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Design, Analysis and Fabrication of a Microflexural AND Gate

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Abstract

Binary logic devices constructed using moving mechanical components can be useful in harsh working environments such as strong electromagnetic fields, environments with high radiations and high temperatures where their electronic counterparts would fail. This paper demonstrates design and development of a novel micro-mechanical AND gate, using flexures to transmit motions and force. Use of flexures eliminates friction, backlash and wear, resulting in an increased operating life. Finite element method using ANSYS is used to analyze the design and obtain the stiffness and stress in the structure. An attempt has been made to fabricate the device using gray exposure of electron beams on SU-8.

Keywords: Mechanical logic gates, flexures, finite element analysis, SU-8, electron beam lithography.

1 Introduction

Binary logic devices are routinely implemented in electronic systems for performing several tasks. Typical gates such as NOT, AND, OR etc. are implemented using transistors. Similar to these, mechanical logic gates in macro domain are constructed using moving mechanical parts such as sliders and gears. Logic devices constructed using mechanical components can have many applications in engineering. This is possible since such devices are capable of handling both forces and logic simultaneously. Such devices have found applications in wide range of fields starting from switchgears to security systems to MEMS [1].

The two states of a binary variable are commonly represented by ‘0’ and ‘1’. In electrical systems, ‘0’ and ‘1’ generally represent low and high voltage levels respectively, while in mechanical systems they may represent the two finitely separated positions of links. Mechanical logic gates can be largely classified into force-closed devices and form closed devices. Basic configurations of mechanical logic gates were proposed by Dewey and Soni [2] using force closed devices while Amarnath and Deo [1] devised form closed devices. Form closed devices overcome several limitations of the force closed ones and provide a additional and interesting features like output locking, back drivability etc [1]. The construction and synthesis of the form closed AND gate described in [1] is given in Appendix A.

1.1 Microflexural Joints

Transforming the gates synthesized in [1] to micro scale would require development of revolute and prismatic joints that are difficult to achieve at that level. This paper proposes a novel design with flexures that overcomes these problems. Flexures utilize the inherent compliance of a material rather than restrain such deformation. There is also the added advantage of using polymer as the structural material. These joints eliminate the presence of friction, backlash, and wear. Further benefits include small-scale accuracy due to their continuous monolithic construction. Such accuracy is important in many micro-applications. The monolithic construction also simplifies production, enabling low-cost fabrication. The flexures are monolithic with the rest of the mechanism for vast majority of applications and this is the source of its advantage over classical joints [3]. Flexure joints however pose design challenges. The behavior of a flexure joint is sensitive to its geometry, thereby demanding high dimensional accuracy during fabrication. Also, flexure joints provide relatively small rotations because of stress limitations. Moreover, the rotation is not pure because a flexure joint is sensitive to axial loading, shear and torsion, in addition to bending. Unlike classical revolute joints that maintain a fixed center of rotation, the center of rotation in a flexure joint is not stationary during the relative motion and its displaced under the action of combined loads [4].

Over the years, many flexible joints have been researched and developed, most of which are one of the two varieties; Notch type joints and Leaf springs [4]. Notch type flexible joints (fillet joints) were first analyzed by Paros and Weisbord in 1965 [4], and have since been well understood by researchers and designers. Today, notch type joint assemblies are widely used for high precision, small rotation mechanisms. Leaf springs, on the other hand, provide the most generic flexible translational joint, and are composed of sets of parallel beams. In addition to their use in high precision motion stages leaf spring joints are also widely used in MEMS devices. People have also worked on fully compliant logic gates [5]

2 Proposed Design of Microflexural AND Gate

The basic structure of a microflexural AND gate, based on the device described in the Appendix, consists of three double parallelogram flexures, two acting as the input links, while a third is the output link. These are connected to each other through flexible links as shown in Fig. (1).

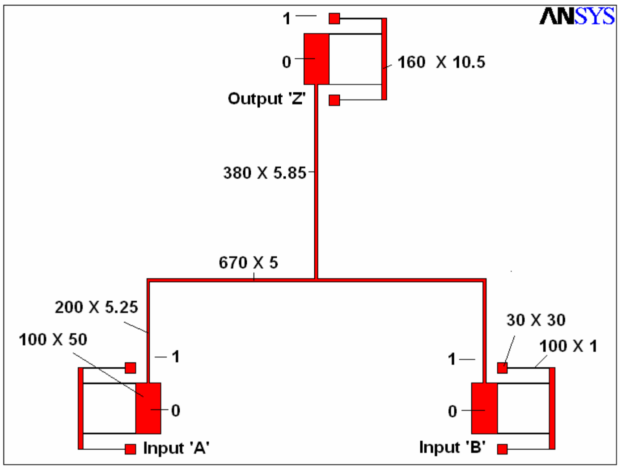

Figure 1: Proposed design of microflexural AND gate.

