Magneto-Mechanical Modeling and Simulation of MEMS Sensors Based on Electroactive Polymers

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Abstract. Mechanical oscillations have been suggested for many applications, such as: acoustic sensors and actuators, telemetric links, or energy harvesting. In common, all these applications require a readout mechanism to translate mechanical oscillations on electrical signals. PVDF (Poly(vinylidene fluoride)), is a polymer with outstanding electroactive properties, which can be used as a readout mechanism. Combined with a permanent magnet layer on a MEMS device, PVDF may provide a passive and resonant magnetic field sensor. The full system simulation becomes very challenging, since it includes three different domains: magnetic, mechanical and piezoelectric. This paper reportson the full system simulation, from an external magnetic field, till the piezoelectric response of the PVDF. From the developed methodology, it was possible to accurately predict the interaction of all the physical variables, and optimize the MEMS device, leading to better sensitivity or harvesting ability.

1. Introduction

Despite being around from more than 10 years, Microelectromechanical systems (MEMS) continues to be an exciting and challenging multidisciplinary field with tremendous progress taking place in research and commercialization. From the beginning, MEMS have been taking advantage of well-established manufacturing methods routinely used in the integrated circuit industry to develop devices capable of sensing, actuating and processing information [1]. In fact, MEMS can be classified in two major categories: sensors and actuators. As a microsensor, it consists of mechanical structures that predictably deform or respond to a specific physical (or chemical) variable.

The recent year's developments in the compatibility of the piezoelectric thin films with the IC technology are increasing the importance of this research driver in the microsystems applications [2]. Among polymers, PVDF (Poly(vinylidene fluoride)) and VDF (vinylideneflouride) copolymers, has remarkable properties leading to electro-optics, electro-mechanical and biomedical applications. The semicrystalline nature of PVDF, combined with the occurrence of at least four crystalline phases (α, β, δ and γ) implies a challenging physical microstructure [3]. The most frequently described and important phase is the βone, due to its high piezo and pyro-electric properties, when compared to theother crystalline phases, and even compared to otherpolymeric materials [4].

Combining a MEMS device with a layer of PVDF, placed at proper positions, is known as a piezoelectric readout mechanism. The changes in PVDF charge (piezoelectricity) results on detectable voltage amplitude variation, which are proportional to the magnitude of the stimulus sensed. This mechanism may be used to detect mechanical variations, though being used to sense and generate mechanical waves, as well to harvest energy from mechanical wave.

A MEMS device may also be used to detect RF electromagnetic waves based on the Lorentz force [5].

That solution requires a current flowing through the MEMS device, which encloses the challenge of routing enough current along the MEMS device, without degrading its mechanical properties. Moreover, that current will contribute for power consumption.

Instead of a current, a layer of a permanent magnet may be applied. In this way, the MEMS device has the benefit of being sensitive to magnetic fields, without the drawback of compromising the MEMS device anchors with routing lines. More extraordinary, is the fact that such MEMS device translates a magnetic field into a detectable voltage, without using any power supply. This leads to more power efficient sensors, for wireless applications, and opens the possibility to harvest energy from magnetic fields, like those produced by the many railways available in our cities. Fig. 1 shows the concept.

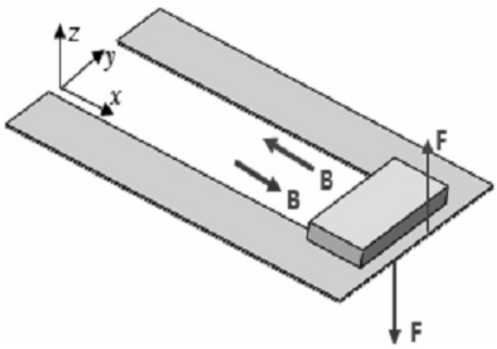

Fig. 1. RF MEMS device based on PVDF and permanent magnetic layer to detect RF magnetic fields.

It is a silicon cantilever, with a top layer of PVDF, and an area with a permanent magnet (represented by the box with applied forces). As seen in figure, the permanent magnet does not interfere with the structure mechanical behavior, if its weight is controlled.

This paper will present a methodology on how to simulate this complex three domain problem. It will show how this structure behaves and a model validation is also presented, where the simulation results are compared to measurements and good agreement is obtained.

2. MEMS Device Modeling

A. U-shaped cantilever was selected to develop this methodology since it allows, simultaneously, to study all the required physical variables and domain interactions, keeping the simulation times at acceptable levels.

