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Experimental and numerical assessment of the multi-physics dynamic response for a MEMS accelerometer at various gaps

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Abstract

The dynamic response of a MEMS accelerometer can be influenced by several multi-physics effects, especially if the gaps between the shuttle and the stator attain sub-micrometric values. The present paper aims at tackling the aforementioned issues by means of a suitable experimental procedure, which has been purposely devised for the problem at hand, and through the execution of numerical analyses (based on the Finite Element Model). The effect of parasitic electrostatic forces and hydrodynamic forces is clearly demonstrated.

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Keywords: capacitive MEMS; finite element simulations; interaction forces; electro-mechanical modelling;dynamical characterization

1. Introduction

The operative reliability of capacitive MEMS can be endangered by the presence of small-scale interaction forces, whose effect is relevant if the gap between nominally flat and parallel surfaces attains the sub-micrometric range [1]. In view of the extreme miniaturization of present (and future) devices, such phenomena represent a real issue, which deserves a specific study in order to obtain a precise assessment of the dynamic behavior in different situations.

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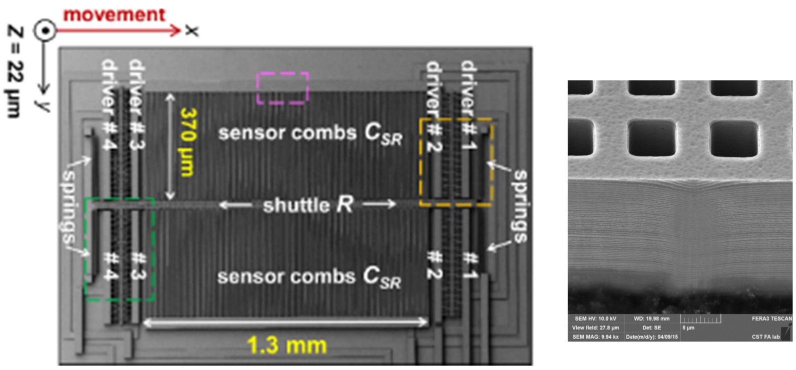

Fig. 1. SEM view of the adopted device, along with a detailed view of the cross-section. The green and yellow squares denote the actuation combs; the magenta square denotes the sensing combs.

This paper is referred to a high-aspect-ratio MEMS device, see Fig. 1, which has been designed with the purpose of investigating, in the static and dynamic field, the effect of nano-scale surface interactions [2]. The driving combs can be used in order to move the shuttle in the horizontal direction, so that the gap between the parallel plates in the sensing combs is progressively reduced until less than 800 nm. The experimental outcomes have been supplemented by a thorough numerical examination, which was useful in order to check the achieved results and to investigate the possible influence of higher modes.

2. Device and experimental characterization

The experimental campaign was based on an ad-hoc setup for electrical measurements, see Fig. 2 [3], with the main objective of the extraction of dynamical parameters (e.g. natural frequencies and quality factors) for different configurations of the device. All the measurements have been carried out on the device, located in a vacuum chamber at low pressure (700 µbar). The environment in the laboratory was controlled, with temperature equal to 23°C and relative humidity equal to 45%. The experimental data have been examined using a reliable, yet simple, lumped-parameter electro-mechanical model which allows for fast simulations and parametric analyses [4]. The model accounted for non-linear behavior, due to the presence of displacement-dependent surface forces and hydrodynamic effects.

In the first steps of the experimental campaign, some static measurements have been carried out in order to identify the electromechanical features of the devices. More specifically, a set of C-V curves has been obtained by applying voltage and measuring capacitance across the sensor combs. The careful examination of the experimental data led to the identification of: (i) the residual potential between the sensing plates and the stator, $V_0 = -34\pm1$ mV; (ii) the initial

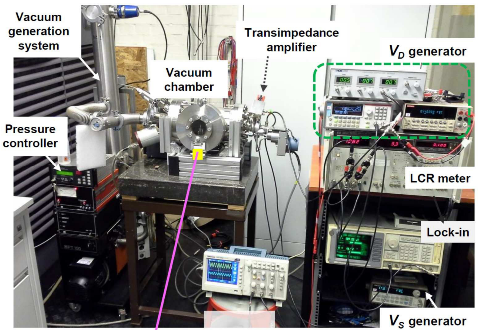

Fig. 2. Experimental setup, located in the lab at the VU University Amsterdam. The magenta line indicates the position of the MEMS on board.

