Low-Frequency, Low-G MEMS Piezoelectric Energy Harvester

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Abstract. This paper reports the design, modeling and fabrication of a novel MEMS device for low-frequency, low-g vibration energy harvesting. The new design is based on bi-stable buckled beam structure. To implement the design at MEMS scale, we further proposed to employ residual stress in micro-fabricated thin films. With an electromechanical lumped model, the multi-layer beam could be designed to achieve bi-stability with desired frequency range and excitation amplitude. A macro-scale prototype has been built and tested to verify the prediction of the performance enhancement of the bi-stable beam at low frequencies. A MEMS scale prototype has been fabricated and tested to verify the frequency range at low excitation amplitude. The MEMS device shows wide operating frequency range from 50Hz to 150Hz at 0.2g without external proof mass. The same device with external proof mass has lower frequency range (<10Hz) with boosted deflection amplitude.

1. Introduction
Energy harvesting at MEMS scale will promisingly advance exciting applications such as large wireless sensor networks, Internet of Things etc. due to its high power generation efficiency and small form factor. However, the mismatches between the operating conditions of current MEMS energy harvesters and the characteristics of the ambient vibrations have long hindered wide applications of this technology. For instance, our previous MEMS device based on nonlinear resonance has achieved high output power of 45µW and wide bandwidth of >20%, while the operation frequency and vibration amplitude are still high (>1000Hz at 4g) [1]. Our new design is aiming to address the remained challenges of applying the energy harvesting technology to the real environment – working at low frequencies (<100Hz) and low g’s (<1g).

Bi-stable oscillator based energy harvesters have been investigated for widening the bandwidth in recent years’ work. Reported designs have achieved bi-stability utilizing mechanisms such as magnetic force [2, 3], mechanical compression [4, 5], and pre-shape [6]. The magnets are not suitable for MEMS device assembly; the pre-shaped curved beams vibrate in plane and are not compatible with piezoelectric materials spin-coating; and manually applying compression is not feasible for MEMS devices. Moreover, most of the bi-stable nonlinear resonance based devices are in macro scale [2-5]. To implement the bi-stable oscillator at MEMS scale, we have proposed to utilize the inherent property of micro-fabricated thin films – residual stress. Basing on the lumped model we have built, the bi-stable oscillator could be designed to achieve buckling and desired frequency and excitation amplitude range.
2. Modeling and Design

2.1. Modeling

An electromechanical coupled lumped model has been developed for analyzing the new design. The model is based on a clamped-clamped rectangular beam, which consists of multi-layer thin films of different material with residual stresses. Two governing equations for the mechanical and electrical domain respectively have been derived using Lagrangian equations [7]:

\[ m \ddot{w} + k_L w + k_N w^3 + b \dot{w} + C_N V_N + C_L V_L = F \]

(1)

\[ C_0 (V_L + V_N) + \frac{V_L + V_N}{R} = I_L + I_N \]

(2)

where \( w, k_L, k_N, b, C_L, C_N \) and \( F \) are the beam center deflection, linear and nonlinear stiffness of the beam, the mechanical damping coefficient, the linear and nonlinear electromechanical coupling coefficients, and the external excitation force respectively; \( I_L = C_L \dot{w} \) and \( I_N = C_N \dot{w} \) are two parts of the electrical current generated by piezoelectric element through coupling; the induced voltages on the electrical port are written in separate parts \( V_L \) and \( V_N \), since they come from two parts of the current respectively and have different frequencies due to different coupling; \( R \) is the load resistance and \( C_0 \) is the internal capacitance of the piezoelectric element. These lumped parameters are functions of the device dimensions and material properties. The nonlinear differential equations are further solved analytically using harmonic balance method, so that the dynamic responses of the post-buckling beam are obtained. The softening and stiffening responses corresponding to the so-called intra-well and inter-well oscillations have been simulated as shown in figure 1(a). The large-amplitude snapping of inter-well stiffening response increases the velocity of the beam oscillation significantly which enhances the power generation at low frequencies.

![Figure 1](image.png)

Figure 1. (a) Two modes of oscillations are simulated for the macro-scale prototype at 3g. Blue and red lines are the softening response and stiffening response respectively. (b) Schematic of the MEMS device being fabricated. Beam thickness and buckling are exaggerated.

2.2. Design

The design of the MEMS-scale bi-stable energy harvesters takes into account the general compatibility with micro-fabrication as well as the PZT spin-coating process. A doubly clamped multi-layer beam design therefore has been adopted. Furthermore, the residual stress as an intrinsic property in micro-fabricated thin films is a critical parameter and should be carefully characterized and designed. The overall effect of the residual stress in different layers is compressing the beam to buckling and inducing bi-stability. Thermal dioxide, LPCVD or PECVD silicon nitride could have compressive stresses, which can also be tuned by changing the gas ratio or plasma frequency [8]. After measuring the residual stress in each material, the thicknesses of the stack of thin films can thus be designed and controlled knowing the deposition rates, to make the doubly clamped beam buckle to the designed level and make the stress...
distribution symmetric with respect to the neutral axis. The geometry and proof mass are also designed to match the targeting frequency range and g range. The MEMS device that has been designed is shown in the schematic in figure 1(b). It is projected to operate at low frequencies (50-200Hz) at low vibration amplitudes (<1g).

