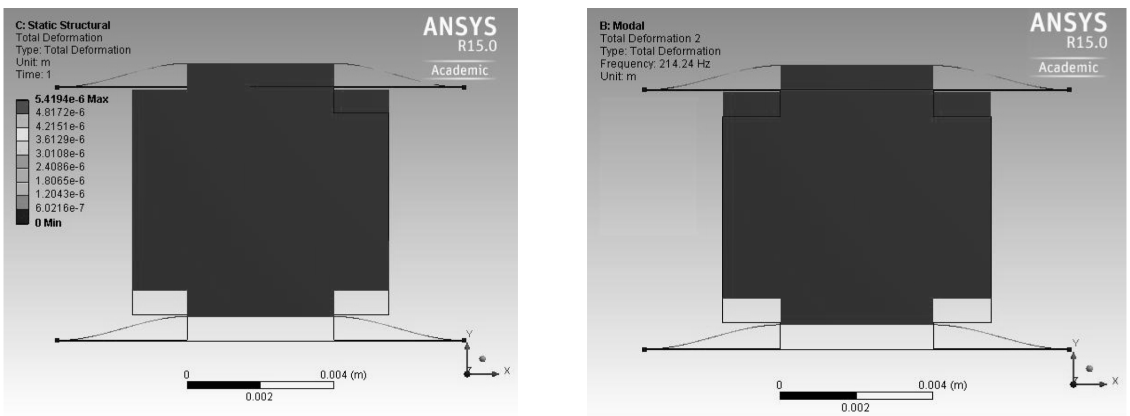
Figure 5 shows the sensitivity of the in plane displacement response and the frequency of the movement, of the accelerometer with extended beams.



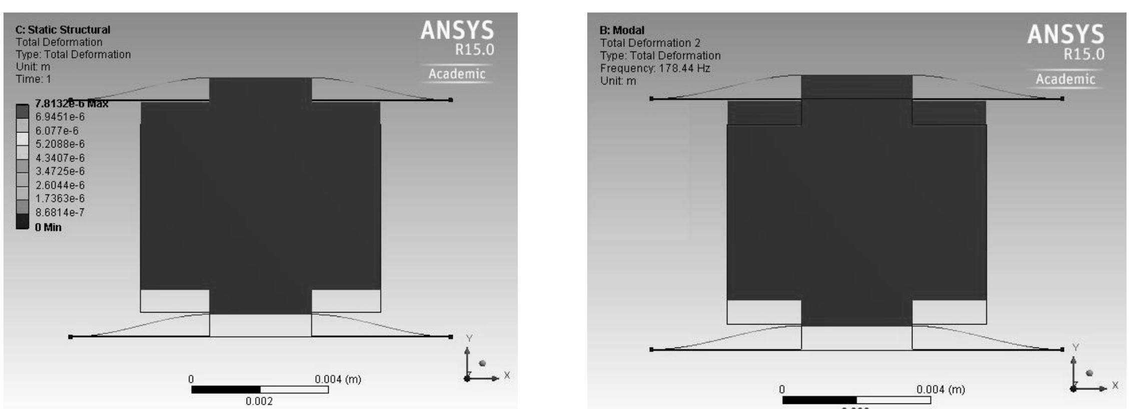
a)


C: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
3.5362e-6 Max
3.1433e-6
2.7504e-6
2.3575e-6
1.9646e-6
1.5717e-6
1.1787e-6
7.8583e-7
3.9291e-7
0 Min
ANSYS
R15.0
Academic
0
0.002
0.004 (m)
B: Modal
Total Deformation 2
Type: Total Deformation
Frequency: 265.2 Hz
Unit: m
ANSYS
R15.0
Academic
0
0.002
0.004 (m)

b)


C: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
5.4194e-6 Max
4.8172e-6
4.2151e-6
3.6129e-6
3.0108e-6
2.4086e-6
1.8065e-6
1.2043e-6
6.0216e-7
0 Min
ANSYS
R15.0
Academic
0
0.002
0.004 (m)
B: Modal
Total Deformation 2
Type: Total Deformation
Frequency: 214.24 Hz
Unit: m
ANSYS
R15.0
Academic
0
0.002
0.004 (m)

c)