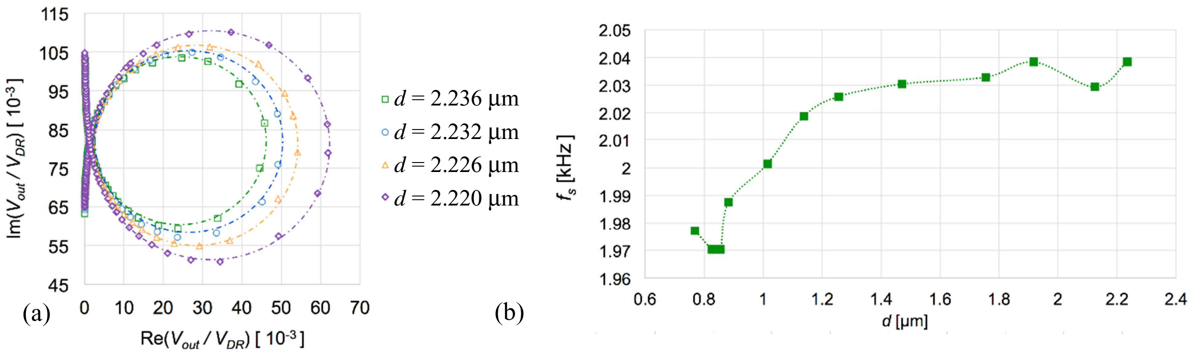

Fig. 3. (a) Nyquist's plot obtained from the experimental data and used to extract the dynamical features of the system; (b) fundamental mechanical frequency f_s of the device as a function of the gap d between the sensing plates.

asymmetry of the gaps on the two faces of each sensor comb, $x_0 = -40\pm9$ nm; (iii) the overall elastic stiffness of the device, $k_0 = 3.62\pm0.02$ N/m. The achieved results are in excellent agreement with previous experimental results, on a similar structure [2]. The dynamic, small displacement tests allowed us to extract the gap-dependent mechanical features, starting from the natural frequency that has been obtained by means of the Nyquist's representation of experimental data, see Fig. 3(a). The frequency at rest is $f_0 = 2.04$ kHz, the corresponding quality factor is $Q_0 = 32.3$. The variation of the natural frequency, see Fig. 3(b), is mainly given by the gap-dependent electromechanical stiffness, which is a consequence of the residual potential. Conversely, the hydrodynamic stiffness is roughly constant with respect to the gap and is equal to $k_h = 0.04\pm0.01$ N/m.

3. Numerical and analytical results

The mechanical behavior has been assessed using a complete simulation of the device, by means of finite-element analyses (Fig. 4). In that way, it was possible to double-check the experimental outcomes and to examine some additional phenomena (e.g. deformation of the lamellae, effect of higher modes, etc.). By using the actual dimensions of the device, Young's modulus of poly-silicon 140 GPa, Poisson's ratio 0.2, the numerical stiffness of the device was equal to 3.745 N/m: a relative error of +3.45% is obtained with respect to the experimental outcomes. It is worth noting that the problem could be also solved by the simple application of the Euler-Bernoulli model to the beams which belong to the folded springs: by-hand computation yielded the analytical stiffness 3.952 N/m, that is +9.17% with respect to experiments.

The dynamic analyses allowed us to evaluate the first natural frequency, which results 2.075 kHz, in excellent agreement with experiments (+1.52% w.r.t. experiments). Also in that case, simple by-hand computations gave acceptable results, i.e. 2.137 kHz (+4.74% w.r.t. experiments).

