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Modal analysis of a four-bar linkage MEMS microgripper with co-operative electrostatic actuation

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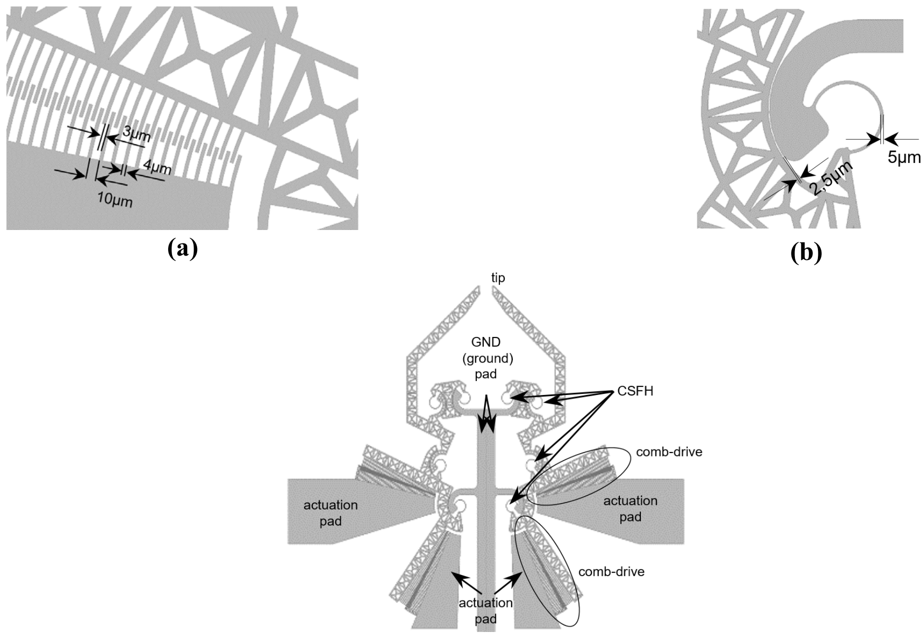
Abstract. MEMS-Technology based microgrippers have been recently used in different fields of applications. These microsystems can be actuated by means of electrostatic actuators, such as linear or rotary comb drives, but the robustness and feasibility of such components in static and as well as dynamic conditions still raises some concerns. In order to contribute to fill this gap, the dynamic properties of a MEMS-Techology Based silicon microgripper, based on four-bar linkage, with co-operative comb-drives, are here numerically analysed. The analysis of the vibrations is essential in many MEMS applications since vibrations may lead to significant positioning errors or undesirable contacts between the anchored and floating fingers of the comb-drives. The present investigation aims to assess the critical modes of a MEMS microgripper in order to ascertain the possibility of impact between the fixed and moving fingers of the comb-drives. The relative displacements between the anchored and the floating fingers are tolerable only if the center of the relative rotation is coincident with the center of the conjugate profiles. Hence, the nature of the relative motion for the first vibration modes has been assessed by means of Finite Element Analysis (FEA) in order to avoid operational issues.

Introduction

The variety of flexure hinges [1] and the actual technological capabilities in MEMS fabrication (micro electro mechanical system) enabled the development of new microsystems for the manipulation at the microscale. The recent progress in micro and nano machining gave rise to the deployment of some multi-hinge and multi-DoF (Degrees of Freedom) MEMS-Technology based microsystem. The crucial issue regards the design and fabrication of lumped flexure hinges that are also the smallest structural elements in the device. New microsystems equipped with Conjugate Surface Flexure Hinges (CSFHs) were conceived and fabricated [2] to improve their positioning accuracy. A CSFH is a peculiar flexure that consists of a curved beam, which provides compliance, together with a portion of conjugate-profiles. It can be shown that parasitic deformations are minimized when the curved beam elastic weights center is overlapping with the center of the conjugate profiles. The CSFH was adopted in several microdevices, such as in micromanipulators [3], micro mechanisms, grippers [4], microtribometers, etc. These microsystems can be actuated by means of electrostatic actuators, such as linear or rotary comb drives, but the robustness and feasibility of such components in static and as well as dynamic conditions still raises some concerns. A MEMS-technology based device may involve dimensions ranging from a few microns to millimeters. In this work, a monolithic microgripper operated by means of electrostatic rotary comb-drives has been considered. Fig. 1c shows the overall geometry of the microgripper that consists of two tip points, 8 CSFHs, 4 comb-drives with electric pads. The grasping task can be obtained by moving the jaws that are attached to the coupler links of the two 4-bar linkage structures that correspond to the pseudo-rigid body equivalent mechanism (PRBM) [5] used to synthetize the compliant mechanism. Since the jaw is attached to the coupler link, the jaw instantaneous rotation axis can be conveniently predefined by the designer. The input link is driven by a pair of co-operating rotary comb-drives supplied with the same voltage. The design requirements suggested the use of monocrystalline silicon as a structural material since it offers mechanical and electrical properties with very good performance. A Silicon On Insulator (SOI) wafer with the following size has been considered: 40 μm thick device layer, 3-4 μm silicon oxide layer, handle layer with a thickness of 400 μm to ensure high structural mechanical reliability.



