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A multi-layered polydimethylsiloxane structure for application in low-excitation, broadband and low frequency energy harvesting

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ABSTRACT

Vibrational kinetic energy is a promising energy source that can be harvested due to its abundance in daily life, especially from human motion. This low frequency vibration poses a challenge in achieving a small device that is practical and wearable. Further, the effective energy harvesting of a linear structure is very limited to a narrow range of frequencies around the resonance. These two limitations call for the development of wide bandwidth energy harvesters that can work at a wider low frequency range. Using low Young's modulus material is a common technique to achieve a low resonant frequency energy harvester. Nonlinear bistability is a potential solution for bandwidth broadening. In this paper, a broadband low frequency vibrational energy harvester using multi-layered soft polydimethylsiloxane (PDMS) will be presented. First, a multi-layered PDMS structure was created by sandwiching a thicker PDMS with two thinner pre-stressed PDMS films. After releasing the prestresses, the multi-layered PDMS structure can settle into two cylindrical configurations. An analytical model that can predict the shapes of this multi-layered structure has been developed using classical lamination theory along with Rayleigh–Ritz approximation technique. Through this model, PDMS shapes can be easily predicted by changing various parameters such as the ratio of side length to thickness, prestrain levels, and Young's modulus. A multi-layered PDMS structure has been further proposed to be used as a bistable energy harvester. The soft PDMS allows working frequencies of lower than 15 Hz. The dynamic response of this harvester under small input excitation shows a softening spring system, before the strong nonlinear 'snap through' effect occurs. This softening spring system is able to broaden the bandwidth of the energy harvesting device.

1. Introduction

Vibration kinetic energy is one promising source for energy that can be harvested due to its ready availability in daily life [1], especially if suitable devices can be developed to harvest energy from the low-frequency excitation produced by human motion. This low frequency vibration poses a challenge in achieving a small device that is practical and wearable. The use of a low Young's modulus material can easily realize an energy harvester resonating at low frequency. Polydimethylsiloxane (PDMS) has been successfully applied in previous research [2,3] due to its low Young's modulus. However, most vibrational energy generators are designed based on the principle of linear oscillation where an inertial mass is mounted on a spring damper and excited at the resonant frequency [4]. They can generate maximum power only when the natural frequency of the generator matches the frequency of ambient vibration. Even a small difference between the two frequencies can lead to a significant decrease in generated power.

In order to avoid this limitation of linear oscillators, many approaches have been investigated to broaden the bandwidth of the harvesters such as using an array of linear oscillators [5], linear oscillators with an amplitude stopper [6], nonlinear oscillators [7–17]. Among these techniques, nonlinear oscillators can provide better performance in terms of the energy extracted from a generic wide spectrum vibration. Nonlinearity can be easily obtained by utilizing large deflection or large strain at low frequency [12], impact (or contact) or non-impact driven frequency up-conversion mechanism [9,18,19], magnetic levitation [13], etc. Mono-stable nonlinear energy harvesters utilize nonlinear stiffness and act as hardening or softening spring [13,20]. They can broaden frequency range with larger amplitude oscillations and provide bigger output compare to linear configuration. However, most of mono-stable generators can only broaden the frequency response in one direction. A bistable oscillator is another popular nonlinear oscillator

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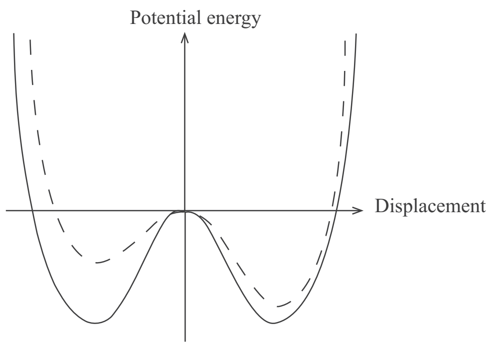

Fig. 1. Potential energy of bistable oscillator. (Solid line shows the symmetric potential energy double-well while the dashed line shows the asymmetric potential energy well.)

design [7,8,21,22], which exploits a unique symmetric or asymmetric potential energy double-well, as shown in Fig. 1. It is well known that a system with double well potential can exhibit chaotic behavior. If the input excitation is small, the state of the device remains within the potential well related to one side of the neutral position. In this case, the device behaves as a regular linear or nonlinear resonant system [23]. However, under sufficiently large excitation, the device will have enough energy input to overcome the potential well and switch state. This condition is called 'snap though' [24]. The complex dynamic response of such a bistable system, if correctly designed, can be favorable to the performance of vibrational energy harvesters.

Arrieta et al. [8] studied a piezoelectric bistable nonlinear energy harvester that was fabricated by bonding a piezoelectric patch to a bistable reinforced composite laminate. This device achieved a broad bandwidth by the elastic buckling of the bistable composite plate. A bistable composite laminate has two stable shapes, giving rise to potentially useful vibration behavior, with nonlinear large amplitude oscillations occurring over a wide frequency range. This is due to 'snap through' between the two stable states, which is strongly nonlinear. The stresses allow the reinforced composite laminates to exhibit multistability results from mismatched thermal residual stress. When cured in a press or autoclave, the initially flat composite laminate develops curvature when cooled to room temperature [25].

