Exploiting nonlinearities of mechanically-coupled microbeams for mass sensing: theoretical and experimental investigation

Toky Rabenimanana*, Fehmi Najar**, Vincent Walter*, Najib Kacem*, and Mehdi Ghommem***

**Univ. Bourgogne Franche-Comté, FEMTO-ST Institute, CNRS/UFC/ENSMM/UTBM, Department of Applied Mechanics, France*

***Applied Mechanics and Systems Research Laboratory, Tunisia Polytechnic School, University of Carthage, B.P. 743, Al Marsa 2078, Tunis, Tunisia*

****Department of Mechanical Engineering, American University of Sharjah, Sharjah 26666, UAE*

Summary. In this work, we consider a MEMS device made of mechanically-coupled microbeams under electric actuation. We conduct an experimental study to identify the occurrence of veering and then investigate its dynamic response for different electric actuations. A slight change in the DC voltage bias from the veering point is observed to affect significantly the frequency response. Indeed, jump to large orbits occurred when perturbing the applied DC voltage while operating near the cyclic-fold bifurcation point. We also develop and validate a mathematical model to simulate the response of the device. The model showed similarities in the softening effect of the DC voltage bias and an added mass when matching their induced shift in the natural frequency. As such, one can exploit mode localization and the significant and abrupt jumps in the deflection of the coupled microbeams to enhance the sensitivity of mass sensors.

Introduction

The deployment of MEMS devices comprising electrically actuated vibrating micro-beams for mass sensing has gained significant interest in the last few years thanks to their outstanding dynamic features in response to small variations in their effective mass. MEMS mass sensor converts the presence of a tiny element (biological entities such as cells and viruses, gas molecules…) into a resolvable electrical signal via a transduction technique (capacitive, piezoelectric...). A new generation of MEMS mass sensors has been recently proposed based on adopting the concept of mode localization [1-4]. These devices have demonstrated significant improvement in terms of sensitivity by up to four orders of magnitude in comparison to their conventional counterparts. Yet, distinctive merits of mode localized mass sensors have been demonstrated over several research studies in the last decade [1]. However, there is still room for improvement of this kind of sensors, especially when exploiting and tuning their associated nonlinearities to increase further their sensitivity and extend their operating range. In this work, we consider a MEMS device made of mechanically-coupled microbeams subjected to electric actuation. We study unconventional nonlinear mass detection mechanisms and assessed their capabilities to enhance the performance of the mass sensors.

MEMS device description and experimental measurements

We consider a MEMS device comprising two mechanically coupled microbeams with slightly different lengths: $L_1 = 98\ \mu m$ and $L_2 = 100\ \mu m$ (see Figure 1). A coupling beam with a length of $L_c = 65\ \mu m$ is placed at a distance $x_c = 4.9\ \mu$m from the clamped end of the microbeams. The electrostatic actuation of the device is made by the application of combined DC and AC voltages via a stationary electrode placed underneath the short beam. The device was fabricated by using the Multi-User MEMS Processes (MUMPs®). The microbeams are composed of a polysilicon layer Poly2 reinforced by a second polysilicon layer Poly1 at the fixed end. The measured gap between the cantilevers and the bottom electrode (Poly0) is around g = 1.35 µm. The MEMS device is placed in a vacuum chamber at a pressure around 0.3 mbar to minimize the damping effect and the actuation voltage is applied with a micro probe. The quality factor Q is found equal to 900. To measure the vibrations at the tip of each cantilever beam, a single point laser Doppler vibrometer is used in order to experimentally confirm the feasibility of the operating principle of the sensor.

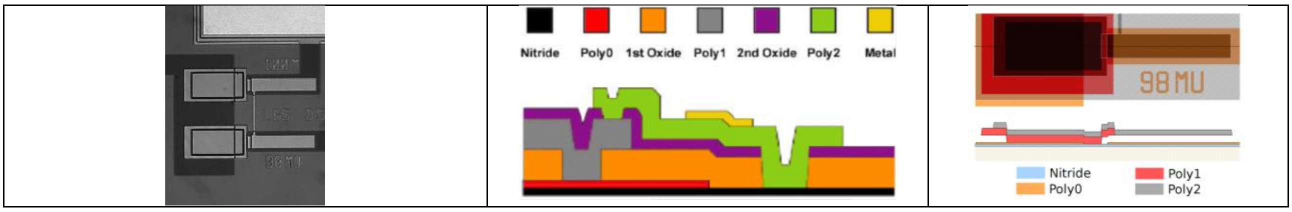
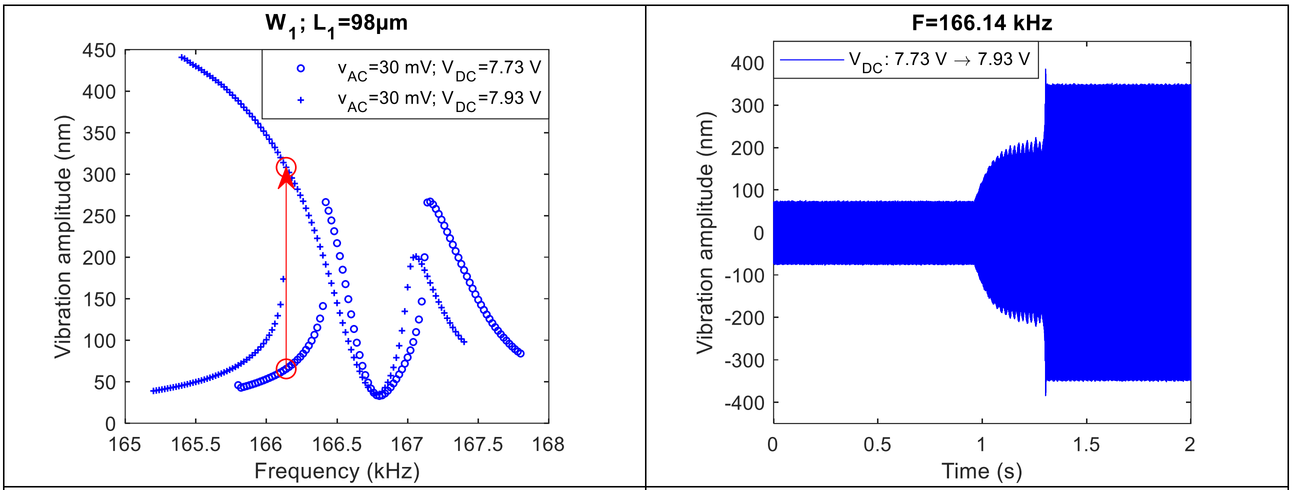