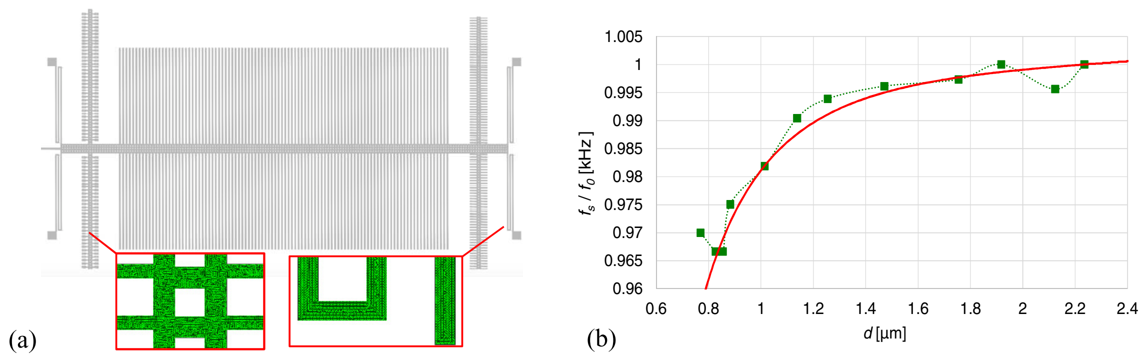

Fig. 4. (a) View of the mechanical model, with a couple of magnified views to appreciate the (very fine) adopted mesh; (b) mechanical frequency of the device f_s (normalized w.r.t. the rest value f_0): experiments (green dots) compared to numerical results (red line).

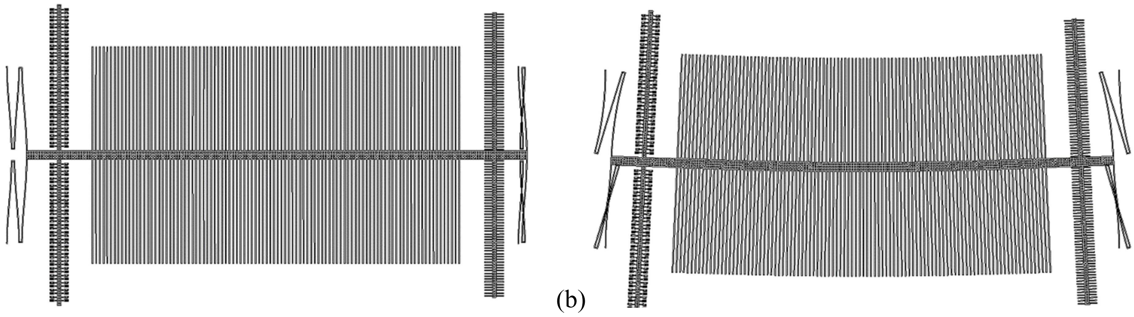

Fig. 5. Deformed shape of the first mode (a), frequency 2.075 kHz, and of the second mode (b), frequency 10.15 kHz (50x amplification).

The numerical variation of the frequency with the sensor gaps fitted properly the experimental data, see Fig. 4(b). Fig. 5(a) shows the deformed shape of the first natural mode, endowed with horizontal translation of the shuttle and bending deformation of the folded springs. Considering higher modes, the closest frequency was 10.15 kHz and corresponded to bending of the central shuttle, see Fig. 5(b). The difference between the first and second eigen-frequencies excluded the interaction between modes during experiments. Similar reasoning could be applied to the local modes, summarized in Table 1, namely the bending vibration of the sensing plate (first frequency 36.64 kHz) and the bending vibration of the beams that carries the driving comb (first frequency 50.06 kHz).

Table 1. Selected vibration modes of the device.

Number	Tipical feature	Frequency (*kHz*)
1	First global mode, translation along *x*	2.075
2	Second global mode, bending of the central shuttle	10.15
3	Third global mode, rotation around *z*	24.15
4	First bending mode of the sensing plates	36.64
5	First bending mode of the driving combs	50.06
6	Second bending mode of the sensing plate	249.4
7	Second bending mode of the driving combs	304.7

4. Conclusions

This paper summarizes the experimental and numerical analysis of a specific device, designed in order to study the dynamic behavior at small surface separation. A new experimental setup has been devised, with the purpose of carrying out static and dynamic tests. The latter highlighted the electrostatic and hydrodynamic stiffness as well as damping behaviour at various gaps. The experimental data have been compared to detailed FE analyses, with satisfactory results. The numerical analyses showed that higher modes are endowed with by far larger frequency than the fundamental one, thus excluding spurious interaction effects.

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