

# Sensitivity Tuning and ON/OFF Switching in a Resonant Micro-accelerometer

Alexandra Zobova,<sup>1</sup> Maxim Drizovsky<sup>1</sup>, and Slava Krylov<sup>1</sup>

<sup>1</sup> Faculty of Engineering, School of Mechanical Engineering, Tel Aviv University, Ramat Aviv, Israel  
alexzobova@tauex.tau.ac.il

**Summary:** We report on a differential resonant accelerometer with electrostatically tunable and switchable transmission of the inertial load from the proof mass to the vibrating sensing beam. The device consists of a proof mass (PM) and two frames, interacting with the PM only electrostatically and connected through a compliant amplification pseudo-mechanism to the sensing beams. Displacement of the PM due to inertial forces affects the electrostatic coupling, the axial tension and the frequency of the sensing beams. ON/OFF switchable and tunable by voltage scale factors registered in the experiments are consistent with the model predictions.

**Keywords:** vibrating beam accelerometer, switchable sensitivity, electrostatic interaction, lumped model, SOI

## Introduction

Microelectromechanical systems (MEMS) resonant accelerometers are widely used in various applications due to their small size, low cost, low power consumption, and better noise characteristics compared to their static counterparts [1]. These devices performance is affected by the trade-off between sensitivity and dynamic range, scale factors (SF), temperature dependency, and drifts [2]. The possibility to actively tune and switch OFF the device sensitivity may open the possibility of in situ self-calibration and therefore could be essential for further improvement of the high-end inertial sensors' performance.

## Architecture and operational principle

We introduce a novel resonant accelerometer architecture with tunable and switchable force transmission from the PM to the vibrating sensing beams (resonators), Fig. 1. The device consists of a PM moving along the (sensing)  $y$ -axis and two force-transmitting frames moving along the  $x$ -axis, all suspended by flexible beams. Each resonator is anchored at one end and is attached to a corresponding frame through a compliant force amplification mechanism at the other end. Non-interdigitated comb-like electrodes attached to the mass and the frames operate in both gap-closing and area-changing modes. There is no mechanical interaction between the PM and the frames/resonators. When the frames are grounded and a steady voltage  $V$  is applied to the PM, the resulting electrostatic (ES) forces lead to the axial tension of both resonators. Acceleration-induced displacement of the PM alters the ES forces and, therefore, the resonators' tension and frequency. The acceleration is extracted by measuring the frequency shifts between the resonators.

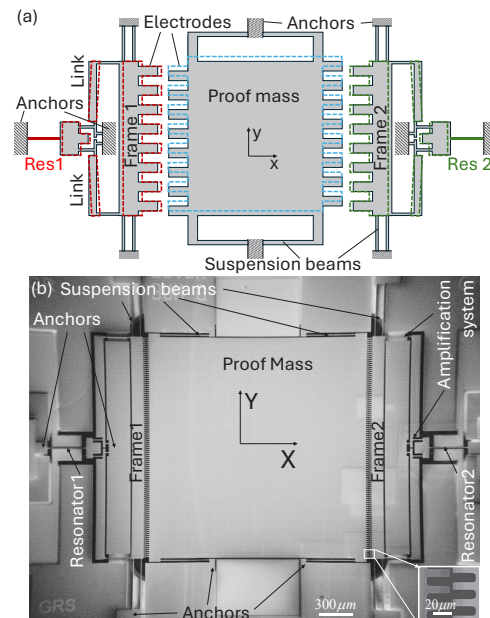


Fig. 1: (a) Schematics of the device; colored dash lines depict the deformed configuration. (b) The scanning electron microscope image of the device. The comb-like electrodes are shown in the inset.

