A broadband vibrational energy harvester

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We propose a design for an energy harvester which has the potential to harvest vibrational energy over a broad range of ambient frequencies. The device uses two flexible ceramic piezoelectric elements arranged in a buckled configuration in the absence of vibrations. Experimental data show that this design allows enhanced harvesting of energy relative to a comparable cantilever design, both for periodic and stochastic vibrations. Moreover, the data suggest that this harvester has its peak energy generation when it responds with chaotic vibrations. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4729875]

Energy harvesters are a promising technology for capturing useful energy from the environment or a machine's operation. Typical vibrational energy harvesters are composed of a mass-spring system with a transducer,[1] where vibrations in the surrounding environment act as inputs and cause the spring-mass system to oscillate. The oscillations of the device are converted into electric energy by electrostatic, piezoelectric, or electromagnetic transduction.[1] Proposed harvesters of vibrational energy are often based on linear mechanical principles. Such devices give appreciable response amplitude only if the dominant ambient vibration frequency is close to the resonance frequency of the harvester. In order to achieve maximum conversion efficiency, the dominant ambient vibration frequency must therefore be known prior to the design process. For a broadband or time-varying ambient vibration spectrum, only a small fraction of the available ambient vibration energy can be extracted by such devices. There have been attempts to overcome such bandwidth limitations while staying within the linear mechanical system framework, e.g., Ref. 2.

Recently, attempts have been made to utilize nonlinear systems to harvest energy, typically with the goal of allowing appreciable energy harvesting for a broader range of forcing frequencies. There are two main approaches: (1) Design a harvesting system to have a hardening frequency response when periodically forced.[3–10] (2) Design a harvesting system to have a double well potential, that is, a bistable system which can jump between the wells due to periodic or stochastic forcing.[9,11–23] The bistability could arise due to the appropriate placement of magnets[11,13–15,19,20] or using a compressive load to buckle a beam.[17] A variation is to design the system to have an essential nonlinearity in which the linear stiffness vanishes, so that the system is, in a sense, between a monostable and bistable regime.[24]

Here, we report on a design for an energy harvester in which the elements are buckled in the absence of vibrations to give a double well potential. This harvester uses two flexible ceramic piezoelectric elements from Advanced Cerametrics, Inc., as shown in Figure 1: a single layer element (catalog #PFC-W14) and a bimorph element (catalog #PFCB-W14), each of which is 132 mm long and 14 mm wide, and 0.3 mm and 1.3 mm thick, respectively. The bimorph has two piezo layers separated by a core. The bimorph element has approximately 40 times the stiffness of the single layer element. The elements are bonded together as shown in Figure 1(b) with a $B = 6$ mm overlap, and the other ends fixed to an aluminum mount so that at equilibrium, the single layer element is slightly buckled, as shown in Figure 1(a). Our harvesting results have proved to be robust to small changes in overlap length, B, overall length, D, and bimorph length, L but are very sensitive to the amount of buckling, as measured by d. The mount is attached to a voice-coil shaker and shaken vertically with the instantaneous acceleration measured by an accelerometer. The shaker has been characterized to provide a constant power output through the frequency range of interest. The relative power input to the device is calculated as the variance of the accelerometer signal divided by the shaking frequency, which represents the root mean square (RMS) velocity times the RMS acceleration to provide RMS power.

The power output of the bimorph layer is connected to a linear load resistance of 2.2 kΩ. The output of the single layer element has been found to be negligible compared to the bimorph and is ignored in this discussion. It was found that, depending on the vibrational power and frequency, the voltage across this resistor can be periodic, quasi-periodic, or

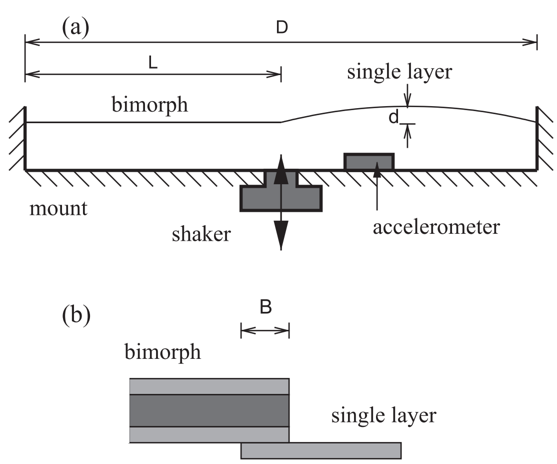

FIG. 1. (a) Sketch of experimental device. (b) Zoom-in on bond, not drawn to scale. Here $D = 235$ mm, $d \approx 6.3$ mm, $L = 116$ mm, and $B = 6$ mm. A short length of each piezo is used to clamp it to the mount.

