Modeling of a Self-Retracting Fully-Compliant Bistable Micromechanism

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ABSTRACT

The purpose of this paper is to demonstrate how a combination of models facilitated the development of a new class of small displacement fully-compliant bistable micromechanisms (Self-Retracting Fully-compliant Bistable Micromechanism, or SRFBM). Two different Pseudo-Rigid-Body Models (PRBM) were used in the early stages to determine the basic form of the device. The use of these models allowed bistable configurations to be rapidly identified. Subsequent finite element modeling concentrated on tailoring the devices for specific behaviors. Furthermore, finite elements models were instrumental in predicting the thermal self-retracting behavior of the mechanism.

Suitable designs have been fabricated and tested for functionality and endurance. Total travel of the devices is 8.5 μm. Bistability, including on-chip actuation and thermal self-retraction has been demonstrated, as well as fatigue testing in excess of 2 million cycles. On-chip force testing has correlated well with model predictions.

Keywords: Bistable, MEMS, Pseudo-Rigid-Body-Model, fully-compliant mechanisms.

1 INTRODUCTION

The development of the SRFBM (see Figure 1) was driven by a need for a mechanism suitable for low-(operating)-power switching applications. A bistable device will maintain either of two stable states without additional energy input. External input is only needed to transition from one stable state to the other. This can result in significant power reductions in comparison to other switching devices. A further benefit is that a bistable mechanism can be configured with an externally constrained stable equilibrium (past the unstable equilibrium, but prior to the second natural stable equilibrium). At the externally constrained stable equilibrium the device will exert a passive contact force. This is useful for reducing the resistance of electrical contacts in switching applications

It was decided that the devices should have a linear travel of approximately 10 μm between stable equilibria. This will help to reduce power requirements and facilitate the interface with the desired actuator. A direct result of this decision was that partially compliant mechanisms[1] (typical of many of the bistable micromechanisms in the literature [1-9]) would be unsuitable. Microfabricated pin joints typically have relatively large clearances due to fabrication limitations. The process used for the initial fabrication of the SRFBM has a minimum linespacing of 2.0 μm, which is significant considering the target displacement of 10 μm. These clearances result in deviations from the desired behavior of the mechanism, including increased displacement.

The decision to develop a fully-compliant mechanism does complicates the design process somewhat, but allows greater freedom in fabrication. Fully-compliant devices can be fabricated from a single mechanical layer, allowing almost any microfabrication process to be used.

2 PSEUDO-RIGID-BODY-MODEL

The development of the SRFBM utilized the Pseudo-Rigid-Body Model (PRBM) [10, 11]. This modeling technique allows compliant segments and mechanism to be accurately modeled as analogous rigid body linkages and *vice-versa*—analysis of compliant mechanisms by rigid-body representation and synthesis by rigid-body replacement[2]. Traditional rigid-body kinematic analysis and synthesis techniques can be thus applied to compliant mechanisms—streamlining the design process by allowing the designer to rapidly develop compliant mechanisms to perform specific functions.

Within the PRBM, compliant segments are represented by appropriately sized rigid links, pin joints and torsional springs. The size of the links and springs is dependent on the loading conditions as well as the material and geometric properties of the compliant segments.

For the SRFBM, a double-slider linkage was selected as the starting point for the design as this is one of the simplest linkages that can be configured for bistability and linear motion (see Figure 2). The double slider is a single degree of freedom mechanism, as such the motion and force-deflection behavior can be solved for analytically.

A common practice in compliant mechanism design is to use flexural pivots—small flexible segments that perform the function of revolute joints. However, as illustrated in

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1. Partially compliant refers to mechanisms that obtain their motion from a combination of flexible segments and traditional kinematic pairs.
2. Replacing rigid-body linkages with the appropriate compliant analogue.

