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Exploring a multi-mass system for multi-functional MEMS accelerometer with enhanced bandwidth and sensitivity

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Summary:

This paper presents the design, fabrication, and experimental validation of a novel multi-mass MEMS accelerometer concept to achieve higher mechanical sensitivity with wide operational frequency bandwidth, in comparison to traditional single-mass MEMS accelerometers. The initial results show that the proposed approach has the potential to develop multi-functional MEMS accelerometers, with a preliminary device with 5.6 kHz resonance and more than 30% sensitivity improvement.

Keywords: Multi-DoF, MEMS Accelerometer, Nested displacement, High-bandwidth, High-Sensitivity

Introduction/State of the Art

In recent years, significant advancements have been observed in the autonomous driving field, highlighting the critical need for a deep understanding of the surrounding environment using advanced sensing capabilities. One of the key demands for such systems is to use multi-functionalization sensors that can detect multiple physical parameters, thus reducing the number of sensors to achieve reliability, reducing cost, power consumption, and area. MEMS accelerometers are widely used in automotive driver assistance systems, airbag safety systems, and electronic stability control [1]. However, for autonomous vehicles, in addition to these applications, the detection of acoustic signals is required for new functionalities [2]. The limitation of the current MEMS accelerometers is the trade-off between the required operational frequency bandwidth (up to 6 kHz) and sensitivity. Recent works have presented MEMS accelerometer with significantly wider bandwidths but at the cost of a reduced resolution due to the sensitivity/bandwidth trade-off [3]. This trade-off arises due to the structural design of traditional MEMS accelerometers, consisting of a single proof mass suspended by mechanical beams that inversely affect resonance frequency and mechanical gain.

Description of the New Method or System

Fig. 1 shows a 4-DoF MEMS accelerometer mass-spring-damper model with an input acceleration $\ddot{y}$ applied to the base and equations of motion are given in Eq. 1. The energy transfer between the masses allows to achieve a dynamically amplified displacement in the mass m_4 (final sensing mass). The displacement amplification in m_4 and the first resonance frequency position (which defines the operational bandwidth) can be tuned by optimizing mass, m, stiffness, k, and damping, c, parameters. As proof of concept, it was initially considered an identical k/m ratio for each mass-spring unit and a damping coefficient of zero, with the exception of c_5, which represents the squeeze-film damping on sensing plates attached to the sensing mass, m_4.

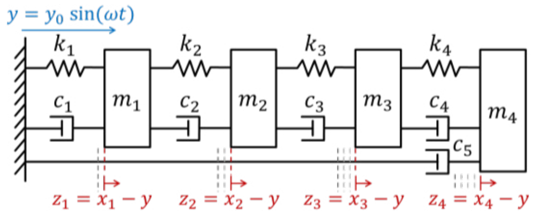

Fig. 1. 4-DoF mass-spring-damper model.

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}\begin{bmatrix} \ddot{z}_1 \\ \ddot{z}_2 \\ \ddot{z}_3 \\ \ddot{z}_4 \end{bmatrix} + \begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2+c_3 & -c_3 & 0 \\ 0 & -c_3 & c_3+c_4 & -c_4 \\ 0 & 0 & -c_4 & c_4+c_5 \end{bmatrix}\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \end{bmatrix} + \begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 \\ 0 & 0 & -k_4 & k_4+k_5 \end{bmatrix}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} -m_1\ddot{y} \\ -m_2\ddot{y} \\ -m_3\ddot{y} \\ -m_4\ddot{y} \end{bmatrix} \tag{1}$$

Fig. 2 shows the proposed multi-DoF MEMS accelerometer frequency response compared with an equivalent traditional 1-DoF for an input acceleration of 1 g. The proposed device presents a clear amplification of m_4 displacement amplitude by a factor of 2.4 with respect to m_1, and by 1.31 to the 1-DoF.

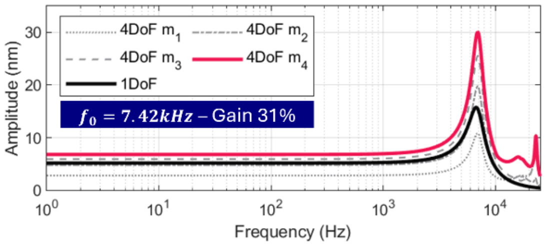

Fig. 2. Frequency response comparison of proposed 4-DoF and traditional 1-DoF model.

