ABSTRACT

A micromechanical amplifier with large-displacement-ratio and self-limited output as a result of bifurcation effect is reported in this paper. The large output displacement is achieved by amplifying a small input motion through the elastic deformation of the compliant configuration, which realizes the self-limited output by bifurcation effect. The configuration of the compliant microstructures is analyzed with the results of as high as 100 times displacement magnification and self-limitation by bifurcation effect. Such kind of amplifier is fabricated by employing deep reactive ion etching (DRIE) process demonstrating the 52.0-µm-output displacement when the input displacement is only 0.96 µm with the displacement ratio of 54.2. Thereafter, the output displacement maintains stable due to the bifurcation effect.

Keywords: Self-Limited, Micromechanical amplifier, large displacement ratio, and bifurcation effect

INTRODUCTION

Actuator plays an incompatible role in the microelectromechanical systems (MEMS) devices generating driving force and providing desirable displacement. Many actuation technologies such as piezoelectric materials, shape memory alloys (SMA), thermal, electromagnetic, and electrostatic actuators have been deeply studied. But the system will be out of balance when the driving force is raised further to realize larger displacement [1]. However, in many cases micro positioning over larger displacement is attractive. Therefore, the design and fabrication of microstructures to provide large displacement is important. The stability of the devices is also dependent on the actuators. Hence, a stable motion that is insensitive to the external turbulence is more attractive and challenging.

Several approaches are currently developed to increase the displacement of MEMS comb-drive actuators. Modifying the comb finger structure [2] and different types of flexure designs are studied with the demerit of instability. Then the tilted folded beam suspension is used to provide a latched rise in the displacement [3]. Another mechanism to realize large displacement is using prior displacement multiplication. This technique is based on a lever arm moving about a pivot joint [4] with the disadvantages, such as the arcuate movement rather than linear and the unstable output displacement interfered by a small input motion.

In this paper, a self-limited, large ratio micromechanical displacement amplifier with stable output displacement is demonstrated. This structure is a linear displacement device with the adjustable displacement ratio ranging from 5 to 100 and the self-limitation is achieved by bifurcation effect where the output displacement keeps stable even though the input displacement changes. Therefore, the limitations of the previous actuators, such as instability even stiction, and small displacement are broken. What is more, many benefits can be achieved by this structure including prevention of assembly, avoidance of stiction, elimination of joint friction, precision, accuracy, repeatability, absence of backlash and etc. The self-limitation assures the stable output eliminating the vibration and the fabrication is entirely compatible with surface and bulk micromachining.

In section 2, the design, simulation of the amplifier is analyzed. In section 3, the fabrication process of the actuator on silicon on insulator (SOI) wafer and experiment results are discussed. In the last section, the brief conclusions are presented.

DESIGN AND SIMULATION

The configuration of the self-limited micromechanical displacement amplifier is schematically shown in Fig. 1. In this novel self-limited actuation system, the driving force is generated by a comb-drive and the displacement amplification is realized by the compliant configurations consisting of six beams that can receive the input force, store the energy as the strain energy by the deformation of the beams, and finally release the energy with predetermined displacement. Also the displacement self-limitation is obtained by the compliant structures when the loading force is over the critical value.

2.1 Displacement amplification

As the compliant microstructure is plane symmetric along x-axis, only half micro compliant structure as shown in Fig. 2 is used to analyze the properties, which
is composed of three beams denoted as a, b and c whose width and depth are 3.0 µm and 20.0 µm, respectively.

Fig. 1 Schematic of the self-limited-displacement micromachined amplifier

The left end of beam a connects with the driving part providing the input displacement at point P1. The right end of beam b is the final amplified output point P2. The left end of beam c is fixed to the substrate. The other ends of the three beams are connected together at point P1. In the micro compliant structure, the cross sectional areas, lengths and the inertial moments of the three beams are A1, L1, and I1 (i = 1, 2 and 3 representing beam a, b, and c) respectively. The configuration of the system is further represented by the angles of α, β, and γ. When point P1 is actuated and obtains an input displacement of δ1, the final output displacement at point P2 reaches at δ2. The displacement ratio is defined as

\[ R = \frac{\delta_2}{\delta_1} \]  

(1)

The sign of ratio R depends on the relative motion directions of the input and output. If they move in the opposite directions, R is negative and vice versa. The amplitude of the displacement ratio is the absolute value of R.

