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The design and analysis of a novel MEMS force amplifier*

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Abstract

Compliant micromechanisms achieve high amplification of forces that can be used as a cutting force in micro- and nanofabrication. In the present study, we designed, simulated, and optimized a novel, simple micro-compliant system by SOI-MUMPs technology. The position and quasi-static analysis of a rigid body model were derived by MATLAB and simulated in ANSYS. It was found that an amplification factor of as much as 11.1 was achieved. The amplification factor increased as the micro-compliant force amplifier got closer to 0, but it decreased as the crank angle was further from 0.

Key Words: Micromechanism, compliant, force amplifier, MEMS, SOI-MUMPs technology

Introduction

Howell (2001) recently explained that microelectromechanical systems (MEMS) are systems that integrate mechanical and electrical components, with sizes ranging from micrometers to millimeters and Si-based microactuators and microsensors found in several commercial MEMS applications. Parkinson et al. (2001) claimed that it is desirable to amplify the force of any actuator in microscale applications. Krishnan and Ananthasuresh (2008) and Su and Yang (2001) showed that compliant mechanisms enable force and motion through elastic beams and play an important role in MEMS due to their mechanical advantages. Due to these advantages, their popularity is much greater than that of traditional rigid body models.

In this study, we aimed to obtain force amplification by means of a novel microcompliant mechanism. The microcompliant mechanism was optimized by changing the size and shape of elastic beams, which achieve large deflections, to have a high amplification factor. Acer and Sabanovic (2007) presented, however, that elastic beams have low strength against high input forces as they could be plastically deformed during deflection and could not spring back to their initial positions.

In compliant mechanisms, $\mathrm{EI}_{elastic} << \mathrm{EI}_{rigid}$ and the range of force amplification makes it possible to explore very interesting applications at the micro- and nanoscales. Li et al. (2005) stated that there are several

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approaches to fabricating micro-compliant systems and that surface micromachining is one of the most utilized technologies.

Kota et al. (1999) and Pedersen and Seshia (2004) recently presented the many advantages of compliant mechanisms, such as high precision, a lack of friction at the joints, monolithic structure, a lack of wear during operation, and no need for lubrication. Moreover, it is possible to manufacture the mechanism with fewer parts, or even as a single part with no joints.

In this study, the system was designed with the silicon-on-insulator multi-user MEMS processes (SOI-MUMPs) fabrication technology that was explained by Miller et al. (2004). For elastic joints, the thickness, b, and width, h, are 25 and 3 μm, respectively, while the thickness, b, and width, h, for all rigid beams are 25 and 45 μm, so as to be suitable for the SOI-MUMPs microfabrication process line, as shown in Figure 1. The system is composed of 2 stages with long rigid beams. The lengths of the rigid beams in the first stage are 500 and 600 μm, and the lengths of the rigid beams in the second stage are 700 and 800 μm. The 2 rigid beams are linked to each other by compliant hinges with lengths of 100-300 μm. All beams are in rectangular cross-sections.

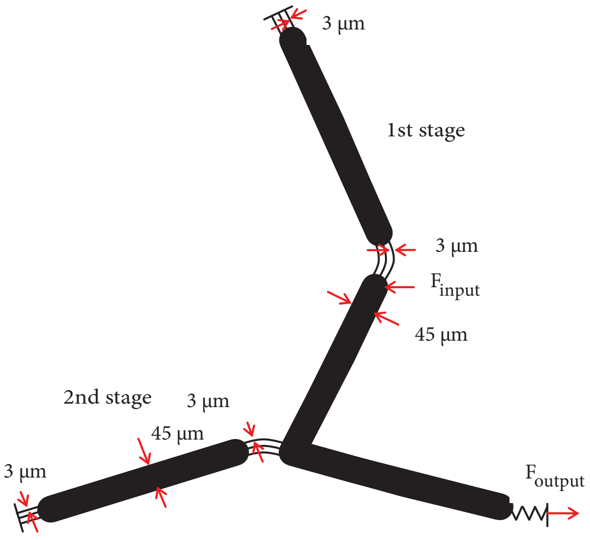

Figure 1. Model of micro-compliant mechanism in ANSYS.