(a) (b) (c)

***Figure 1** A detailed view of: the comb drives (a), the CSFH (b) and the overall geometry of the proposed four-bar linkage microgripper with co-operative electrostatic actuation.*

It is worth noting that the structural reinforcement is provided in the elements that do not show any motion during the actuation, i.e. the pads and the central frame structure for the CSFHs (Fig. Ec). The device structure consists of elements with heterogeneous dimensions and, among these, some parts may provide functional constraints. For instance, the comb-drive fingers and the gap between non-moving and moving fingers should be limited to a few microns (see Figure 1a,b).

More details regarding the considered CSFH flexures and comb-drives are listed in Table 1.

Table 1

Component	Label	Value
Finger	Width	4 μm
	Out-of-plane thickness	40 μm
	Distance	10 μm
	Finger clearance	3 μm
SOI wafer	Handle layer	400 μm
	Device layer thickness	40
Overlapping	Initial angle	2°
	Rotor-stator finger gap	3 μm
CSFH	Curved beam width	5 μm
	Curved beam length	252 μm
	Curved beam thickness	40 μm
	Conjugate surfaces clearance	2,5 μm
	Curvature radius	62,5 μm

Numerical microgripper modal analysis

The versatility of the CSFH is appealing for several MEMS applications such as microsurgery, biological tissue manipulation, etc. The modal analysis turns out to be insightful on how the device dynamic operation may be affected. As a matter of fact, vibrations may substantially affect positioning accuracy or unwanted stator-to-rotor fingers impact that result in hazardous short circuit or mechanical damage [6]. On the other hand, vibration may enhance the releasing of micro objects or the assessment of the biological soft tissues mechanical properties [7]. In this work, the eigenmodes have been conveniently analyzed, via Finite Element Analysis, by implementing a COMSOL Multiphisycs code. Symmetry boundary conditions have been conveniently exploited to reduce the computational costs, so only one-half of the microgripper has been considered (Fig. 2). The considered mechanical boundary conditions are reported below:

- the non-moving fingers are anchored (A);
- the moving fingers and the remaining gripper links (B) are free to move;
- the frame link is fixed (C);
- the symmetric boundary condition is applied to the surface (D).

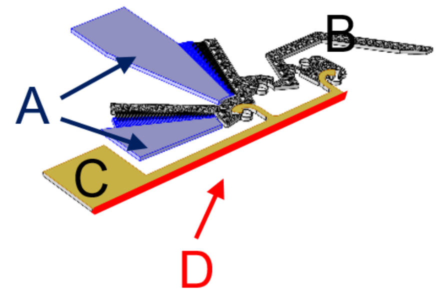
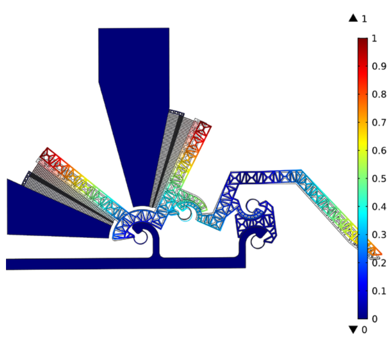
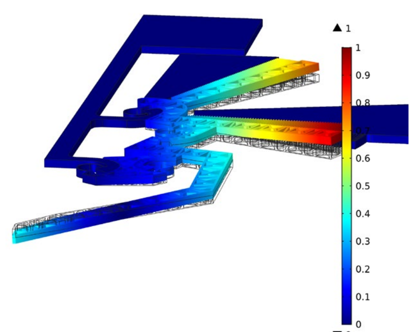


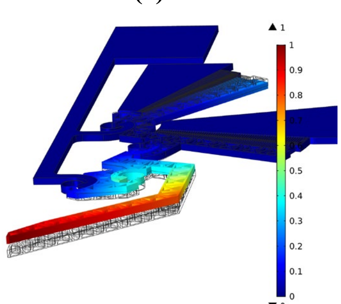
Figure 2 *Boundary conditions adopted in FEA simulations: anchored non-moving fingers (A), the moving fingers and the remaining gripper links are free to move(B), the frame link is fixed (C), the surface (D) represents the symmetric boundary condition.*



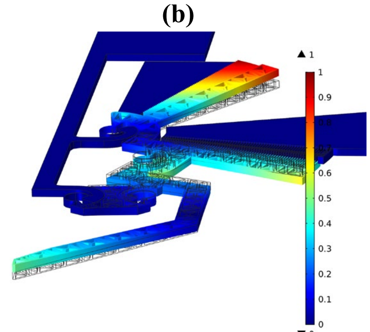
(a)