C: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
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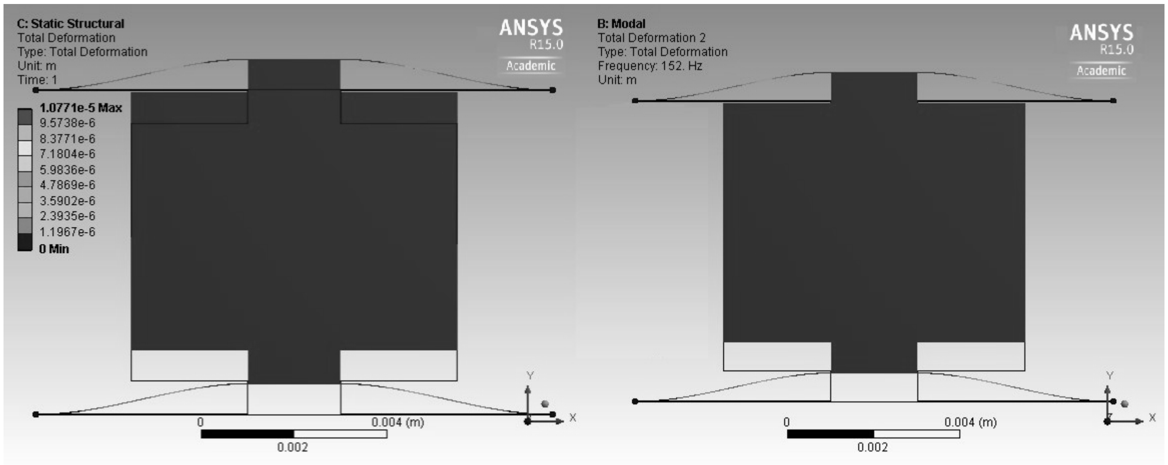
6.9451e-6
6.077e-6
5.2088e-6
4.3407e-6
3.4725e-6
2.6044e-6
1.7363e-6
8.6814e-7
0 Min
ANSYS
R15.0
Academic
0
0.002
0.004 (m)
B: Modal
Total Deformation 2
Type: Total Deformation
Frequency: 178.44 Hz
Unit: m
ANSYS
R15.0
Academic
0
0.002
0.004 (m)

d)



e)

Figure 5. *Sensitivity and frequency response of the in plane displacement of the accelerometer with extended beams with several length beams.*

In Table 4, the results of sensitivity and frequency of the in plane displacement are shown, under analytical and simulation calculations, as well as the length of the suspension beams.

Table 4. *Comparison of obtained results.*

Figure	Length of suspension beams	Sensitivity of in plane displacement (calculated)	Sensitivity of in plane displacement (simulated)	Frequency of in plane displacement (calculated)	Frequency of in plane displacement (simulated)
5a	2.5 mm	2.08 µm/g	2.12 µm/g	345.07 Hz	342.45 Hz
5b	3 mm	3.50 µm/g	3.53 µm/g	266.43 Hz	265.2 Hz
5c	3.5 mm	5.39 µm/g	5.41 µm/g	214.69 Hz	214.24 Hz
5d	4 mm	7.79 µm/g	7.81 µm/g	178.52 Hz	178.44 Hz
5e	4.5 mm	10.74 µm/g	10.77 µm/g	152.06 Hz	152 Hz

In Figure 5, changes in the geometry of the mass and in the form of suspension beams can be observed. The sizes of the suspension beams increase by 0.5 mm in each case, from 2 up to 4.5 mm. It can be seen that as beam length increases, the sensitivity of displacement also increases. However, the frequency of displacement in plane decreases. This fact is due to the commitment with the increasing of the sizes of the suspension beam.

4.2 Simulation results of the accelerometer of extended beams

Due to the bigger sensitivity of displacement, the accelerometer of Figure 5e was chosen. Its sizes are shown in Figure 6.

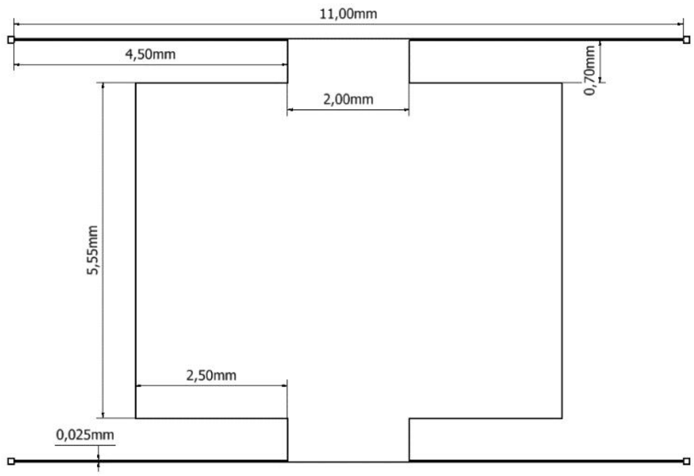


Figure 6. Sizes of the accelerometer with expanded beams.

Outcomes through simulation in the case of sensitivity, a percentage error of 0.3 was gotten. For the case of the frequency, the percentage error is 0.04, with respect to the calculated results.