The detailed MEMS layout and cross-sectional views are presented in Fig. 3, highlighting in different colors the multiple masses. The design enables differential sensing of the m_4 amplified displacement, relative to the fixed frame through two sets of differential sensing electrodes. The handle layer proof-masses were thinned and used as a mechanical bridge linking different parts of the movable masses (CS B), therefore achieving mechanically coupled structures while remaining electrically decoupled. This approach avoids the need for a direct electrical connection to a device's inner part, reducing the possible damage during wire bonding process.

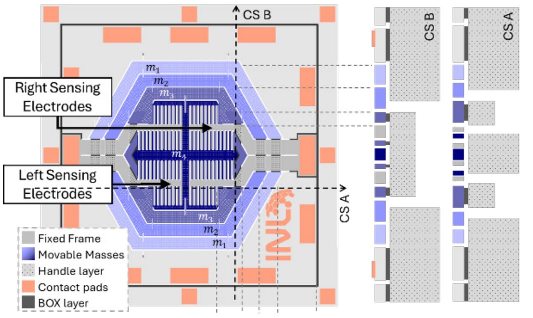

Fig. 3. MEMS accelerometer design layout.

The devices were fabricated through an in-house process on a 50 µm-thick silicon-on-insulator (SOI) wafer, taking into advantage the multi-mass SOI-based fabrication process presented in [4], which allows the development of hierarchical, matryoshka-like MEMS structures. The main fabrication steps are presented in Fig. 4, as well as the SEM images of the fabricated device.

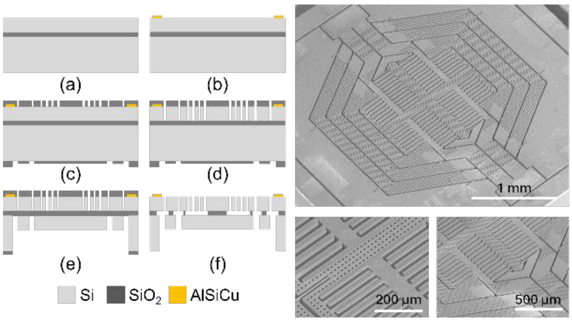

Fig. 4. Fabrication process, and SEM images:(a) SOI-wafer preparation; (b) AlSiCu patterning; (c) FS and BS HM PECVD and patterning; (d) FS DRIE; (e) BS multilevel DRIE; (f) HF structure release.

Experimental Results

The device frequency response, from 1 to 30 kHz, was experimentally evaluated, Fig. 5, using the sensing electrodes as electrostatic actuators, while measuring the in-plane motion using Polytec MSA-500 stroboscopic video microscopy. The first resonance frequency was measured at 5.6 kHz, lower than the designed 8.51 kHz. This shift is due to the over-etch and larger thinned handle thickness registered in the fabrication process, which lead to lower resonant modes (thinner springs and larger masses) and higher quality factors (larger gaps). The fabricated devices parameters $(m-k-c)$ were measured, and the analytical response was recomputed, Fig. 5. The results show a strong correspondence between analytical and experimental data, thus validating the analytical model. This proves that when compared with the typical 1-DoF MEMS device (assuming equivalent mass and stiffness proportional to resonance frequency of 5.6 kHz), this device has a 30% increase in displacement for the sensing mass m_4. These preliminary results are promising, showing that multi-DoF inertial MEMS can achieve high bandwidth with relatively better sensitivity, enabling their use as multipurpose sensors in autonomous vehicles. Future work will focus on the optimization of mass-stiffness parameters for higher mechanical gain and wider bandwidth, as well as damping to achieve flat frequency response.

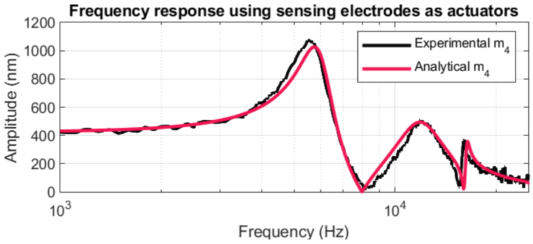

Fig. 5. Experimental and analytical model frequency response, using sensing electrodes as actuators.

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