The mechanism has two input links, A and B. Each of these input links can occupy two states, `0' and `1'. Thus there are four possible input link position combinations - (0,0), (0,1), (1,0), (1,1). For the first three of these combinations, the output link Z should remain at `0'. Only when both the input links are at `1', should the output link Z be displaced substantially to move to `1' thereby enabling the realization of the boolean function Z = A.B.

Table 1: Defining 'Low' & 'High' of AND gate in terms of link displacements

	Input	*Output*
Low (0)	0 – 2 µm	0 – 4.8 µm
High (1)	7.5 – 10 µm	6 – 8 µm

Table 2: Various states of AND gate in terms of link displacements (in µm)

Input 'A'	*Input 'B'*	*Output 'Z'*
0 (Low)	0 (Low)	0(Low)
2 (Low)	10 (High)	4.8 (Low)
7.5 (High)	7.5 (High)	6 (High)
10 (High)	10 (High)	8 (high)

Table 1 shows the range of motions of input and output links from the reference position that is center of the link in its initial rest position. Table 2 lists the displacement of output link for various combinations of displacement of the input link. Since the mechanism is symmetric, interchanging displacement of the input links does not make any difference to the displacement of the output link. The first row of the Table 2 is the rest position of the mechanism. The second row shows the combination of maximum possible displacement of input links for which the output needs to be in state `0'. The displacement of output link will be between 0 µm and 4.8 µm for any combination of input link displacements (in microns) between 0 - 0 and 10 - 2. Similarly, the third and fourth row of Table 2 show the minimum and maximum displacement combinations of input links respectively for which the output needs to be at '1'.

The dimensions of the AND gate are chosen such that this definition is satisfied. The selected dimensions are shown in Fig. (1). No attempt has been made to tune the geometry of the mechanism to improve performance.

3 Finite Element Analysis

The mechanism with dimensions shown in previous section is modeled in ANSYS and analyzed to find the output displacement, maximum Von Mises stress developed and its location. The structure is modeled using SOLID 187, having 3 degrees of freedom at each node. The solid 3-D element was chosen for analysis as the structure is capable of out-of-plane deformations and the element is capable of simulating deformations of nearly any kind of material.

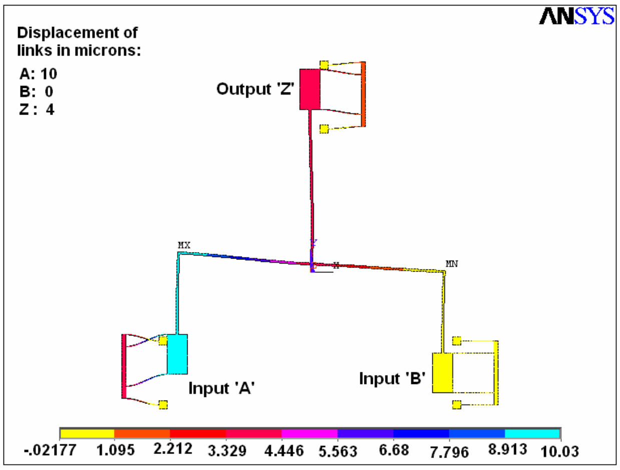

Figure 2: Displacement of links in 1-0 state of proposed AND gate.

