A breakthrough in

Compliant mechanisms play an important role in micromechanical structures for MEMS applications. However, the positive stiffness of these mechanisms remains a significant drawback. This stiffness can be compensated by including a static balancing mechanism (SBM), resulting in a statically-balanced compliant micromechanism (SB-CMM). This article presents design methods, concepts and simulation results of such mechanisms, which could be applied to MEMS (SB-MEMS). Two categories of SB-CMMs are presented, with the preloading force and travel path either (1) perpendicular to each other, or (2) parallel to each other. These concepts provide compliant mechanisms with approximately zero stiffness in a finite range of motion. Their application can ultimately result in a reliable, smaller, and energy-efficient microsystem, having a larger useful travel range.

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Mechanisms and linkages based on rigid bodies in some cases can be replaced by compliant mechanisms to achieve the same function. Compliant mechanisms are those mechanisms that achieve their mobility through the deformation of one or more slender segments of their members; they do not rely exclusively on the relative motion between joints and rigid links.

Benefits

Compliant mechanisms introduce two performance benefits over conventional rigid-link mechanisms, namely no relative motion among pieces and no overlapping pieces. The absence of relative motion implies the absence of sliding friction, which eliminates wear, noise, vibration and the need for lubrication. Consequently, less maintenance is required. Furthermore, backlash is eliminated, which leads

Authors' note

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to reduced positioning error and therefore increased precision. The fact that there are no overlapping pieces allows fewer parts and single-piece production, which reduces the assembly and weight. Therefore, compactness and miniaturisation are enhanced while production costs are reduced. All these benefits help to create more innovative designs and actuation arrangements which increase the solution search space.

Challenges

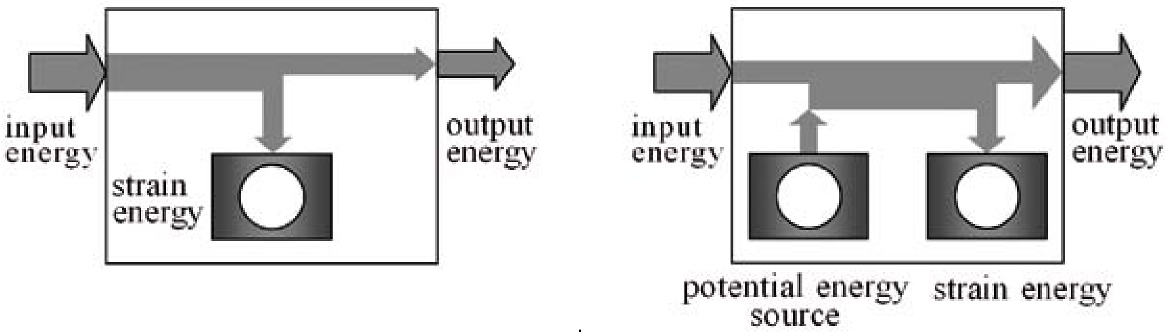
Apart from the above advantages, the monolithic nature of compliant mechanisms also gives rise to some drawbacks. Due to the strain energy storage in the deformed compliant segments, the input-output relationship is affected. In particular, energy efficiency is challenged because part of the input energy is not transferred to the output but used for the deformation of the compliant segments of the mechanism. This deformation energy is often regarded as a 'necessary evil' of compliant mechanisms. However, the deformation energy is not dissipated, it is stored and thereby conserved.

Static balancing

Consequently, a way to overcome this disadvantage is by reintroducing the strain energy into the energy stream between input and output from another source of potential energy; see Figure 1. Pre-stressing the compliant mechanism is a simple way to introduce the compensating energy [1, 2]. During motion the energy will flow from the pre-stressed to the deforming area. A compliant mechanism where the strain energy has been compensated to keep the elastic potential energy constant is said to be statically balanced. Statically-balanced compliant mechanisms (SBCMs) are useful in the design of applications requiring the monolithic characteristics from compliant mechanisms together with the energy-free and zero-stiffness behaviour from static balancing.
Now the question is, how to design statically-balanced compliant mechanisms? To find the answer, the question is split in two: how to design compliant mechanisms, and how to add static balance? And what defines a statically-balanced state?

Design methods

The design of compliant mechanisms tends to be a trial-and-error process highly dependent on the designer's experience due to the aforementioned disadvantages. Besides, if large deflections are involved, nonlinearities can not be avoided and hence kinematics and dynamics can not be considered independently during the synthesis and analysis. Dimensions of the members are not only determined by the kinematics requirement but also by the stress distribution. This design difficulty prevents the wide use of compliant mechanisms. Although compliant mechanisms have been used for more than a century, it is in the last twenty years that they have shown a growing



a b

Figure 1. Functional representation of (strain) energy storage in:
(a) a compliant mechanism (CM);
(b) a statically-balanced compliant mechanism (SBCM).

stream of publications with a proliferation of new methods for analysis and synthesis.