Figure 2 shows the proposed MEMS simulation domain simulations may be found in Table 1.

Table 1. Material properties

	CANTILEVER	MAGNET
Material	**PVDF**	**Neodymium**
Length (x) Width (y) Thickness (z)	25 mm 18 mm 110 µm	4 mm 10 mm 1 mm
Density	$1800\frac{Kg}{m^3}$	$7400\frac{Kg}{m^3}$
Young's Modulus	$3 \cdot 10^9\ \frac{N}{m^2}$	1.7×10^{10} N/m^2
Poisson Ratio	0.35	0.281
Piezoelectric strain coefficient	-28×10^{11} m/V	-
Residual magnetism	-	1.43 T
Coercive field strength	-	9.3×10^5 A/m

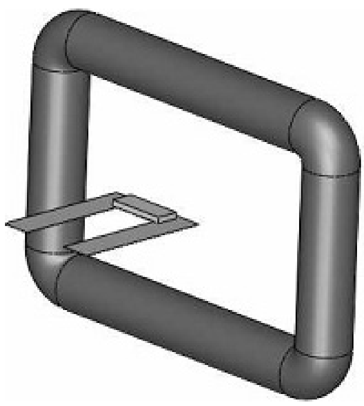

Fig. 2. MEMS device model, including the cantilever and magnetic coil to generate real magnetic field lines.

A. U-shaped cantilever description

As it is shown in Fig. 1, a force (F) acts on the cantilever when it is exposed to an external magnetic field (B). When the magnet is polarized along the z axis and the applied magnetic field vector has a component on x axis, a force (Lorentz force) will lead to a displacement in z axis. However, this MEMS structure will move only when the Lorentz force overcomes the elastic force, which means a minimum magnetic field must be applied in order to force the structure to move [5]. This "minimum" magnetic field can be reduced since the cantilevers' displacement is greater the closer are the frequencies of the external magnetic field and the eigenfrequency of the cantilever.

B. Magnetic Field Generator

Instead of assuming a specific magnetic field line distribution, a magnetic field was generated with a coil and applied to the cantilever, placed 2 mm away, as shown in the Fig. 2. The cantilever was aligned with both axis of the coil, so then it would be possible to maximize the magnetic field for the same voltage.

To mimic the measuring setup, the coil has 200 turns of copper, with 200 micrometers in diameter. It was fed by a signal generator, at the resonant frequency, with a signal of 5 V in amplitude. It was also possible to change the frequency of this signal, depending on the cant displacement.

3. MEMS Device Simulation

A. Introduction

Due to the multiplicity of simulation domains, simulations were performed using *Ansys Multiphysics*. This very powerful software allows the simulation of different environments, being the reason why is used in so many different industries and universities.

Once the simulation of this system encompasses piezoelectric, electrical, magnetical and mechanical magnitudes it comes mandatory the use of more than one single element. The adopted methodology was based on building the final result by iteratively combining the simulation in each simulation domain. That requires the use of the called "coupled-field analysis", where results moves from one domain to other through "import" features available in Ansys.

The "load transfer coupled-field analysis" was used to perform a magneto-structural analysis, in which it was given the voltage at the coil as an input and it returned the cantilever displacement as an output. So, this method is the combination of different engineering disciplines that interact to solve a global engineering problem. In this case, a magnetic simulation and a mechanical simulation (normally referred as magneto-mechanical simulation) were performed to analyse the displacement of the cantilever in function of the voltage on the coil.

As final step, the final displacement was used as an input in the piezoelectric analysis. However, the magnetic and the mechanical simulations were performed with the 3D model and piezoelectric on a 2D model.

B. Magnetic Simulation

Fig. 3 shows view of the model used for magnetic and mechanical simulation. Instead of attempting to simulate the full model, shown in Fig. 2, symmetry facilities were used to reduce the simulation domain. So, to perform the magneto-mechanical simulation it was used a halfsymmetry model, where the outer box is an air shell involving the entire model. The coil is the U shaped volume and the smaller box is another box of air containing half cantilever and half magnet inside.

The Solid97 was the element selected for the magnetic simulation. It is an eight-node 3D magnetic solid element and it is appropriate to simulate magnetic vector potential together with the VOLT degree of freedom. A 3D static magnetic analysis was performed using this element, together with different voltages at the coil.