3. Prototypes and Testing

3.1. Macro-Scale Prototype
A macro-scale prototype has been built to test the design concept (figure 2(a)). The tested prototype has an aluminum sheet (76mm×20mm×0.4mm) as the elastic substrate, which is pre-compressed to buckle and then clamped at both ends. A proof mass of 16.5 grams is clamped at the center of the beam. Two PZT fiber based energy harvesters (Smart Materials Corp.) were attached on the substrate on both sides of the proof mass to generate electrical power. The energy harvesters were directly connected to a load resistor of 2MΩ for power measurement. The device is tested on an electromagnetic shaker, which is monitored by an accelerometer and controlled in real time by Labview. The generated power was measured at various frequencies at fixed excitation amplitude to generate the frequency response.

![Figure 2. (a) A photo of the macro prototype mounted on the electromagnetic shaker. The clamped-clamped beam consists of an aluminum sheet of 76mm×20mm×0.4mm as the elastic substrates and two PZT fiber-based energy harvester patches. The center proof mass is 16.5g. (b) A photo of the fabricated MEMS prototype with a schematic of the beam composition. The beam is 15mm×12mm with backside silicon mass (3mm×12mm×530µm).](image)

3.2. MEMS-Scale Prototype
To verify the frequency range and excitation amplitude range of the MEMS device, a simplified design has been fabricated first (figure 2(b)). The MEMS device leaves out the piezoelectric layer so that the fabrication cycle has been reduced significantly, while the device is similar enough to the original design to test the dynamic response. The MEMS device is smaller than a quarter coin, having a beam of 15mm×12mm (L×W). The beam composition is similar to the real design with four layers. The PECVD Si₃N₄ is the elastic substrate since its residual stress is compressive and can be easily altered in a wide range. The tensile Si₃N₄ is introduced to emulate the tensile PZT layer in the real device and achieve stress balance. Backside DRIE was used to release the beam and define the silicon proof mass on the backside of the beam (3mm×12mm×530µm). An optional tungsten proof mass of 0.24g could be attached on the silicon proof mass as an external mass. The fabricated device was tested with an electromagnetic shaker and a laser vibrometer. The shaker was excited harmonically with sweeping frequencies, so that the deflection of the beam could be measured in frequency domain.
4. Results

4.1. Macro-Scale Prototype
The power measurement at various frequencies and fixed excitation amplitude was done for both mono-stable and bi-stable configurations at high g. It should be noted that the two configurations are essentially the same in terms of the materials, with the only difference that the bi-table configuration is the beam with pre-compression to buckling. The testing was carried out at 3g (figure 3(a)). It is clear that the bi-stable system outputs higher power in a wide frequency range. The frequency response of the bi-stable system shifts to lower frequencies proves the enhancement of the output at lower frequencies of the bi-stable system.

The bi-stable configuration has also been tested at lower g (1g) by first sweeping frequency up and then sweeping down slowly (figure 3(b)). Since the input excitation does not provide enough energy to overcome the energy barrier, the bi-stable system oscillates around one of its equilibria (intra-well). The hysteresis clearly shows the characteristic softening response of the oscillation and verifies the model.

![Figure 3](image)

Figure 3. (a) RMS power responses of mono-stable and bi-stable configurations at 3g. The frequency cannot be set higher so that the jump-down has not been reached due to the limitation of the shaker. (b) RMS power responses of the bi-stable configurations at 1g shows softening response.

4.2. MEMS-Scale Prototype
The device shown in figure 2(b) was firstly tested without external mass by sweeping the frequency forward and backward (figure 4(a)). The excitation amplitude was monitored to have a maximum of 0.2g and g values close to it in a wide frequency range, and lower g’s at low frequency range. The center and the frame of the device was scanned during sweeping to measure the center deflection at each frequency. During the forward frequency sweep, the beam center deflection increases gradually and jumps down at 140Hz. Backward frequency sweep was also done, and the system jumps up at 100Hz. The spring stiffening response has a wide bandwidth below 150Hz.

An external tungsten proof mass of 0.24g was attached to the backside silicon mass of the device to go through the same frequency sweep testing (figure 4(b)). It can be noticed that the frequency response shifted to much lower frequencies due to the heavier mass, and the large-amplitude region is below 10Hz. The deflection amplitude is also significantly increased compared to the same device without external proof mass. It is reasonable to infer the device with piezoelectric material will have a boosted power output due to the increased mass.
Figure 4. (a) Frequency response of the MEMS device without external proof mass. (b) Frequency response of the MEMS device with 0.24g external proof mass.

Currently, the full energy harvester with embedded PZT is under fabrication, and the results will be reported in near future.

5. Conclusions
Bi-stable buckled beam on MEMS scale has been proposed, designed and fabricated for low-frequency, low-g vibration energy harvesting. The analytical model derived from Lagrangian equation and solved with harmonic balance method presents the stiffening and softening frequency response for bi-stable system at high and low excitation amplitude respectively. With the model considering the multi-layer beam structure with residual stress embedded, we could design the MEMS device to achieve buckling and desired frequency and excitation amplitude range.

A macro-scale prototype has been built and tested, and verified the bi-stable system has higher power at lower frequencies than the mono-stable system at high g. At low g, the prototype display the characteristic spring softening response as simulated by the analytical model. A MEMS device prototype has also been fabricated and tested using the laser vibrometer. Test results show that both the devices with and without external proof mass meet our design targets, with high-amplitude responses below 150Hz frequency at 0.2g.

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