Three main different design synthesis approaches for compliant mechanisms are distinguished; the kinematics based approaches, the building blocks approaches and the structural optimisation based approaches [3, 4].
The kinematics based approaches make use of knowledge on rigid-body kinematics. Here two methods excel: the rigid-body-replacement method based on flexure joints and pseudo-rigid-body models [5, 6], and the freedom-and-constraints-topologies or FACT method [7, 8].
In the building blocks approach the idea is to concatenate multiple compliant mechanisms that perform simple functions to create compliant mechanisms that can perform more complex functions. Two methods are identified: the instant center approach and the flexible building blocks.
The structural optimisation approaches are based on the use of optimisation and search techniques to obtain the design topology, shape and size of a compliant mechanism that satisfies an objective function and its constraints for a set of design parameters.

Design synthesis approaches for compliant mechanisms can be summarised as:
- Using the well-known kinematics of rigid-body mechanisms. The conventional joints obtained in this way are replaced by compliant joints to obtain a compliant mechanism.
- Starting from the premise ”divide and conquer”, where the design problem is divided in smaller subproblems and where the final design is obtained by composing the solutions to the subproblems into a complete design. The subsolutions can be obtained either by some automated process or using the well-known kinematics from rigid-body mechanisms.
- Automating the search of a solution that fulfils a desired function and constraints. Find the proper way to describe the topology, shape and size (the parametrisation), and find what has to be fulfilled to get the proper design (the objective function).
- Any combination of the previous.

What defines a state of static balance for a range of motion is the observance of five conditions or criteria along this range of motion: the system has constant potential energy; it is in a state of continuous equilibrium; it shows zero stiffness or neutral stability; its virtual work is zero at any point in the range of motion; and finally, it exhibits zero natural frequency and moves with constant speed in the absence of external forces [9].
Now for the design of statically-balanced compliant mechanisms, it is proposed to use the three main design approaches for compliant mechanisms, in order to satisfy the static balancing criteria. Such combination leads in theory to fifteen design methods. In the kinematic approach only the use of the rigid-body-replacement method is feasible.

Application to micromechanisms

At microscale, performing micro-assembly tasks is technologically highly complicated due to the small part dimensions involved and the high-accuracy demands in positioning which could cost sometimes up to 80% of manufacturing cost [10]. Besides, manufacturing of pin joints which are rather small compared to the whole design, is costly and requires a tight position resolution as well [11]. On the other hand, compliant design has less clearance due to pin joints, resulting in higher precision [12, 13]. Therefore, the compliant mechanism seems to be promising in the design of micromechanical structures for MEMS (micro-electromechanical systems) applications [6, 13]. But, the positive stiffness of the mechanism remains a significant drawback [14]. This fact results in insufficient travel range, non-accessible actuation force, larger actuators and therefore larger size of the final design and lower energy conservation. Actually, a statically-balanced compliant micromechanism for application as MEMS (SB-MEMS) may be a breakthrough in precision engineering. In this mechanism, energy is transferred between the mechanism and the balancer.

The following sections will elaborate on the overall aim of this research. Two cases of SB-MEMS are presented for different applications: the balancing force and loading are either in same direction (case I) or perpendicular to each other (case II). These concepts provide a compliant mechanism with zero stiffness at the start and the end of its travel range, respectively.

Case I

It has been shown that the horizontal stiffness of the beam elements of a straight guided mechanism is reduced by an applied compression force, in the same way that in a conventional slider-crank mechanism the stiffness along the travel path is decreased by the balancing compression force applied to the crank's spring [15]. Besides, the moment produced from the compression force generates a larger balancing force. The initially curved beams as balancing elements avoid ramping up of a high buckling load, which will result in a better distributed force compared to straight beams. Considering fabrication and performance constraints and the above-mentioned issues, the concept has been proposed [16] as shown in Figure 2 and the results are shown in Figure 3.

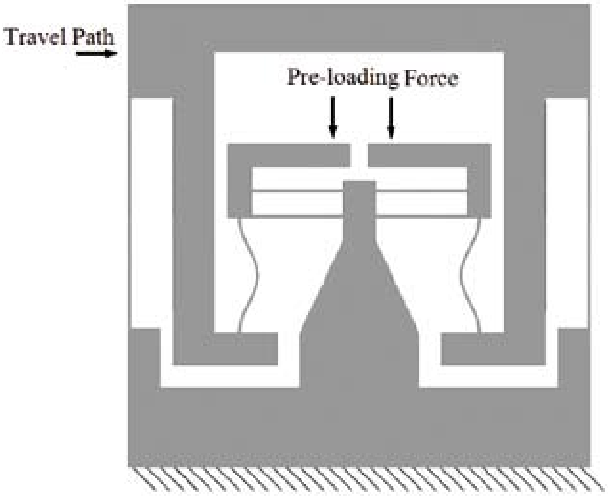


Figure 2. Concept of the statically-balanced compliant micromechanism of case I.