The driving force applied to the half structure along the displacement direction is half of the driving force F according to the characteristics of symmetry of structure system as shown in Fig. 2. The generated reacting forces and moments that come from the other half are F1, F2, M1 and M2. The internal forces Ni and momentum Mi of the individual beams in the linear amplification range can be expressed as

\[ N_i = F_i \sin \alpha - \frac{F}{2} \cos \alpha \]  

(2a)

\[ M_i = M_{i+1} + F_i \cos \alpha \cdot x + \frac{F}{2} \sin \alpha \cdot x \]  

(2b)

Similarly,

\[ N_2 = F_2 \sin \beta \]  

(3a)

\[ M_2 = M_{2+1} - F_2 \cos \beta \cdot x \]  

(3b)

\[ N_3 = \frac{F}{2} \cos \gamma - F_3 \sin \gamma - F_2 \sin \gamma \]  

(4a)

\[ M_3 = M_4 + M_2 + \frac{F}{2} l_1 \sin \alpha - F_3 l_2 \cos \beta + F_1 l_1 \cos \alpha - F_2 \sin \gamma \cdot x \]  

(4b)

The elastic strain energy of the beam system can be expressed as

\[ U = \sum_{i=1}^{3} \left( \int_{x_i}^{x_{i+1}} \frac{N_i^2}{2E_i} dx_i + \int_{x_{i+1}}^{x_{i+2}} \frac{M_i^2}{2EI_i} dx_i \right) \]  

(5)

where E is the Young's modules of the structure material that is equal to 150 GPa for single crystalline silicon. According to the boundary conditions, the translational and rotational displacements at points P1 and P2 should be zero. The well known Castigliano’s theorem [10] states that if a structure is subjected to an external forces fi and only one virtual displacement δi is applied in the direction. The expression for δi is:

\[ \delta_i = \frac{\partial U}{\partial f_i} \]  

(6)

where δi is relative generated displacement. Therefore, for the micro compliant structure, the strain energy and generated force has the following relations

\[ \frac{\partial U}{\partial F_m} = 0 \text{ and } \frac{\partial U}{\partial M_m} = 0 \]  

(7)

where m is 1 and 2 representing the reacting forces and moments from the other half. Thus, the relationship is described as

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} & F_1 \\
C_{21} & C_{22} & C_{23} & C_{24} & F_2 \\
C_{31} & C_{32} & C_{33} & C_{34} & M_1 \\
C_{41} & C_{42} & C_{43} & C_{44} & M_2 \\
\end{bmatrix}
= 
\begin{bmatrix}
D_1 \\
D_2 \\
D_3 \\
D_4 \\
\end{bmatrix}
\]  

(8)
The coefficient matrix \([C]\) is a function of the geometric configurations and the structure stiffness while the column matrix \([D]\) depends on the external force \(F\). Thus, \(F_d\) and \(M_e\) can be expressed by the loading force \(F\), the structure configuration and individual stiffness of beams. Therefore, the displacements of points \(P_1\) can be obtained. Similarly, the displacement of point \(P_2\) is obtained by assuming a virtual force \(P\) as shown in Fig. 2. By substituting Eq. (8), the displacements of the input point \(P_1\) and output point \(P_2\) are obtained and the amplification factor is obtained by using Eq. (1).

The configuration can also be represented by the coordinates as \(x_1, x_2, x_3, h_1\) and \(h_2\) (see Fig. 2). The effects of the individual parameter on the amplification are analyzed based on the optimized dimensions listed in Table 1 (see end of the paper).

Figure 3 illustrates the effect of \(x_2\) on the amplification where \(x_2\) sweeps from -100 µm to 400 µm and the other parameters and loading force maintain fixed. The most significant phenomena is that the amplification changes from positive to negative when \(x_2 = 0.0\), which means the output point \(P_2\) alters motion direction at this critical point though the input displacement keeps its direction. Therefore, the output displacement direction can be adjusted by designing the position of the output point. When the output point \(P_2\) is located at the right side of the original point \(O\), \(x_2\) is positive and the amplification is negative. The maximum negative amplification is attained when \(x_2\) is 20.0 µm and it decreases with the rise of \(x_2\). The amplification decreases significantly from 150 to 26.5 when \(x_2\) increases from 20.0 to 200.0 µm while it maintains nearly a constant of 14.6 afterwards. The effect of the other parameters such as \(x_1\) and \(x_3\), the orthogonal coordinates of the joint point and fixed point representing by \(h_1\) and \(h_2\) are also analyzed by using these analytical formulas. The optimized design dimensions are listed in Table 1.

