Dynamic Characterization and Mechanical Simulation of Cantilevers for Electromechanical Vibration Energy Harvesting

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Abstract: Energy harvesting from ambient vibrations has become an interesting topic for powering small-scale wireless electronic devices, medical devices and sensors. Usually, ambient vibrations are sub-1 kHz. Hence, for efficient energy harvesting, resonant microdevices based on MEMS, that can provide a resonant behavior at low frequency, have become of central importance. Indeed, the power produced at resonance is at least one order of magnitude larger than off frequency power since the largest strain is obtained at resonance. In this context, in order to obtain large strain for efficient electromechanical energy conversion, polymer materials, which are more flexible than silicon ones, have been considered for the vibrating devices. In this paper, two preliminary resonant microcantilevers made of viscoelastic polymer have been simulated with COMSOL to deduce both the resonant frequency and quality factor of the first flexural resonance mode. Simulation results are presented and compared with experimental ones. We have also investigated how the resonant frequency and the axial strain vary with the microcantilever thickness, to optimize the behavior of such MEMS resonators as electromechanical energy harvesters.

Keywords: Ambient energy harvesting, low resonant frequency, viscoelastic polymer microcantilevers.

1. Introduction

Vibration energy harvesters convert mechanical energy from ambient vibrations into electrical power. They can be used, for instance, as low-power sources for wireless sensors networks [1] - [3]. Usually, the environmental energy sources are characterized by a relatively low level of acceleration (sub-1g) [4] and low frequency vibrations (sub-1kHz) [5] - [7]. With this in mind, the maximum amount of power is achieved at the resonant frequency of mechanical devices since a large strain can be obtained for efficient mechanical-electrical conversion. Hence, the power produced depends on the resonant frequency of the structure, its volume and the material properties of the mechanical part [8] - [9]. In this context, polymer materials, which are more flexible than silicon ones, have been considered for the vibrating devices since they can combine low resonant frequency and large strain. In parallel, the cantilever beam and the tapered beam designs are the most often used for their relatively low resonant frequency and high average strain [8], [10] - [12].

In this paper, microcantilevers beams with parallelepiped shape have been fabricated, characterized and simulated with COMSOL to deduce the resonant frequencies and the quality factors of such devices. A study of beam thickness variation is proposed to optimize the effect of this parameter on the resonant frequency and the axial strain.

2. Design and Fabrication

The microcantilevers are designed to achieve resonant frequency under 1 kHz for compatibility with low frequency ambient sources vibrations. The beams have parallelepiped shape with large lengths; they are based on polymer (epoxy) as mechanical element for flexibility. The considered dimensions of the different cantilevers fabricated (Figure 1) are given in Table 1. A tip-mass with various dimensions is added to increase the resonator mass; this allows achieving low resonant frequencies in order to test the devices with ambient input vibrations.

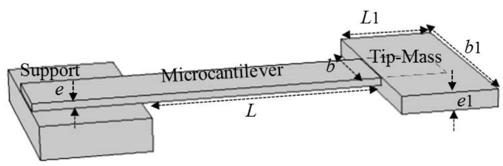
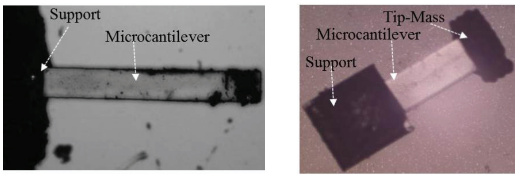


Figure 1. Schematic diagram of viscoelastic polymer microcantilever.