Figure 1: MEMS device and cross sections showing the layers of the MUMPS® process.

Results and discussion

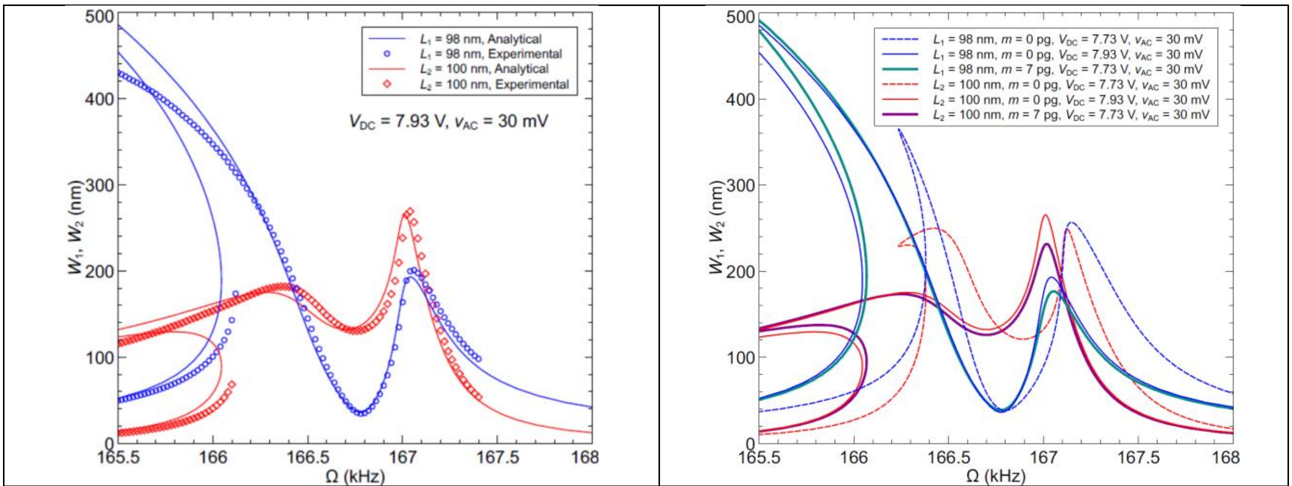
We plot in Figure 2(a) the experimental frequency response of the MEMS device obtained at two different DC voltages. The results are shown for the short beam. We note that the electrostatic force is applied only to the short beam while operating at veering and setting the AC voltage at 30 mV. The needed DC voltage to reach veering is found experimentally equal to 7.73 V. Adding a DC voltage bias of 200 mV induces a significant jump in the beam deflection when operating at a suitable and a fixed excitation frequency near the cyclic-fold bifurcation, as indicated by the arrow at $\omega = 166.140$ kHz in Figure 2(a). This jump is illustrated further in the time response shown in Figure 2(b). A DC voltage bias of 200 mV is introduced at $t = 1$ s. The softening effect induced by the DC voltage is equivalent to that of an added mass deposited on one of the microbeams as will be demonstrated next. As such, the observed jump to large orbits can be exploited for mass sensing purposes.



(a) Frequency response (short beam) | (b) Time response: sensitivity to DC voltage bias

Figure 2: Dynamic response of the MEMS device for different DC voltages (experimental results).

Following Euler-Bernoulli beam theory, we develop a nonlinear mathematical model governing the vibrations of the two mechanically coupled microbeams. The weak mechanical coupling is approximated by a torsional spring with rotational stiffness. We derive a reduced-order model using the Galerkin decomposition method [3]. In Figure 3(a), we compare the frequency response curves obtained using the developed nonlinear model (solid lines) against those measured experimentally (dotted lines). A good agreement between the numerical and experimental data is obtained. These simulation results demonstrate the capability of the nonlinear dynamic model to properly capture the dynamic response of the MEMS device. We show in Figure 3(b) the simulated frequency responses for different DC voltage biases (with respect to the veering DC voltage). We also plot the frequency response obtained when adding a mass of seven pg on the short beam. Of interest, the frequency response obtained for a DC voltage bias of 200 mV matches with that obtained for an added mass of seven pg. We note that increasing the applied DC voltage by 200 mV and adding a mass of seven pg lead to same shift in the natural frequency of the microsystem. As such, given these similarities, one can use the abrupt and significant jump to large orbits observed in mechanically coupled beams for mass sensing applications.



(a) Model validation (short and long beams) | (b) Simulated frequency responses

Figure 3: Frequency responses of the MEMS device: (a) numerical simulations (solid lines) vs. experiments (dotted lines), (b) Simulated frequency responses.

References

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