THE CANTILEVER MICRO-BEAM BEHAVIOR FOR ENVIRONMENT CHECK

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Abstract:

In this paper, a new model of a vibrating micro-cantilever is presented, which can be heavily utilized in a microelectromechanical system (MEMS). With our new prototype, several risks associated with the previous means are eliminated, and the rheological sensation is enhanced. The cantilever beam is made out of silicon (Si) engraved by a laser etching machine in an exponential shape ending with a thin array of eight cantilevers with a size of (500 x 140 x 10) µm³. Based on the behavior of the natural frequency, it is possible to estimate the variation of the density of a fluid or the presence of markers in a gas or liquid. To select the target analyte, it is necessary to identify the binding site as well as the covalent or noncovalent interactions between the functional monomer and the analyte. It can monitor natural, industrial, and residential areas by analyzing the eigenfrequency change when the micro-beam is immersed in a sample of these mediums. The numerical analysis using COMSOL Multiphysics software conducted was based on theoretical computations. The frequency resolution of the self-sensing micro-cantilever achieved in the fluid is 50 Hz/mmol.L-1 with mode 7th around 1.14 MHz However, we have noticed that this device can detect changes in density up to 0.054%.

Keywords: Environment, Rheology, Eigenfrequency, Adsorption particles.

1. INTRODUCTION

The Micro Electromechanical systems (MEMS) use micro-sized components for sensors, transducers, actuators, and electronics. The MEMS appeared in the 1960s, and were quickly integrated into electronic products, they appeared with the arrival of microelectronic technologies, and cantilever microbeams are sensors from this MEMS family. The first uses of vibrating cantilever microbeam for mass detection date back to the 1980s. Nowadays, cantilever microbeams are widely used to detect biological and chemicalmicroparticles[1], probe the viscosity and density of liquids[2-3], or detect mass, stress, or temperature changes[4]. As a general rule, there are two ways to measure the detection mode: by deflection in static mode or by shifting resonance in dynamic mode like in our study. There are a variety of ways to make a beam vibrate, different types of excitation are used, including electromagnets, thermal noise, or piezoelectric, such as in this case. The vibration of the micro-beams by means of a piezo element embedded into the main structure [3] allowed an objective analysis of the rheological characteristics of a charged fluid. Hence, this system can provide air and water monitoring in multiple areas while being highly sensitive compared to other systems.

1. MATERIALS AND METHODS

Our ‘sensor' concept (Figure 1) is shaped by laser engraving in a 2 mm thick silicon wafer and this is in accordance with a numerical model resulting from a Multiphysics numerical approach (COMSOL). Through the latter, we were able to illustrate the physical vibration behavior by charge effects on micro-beams of size (500 x 140 x 10) µm³ excited by a PZT source integrated in the mass of the sensor. An exponential form distinguished on the basis of micro-lamellae has been adopted in order to favor an amplification of the vibratory modes by purely mechanical means.

From a physical point of view, the resonant frequencies of the beams will be affected by the properties of the analysis medium. This assignment which results from the load effect will give access to a law of variation translating the link between the density and/or the viscosity of the medium and the frequency drift of resonance modes.

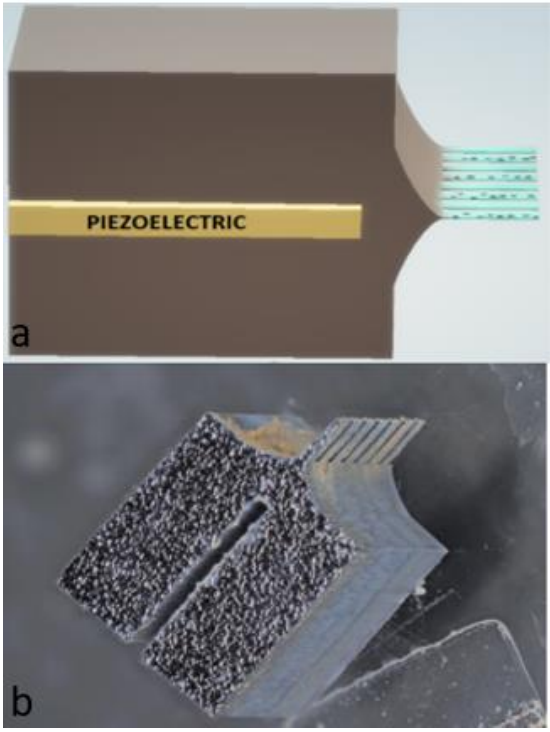

Figure 1: (a) Mechanical Structure of our device where coated beams are in place. (b) Prototype as viewed through SEM.