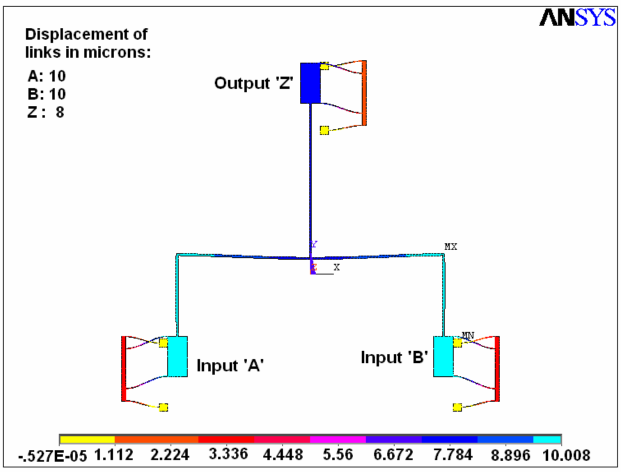

Figure 3: Displacement of links in 1-1 state of proposed AND gate

Earlier work on NOT Gate [5] had indicated that out of plane deformations are not significant compared to the in plane deformations and hence no attempt was made to determine the same. Model and analysis does not account for stress concentration at fillets and geometric non-linearities.

For analysis of (1, 0) state, input A is given a displacement of 10 µm when input B is fixed at its reference position and the simulation is performed. For analysis of (1, 1) state both input A and input B are given displacements of 10 µm and simulation is performed. Fig. (2) and Fig. (3) respectively shows displacement of the output link in (1, 0) and (1, 1) states of the input links. It can be seen that the displacement of output link in Fig. (2) is ~ 4 µm. In Fig. (3) it can be observed that this displacement is ~ 8 µm. (Note: From simulation figures it may appear that beams overlap when actuated. However, this is not the case in reality as the overlap is only because of animation problems in ANSYS.)

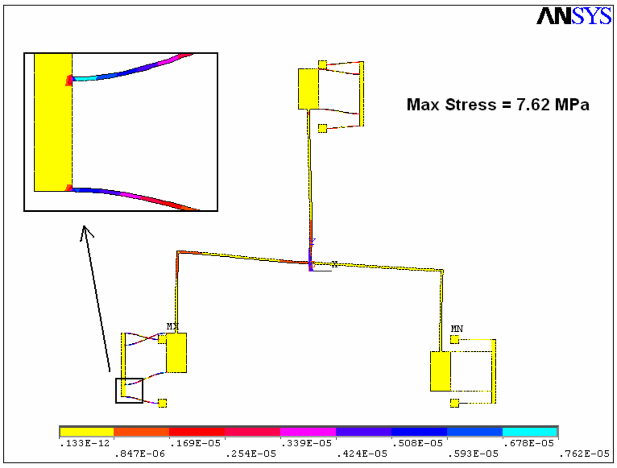

Figure 4: Von mises stress variation in 1-0 state of proposed AND gate

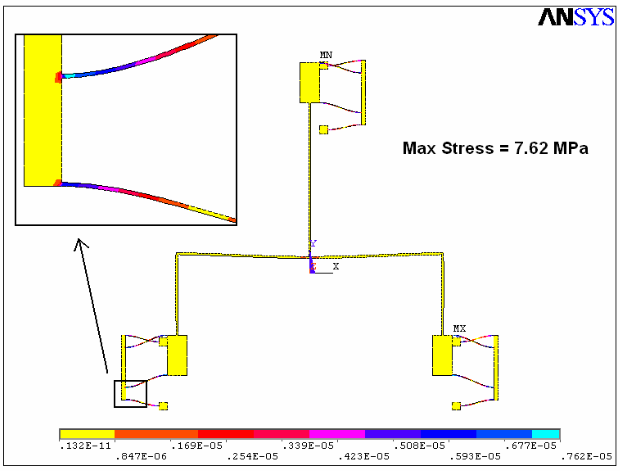

Figure 5: Von Mises stress variation in 1-1 state of proposed AND gate

Fig. (4) and Fig. (5) show the maximum Von Mises stress developed and its location in the mechanism for the states (1, 0) and (1, 1) respectively. It can be seen that the value of maximum stress remains same for both the states and is 7.62 MPa, which is considerably smaller that the fracture strength of the material used for fabrication, viz. SU-8 (Fracture strength: 34MPa). As the mechanism is symmetrical with respect to the input links, no separate analysis is required for states (1, 0) and (0, 1).