Bistability can also be accomplished at the material level by prestretching two isotropic plates and then bonding them to opposite sides of an unstressed middle third plate. Inspired by bistable natural systems such as the Venus flytraps plant [26] which can switch between different functional shapes upon actuation, Chen et al. [27] developed a prestretched bistable structure. Here the terminologies of prestretch and prestrain are used interchangeably to create prestress. Two thin latex rubber sheets were prestretched by equal amount and bonded to an elastic strip to create a multi-layered structure. Releasing the prestresses will then result in a stress distribution within the structure and cause out-of-plane displacement into bistable configurations (cylindrical shapes) or monostable configuration (saddle shape). Comparing to the reinforced composite laminates, this prestretching technique is much easier to implement because it only involves processes at room temperature and simple plain structural material without any filling materials.

In this paper, square three-layer soft PDMS structures have been fabricated using the prestretching method. An analytical model of this multi-layered structure based on classical laminate theory (CLT) has been developed to predict the configurations and consequently to aid the design of energy harvester. The dependence of configurations on various geometrical and mechanical parameters were studied and characterized. A multi-layered PDMS cylindrical structure was used to demonstrate its potential as a low frequency bistable energy harvester. Frequency sweep experiments with small excitation vibration have been carried out to characterize the device. The device demonstrates broadening of the useful energy harvesting bandwidth before 'snap through' occurs.

2. Experimental

Top and bottom thin PDMS films are subjected to the same amount of strain and will sandwich a thicker PDMS film. The bonded structure will deform after the stresses were released. The following details are the fabrication process of a multi-layered PDMS structure.

2.1. Prestretched PDMS

In our previous work, it has been shown using an orthogonal experiment design that the Young's modulus of PDMS can be predicted by three parameters: curing time (t), curing temperature (T) and mixing ratio (R) [3]. In order to achieve a soft PDMS of Young's modulus 8×10^5 Pa, Sylgard 184 A:B = 20:1 in weight was used to prepare the PDMS films. PDMS base A and curing agent B were mixed thoroughly, degassed under vacuum, and poured into three molds. These molds were 3-D printed from acrylonitrile butadiene styrene (ABS) plastic with different depth. The PDMS was then cured in an oven for 30 min at 90 °C. In order to ensure that the accuracy of the thickness of the thin PDMS films, the weight of PDMS mixture poured into the mold has been measured by an electronic scale.

Fig. 2 shows the PDMS bonding process. After prestretching the top (A) and bottom (C) layers by an equal amount of stress f, three PDMS films were bonded together to achieve the final PDMS structure using oxygen plasma. Oxygen plasma treatment is a simple and effective method to activate the surface of PDMS layers, so that a strong PDMS to PDMS bond can be produced [28]. Here, two prestretched PDMS thin films (A, C) and one unstretched PDMS square film (B) were surface treated for 30 seconds with a RF power of 50 W and pressure of ~450 mTorr (Fig. 2(a)). After oxygen plasma treatment, three films were quickly brought into contact (Fig. 2(b)). A strong bond is immediately produced. The fixtures used to prestretch layers A and C before bonding are shown as in Fig. 3.

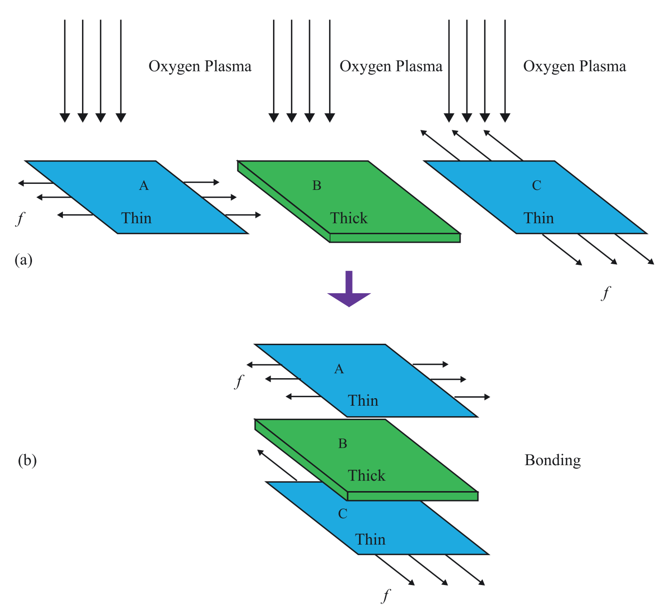

Fig. 2. Bonding process. (a) Oxygen plasma treatment on one side of prestreched PDMS A, C and both sides of unstretched PDMS B. (b) Three layers are bonded together.