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High Sensitive Mass Detection using Piezoelectric Coupled Microcantilevers

Tony Chopard, Alex Bienaime, Céline Elie-Caille, Thérèse Leblois *

FEMTO-ST Institute
University of Franche-Comte
Besançon 25044, France

Abstract

This paper demonstrates the improvement of mass detection sensitivity using a new method of analysis applied to a piezoelectric coupled sensor. First, we prove the performances of an original method of analysis, based on the structures resonance amplitude, which significantly increases the mass detection sensitivity and improves the response time. Second, we show the advantage of coupled microcantilevers with a piezoelectric detection, that leads to a relative voltage variation of 8% /0.1 fg in the range [1 zg, 0.1 fg] versus an interferometric measurement. That opens the door to an ultrasensitive detection of highly diluted analytes in biological fluids.

Keywords: Piezoelectric transducer; coupled microcantilevers; sensitive mass detection;

1. Introduction

Piezoelectric mass sensors are becoming very attractive mainly in biological [1,2], environmental [3] and chemical [4] fields to detect small particles like molecules and even ions. Sensors have to become more and more sensitive, which implies a drastic reduction of their size. An important miniaturization of transducers [1-5] is then necessary, and requires the development of new complicated technological processes that increase prices. Moreover, the sensing structure will reach a nanometric size and then will become very brittle. An alternative to this miniaturization is the design of coupled structures. Coupled structures present also other advantages such as the opportunity to perform on the same substrate

* Corresponding author. Tel.: +33 3 81 85 39 74; fax: + 33 3 81 85 39 98.
E-mail address: therese.leblois@femto-st.fr.

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differential measurements or to obtain a multiplexed analysis of the analyte. These remarks lead to sensors networks. For coupled resonant sensors, whether a piezoelectric, electrostatic or ultrasound excitation, the usual method is based on the amplitude measurement of the resonance peak [6-8]. This method is preferred to the frequency shift measurement which is commonly used in the case of single resonant transducer and which doesn't improve sensitivity in the case of coupled structures. In this paper, after a state of the art in measurement methods, we propose a new design of sensing electrodes and an original method of analysis with coupled structures. To compare the results obtained with this new method, the analysis was performed using a cantilever structure for which several results are already given in the literature [9].

2. Analysis of results given by different methods of measurements

2.1. FEM Model and usual detection of mass

To compare results given by the different methods, we decided to work with coupled resonant cantilevers vibrating on an antisymmetric bending mode. This mode gives higher amplitudes than the symmetric one. The device was performed in a GaAs wafer because of its piezoelectric properties (in the case of undoped crystal) and its well developed technological processes. The design of the device and a simulation of the displacement of the structure are given on figure 1. With this configuration and geometry, the resonance frequency is obtained at f_R=109 kHz.

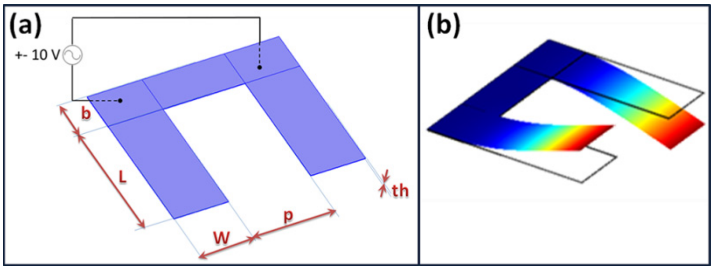

Fig.1. Coupled microcantilevers excited on the first antisymmetrical bending mode. Design (a) and simulation results (b) obtained using COMSOL Multiphysics® software. Gold electrodes thickness is 100 nm. L=25µm, w=10µm, th=0.1µm, b=8µm.

The main method is based on an optical interferometric detection. The method consists on a frequency sweep of the excitation signal to determine, with or without an added mass, the maximum amplitude of the resonance peak. The amplitude variation (ΔA) is an image of the mass variation (Δm) in a quasi linear function [12] as shown in equation (1):

$$\frac{\Delta A}{A} = \frac{k(\Delta m)}{4k_c\, m} \qquad (1)$$

where k is the mechanical structure spring of the cantilever and k_c the coupling spring.

The frequency shift obtained for an added mass (Δm) is determined with equation (2):

$$\frac{\Delta f_R}{f_R} = \frac{\Delta m}{2m} \qquad (2)$$

So, as soon as k_c<2k, the amplitude measurement gives better results. In the range [0, 120fg], both methods have quasi linear responses for relative variation of amplitude or frequency versus added mass, and the slope are 7800 ppm/fg and 1.9 ppm/fg respectively. These values confirm the advantages of the amplitude method on coupled microcantilevers.