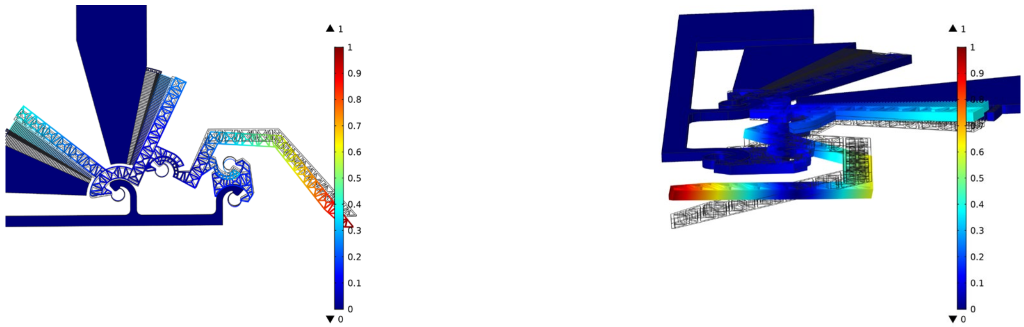
(b)



(c)



(d)



(e) (f)

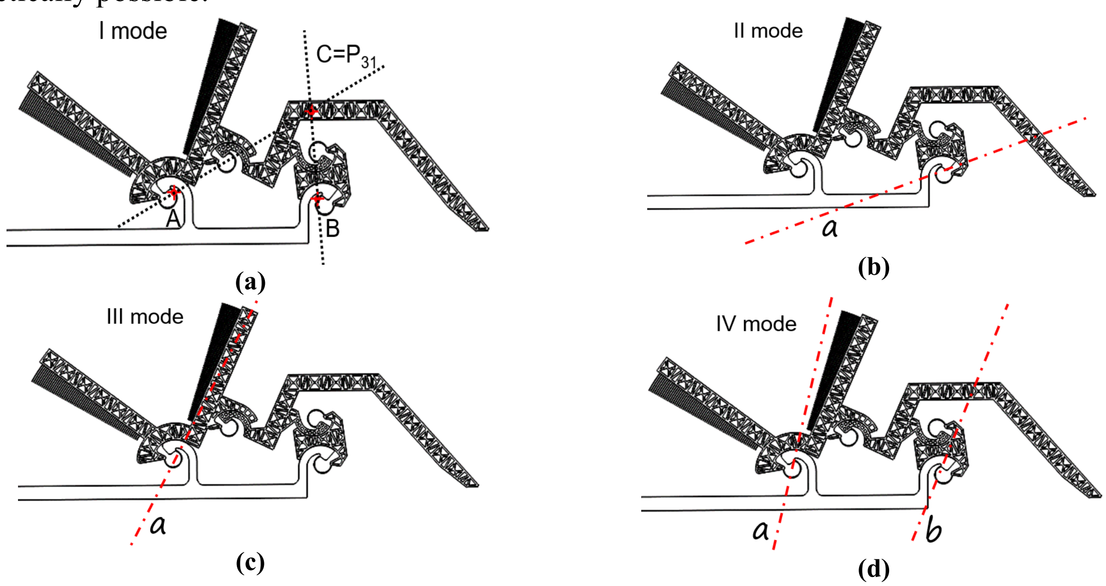
Figure 3 *First six eigenmodes of the proposed microdevice: I mode (a), II mode (b), III mode (c), IV mode (d), V mode (e) and VI mode (f).*

The first six eigenmodes and natural frequencies are respectively reported in Figure 3 and in Table 2.

Table 2

Mode	Frequency (kHz)	Critical	Plane	Rotation axes
I	1,45	no	in	3
II	2,00	no	out	1
III	2,70	no	out	1
IV	3,67	no	out	2
V	6,09	yes	in	3
VI	6,98	no	out	2

The relative displacements between the anchored and the comb-drives moving fingers are acceptable whenever they correspond to a relative rotation and its center overlapping with the conjugate profiles center. Thereby, it is crucial to evaluate the relative motion nature of all the vibration modes that may be excited during the operational stages. In particular, the first and fifth modes present radial displacements for the fingers and therefore finger contact appears to be theoretically possible.