## Model

The lumped model of the device was built under common assumptions of perfectly rigid proof mass, links, and frames, along with massless suspension beams, compliant mechanism pseudo-hinges, and resonators [3]. The device is considered as a three-degree-of-freedom (DOF) system, with the displacements of the PM and each of the two frames (in the  $y$  and  $x$  directions, respectively) as the generalized coordi-

nates. From equilibrium equations of the system, for the applied voltage  $V$  and the inertial load, we determine the resulting axial forces, which shift the resonant frequencies according to the double-clamped stretched beam model. Thus, for each resonator's frequency, we get:

$$f_i(V, \hat{a}_x, \hat{a}_y) = f_0 \left[ 1 + SF^V V^2 + (-1)^{i-1} SF^x(V) \hat{a}_x + (-1)^i SF^y(V) \hat{a}_y \right].$$

Here  $i = 1, 2$  refers to the left and right resonator, respectively,  $f_{0,i}$  is the frequency of the unstretched resonator,  $SF^V$  is a relative voltage scale factor — a coefficient defining the tunability of the resonant frequency of the correspondent resonator only by the voltage, without inertial input;  $SF^x(V)$  and  $SF^y(V)$  are non-differential relative sensitivity (relative scale factor) of the frequency to the acceleration in the  $x$  and  $y$ -direction respectively;  $\hat{a}_{x,y} = a_{x,y}/g$  is non-dimensional acceleration, and  $g = 9.81 \text{ m/s}^2$  is the acceleration of gravity. Both relative scale factors depend on the applied voltage:

$$SF^x = SF_0^x(1 + C^x V^2), \quad SF^y = C^y V^2$$

### Experiment

The device was fabricated from a highly doped device layer of an SOI wafer with (100) upper surface orientation using the SOI MUMPS process. The device was wire-bonded to a printed circuit board (PCB) and mounted in a custom vacuum chamber (VC), operating at a stabilized room temperature and pressure between 2.9 and 4 mTorr (Fig. 2(a)). The capacitive sensing was adopted to measure the resonators' frequencies in open and close loop modes [4]. In the zero inertial load experiment, the resonators' frequencies were measured in open-loop mode for a range of voltages; the sensing plane ( $x, y$ ) of the device mounted in the VC was horizontal. In the turn-table experiment, the VC with the device inside was mounted on a dividing head, allowing angular rotation of the vertical sensing ( $x, y$ ) plane about the  $z$ -axis.

The tunability of the frequencies due to an inertial input in the  $x$  and  $y$  directions and by voltage was shown in the experiment. The results of the experiments are shown in Fig. 2. By analyzing the data, the following figures of merit were obtained: the baseline resonator frequency  $f_0 = 292.5 \text{ kHz}$  (an average for two resonators), the sensitivities  $SF^V = 8.6 \text{ ppm/V}^2$ ,  $SF_0^x = 235 \text{ ppm/g}$ ,  $C^x = 25 \text{ ppm/V}^2$ ,  $C^y = 0.075 \text{ ppm/(g}\cdot\text{V}^2)$ . Differential electro-statically tuned sensitivity along the  $y$ -axis reaches 86.6 Hz/g at  $V = 45 \text{ V}$ .

### Conclusion

We propose a novel vibrating beam accelerometer with a controllable electrostatic transmission of inertial input from the PM to the sensing elements. The device demonstrates tunable

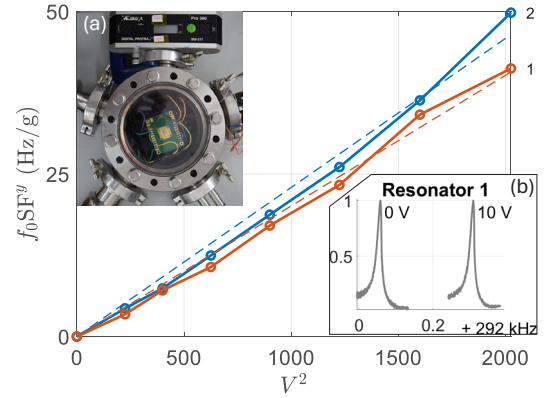


Fig. 2: Tunability of the scale factor in  $y$ -direction by applied voltage; solid lines correspond to the experimental data for Resonators 1 and 2 (numbers), dashed lines depict linear fit. Insets: (a) fabricated device on the PCB inside the vacuum chamber; (b) open-loop frequency response curves of Resonator 1 for  $V = 0, 10 \text{ (V)}$  in the zero inertial load experiment.

resonator frequencies and switchable sensitivity. The results lay the groundwork for optimizing electrode and frame designs, with potential applications in online calibration and noise reduction in MEMS inertial sensors.

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