With our design [3], stresses are efficiently transferred from the box to the beams, reducing loss and increasing quality factors. A preliminary result shows that the beam has an appropriate movement for the order of vibration of the 1st, 2nd, 3rd, 4th, 5th,6th, and 7th harmonic modes immersed in water (as a referential medium) as shown below in figure2.

We have also been able to observe that this frequency drift is proportional to the ascending rank of the harmonic components, enabling us to better notice if any medium features have changed.

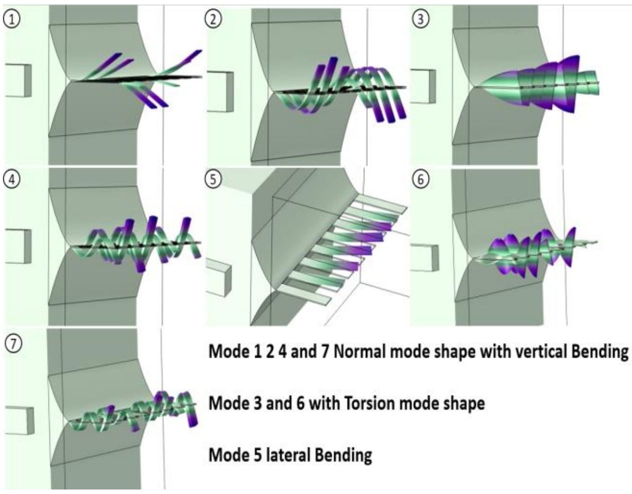

Figure 2: Several harmonics mode shapes for cantilever array

For specific molecular applications, a functionalization of the surfaces of the beams will be necessary in order to create a coating (often based on a polymer) playing the role of a specific and selective bio-sensor for the analyte of interest. In addition, the microbeams can be oxidized to create SiO2, which is a porous material, whose pore dimensions can be of the same order of certain pollutants in a solution (lead for example) thus giving this device the power and the potential to detection by frequency drift by added mass.

In order to assess the impact of the (bio-chemical) composition of the medium, the cantilever network was immersed in different microcapillaries with various bio-chemical properties. As shown in Figure 3, the resonance in the 4th harmonic mode of micro-beams is largely influenced by the nature and composition of the medium (incompressible fluid). In addition, the micro-beams which have not been subjected to the constraint of the environment display a permanent stability thus confirming that the natural frequency depends on the nature and characteristics of its environment.

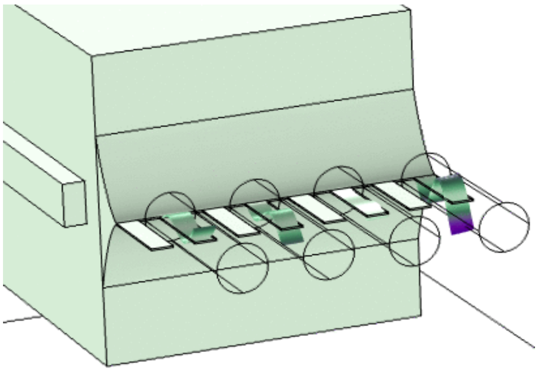

Figure 3: Cantilever array with the insertion of several microcapillaries each containing a different blend in mode 4th.

We deduced that the 1st, 2nd, 4th, 7th harmonics modes are normal with vertical bending, which helps us to reach the possibility of adsorption on the beam while avoiding the fall of particles from the pores with an appropriate bending of the beam. Following that, we will compare the theoretical calculation results to our numerical work based on Van Eysden and Sader's[5] models to verify the accuracy of the proposed model.

The eigen frequency $\boldsymbol{f_{0n}}$ is characterized by this equation (1) in the absence of damping with:

$$f_{0n} = \frac{\alpha_n^2}{2\Pi}\sqrt{\frac{k}{3(m_c+m_l)}} \qquad (1)$$

Where $\boldsymbol{\alpha_n}$ are related to the different eigenvalues of the harmonics, $\boldsymbol{m_c}$ is the mass of the cantilever, $\boldsymbol{m_l}$ is the virtual mass of the liquid, k is the spring constant given by $k = 3\frac{EI}{L^3}$ where EI is the flexural rigidity, with E Young's modulus and I the moment of inertia and L is the length of the cantilever. The peak frequency $\boldsymbol{f_n}$ is characterized by this equation (2) in the presence of damping with:

$$f_n = \sqrt{f_{0n}^2 \frac{-\gamma^2}{2\pi}} \tag{2}$$

Where the damping factor $\boldsymbol{\gamma}$ is defined by:

$$\gamma = \frac{c_0 + c_v}{\left(\frac{2}{L}\right)(m_c + m_l)} \tag{3}$$

where $\boldsymbol{c_v}$ is the dissipation coefficient, $\boldsymbol{c_0}$ is the intrinsic damping coefficient per unit length that describes internal losses.

