Harmonic Simulation of Viscoelastic Cantilevers for Electromechanical Vibration Energy Harvesting

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Abstract: Electrostrictive polymers have been of significant interest over the last years for energy harvesting. Principle is based on the conversion of a mechanical deformation into electricity. The stored energy basically depends on the mechanical strain induced into an electrostrictive polymer by the mechanical resonant vibration of a microcantilever supporting the electrostrictive layer. In this work, in order to obtain large strains, polymer materials, which have small Young's modulus, have been considered for the vibrating microcantilever. However the drawbacks of such materials are their viscoelastic properties which cause the major losses of the vibrating system. In this paper, microcantilever made of viscoelastic polymers is simulated with COMSOL using two different vibration methods to deduce the losses in the system and then the quality factor, which is an important parameter for the energy harvester design.

Keywords: Electrostrictive polymers, viscoelastic polymers, microcantilevers, energy losses.

1. Introduction

Ambient energy harvesting has become an interesting topic for powering small scale wireless electronic devices, medical devices and sensors [1] - [3]. Among the various possibilities to convert mechanical vibrations into electrical power, there is the use of capacitance variation induced into electrostrictive materials. Such use of electrostrictive materials is not the more common one because in last years, much the focus was placed on the development of electrostrictive polymers for high-strain actuators [4]. In fact for energy harvesting, in order to obtain a large capacitance variation of the electrostrictive material, a large strain variation is necessary into the material. In mechanical structures the larger strain is obtained at the resonant frequency. As for energy harvesting devices using piezoelectric materials, the power harvested increases by increasing the average strain into the structures [5] - [6]: then the resonant frequency of the mechanical device has to be adjusted in order to be tuned to the one of the ambient mechanical vibration that has to be harvested. In order to have low resonant frequency and high strain, polymer materials, which are more flexible than silicon ones, have been considered for the resonant device. However, polymers exhibit a viscoelastic behavior that affects the quality factor due to the viscoelastic losses which are the major losses of the system [7] - [8].

In this paper, microcantilevers with parallelepiped geometries have been simulated with COMSOL to deduce the resonant frequencies, the energy losses and the quality factors of the structures.

2. Use of COMSOL Multiphysics

2.1 Geometry

A 3D geometry is considered for the simulation. Figure 1 shows the COMSOL model of the viscoelastic microcantilever. The length and the width of the beam are 600 µm and 300 µm respectively, while its thickness is 10 µm.

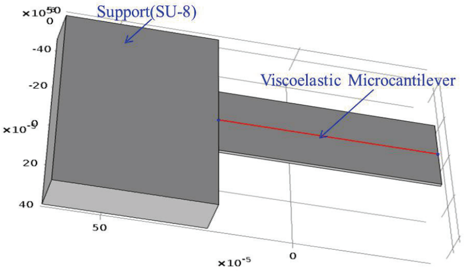
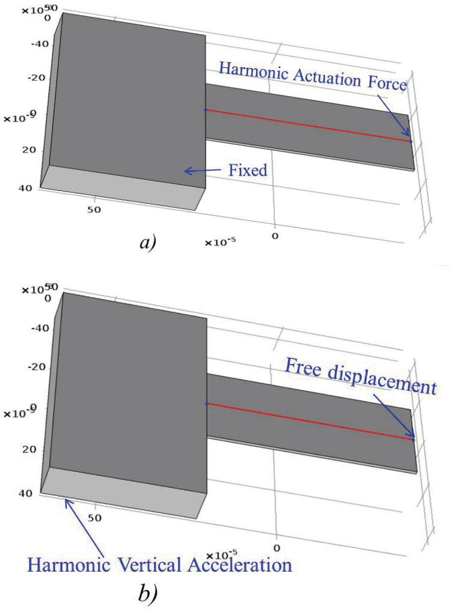


Figure 1. Schematic diagram of viscoelastic polymer microcantilever with its mechanical support.

For a viscoelastic material, the Young's modulus (*E*) is in a complex form: the imaginary part (*E*'') reflects the viscous energy dissipated into the material and the real part (*E*') reflects the mechanical energy stored into the material. The material parameters of the cantilever polymer are as follows: its density is $\rho = 1190$ kg/m^3, its real and imaginary parts of Young's modulus are $E' = 3$ GPa and $E'' = (0.1$ GPa, 0.4 GPa and 0.8 GPa), respectively. The support is made of a SU-8 where $\rho = 960$ kg/m^3, $\nu=0.44$ and $E = 3$ GPa.

2.2 Methods

The resonant frequency (f_r) and the quality factor (Q) of the first out-of-plane mode of the cantilever are calculated through frequency analysis using the frequency domain and "pardiso" as linear system solver. Here the "Solid Mechanics" model is used to solve the mechanical simulation. Figure 2 shows the two methods used with COMSOL to deduce both the resonant frequency and the quality factor. Figure 2 (a) is for an harmonic actuation force at the microcantilever free-end, while Figure 2 (b) is for an harmonic mechanical vibration of the support. In the latter case, the excitation by a vertical acceleration ensures the out-of-plane vibration of the structure. These simulations allow to deduce the resonant frequency, the total quality factor and also to separate the quality factor due to viscoelasticity of the polymer used for the microcantilever and the one due to the mechanical losses into the support.



a)

b)

Figure 2. Out-of-plane vibration generated a) by a free-end force or b) by a vertical vibration of the support.