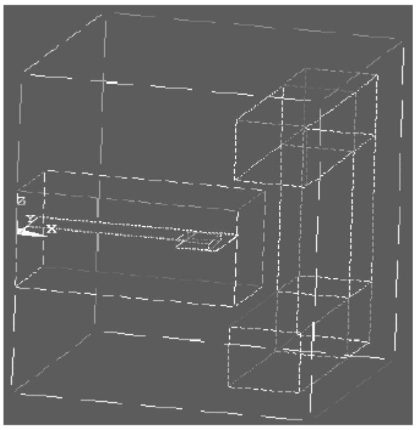

Fig. 3. Simulation model, showing all boundary lines for the simulated volumes.

After simulation, with proper coil voltages and using magnetic properties of the neodymium magnet listed on Table 1, the magnetic force at the magnet was obtained. This magnetic force on the magnet was then used as an input to the displacement simulation of the cantilever.

C. Mechanical Simulation

After the magnetic simulation, all the volumes and attached nodes representing the coil and the outer air shell are deleted and just the inner air shell, cantilever and magnet remains to the next simulation domain. Then, all the volumes are meshed with the Solid98 element (with displacement degree of freedom) and the force vector values in the database are imported and applied to the new magnet elements. Together with this, mechanical properties listed in Table 1 were used.

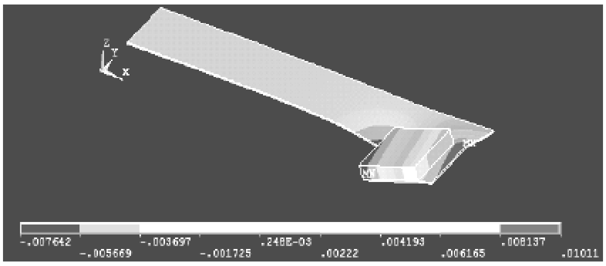

Fig. 4. Cantilever deformation, for a coil voltage of 5 V.

After performing a static simulation, the deformed cantilever is obtained, as shown in Fig. 4. From the Fig. 4 it is possible to observe that the structure deformation is not uniform. This means that proper design of this type of devices should rely on advanced simulations, rather than on simple equations modelling interaction between the different physical variables.

D. *Piezoelectric Simulation*

In order to allow the use of the cantilever as a magnetic field sensor, the PVDF performance is a key factor. Effectively, larger piezoelectric coefficients will provide higher voltages for a given deformation. In the thickness mode, piezoelectric actuators increases or decreases its thickness following the inverse piezoelectric relation:

$$\varepsilon_3 = d_{33} E_3 \tag{1}$$

where ε_3 is the strain of the actuator, d_{33} is the piezoelectric coefficient and E_3 is the applied electric field. In eq. (1), the index 3 means that only the cantilever thickness (z direction) is considered.

Theoretical calculations lead to a value of $|d_{33}| \sim 25.19$ pC.N^{-1} [6], which is closed to the experimentally obtained $|d_{33}| \sim 28$ pC.N^{-1}[7]. This experimental piezoelectric coefficient was the one used as input in the piezoelectric simulation.

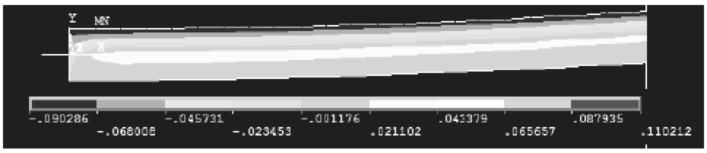

Fig. 5. PVDF voltage in the simulated cantilever beam.

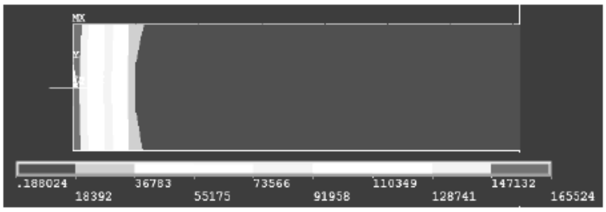

Fig. 6. PVDF electric field distribution.

The piezoelectric simulation was performed by a 2D model, using the 8 node coupled-field solid element Plane223. This element has the piezoelectric analysis capability, so that the maximum displacement was given (about 1 cm from the mechanical simulation) as an input load and it returned the voltage and electric field distribution as shown in Fig. 5 and Fig. 6.