As illustrated in Figure 3, adding the negative stiffness of the SBM (dotted circular line) to the increasing positive stiffness of the CMM (solid star line) results in a SB-CMM (dashed diamond line) with an approximately zero force (*F*) versus displacement (*X*) curve and therefore a zero-stiffness mechanism. As shown in this figure, the SBM effectively compensates the CMM from the starting point of the travel range because of approximately opposite stiffnesses. Therefore, the system is in static equilibrium from the start of the travel range. However, the mechanism can be only statically balanced for a certain range of motion, as the difference in nonlinear stiffness characteristics of the SBM and CMM increases along the travel path. In this concept, it has been assumed that the balancing elements are already preloaded externally.

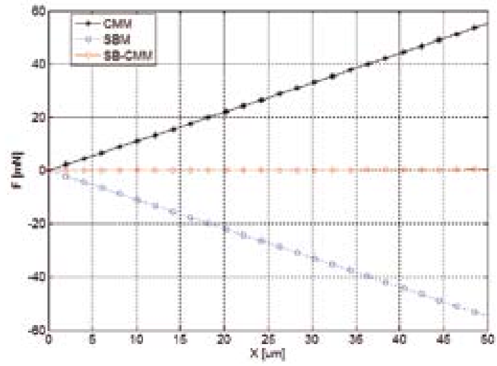


Figure 3. Actuation force versus displacement for case I – comparison of conventional micromechanism (CMM), statical balancing mechanism (SBM) and statically-balanced compliant micromechanism (SB-CMM).

Case II

In this case the directions of travel path and balancing load are assumed to be parallel and the mechanism is in static equilibrium at positions further along the overall mechanism travel range.

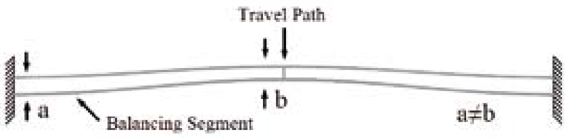


Figure 4. Concept of the statically-balanced compliant micromechanism of case II.

Figure 4 presents the initial concept [16] and the results are shown in Figure 5. Solid star and dotted circle lines present the CMM and SBM, respectively, and dashed diamonds show the total force from the SB-CMM. As shown in this figure, by combining a bi-stable mechanism (SBM) with another bi-stable mechanism (CMM), the positive stiffness of the combined structure (SB-CMM) may reduce if the second and first stable positions of the CMM and SBM are nearly in the same position (see Figure 5). In this case, when the positive stiffness of the CMM after its second bifurcation point is compensated by the negative stiffness of the SBM after its first bifurcation point, the system can be in approximate static equilibrium for a certain range of motion around the matching stable position.

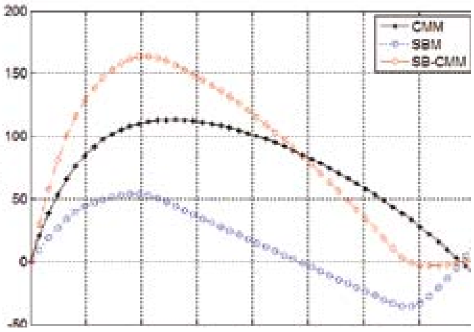


Figure 5. Actuation force versus displacement for case II – comparison of conventional micromechanism (CMM), statical balancing mechanism (SBM) and statically-balanced compliant micromechanism (SB-CMM).

In other words, the mechanism is approximately statically balanced internally for a certain range of motion instead of in one or two positions. This concept resembles those presented in [12]. But here a double buckling mechanism is proposed with a *difference in rise* of the beams (i.e. a ≠ b), which results in a significant change of buckling behaviour in which the system is statically balanced internally for a certain range of motion. The same principle has been used to design a nonlinear static balancing mechanism by combination of different balancing mechanisms [17].

Conclusion

Design methods, concepts and simulation results of statically-balanced compliant micromechanisms (SB-CMMs) have been presented. These concepts provide compliant micromechanisms with approximately zero stiffness in a finite range of motion. The simulation results confirm the validity and performance of the concepts, which have been optimised for further evaluation. Incorporation of these concepts can ultimately result in a reliable, smaller, and energy-efficient microsystem, having a larger useful travel range.

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