3. Theory

The total quality factor (Q_{tot}) expresses the losses influence into the system, low losses devices will have a high quality factor. It is an important parameter for the energy harvesting devices: it defines the bandwidth of the resonant phenomenon and also the energy that is lost into the system and that consequently cannot be harvested.

For microcantilevers resonating in air, the quality factor depends on the viscous losses and acoustic radiation in the surrounding medium, on the viscoelastic losses in organic microcantilever and on the losses into the support [9]. In this paper, the microcantilevers are simulated in vacuum, so that the quality factor is function of only two losses (viscoelastic losses and support losses). In this case, the theoretical total quality factor (Q_{tot}) is given by:

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_{\text{viscoel}}} + \frac{1}{Q_{\text{supp}}} \tag{1}$$

Where Q_{viscoel} and Q_{supp} are the quality factors associated with the viscoelastic losses into the viscoelastic polymers and the mechanical losses into the support, respectively.

One unconventional way to estimate the quality factor of a resonator is to use the relation between the undamped natural frequency (f_0) and the resonant frequency [10]:

$$Q_{\text{tot}} = \frac{1}{\sqrt{2\left(1-\left({f_r}/{f_0}\right)^2\right)}} \tag{2}$$

3.1 Viscoelastic and support losses

For a cantilever made of viscoelastic polymer where the Young's modulus is in a complex form ($E=E'+j\,E''$), energy losses generated by this viscoelasticity should be considered. In this case, the quality factor due to viscoelastic losses can be defined as the ratio between E' and E'' [8]:

$$\frac{1}{Q_{\text{viscoel}}} = \frac{E''}{E'} \tag{3}$$

Therefore, for the different materials considered in this work, the values of Q_{viscoel} are 30, 7.5 and 3.7 respectively.

In addition, when the structure vibrates, the microcantilever produces a mechanical work on the support which generates an elastic wave into the support. The latter causes a power loss by propagation [9].

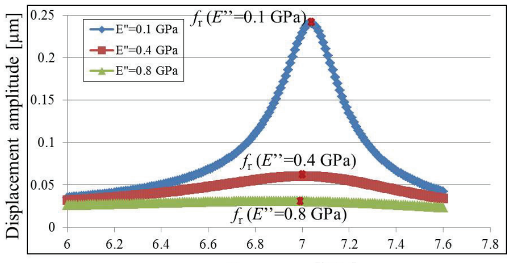
4. Frequency analysis

Table 1 shows the simulated values of the quality factor due to viscoelastic losses in the case of actuation by a free-end force $F = -6\text{x}10^{-3}\sin(\omega t)$. In this simulation, the entire support is fixed, then there is no support losses. A good agreement between COMSOL simulation and theory is obtained for the quality factor associated to the viscoelastic losses.

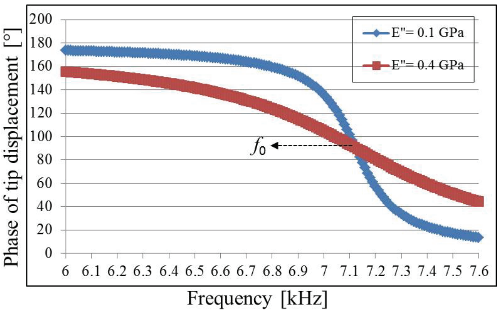
Table 1: Theoretical and simulated values of Q_{viscoel}.

E'' (GPa)	Q_{viscoel} (Theo)	Q_{viscoel} (Sim)
0.1	30	30
0.4	7.5	7.5
0.8	3.7	3.7

Figure 3 presents the results of resonant frequencies (f_r) and undamped natural frequencies (f_0) obtained in the case of an harmonic vibration of the support, with vertical acceleration $a = 9.8\sin(\omega t)$. There is a shift of the resonant frequency for different values of E'': this is due to the variation of the total quality factor (Q_{tot}) which is modified by the energy lost into the viscoelastic polymer (Q_{viscoel}). Table 2 shows the values of these frequencies, the total quality factor and the quality factor (Q_{supp}) obtained from Equations (1) and (2).



a)



b)

Figure 3. (a) and (b), simulated amplitude and phase spectrum of the deflection of viscoelastic polymers cantilever.

Table 2: Simulated values of the undamped natural frequencies (f_0), of the resonant frequencies (f_r) and of the quality factors (Q_{tot} and Q_{supp}) for different cantilever materials.

E'' (GPa)	f_0 (kHz)	f_r (kHz)	Q_{tot}	Q_{supp}
0.1	7.0417	7.0370	19	55
0.4	7.0400	7.0000	6.6	58
0.8	7.0120	6.8700	3.5	60

From Table 1 and Table 2, it can be seen that for a viscoelastic polymer with high values of E'' the viscoelastic losses are dominant in the structure and thus sufficient to calculate the total quality factor ($Q_{\text{tot}} \approx Q_{\text{viscoel}}$). Moreover, the support losses are almost constant.

6. Conclusions

In this work, we have validated the ability to use COMSOL in harmonic analysis to determine the different energy losses into viscoelastic polymers MEMS. Two methods were used with COMSOL to deduce these losses: the first one is by an harmonic actuation force at the microcantilever free-end and the second one for an harmonic mechanical vibration of the support. These simulations confirm that for a low value of imaginary part of Young's modulus of the viscoelastic polymer, the support losses cannot be neglected. The quality factor associated to the viscoelastic losses obtained by COMSOL simulation is validated from theoretical calculations.

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)