2.2. Original method of measurement

Looking at the spectra given on figure 2(a) for an added mass Δm=3 fg and without added mass, we plan to determine the relative amplitude variation of the vibration at a fixed frequency. This frequency f_{R0} is the resonant frequency value obtained without added mass. Thus, figure 2 shows a significant increase of the variation of amplitude ΔA/A. This method called "method 2" allows not only the improvement of the sensor sensitivity but also the improvement of the response time. Indeed, the frequency sweep can be omitted.

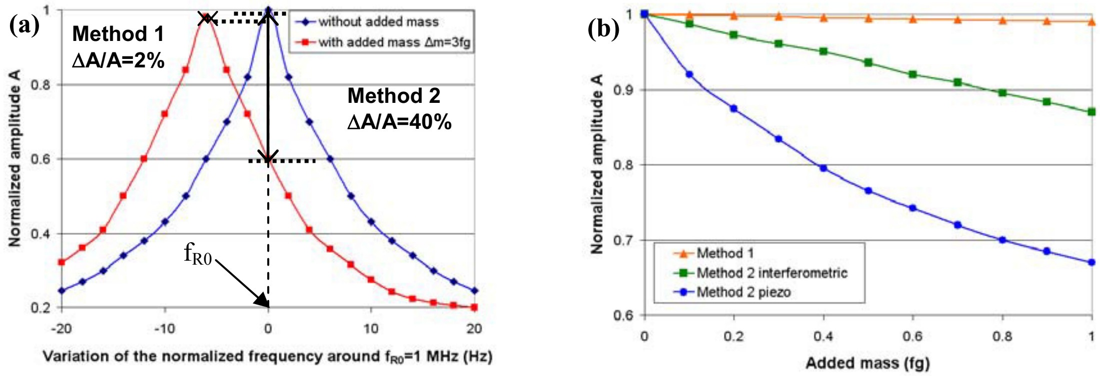

Fig.2. Normalized amplitude A versus normalized frequency (a) plots. Comparaison of the relative amplitude variation with method 1 (maximum of the resonant peak) and method 2 (at the fixed frequency f_{R0}). Normalized amplitude A versus added mass plots (b).

It is clear that the higher the quality factor, the higher the sensitivity of the transducer. The operating range is an important criteria to characterize the transducer. The sensor range can be deduced (equation (3)) from the resonant frequency f_{R0} for the selected mode, the mass of the cantilever m and the half-width of the resonant peak at 10% of the relative variation ($\Delta f_{10}/f_{R0}$).

$$\frac{m\,\Delta f_{10}}{f_{R0}} = Range \quad (3)$$

Thanks to this new method, we get a resolution 15 times higher (green curve) than the usual method (orange curve) in the range [0-1fg] as seen in figure 2(b). Nevertheless, the tangent at Δm=0 remains relatively close to zero. So, we changed the detection transducer to further increase the resolution at low added mass and to overcome the expensive equipment for measurement acquisition. A piezoelectric detection is chosen for its opportunity to miniaturize the device and to obtain an even and an odd voltage response versus frequency according to the electrodes positions on the coupling device. The blue curve on figure 2(b) shows the increase of the slope value around Δm=0. Figure 3 shows that each method presents an advantage: a large operating range with method 1 and a high resolution at low operating range with method 2. So it seems relevant to exploit these two advantages to optimize the sensitivity of the transducer. We propose to use method 2 for good resolution at low mass and to switch on method 1 when the mass exceeds m_{switch}. The threshold for switching between both methods is the mass value where the derivatives of the curves are the same. In our case of geometry, the value of m_{switch} is 15 fg which corresponds to a relative variation in the maximum deflection of 11%/fg. The resulting characteristic is then given by the dotted green curve (method 3).

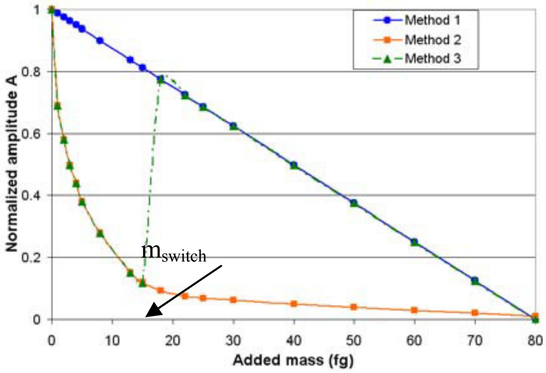

Fig.3. Comparison of the normalized amplitude A versus added mass for the three methods of measurements in case of piezoelectric detection.

3. Conclusion

In this study, we have proved the benefit of an original measurement method which greatly increases the sensitivity of the transducer for the addition of a weak mass on coupled cantilevers and improves the time response. We showed that piezoelectric transduction could be more convenient than interferometric detection at $\Delta m<15$fg thanks to an adequate disposition of the detection electrode. These results are promising for ultra sensitive detection of analytes in biological fluids.

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