4 Actuation of the Device

Smart micro mechanical actuators are the focus of the world wide ongoing research. New actuator concepts and materials are being developed across the world. Piezoelectric, electrostatic and shape memory alloy (SMA) actuators are used to realize actuation of complex micro-systems. Each of these actuators has its own advantages and disadvantages. A novel approach is the use of compressed air as driving force in a micro actuator [5]. This actuation principle has several advantages:

- high energy density
- large achievable displacements
- high generated force
- excellent dynamic behavior
- usage of various fluids as driving medium
- usage of final controlling element with continuous action
- high design flexibility

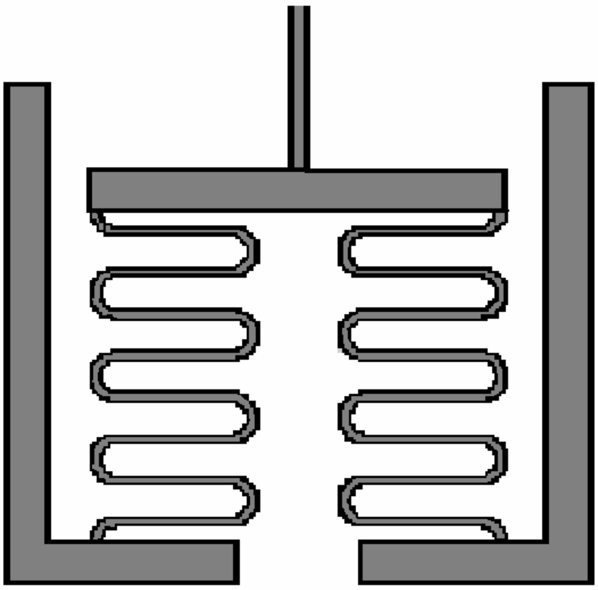

Figure 6: Design of micro-pneumatic actuator modeled in ANSYS

A micro-pneumatic actuator is developed with the SU-8 structure for driving the device (Fig. 6). The basic structure of the actuator consists of a piston connected to a housing by two spring elements [6]. These spring elements enable the piston to move when a pressure is applied, and the piston in turn moves the input link. The overall dimensions of the actuator (anchors + springs) are 2250 µm **x** 1800 µm, the springs being 10 µm thick in-plane. Air pressure is communicated through flexible micro tubes. The resultant force generated at the input link has linear relation with the applied pressure [6].

5 Fabrication Process

SU-8 fabrication processes are much faster as compared to traditional silicon surface micromachining technologies. This is particularly helpful for research applications as it allows a large number of successive fabrication runs in a relatively small time duration.

In-house fabrication of the device has been attempted with SU-8 as the structural material (Fig. 7). The devices are developed using a gray exposure of electron beams on SU-8, thus eliminating the need of any sacrificial layers. Also, the structural layers, anchors and the actuators can be fabricated in a single step using this method. In this process, an electron beam is scanned over SU-8 layer spun on a silicon wafer. Beam current, acceleration voltages, etc. are varied for writing different layers in the design to produce entire structure in a single step. Entire process flow for developing the SU-8 devices is as follows:

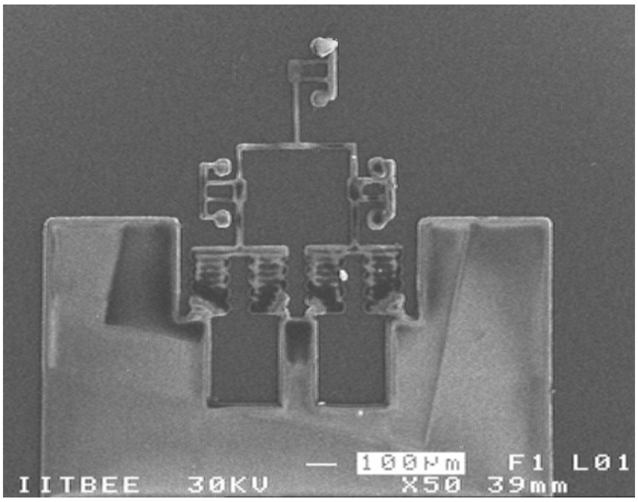

Figure 7: SEM of microflexural AND gate fabricated with SU-8

1. RCA clean silicon wafer. This process has 3 steps:
   - *Organic Clean*: Removal of insoluble organic contaminants with a 5:1:1 H_2O: H_2O_2:NH_4OH solution.
   - *Oxide Strip*: Removal of a thin silicon dioxide layer where metallic contaminants may accumulated as a result of the previous step, using a diluted 50:1 H_2O:HF solution.
   - *Ionic Clean*: Removal of ionic and heavy metal atomic contaminants using a solution of 6:1:1 H_2O:H_2O_2:HCl.
2. Sputter 50 nm Cr onto the wafer. This is because SU-8 shows superior adhesion to chrome as compared to silicon.
3. SU-8 2015 resist is then spun on the chrome sputtered silicon wafer. The spinning is done at 2000 rpm for 30 sec to produce nearly 19.8 µm of SU-8.
4. After applying the resist to the substrate, it is soft baked to evaporate the solvent and the film thus becomes denser. The soft bake is for 15 minutes at 70ºC and at 90 ºC for 10 minutes successively.
5. The photo resist is then exposed to electron beam. The process parameters used are as follows: The anchors are exposed to a beam current of 60 pA, with an acceleration voltage of 40 kV at an area step size of 0.1953, whereas the structures are exposed to a beam current of 30 pA, with an acceleration voltage of 28 kV at an area step size of 0.1953.
6. Following the exposure, a post expose bake is performed to selectively cross-link the exposed portions of the film. Post expose bake is at 70 ºC for 10 minutes and at 90 ºC for 15 minutes successively.
7. The development of the SU-8 structures is done by using SU-8 developer, followed by a rinse in isopropyl alcohol (IPA). The wafer is then allowed to dry at room temperature until the IPA evaporates.
8. A post release or hard bake is performed on the wafer to ensure that all the remaining solvent has been removed from the cross-linked SU-8 structures. Also, it increases the mechanical and thermal stability of the structures.

Fig. (7) shows one result of the ongoing trials.

6 Conclusions

In this paper, a novel design of compliant mechanism using flexures for an AND gate is proposed. “High” and “low” states are defined in terms of position of the link with respect to a reference position. The mechanism is modeled in ANSYS and is analyzed with material properties of SU-8 for stress variation in different states of input links ((1, 0), (1, 1)). It is observed that maximum Von Mises stress developed remains same for both these states and is well below the fracture strength of SU-8. In-house fabrication of the proposed design is done using Electron Beam Lithography (EBL) with SU-8 as the structural material.

Acknowledgment

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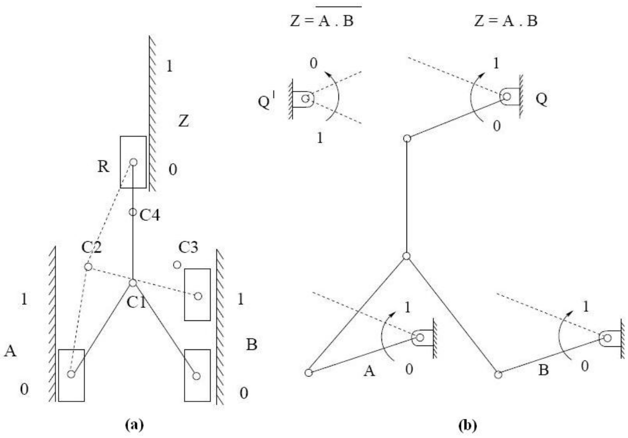
Appendix

A Form closed mechanical AND gate as described in [1]

Fig. (A 1a) shows a seven-link mechanism with two sliders *A* and *B* as inputs. These inputs occupy two positions "0" and "1". Points C1, C2, C3 and C4 are the positions of the joint C for the four possible input combinations (*A*, *B*) = (0, 0), (0, 1), (1, 0) and (1, 1) respectively. The pivot R on output slider *Z* is the center of a circle passing through C1, C2 and C3. With pivot R so chosen, output slider *Z* occupies position "1" only when both inputs *A* and *B* are "1" otherwise slider *Z* is at position "0". The companion Fig. (A 1b) shows the same gate, but with rotary inputs and outputs, the synthesis procedure being similar to the earlier.



FigureA 1: Mechanical AND gate

A NAND gate can be obtained from the AND gate of Fig. (A 1b), simply by locating the fixed pivot Q of the output link at Q' as shown in Fig. (A 1b). Hence an input which causes a clockwise rotation of the output link of the AND gate, will result in an anti-clockwise rotation of the output link of the NAND gate.

The devices in Fig. (A 1) are approximate devices, in the sense that a transition from (*A, B*) = (0, 0) to (*A, B*) = (0, 1) or (1, 0) results in a slight motion of output link *Z.* This structural error however is an insignificant percentage of the net stroke and it is observed that in most applications the clearance or compliance in the system accommodates this error.