The simulated cantilever beam was 100 µm thick and 2.5 cm long. Fig. 5 and Fig. 6 shows only one beam end, because, as it can be seen on Fig. 7, it was the region where the experimental readout was implemented. In Fig. 5, the resulting voltage amplitude (corresponding to the maximum displacement and voltage on the coil–from the mechanical and magnetic simulations) is around 90 mV, which means a 180 mV peak-to-peak signal.

4. Experimental Results

The experimental setup that was used to validate the simulated structures and models is shown on Fig. 7.

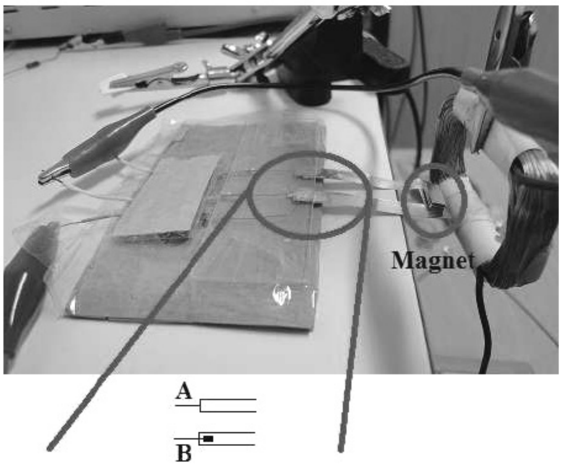

Fig. 7. Experimental setup.

The electrodes are on the base of the cantilever and they were connected to an acquisition system, and the measured result when a 5 V *ac* signal was applied on the coil is shown on Fig. 8.

The output of the cantilever was connected to an acquisition board from NI, and the signal was recorded when a voltage was applied on the coil. The measured result was a 200 mV peak-to-peak signal, which is just 20 mV more than the value from the simulation. Fig. 8 shows the circuit schematic that was used as a receiver. The electrodes (from the cantilever) that can be seen in Fig. 7 are connected to this amplifier.

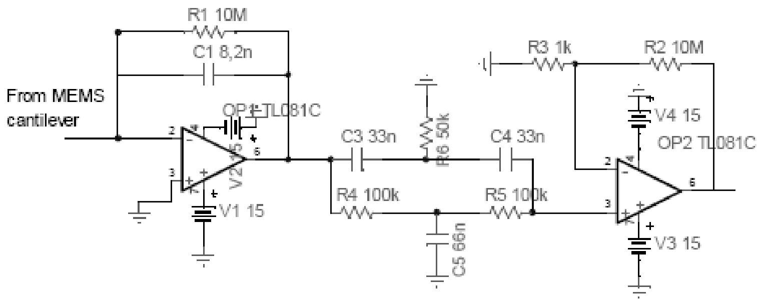

Fig. 8. Charge amplifier schematic.

It is a charge amplifier, followed by a 50 Hz notch filter and a voltage amplifier. With this circuit, it was possible to detect the signal shown in Fig. 9.

It was possible to receive a 200mV, 12 Hz signal, frequency that corresponds to the resonant frequency of this cantilever with the magnet.

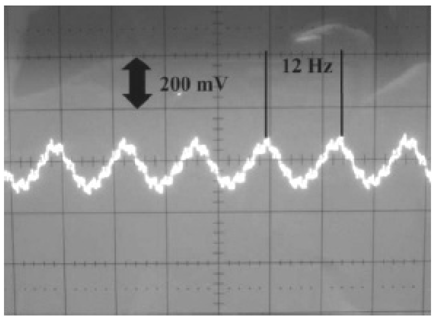

Fig. 9. Signal obtained from the vibrating cantilever, after amplification and filtering.

5. Conclusions

Despite the use of piezoelectricity, as a readout mechanism, has not been widely used so far, due to lack of piezoelectric materials integration technology.

The presented work takes advantage from the recent developments to predict its behaviour on a MEMS device. After modelling and simulation, a MEMS resonant structure was used to establish a low-frequency RF link.

The type of finite element coupled-field analysis implemented allowed to simulate the cantilever behaviour in the presence of an RF magnetic field generated by an external coil. The full model domain was simulated, from the generation of the external magnetic field till the voltage generated by the PVDF. The model is feasible and stable.

An experimental validation was performed, where good agreement between measurements and simulations was observed. However, improvement to a 3D piezoelectric, simulation is still possible, where a realistic cantilever may be simulated instead of only a beam.

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