2. RESULTS

Resonant silicon microbeams have been demonstrated to be micro rheometers capable of analyzing fluid viscosity and density over a wider frequency range than a standard rheometer. The measured parameter modifies the stiffness, mass of the vibrating element to induce a change in resonance frequency. The dynamic behaviour of a structure in a liquid medium is influenced by the fluid physical parameters. Results have shown that the frequency changes increase as we move up in harmonic mode. Taking this property into account, we focused on a density/harmonic coupling features in order to define for a given mode the optimum of the quality factor which is estimated by a minimum electrical impedance and an almost non-existent lateral bending of the beams.

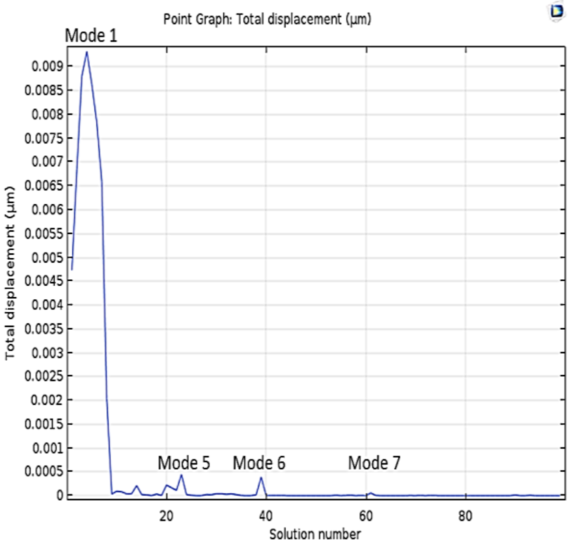

Figure 4 Total displacement for the beams immersed in water while increasing in the frequency spectrum of harmonic mode.

It should be noted that there is a good compromise between the choice of the high harmonic and the signal-to-noise ratio. Indeed, beam networks should not be tuned to very high frequencies to avoid introducing interference noise. Seven first harmonic modes were considered in this work (figure 4) with a certainty that the 7th mode has the most promising functionalities in terms of sensitivity. It is a frequency of 1.2 MHz when the beams are totally immersed in water, where the quality factor is in good condition (Figure 5).

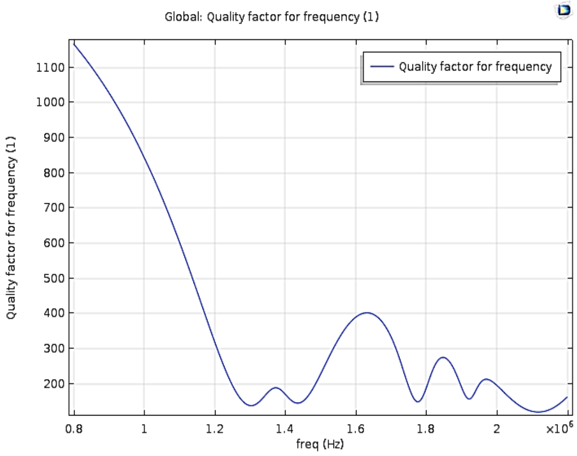

Figure 5 Quality factor for frequency while the beams totally immersed in water.

The impedance feature variation for the seventh mode can be seen in Fig 6. The peak in the imaginary part corresponds to the resonant equivalent circuit for the associated natural resonance frequency.

Given the sensitivity of this quantity to the physical properties of the medium, the impedance variation of mode 7 at resonance is considered to be a significant quantity for the objective evaluation of the molecular or/and particle rate charging a given medium.

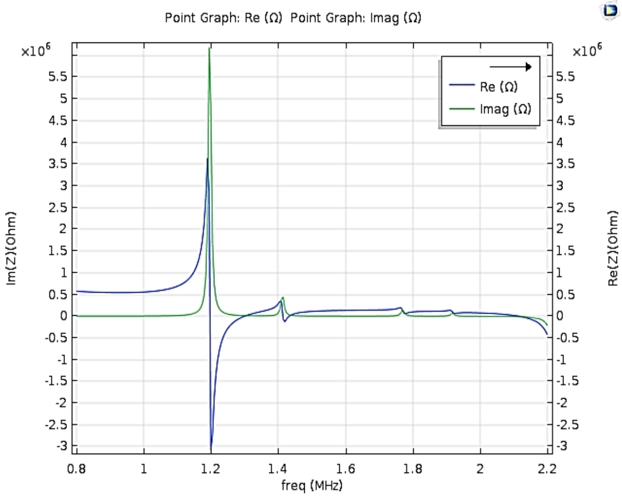

Figure 6 Frequency response of the impedance for the seventh resonant modes while the beams totally immersed in water.