The micro-compliant mechanisms are operated at small degrees, from about 0° to 10°, from which it is expected to obtain a high amplification factor. The amplification factor is defined as $A = F_{out}/F$ in, where Fin is the input force applied to the system and Fout is the output force obtained from the micromechanism.

Analysis in MATLAB and ANSYS

In MATLAB, we derived a rigid body model of the microamplifier. We saw that if we took the long length of the rigid beams at both stages to be close to each other, it increased the amplification factor. Furthermore, the rotation of the rigid beams in the first stage was much greater than the rotation of the second stage rigid beams. It was also important to adjust the toggle position of the mechanism. Thus, the initial positions of the first and second stage beams were different from each other. Running the quasi-static analysis, it was observed that the amplification factor went to infinity when both of the stages of crank angles were at 0°. The amplification factor increased as the micro-compliant force amplifier got closer to 0 and decreased as the crank angle got further from 0.

The rigid body model, as shown in Figure 2, is defined by 2 vector loops in Eqs. (1) and (2). Eqs. (1a), (1b), (2a), and (2b) are the extended expressions used in position analysis in MATLAB.

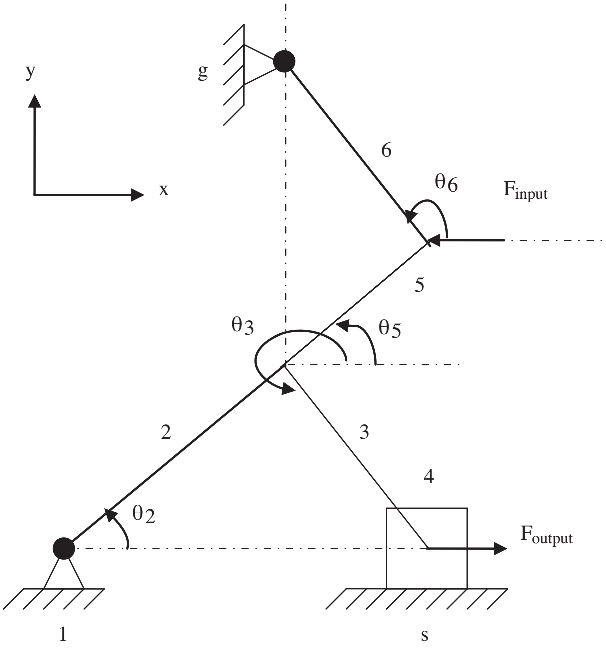

Figure 2. Rigid body model of micromechanism.

1. Vector loop equation:

$$R_2 + R_3 = R_1 \tag{1}$$

Deriving equations according to coordinates of x and y:

$$r_2(x)cos\theta_2 + r_3(x)cos\theta_3 = r_1 \tag{1a}$$

$$r_2(x)sin\theta_2 - r_3(x)sin\theta_3 = 0 \tag{1b}$$

2. Vector loop equation:

$$R_2 + R_5 + R_6 = R_g \tag{2}$$

Vector loop equation along x axis:

$$r_2(x)cos\theta_2 + r_5(x)cos\theta_5 + r_6(x)cos\theta_6 = r_g(x)cos\theta_0 \tag{2a}$$

Vector loop equation along y axis:

$$r_2(x)sin\theta_2 + r_5(x)sin\theta_5 + r_6(x)sin\theta_6 = r_g(x)sin\theta_0 \tag{2b}$$

l_1 = length of shortest beam
l_2 = length of longest beam
p, q = lengths of intermediate beams

Grashof's theorem states that if $l_1 + l_2 \leq p + q$, the mechanism can rotate; otherwise, the mechanism will not rock. Therefore, the sum of the length of its shortest and longest links must be less than or equal to the sum of the lengths of intermediate beams.