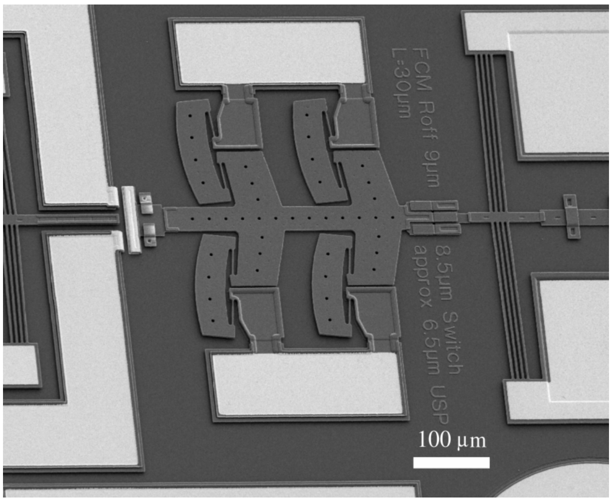

Figure 1: SEM image of SRFBM system

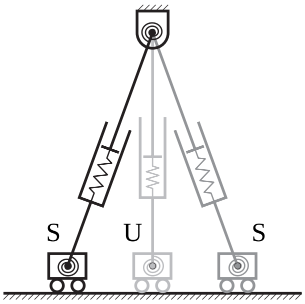

Figure 2: (a) PRBM of double-slider showing stable (S) and unstable (U) positions.

Figure 2, the pin joints (or the analogous compliant segments) will be subject to compressive loading during the motion of the device. This is undesirable for this mechanism, as compressive loading of compliant segments can lead to stress softening and increased mechanism displacement.

A technique has been developed to deal with compressive loading using *tensural pivots.* Tensural (tensile-flexural) pivots are integrated into the overall design of a mechanism in such a way that they are subject primarily to bending and tension (see Figure 3). The adjacent segments carry the compressive loads. The result of the use of tensural pivots can be seen in Figure 4, which shows the basic geometry of an SRFBM leg overlaid with a double-slider PRBM (the stiff segment connecting the two tensural pivots is called the "C-beam"). As a new class of compliant segment, tensural pivots do not yet have a fully characterized PRBM, but the PRBM techniques are still very useful as will be seen in subsequent comparisons.

One possible improvement in the modeling of tensural pivots (and thus of the SRFBM) is to treat them as fixed-guided segments. This is a more accurate representation of their behavior, but introduces additional degrees of freedom. The resulting model is kinematically indeterminate. The energy storage of the compliant segments allows the principle of virtual work to be applied. The resulting system is fully constrained, but requires the simultaneous solution of three nonlinear equations.

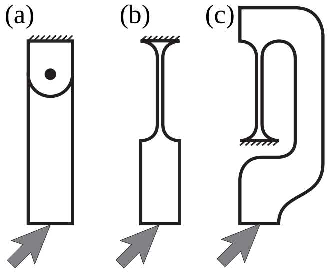

Figure 3: Comparison of combined compressive loading of (a) pin joint, (b) conventional flexural pivot, and (c) tensural pivot.

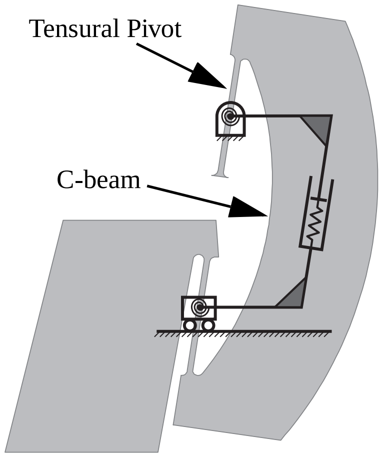

Figure 4: Double-slider PRBM overlaid on SRFBM leg geometry (rigid offsets do not effect function).