Table 1: Dimensions parameters for two types of resonant structures. A without tip-mass and B, C and D with tip mass

Structures	*L* (mm)	*b* (µm)	*e* (µm)	L1 (µm)	*b*1 (µm)	*e*1 (µm)
A	1	200	20			
B	0.94	600	24	380	0.91	48
C	0.94	600	25	380	0.91	48
D	0.94	300	30	380	0.91	70

The cantilevers are fabricated by combining two microfabrication techniques: photolithography and screen-printing. An omnicoat sacrificial layer (~160 nm) is first deposited on a silicon wafer by spin coating in order to allow the release of the microstructures after their fabrication. The second step consists in fabricating the cantilever mechanical part of thickness *e*: it is made of SU-8 (3050) patterned by photolithography. Then, the tip mass (thickness *e*1) and the support (~150 µm), made of Ag-polymer based paste (ESL1901) are screen-printed. Figure 2 shows examples of successfully fabricated hybrid microcantilevers (with and without tip-mass).



a) b)

Figure 2. (a) Optical image of resonant structure A. (b) Optical image of resonant structure C.

3. Characterization method

The proposed designs are characterized by means of a Polytec MSA 500 laser vibrometer. The resonant behavior (amplitude and phase) of the vibrating structures is observed in air. A picture of the experimental setup is shown in Figure 3. The use of cantilevers in the out-of-plane flexural vibration modes is essential for efficient energy harvesting; an external piezoelectric actuator ensures the out-of-plane vibrations of the cantilevers. The measured resonant frequencies for the devices without seismic mass are between 4.47 kHz and 5.10 kHz, while these values become between 1.28 kHz and 1.68 kHz with the seismic mass, confirming experimentally the effect of the tip-mass on the resonant frequency of the cantilevers.

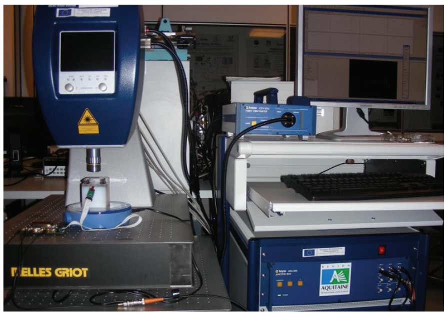


Figure 3. Photo of the vibrometer (left) with data processing (right) .

4. Use of COMSOL Multiphysics

Two 3-dimensional geometries are considered for the simulation. Figure 4 shows the COMSOL model of structures A and C. The support is made of PMMA using the isotropic material library. The beam is made of a SU-8 viscoelastic polymer where the Young's modulus is in complex form ($E=E'+jE''$). The material parameters of the polymer are as follows: its density ρ=1150 kg/m^3, its Poisson's ratio ν=0.4 and its young's modulus E=4.6 GPa + j0.1 GPa. To increase the axial strain into the beam and to reduce the resonant frequency of the microcantilever, a heavy tip-mass of ρ_m=4500 kg/m^3, is placed at the free-end of the cantilever where ν_m=0.4 and E_m=50 GPa.

The frequency response of the microcantilevers is simulated using a harmonic analysis in COMSOL. Here the "Solid Mechanics" module is used to solve the mechanical simulation. The structure is fixed at one end on the support while tip of the cantilevers is free for vibration. Excitation of the base of the support by a vertical acceleration ensures the out-of-plane vibration of the structures.

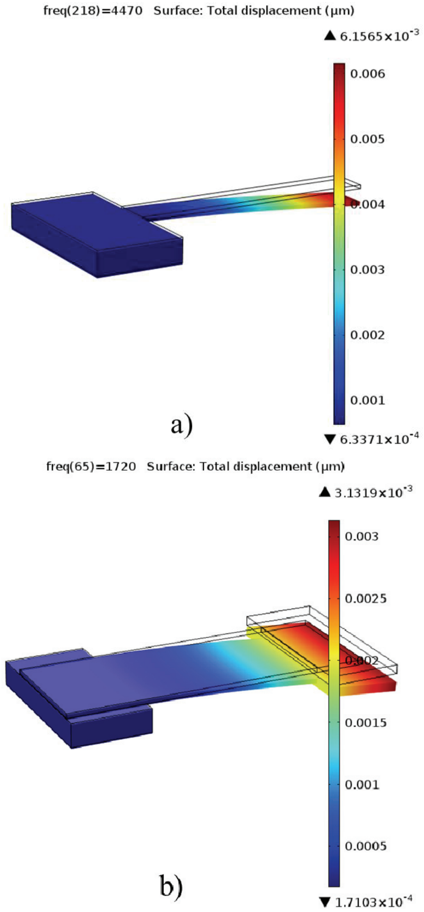


Figure 4. FEM modeling of (a) structure A and (b) structure C.

