Vibration Energy Harvester with Bi-stable Curved Beam Spring Offset by Gravitational Acceleration

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Abstract. We developed MEMS bi-stable spring for vibration energy harvester (VEH), which consists of intrinsically curved shape spring and gravitational acceleration. By applying the gravitational acceleration, the curved beam is offset to the gravity direction. It will make more symmetrical bi-stable motion and the symmetry is improved from 3.3 to 65.4%. We proposed that the combination between curved beam and gravity acceleration for decreasing snap-through acceleration. From the analytical result, we investigate the combination can effective to use for decreasing of snap-through force. We also fabricated the prototype device by using MEMS fabrication process. The frequency response for horizontal direction and the acceleration response for vertical direction are measured. The acceleration response shows that the gravitational acceleration improves the symmetry of snap-through force.

1. Introduction
Recently, vibration type energy harvesters (VEHs) are widely noticed as an alternating battery for various sensing systems. Our group have been studying the human sensing system [1] that can effectively use for health monitoring and risk prediction etc. For human sensing systems, the VEHs should be suitable for human motion. The human motion was consisted by combination of lower frequency and pink noise band vibration [2]. In order to collect the sufficient mechanical energy, we have developed the bi-stable spring system that can scavenge low frequency vibration by bi-stable snap-thorough motion with nonlinear behaviours [3]. Generally it was known that the snap-through is happened when the external force exceed the snap-through force. On typical type of bi-stable mechanism, snap-through force depends on the curvature of clamped-clamped beam, and it can be controlled by compressed axis force [4]. However, it was difficult to develop the compression force in MEMS (micro electromechanical systems). In regard to bi-stable beam in MEMS technology, we proposed and designed the novel bi-stable mechanism by using intrinsically curved beam for snap-through motion [5]. In our previous work, curved beam spring was designed for low acceleration operation, however it still required more than 1 G (G; gravitational acceleration) acceleration. By introducing the parallel type curved beam, we achieved lower acceleration of 0.24 G for snap-through. In this paper, we propose the additional gravitational acceleration to improve the symmetry for intrinsically curved beam spring.


2. Snap-through motion with gravitational acceleration

2.1. Bi-stable operations on difference structures

The snap-through motion is decided by the applying force (acceleration), the curvature and the geometry of clamped-clamped beam spring. Figure 1 shows the comparison of (a) typical bi-stable spring model, (b) identically curved spring model and (c) curved beam with gravitational acceleration. The typical type shows good symmetry for snap-through forces i.e. Force1 and Force2 are equal. Since the curved spring with curvature of $\delta$ was formed and adjusted by applying in-plane force to the straight beam (Fig. 1a). The Force1 or Force2 exceed the snap-through force, the beam jumps from one stable position to another and vice versa, when the device is vibrated along to horizontal direction. However, it is difficult for MEMS harvester applying the in-plane force to the spring after the fabrication. Thus the curved spring was intrinsically designed and fabricated with curvature of $\delta$. In that case, the snap-through force should be asymmetry i.e. Force2 is greater than Force1 (Fig. 1b). In order to improve the symmetry of snap-through force, gravitational acceleration was useful for applying the bias force. Fig. 1(c) shows similar curved beam but the beam is vibrated along to the vertical direction. Although a proof mass was omitted in the simplified model, the mass is connected on the center of the beam. By using the gravitational acceleration, the snap-through force can be balanced by adjusting weight of proof mass.

![Figure 1](image)

Figure 1. The comparison of snap-through motion for conventional spring and intrinsically curved beam spring

2.2. Spring characteristics and static energy analysis

The spring characteristic for force vs. displacement ($F-X$ curve) and static energy for three types of bi-stable structures are evaluated. The $F-X$ curves were obtained by FEM simulator (Ansys Ver.15.5) with static structure analysis. By applying the force on the center of beam, the spring jumps from position A to B as shown in Fig. 2. Before snap-through motion, the beam has softening characteristic by non-linearly beam. As described before, the typical type shows good symmetry of $F-X$ curve. However, the previous type shows asymmetry curve with force offset. The present type that has curved beam with gravitational acceleration improves the symmetry of $F-X$ curve.
Furthermore, the static energy was also calculated from the $F$-$X$ curve. The static energy also shows the symmetry of three types of structure. The elastic energy of the typical type is completely symmetric. The energy for the previous type is asymmetric and it has no energy stable position. The difference of the static energy $P_1$ and $P_2$ can be used as an index of symmetry. In present type, the index of symmetry is improved by applying gravity with optimized proof mass.

3. Fabrication of curved beam in MEMS

3.1. Prototyping for design and fabrication process evaluation

For preliminary evaluation, we fabricated the test prototype for spring design. The structure was fabricated on the n-type single crystal silicon with thickness of 525 $\mu$m. The proof mass and curved support spring were fabricated by deep-RIE process as shown in Fig. 4. The 15 mm length beam supports the 12 mm $\times$ 15 mm proof mass. From the calculated proof mass weight, the gravitational acceleration generates an offset force of 2.13 mN to the curved beam. The upper left figure shows close up of beam part and. It’s surface profile measured by a Scanning White Light Interferometer (New View 7300; Zygo Corporation). We confirmed the spring width shows 40 $\mu$m as same as designed value.

Figure 2. $F$-$X$ curves from FEM buckling analysis.

Figure 3. Elastic energy comparison for displacement.

Figure 4. The Photograph of Silicon mass structure and surface profile result
4. Experimental result
Vibrational measurements are carried out by a shaker (M060;IMV Corporation). Firstly, we measured the frequency response without gravity acceleration by horizontal shaker. The figure 5 (a) shows just a resonant frequency of the curved beam in each amplitude of acceleration. The maximum displacement points are decreased as increasing the applied acceleration. This softening spring effect is usual characteristics for bi-stable spring structure before the snap-through phenomenon. The bi-stable should response represented hard spring response. We supposed that the spring was used for dozen hertz. However in low frequency band, we could not get enough displacement so the external acceleration should be increased for low frequency band.

Secondly, we measured the acceleration response with applying the gravity acceleration at 28Hz. The response shows the suddenly increasing the displacement. Because, the snap-through phenomenon was happed at 0.28 G. In spite of the small acceleration and low frequency, we could get snap-through phenomenon. We sure that the gravitational acceleration was controlled by weight of proof mass.

5. Conclusion
We presented the combination about gravity acceleration and curved beam system. In FEM analysis, the gravitational acceleration can improves the symmetric of bi-stable characteristic. We fabricated the prototype by MEMS process. Finally the prototype has good advantage with applying acceleration. We sure that this good advantage was generated by improvement of symmetrically.

6. References
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