3 FINITE ELEMENT MODELING

Finite element models were used to refine the final geometry of SRFBM designs identified by the PRBMs and to investigate the possibility of thermal self-retraction. In the second stable equilibrium position, energy is stored in the device (as strain energy of the compliant segments, including the stiff "C-beam" which is compressed 1/8 μm over its 100 μm span). Heating the tensural pivots causes them to expand (in practice this is done by passing a current through the device), resulting in a release of strain energy in the rest of the system, and an effective change in the potential energy profile. If the heating releases enough strain energy, the system will no longer be bistable and the mechanisms will return to the initial position.

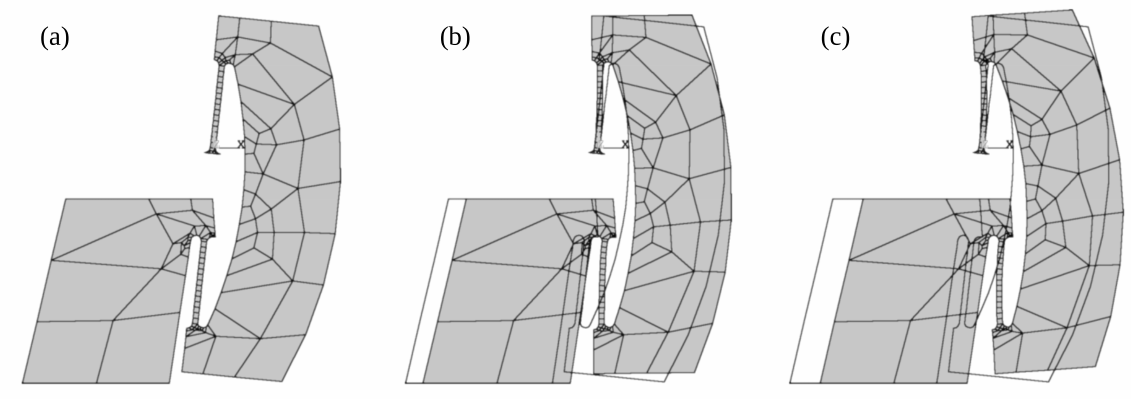

Figure 5: Geometry of plane element model of the SRFBM leg (a) undeflected position, (b) displaced near the unstable equilibrium position (6.65 μm), and (c) at the second stable equilibrium position (11.36 μm).

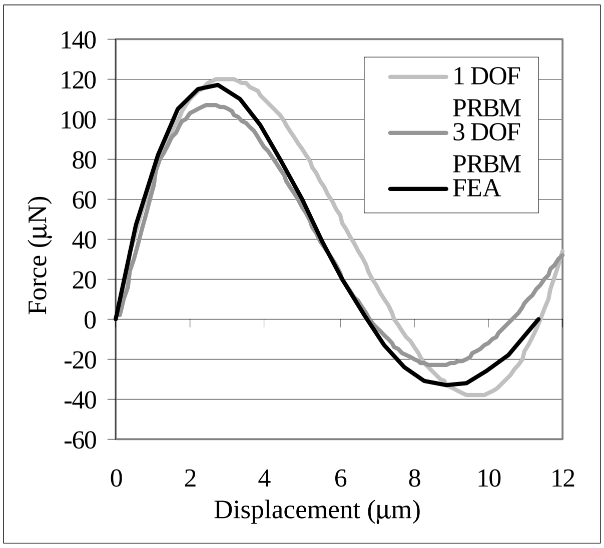

Figure 6: Comparison of SRFBM models showing force-deflection results for a single leg.

A simple beam element model was developed for the evaluation of thermal self-retraction (and verification of the bistable behavior predicted by the PRBMs). The beam element model predicted that thermal self-retraction would occur with heating of less than 400°C.

A detailed finite element model, using plane elements was also developed to evaluate the final geometry as it would be fabricated. Figure 5 shows a representative mesh in three positions: the initial undeflected position, near the unstable equilibrium (6.65 μm displacement), and at the second stable equilibrium position (11.36 μm).