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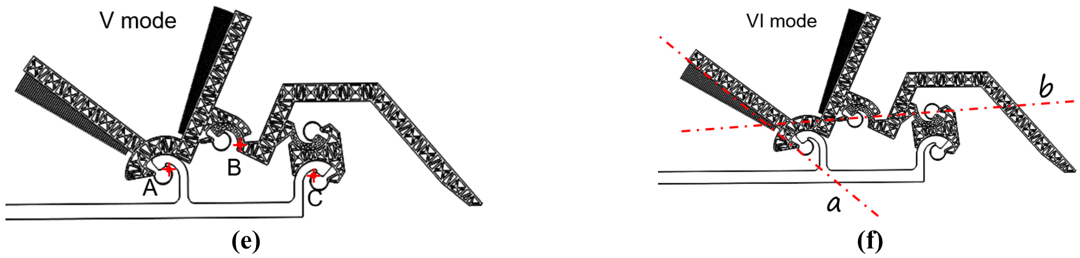

Figure 4 *Axes of rotation for to the first six eigenmodes: (a) axes of rotation for the I mode (the axes are normal to the xy plane, red cross marks), (b) out-plane rotation axis for the II mode (red line), (c) out-plane rotation axis for the III mode (red line), (d) out-plane rotation axis for the IV mode (red lines), (e) in-plane rotation axes for the V mode (red cross marks), (f) out-plane rotation axes for the VI mode (red lines); black dotted lines represent geometric properties of the PRBM, while red lines represent the nodal lines.*

FEA results have been used to identify the minimum displacement areas for each vibration mode. Such zones can be easily identified and the structural behaviour can be physically interpreted by tracing the nodal rotation axes. When the first mode is excited (Figs. 3a, 4a) three elements of the structure act as pseudo-rigid bodies, i.e. the coupler and the two rockers links. Motion is provided by the four flexure hinges and all the mechanism elements are characterized by an in-plane motion. The nodal rotation axes are normal to the *xy* plane (red crosses), thereby their intersections with the mechanism plane are identified by the points A, B and C depicted in Fig. 4a. It is worth noting that the third axis of rotation (c) passes through the instantaneous center of velocity of the coupler with respect to the frame link (P_{31}). Hence, the first mode motion is compatible with the microsystem design, so the involved deformations are compatible with the comb-drives geometry since the relative rotation axes are practically coincident with the CSFH rotation axes and no stator-to-rotor fingers contact is implied. The second mode analysis (Figs. 3b, 4b) shows that the whole mechanism behaves as a plate that rotates around the axis (a) (red line) passing through the center of the CSFH that links the frame to the second rocker (which has no comb-drive mounted on). This axis lies in the *xy* plane so out-of-plane vibrations are entailed. However, the moving fingers are all located on one side of the axis, thereby their motion acts along the perpendicular to the gap between the fingers. As a consequence, the fingers contact is still unlikely. The third mode (Figs. 3c, 4c) is similar to the second but its nodal axis passes through the center of the hinge that joins the frame to the rocker equipped with the comb-drives (red line) . The nodal axis lies in the mechanism plane and the moving fingers are still located on one side of this axis, hence fingers contact seems to be unlikely. The modal analysis for the fourth mode (Fig. 3d) reveals that the microgripper inflects around two parallel axes a and b depicted in Fig. 4d (red lines). Such axes lies in the *xy* plane, then the displacements will occur out-of-plane. The system behaviour is similar to a flexible plate which oscillates around a and b nodal axes, resulting in three different zones. For instance, if the central area inflects downwards, the lateral zones will inflect upwards and vice versa. From the perspective of preventing contact between moving and non-moving fingers, the fifth mode (Figs. 3e, 4e) represents the most critical one. In fact, the system behaves, approximately, as a pseudo-rigid plate that rotates around an axis (c). Such axis passes through the point C and is located within the internal zone of the mechanism, as depicted in Fig. 4e (red crosses). Unfortunately, such motion can be rather detrimental for the comb drives since the moving fingers do not rotate about the CSFH centers. As a consequence, the fingers will no more travel along the natural span of the fixed fingers gap, therefore the moving fingers may collide with the fixed ones. In such a situation, the moving fingers undergoes a radial displacement component since the rotation does not occur around the original center of rotation. The sixth mode has a rather complicated shape and three nodal axes can be identified (red lines in Figs. 3f,4f). The axes lies all in the mechanism plane. The microgripper acts as a flexible plate that inflects around the nodal lines and out-of-plane displacements are entailed, but no critical configuration is expected for the comb-drives. Since fingers contact can be expected only when the fifth mode is excited, its occurrence has a limited impact on the microgripper dynamic operations.

Conclusions

The present investigation has shown that the proposed microgripper may experience contact issues between moving and non-moving fingers of comb-drives when, during its dynamic operation, the fifth mode is excited. FEA has been exploited to identify the main modes of vibration, whose examination is required to prevent critical configurations that happen when there is a contact among moving and non-moving fingers of comb-drives. The modal analysis confirmed that the proposed microgripper unlikely undergoes to critical configurations, providing significant reliability during dynamic operations and it is promising for biomedical and soft tissue manipulation applications.

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