5. Results

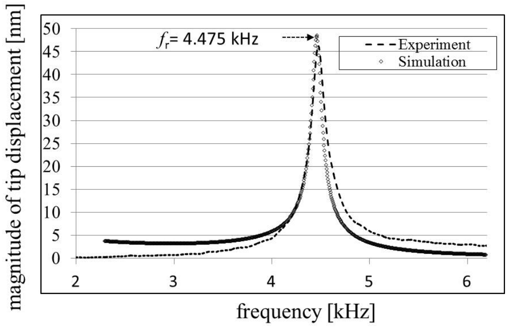
5.1 Harmonic analysis

The resonant frequency (f_r), the undamped natural frequency (f_0), and the quality factor (Q) of the first flexural resonant mode of the cantilevers are obtained through frequency analysis using the frequency domain and "pardiso" as linear system solver. Figure 5 shows both experimental and simulated values of the resonant frequency and the undamped natural frequency for structures without and with the tip-mass (A and C). Table 2 shows the comparison between experimental and simulation results for the four designs. A good agreement is obtained. Also, as predicted, it can be observed that the tip-mass presence decreases the resonant frequency, which becomes 1.28 kHz for structure D.

Then, the method used to calculate the quality factor is based on the use of the equation [13]:

$$f_{r\_sim} = f_{0\_sim}\sqrt{1-1/\left(2Q^2\right)} \qquad (1)$$

We found the simulated Q_{sim} to be 39.9 which is equal to the experimental values obtained for two structures (A and C) where Q_{exp}=40. This result confirms that the tip-mass has an effect only on the resonant frequency of the cantilevers since the same value of quality factor is obtained with and without the patterned tip-mass.



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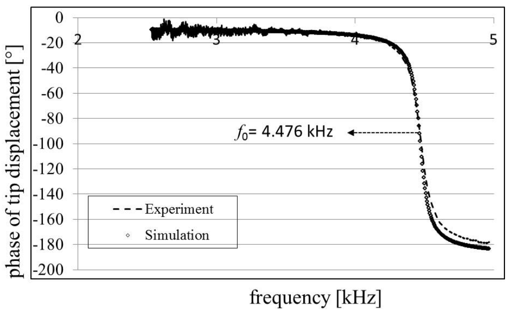

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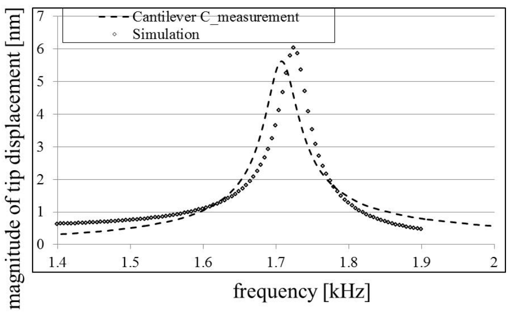
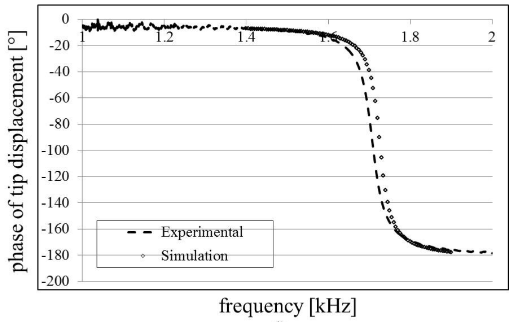


c)



d)