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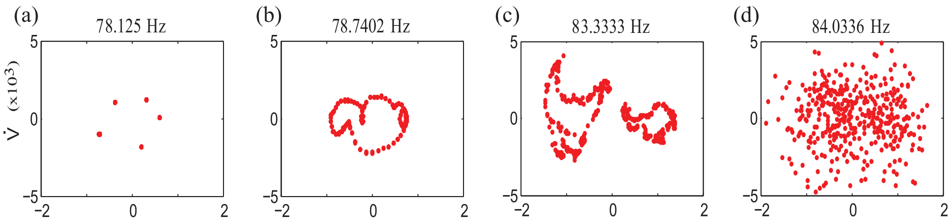

FIG. 2. Poincaré maps demonstrating a typical transition from a periodic orbit to chaotic oscillations as the forcing frequency is varied. The dots indicate instantaneous values of voltage (V) and rate of change of voltage ($\dot{V}$) once per forcing cycle. (a) shows a period-5 periodic orbit. (b) shows a quasi-periodic orbit, which wrinkles and folds, as seen in (c), until all recognizable order is lost and a chaotic response is achieved, as seen in (d).

chaotic in time. Appreciable power is only generated when the beam responds by moving between the two equilibrium positions.

Figure 2 shows the rich variety of responses that can occur for periodic forcing of this device. These plots demonstrate the transition from periodic to quasi-periodic to chaotic response. The range of forcing frequencies in this transition is quite small, spanning approximately 6 Hz in going from a period-5 periodic orbit to a fully chaotic response. Transitions such as the one shown here occur throughout the examined range of frequencies and can be interpreted in terms of Arnold tongues in the amplitude-frequency parameter space, with the transition to chaos showing the hallmarks of a torus which wrinkles until it loses its form, giving chaos, as has been observed in Refs. 25 and 26. The time series and broad power spectrum of a different chaotic response for forcing at 167 Hz, producing 0.4 mW, is shown in Figure 3.

Investigations of this energy harvester were focused on the frequency range of 20–500 Hz, as dictated by the characteristics of the beams and the range of frequencies over which we could acceptably control the shaker. This range was examined as a set of 175 discrete frequencies recorded in hertz with approximately even logarithmic spacing. A simple cantilevered beam has been subjected to the same series of tests for comparison; this cantilever was configured as a bimorph element of equal dimension as used in the buckled device but clamped approximately in the middle and allowed to vibrate on both ends, with resonant frequencies in the neighborhood of 80 Hz. Figure 4 demonstrates the increased

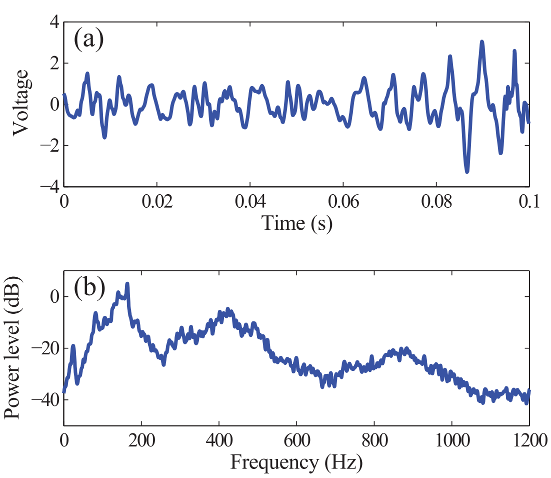

FIG. 3. (a) Example chaotic time series for shaking frequency 167 Hz, producing 0.4 mW of power. (b) Power spectrum for time series shown above; the broad spectrum is characteristic of chaotic behavior.

bandwidth our design produces compared to the linear cantilever. Cantilever data are plotted as dashed lines, while the buckled device data is plotted as solid lines. The RMS input power is 13 W at the highest level, drawn as red with dots, 7.5 W at the intermediate level, drawn as green with x markers, and 3.2 W at the lowest level, drawn as blue with no markers. Observe that the two halves of the cantilever have slightly different resonances, and the peaks are located at approximately 60 and 100 Hz, providing a maximum output power of 1.0 and 0.3 mW, respectively, for the highest power input. The first snap-through mode of the buckled beam design has been experimentally determined to be approximately 21 Hz. Due to the nonlinearity associated with snap-through dynamics, linear resonance is not observed in the examined range of frequencies and power levels.