Moreover, figure 6 shows that the Imag (Z) has a low rate of variation, because it is moved away from the resonance peak, indicate that the cantilever acts always as an inductive device, with a loss resistance parallel to the resonances [6].

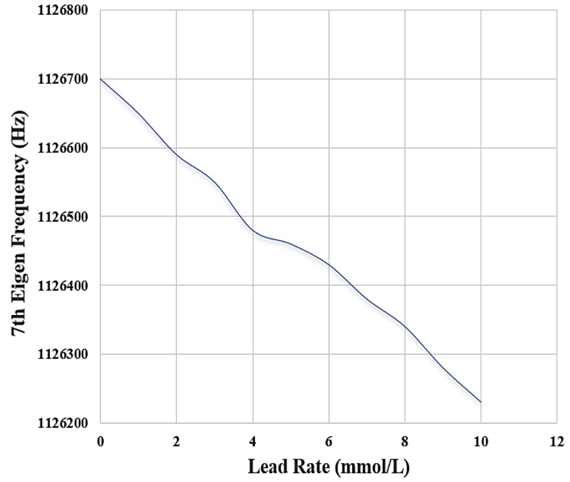

Figure 7 Δf Num in fluid for Mode 7th while adding Lead to a water-filled microcapillary.

From the practical point of view, the lead level in mmol/L for example can affect the water density in kg/m³ according to this equation $\boldsymbol{C_m = C_M \times MM}$ where $\boldsymbol{C_m}$ is mass concentration in g/L, $\boldsymbol{C_M}$ is molar concentration in mol /L and $\boldsymbol{MM}$ is the lead molar mass, equals to 207.2 g/mol.

The density of water is 997 kg/m³ is associated with an average value of a resonant frequency of 1,126,450 Hz. Thus, Figure 7 shows a linear law which is established between the molar variation of the lead content in water and the frequency drift. Indeed, the variation in the lead level between 0 and 10 mmol/L induces sensitivity to the frequency drift around of 500 Hz. Such sensitivity opens up the prospect of a multitude of potential applications both on the quality of the environment as in cell biology and/or chemistry domain.

3. CONCLUSIONS

In this paper, we have shown the potential of a micrometric device with vibratory beams in the physical characterization of complex media. Its advantages lie in its low cost, the simplicity of its implementation and in its dynamic sensitivity. In the current context of our way of life, we are often exposed to an increasing level of pollution both in the air and in the water of the phreatic aquifers. This is why our next objective is to refine the sensitivity of the devices towards the detection of more polluting markers present in our environment that can impact public health.

4. REFERENCES

[1] C.-H. Chen et al., « A Wireless Bio-MEMS Sensor for C-Reactive Protein Detection Based on Nanomechanics », Biomedical Engineering, IEEE Transactions on, vol. 56, p. 462-470, mars 2009, doi: 10.1109/TBME.2008.2003262.

[2] N. Belmiloud, I. Dufour, A. Colin, et L. Nicu, « Rheological behavior probed by vibrating microcantilevers », Appl. Phys. Lett., vol. 92, no 4, p. 041907, janv. 2008, doi: 10.1063/1.2837181.

[3] V. Elias, F. Braud, P. Champagne, et G. Nassar, « Investigation of the Eigen Frequency of a cantilever microbeam immersed in a fluid under the piezoelectric effect », Sensors and Transducers, vol. 254, p. 31-37, déc. 2021.

[4] I. Voiculescu, F. Liu, T. Ono, et M. Toda, « Investigation of bimaterial cantilever beam for heat sensing in liquid », Sensors and Actuators A: Physical, vol. 242, p. 58-66, mai 2016, doi: 10.1016/j.sna.2015.11.030.

[5] C. A. Van Eysden et J. E. Sader, « Resonant frequencies of a rectangular cantilever beam immersed in a fluid », Journal of Applied Physics, vol. 100, no 11, p. 114916, déc. 2006, doi: 10.1063/1.2401053.

[6] J. Vázquez, P. Sanz, et J. L. Sánchez-Rojas, « Behaviour of forbidden modes in the impedance characterization and modeling of piezoelectric microcantilevers », Sensors and Actuators A: Physical, vol. 136, no 1, p. 417-425, mai 2007, doi: 10.1016/j.sna.2006.11.005.