Bifurcation occurs for this configuration with the increased displacement under a high loading. The nonlinear large displacement and large deformation bifurcation analysis is carried out by using commercial software MSC/NASTRAN to analyze the bifurcation effect. It is observed that the bifurcation effect happens and new stable status is achieved after the critical load. This is because the stiffness of system is governed and contributed by beams \(a\), \(b\) and \(c\) before the bifurcation. However, only beams \(a\) and \(c\) control the stiffness of system after bifurcation, where the deformation of beam \(b\) is ignorable compared to those of beams \(a\) and \(c\). At this stage, beam \(b\) gives a big contribution to very large longitude or tension stiffness, which means that the exterior force \(F\) (driving force) has no contribution to transverse deformation of beam \(b\). Fig. 4 shows the bifurcation effect where the input displacement increases from 0 to 0.088 µm continuously while the output displacement increases to 1.95 µm till the loading reaches 52% and keeps the output even though the loading raises to 60% and input displacement increases to 0.11 µm.

**FABRICATION AND EXPERIMENT RESULTS**

In this study, the micromachined actuator is fabricated on silicon on insulator (SOI) wafer. After patterning all of the microstructures including comb fingers, folded beams, the compliant beams and the electrodes, DRIE etching is carried out to obtain the high aspect ratio beams and isolate the electrodes from the substrate [5]. Then the backside deep etching and release technology are employed. Finally, the metal is deposited onto the electrodes by employing shadow mask. The scanning electrons micrograph (SEM) of the fabricated self-limited micromechanical actuator with large displacement ratio is shown in Fig. 5.
The amplifier is characterized and the output displacement at point \( P_2 \) versus the displacement of input \( P_1 \) is plotted in Fig. 6, where the input displacement ranges from 0 to 38.0 µm. It indicates that the stable output displacement of 52.0 µm is obtained within the tolerance of the testing as a result of the bifurcation effect. The maximum output displacement is achieved when the input displacement reaches 0.96 µm and the output keeps fixed though the input displacement increases further to 38.0 µm. Before the bifurcation, the output displacement increases with the ramping of the input displacement. For example, the output is -17.16 µm when the input displacement is 0.24 µm. In this range, the input displacement is amplified effectively as shown in Fig. 7. Before the bifurcation point where the input displacement was 0.96 µm, the displacement ratio is as high as 100 and decreases with the rise in the input displacement. After this critical input point, the displacement ratio drops as a result of the self-limited output displacement. These experimental results agree well with the simulated curve that is plotted in Fig. 7.

### CONCLUSIONS

A self-limited micromachined displacement amplifier with a large ratio is designed, simulated, fabricated, and characterized in this paper. The compliant structure consists of six symmetrical beams along the \( x \) direction. The theoretical model is built up and employed to derive the optimum design. This analysis shows that the proposed structure can realize large displacement ratio by elastic deformation of the compliant structures. The bifurcation effect is used to attain the self-latched stable output displacement. The experimental results agree well with the analytical and numerical simulation results. The output displacement of 52.0 µm is achieved by amplifying the input displacement of 0.96 µm with the displacement ratio of 54.2. The displacement ratio is as large as 100 before this particular output displacement. Thereafter, the output displacement maintained stable by the bifurcation effect even though the input displacement increased further to 38.0 µm. This self-limited micromachined amplifier with large displacement ratio can be used in many applications to provide an effective displacement amplification and a stable output large displacement.

### References


### Table 1. Dimensions of the compliant mechanical amplifier

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>( w_i )</th>
<th>( t_i )</th>
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</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>1002.5</td>
<td>51.5</td>
<td>1014.0</td>
<td>1432.5</td>
<td>296.5</td>
<td>3.0</td>
<td>25</td>
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