Figure 6 compares the force-deflection characteristics for one of the final mechanism configurations as modeled by the two Pseudo-Rigid Body Models and the detailed FEA model. It should be noted that the parameters used in the PRBMs shown here are essentially best fit, as tensural pivots have not been fully characterized. However, other parameter sets used earlier in development resulted in curve shapes that showed similar bistable behavior and displacements, but with different force magnitudes.

The correlation between the models (especially with regards to the location of equilibrium positions) is very good, illustrating the value of the PRBM for design, as it can be implemented easily and used to rapidly identify suitable designs. Further refinements with FEA accounts for features that can not be modeled by the PRBM.

4 FABRICATION

Four suitable SRFBM designs were fabricated using the CRONOS MUMPs Process [12]. This process provides three structural layers, two of which are mechanical, and 2.0 μm minimum features and spaces. The laminate (3.5 μm thick) of the two mechanical layers was used to fabricate the SRFBM.

The four designs vary primarily in the length of the tensural pivots and the thickness of the C-beam. The overall dimensions of all the SRFBM configurations are less than 300 μm long (along the axis of travel) and 300 μm wide. Overall system dimensions, including all actuators and electrical contacts are 1140 μm long by 625 μm wide. Figure 1 shows an SRFBM system, the forward actuator is on the right of the device, with electrical contacts and the return actuator on the left.

5 TESTING

The finished devices were tested for functionality and reliability. Functionality testing included bistability, on-chip actuation, critical force (force necessary to transition between stable states) and electrical switching. Reliability included fatigue testing and evaluation of the robustness of the devices.

All designs that were selected for fabrication demonstrated bistability. On-chip actuation (with Thermal In-plane

Table 1: Force tester results and comparison

Force μN (Fwd/Ret)	SRFBM 1	SRFBM 2	SRFBM 3	SRFBM 4
Predicted (FEA)	512/ 152	492/ 144	484/ 140	464/ 132
Measured	557/ 317	396/ 254	594/ 341	396/ 240

Microactuators) was demonstrated with forward and return[3] actuation requiring as little as 150 mW and 70 mW respectively with pulses of 50 ms (faster switching can be achieved but requires more power and can damage the actuators). Thermal self-retraction required only 28 mW to return the SRFBM to the initial state.

Critical forces were measured using on-chip force testers [14]. These allow actuation force to be calculated from an observed deflection of folded beam structures. Table 1 presents these results. The measured values are based on five repetitions with the same devices. The modeled and measured values correspond well for forward actuation. Measured return forces are approximately double the predicted values. SEMs later showed that the SRFBMs contact the substrate in the second stable position. This may introduce friction, accounting for the discrepancy. Despite this finding, no SRFBMs were observed to have problems with stiction. An SRFBM was tested at 17.5 Hz for approximately 2 million cycles without failure.

6 CONCLUSIONS AND RECOMMENDATIONS

A combination of Pseudo-Rigid-Body and finite element models have been used to develop a a Self-Retracting Fully-compliant Bistable Micromechanism with an overall system travel (to the externally constrained stable position) of 8.5 μm. The PRBMs, especially the single degree of freedom model, offer the designer significant accuracy and speed to rapidly identify suitable mechanism geometries. This greatly reduced the amount of detail modeling and fabrication trial and error needed to obtain final designs.

Devices were fabricated and tested for functionality, demonstrating bistability, on-chip actuation, and thermal self-retraction. Critical force measurements correspond well with those predicted by the models. Reliability was evaluated by a fatigue test, resulting in 2 million cycles without failure.

Development of the SRFBM is continuing including adaptation to other processes, such as LIGA, amorphous diamond and Sandia National Laboratories SUMMiT V process.

Work is also continuing to fully characterize the PRBM of tensural pivots to facilitate other design work and to augment Pseudo-Rigid-Body Model theory.

3. Return actuation with an external thermal actuator.

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