Force and moment equations were derived and quasi-static analysis was done by MATLAB.

For 2° of rotation, we could gain an amplification factor of 77, as shown in Figure 3.

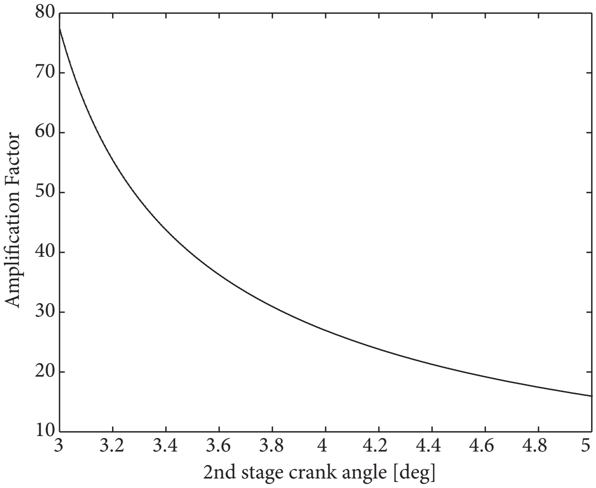

Figure 3. Amplification factor according to second rigid beam at second stage crank angle in Figure 2.

We designed various hinge geometries at the conjunction of the rigid beams, such as a triangle, a rectangle, and straight beams with a small curvature, as shown in Figure 4. We analyzed each different design of the microamplifier at different conditions.

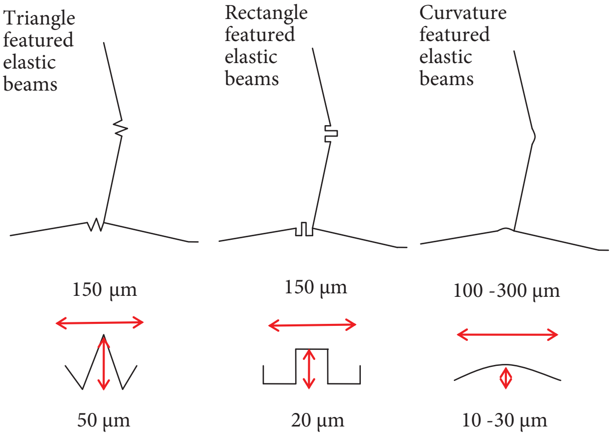

Figure 4. Different featured elastic beams.

We wanted to examine the effect of curvature and length of different compliant hinges, so we designed flexible hinges of 150, 200, and 300 μm in length, and we observed that when the length of the beams decreased from 300 to 150 μm, the amplification factor increased. Moreover, the height of the curve on the hinges improved the magnification of forces as it decreased from 30 to 10 μm.

Since we utilized the SOI-MUMPs processes, the optimization of the micro-compliant system was limited by the fabrication design rules. The optimization also depended on the input force and stiffness of materials, such that different stiffness at the output point enabled us to obtain a range of amplification factors.

The micromechanism, as seen in Figure 1, was modeled in ANSYS. Three different element types were used for elastic, rigid beams, and output spring. A large displacement dynamic simulation was run under the input force, 0.00047 N.

Figure 5 shows that, the amplification factor of the microsystem having a horizontal length of 100 μm and a 10-μm offset with curvature elastic beams 3 μm in width, as seen in Figure 1, the amplification is 11.1 at the output spring nod with an input force of 0.00047 N.

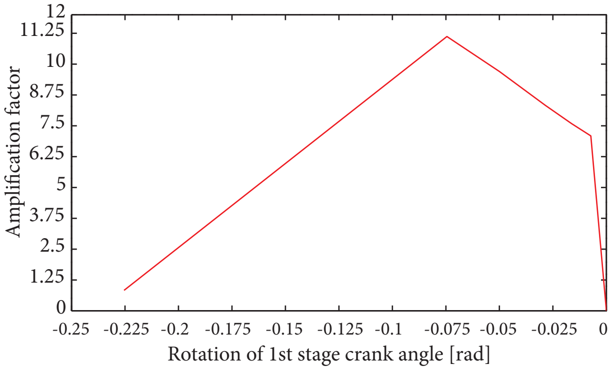

Figure 5. Amplification factor according to rotation of first stage crank angle.