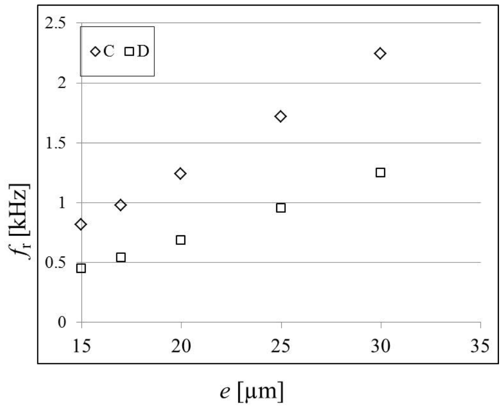
Figure 5. Experimental and simulated amplitude and phase spectra of viscoelastic polymer cantilevers. (a) and (b) for structure A $f_{r,sim}$= 4.475 kHz, $f_{0,sim}$= 4.476 kHz and Q_{sim}= 39.9; $f_{r,exp}$= 4.471 kHz, $f_{0,exp}$= 4.475 kHz and Q_{exp}= 40. (c) and (d) for structure C $f_{r,sim}$= 1.725 kHz, and $f_{0,sim}$= 1.726 kHz ; $f_{r,exp}$= 1.703 kHz and $f_{0,exp}$= 1.704 kHz.

Table 2: Experimental and simulated values of the resonant frequencies for different structures.

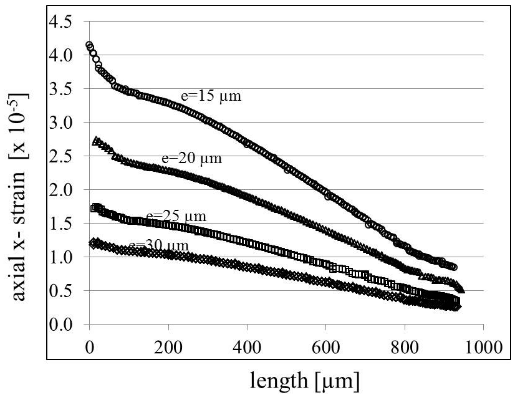
Structures	$f_{r,exp}$ (kHz)	$f_{r,sim}$ (kHz)
A	4.47	4.47
B	1.59	1.62
C	1.70	1.72
D	1.28	1.25

5.2 Mechanical analysis

The beam thickness is a parameter that can be easily controlled experimentally. Its effect on the resonant frequency and the axial strain has been thus studied with COMSOL. The resonant structures are targeted to exhibit a resonant frequency sub-1 kHz. From the plots of Figure 6 (a), it is observed that decreasing beam thickness from 30 µm to 15 µm results in a resonant frequency decrease from 1250 Hz to 450 Hz for structure D. A similar result is obtained for structure C. In parallel, Figure 5 (b) shows a COMSOL simulation of the distribution of the longitudinal strain, at resonance, over the surface of the beam for different thickness values. It can be seen from this figure that the distribution of the strain over the surface of the beam increases when beam thickness decreases. For instance, decreasing the thickness from 30 µm to 15 µm gives an improvement of a factor of about 4 for the axial strain at the clamped edge of the cantilever. These simulation results let us think that decreasing the thickness of the beam should improve the performances of our resonating cantilevers as mechanical energy harvesters (low resonant frequency and high strain at resonance).



a)



b)

Figure 5. (a) Resonant frequency and (b) axial strain variation along the length (*L*) for D for different cantilever thicknesses *e*. The actuation is made by a vertical vibration of the support with *a* = 1 g*sin(ωt).

6. Conclusions

In this work, we have validated the ability of using COMSOL in harmonic analysis to simulate resonating MEMS devices made of viscoelastic polymers as energy harvesters in the sub-1 kHz range. Also, this paper shows how FEM simulations can be used for optimizing the design of microcantilevers (geometry, mechanical properties) to obtain low resonant frequency and large strain.

7. References

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8. Acknowledgements

This work was supported by the French National Agency (ELENA project no ANR-12-NANO-0002-03)