From table 5, it can be seen that the sensitivity of the in plane displacement for the case of chosen accelerometer, is approximately 10 times greater than in the case of the conventional one, but in the case of the frequency, the answer is 3 times less. This can be explained by the equations analyzed in this work, showing that there is a direct proportionality between the length of the suspension beams and the sensitivity of displacement. In addition, there is an inversely proportional relationship between the reduction in the mass and the frequency, which corresponds to the displacement in plane. The direct and inverse proportionality constants are 2.4 and 48, respectively.

In addition, the shape of suspension beams was modified (Figure 7). As a result, an improvement in the sensitivity of displacement was obtained (Table 5).

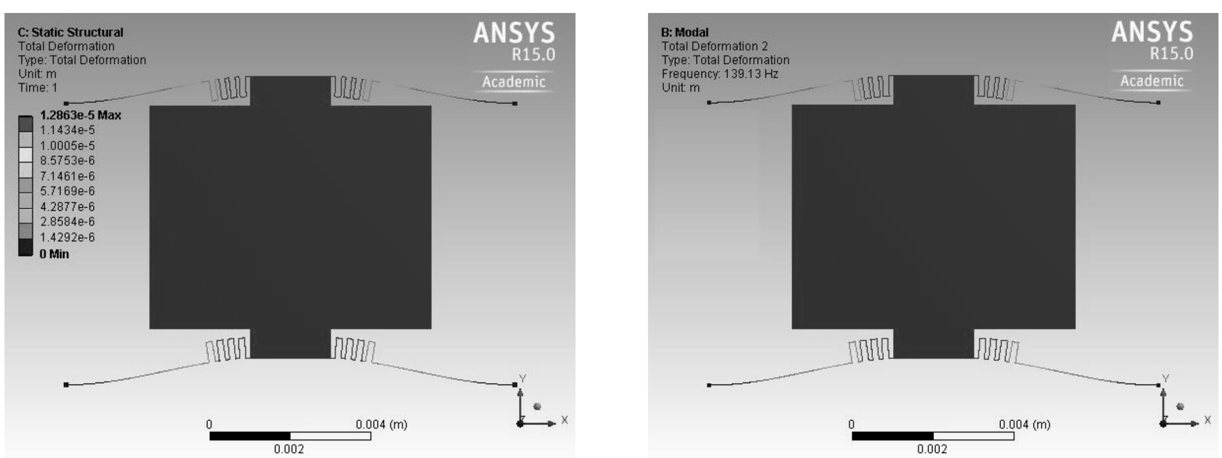


Figure 7. *Sensitivity and frequency response of in plane displacement of the accelerometer with suspension coil-shaped beams.*

Table 5. *Comparison of results of the accelerometer with suspension coil-shaped beams.*

Length of suspension beams	Sensitivity of in plane displacement (calculated)	Sensitivity of in plane displacement (simulated)	Frequency of in plane displacement (calculated)	Frequency of in plane displacement (simulated)
4.5 mm	10.84 µm/g	12.86 µm/g	151.35 Hz	139.13 Hz

With the accelerometer with one end of the coil-shaped suspension beams, the sensitivity increases 19% with respect to the chosen accelerometer of extended beams. It is important to mention, that the results obtained analytically are not very close to those obtained through simulation. This is because these equations are used for straight suspension beams, and they do not apply to the form displayed in this accelerometer. So, it is required to adapt it.

Khan & Ananthasuresh (2014) reported a sensitivity value of displacement of 0.102 µm/g, with approximate sizes of 2 mm x 6 mm for the mass area and length of beams of 1.5 mm. They presented a very complete analysis that we employed as a basis for the development of our accelerometers, in principle in the same sizes, in order to compare our results. Later, the accelerometers with the proposed sizes and modifications were developed.

5. Conclusions

From the analysis of the equations for in plane sensitivity and frequency calculations, the accelerometer of extended beams was proposed. With it, the sensitivity is increased by approximately 10 times, compared with a conventional capacitive accelerometer. However, the frequency of displacement response decreases by 68%. The implementation of displacement amplifiers could reduce the dependence of sensitivity with respect to the frequency of displacement in plane.

The simulation results with respect to the values obtained analytically with the developed expression, are closest to the case of the accelerometer of extended beams, providing a percentage error of 0.3 for the sensitivity and 0.04 for the frequency shift, compared with the case of the conventional capacitive accelerometer.

Due to the sensitivity of displacement for the accelerometer of extended beams, this device can be useful for industrial applications requiring a low g, such as monitoring of or seismic vibrations, among others.

For the coil-shape beams, a bigger sensitivity of displacement (19% compared to the one with extended beams) was observed in the corresponding simulations. The equations used in the case of the linear shape beams requires an adaptation in order to be applied to other geometry of the beams.

6. References

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