Optimizing

Based on the findings in the simulations, it could be observed that the amplification factor increased with multiple elastic beam designs. Thus, the rigid beams were linked by triple elastic beams in a micro-compliant force amplifier.

We designed a novel micro-compliant mechanism by SOI-MUMPs technology with different hinge geometries. We found that the amplification factor was 9.9, 8.5, and 7.8 for straight beams with lengths of 150, 200, and 300 μm respectively, as shown in Figure 6. The straight beams had a small offset at the center and the total height was only 10 μm. For the hinges with rectangular and triangular shapes, the amplifications were 11.1 and 8.9, respectively. Moreover, the amplifications of the 200-μm straight beam with 10, 20, and 30 μm offsets at the center were 8.5, 7.0, and 6.0, respectively. Thus, the offset at the center and the length of the straight beams affected the magnification factor of the compliant system.

Miller et al. (2007) found that silicon material in SOI-MUMPs microfabrication technology has a young modulus, E, that is 169 GPa with a characteristic feature strength of 1.97 GPa. The factor of safety was taken as 1.5 in all analyses. We also tried to develop the amplification factor by changing the width of the elastic beams. The thickness of SOI is constant due to the limitation of SOI-MUMPs. When the width is increased, the amplification goes down from 11.1 to 4.5 for the microamplifier, as depicted in Figure 1, with a spring constant of 3500 N/m. Furthermore, the amplification factor was also changed from 1.2 to 9.9 by the spring constant at the output as the spring constant altered from 100 to 5000 N/m, respectively.

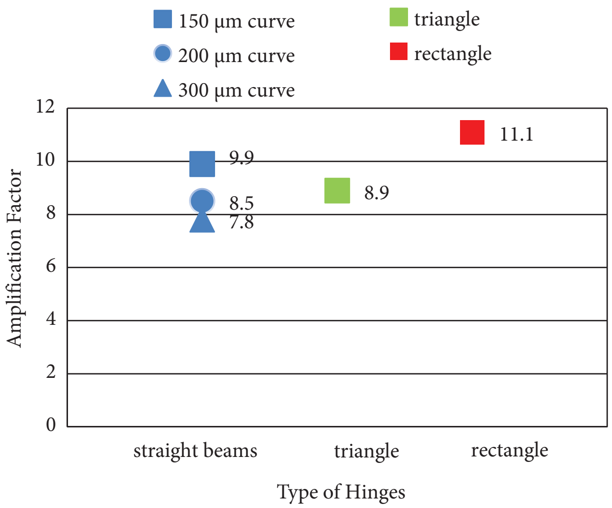

Figure 6. Amplification factors for straight, triangular, and rectangular hinges with different lengths.

Conclusion

A novel micro-compliant force amplifier was designed, simulated, and optimized in this study. The shape of the elastic beams was a significant issue for force amplification.

The topology optimization and the geometry of beams are 2 important factors in obtaining a high amplification factor in compliant MEMS. It was found that the geometry of the elastic beams played an important role in the characteristics of the compliant system, such that the amplification factor varied from 6.0 to 11.1.

In addition, the topology or the type in the linking of the beams in ANSYS could be changed and developed to obtain a high amplification factor, comparable to the MATLAB results. The micro-compliant force amplifier with spring output could also be characterized.

Nomenclature

F_i	force	b	thickness
R_x	x component of vector	h	height
R_y	y component of vector	l_i, p, q	beam length
θ_i	angle	E	young modulus
I_i	inertial moment	A	amplification factor

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