Note that the largest peak in the power output of the buckled device is close in magnitude to the resonant peak of the cantilever, and that the location of this peak increases in frequency as the input power is increased. For example, at the lowest input power level, the largest peak occurs at about 153 Hz producing 0.4 mW of power and maintains power generation over 0.1 mW from 130 to 250 Hz and from 400 to 475 Hz. The cantilever produces peaks of 0.23 and 0.12 mW, and the output is only maintained over 0.1 mW near the resonant peak. At the highest input power level, the maximum peak of the buckled device shifts to 213 Hz with power output of 1.1 mW. Power generation is maintained over 0.2 mW from 165 Hz to 285 Hz and from 380 to 475 Hz. The cantilever produces peaks of 1.0 and 0.3 mW, with no appreciable power generation away from resonance. Note also that the peak of highest power generation for the buckled device is followed closely by a dip, and a second peak, where none of these frequencies are necessarily multiples of the resonant frequency. This shape remains consistent at all tested input power levels.

While observing the system, it can be seen that the oscillations of the beam shift between periodic, quasi-periodic, and chaotic response as the forcing frequency is varied. Observations indicate that regions which produce a chaotic voltage output result in significant power generation. An interesting viewpoint for understanding the large response over a broad frequency range is the following: suppose we have an oscillator which can undergo chaotic oscillations, which could be transient or attracting. It is known that embedded within a chaotic set are an infinite number of unstable periodic orbits, each of which generically has a different frequency.[27] Indeed, chaos can be viewed as the system "bouncing around" amongst these unstable periodic orbits; this is an interpretation for why the power spectrum for a

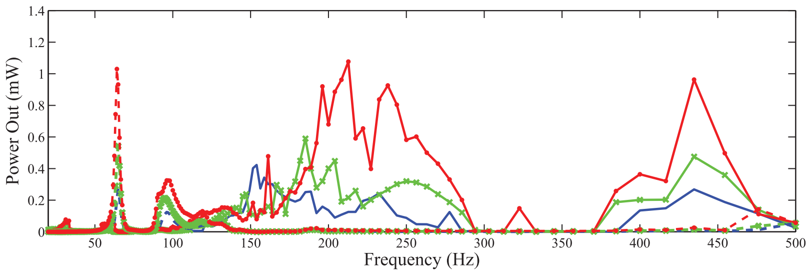

FIG. 4. Response of system shown in Figure 1 (*solid*) and reference cantilever (*dashed*) to three different power input levels. RMS input power is 3.2 W for the blue lines with no markers, 7.5 W for the green lines with x markers, and 13 W for the red lines with dots.

chaotic signal is broadband.[28] The response of oscillators in the chaotic regime might be related to resonances between the drive frequency and the various unstable periodic orbits embedded in the chaotic set.

In addition to the single frequency tests, our design and the reference cantilever were subjected to a series of inputs with a wide energy spectrum. A representative input frequency response can be seen in Figure 5(a), with a comparison of the output of the buckled design and the cantilever arrangement in the lower portion. This input shape was selected to mimic a vibration spectrum that might be available for harvesting, rather than a specific single frequency input as was used in the prior experiments. Tests were conducted through the same frequency range but with reduced frequency resolution. The buckled device harvested more energy over the range from 150–200 Hz than the cantilever device was able to harvest when excited near its resonant frequency(s). This can be explained by the effects of spreading power over a range of frequencies and the chaotic tendencies of the new design. Many unstable periodic orbits are able to exist in the chaotic regime, allowing the experimental device to respond to many different frequency components, which makes the total effective power being used to excite the system larger than the input power at any specific frequency. The cantilever only responds to input power at its resonant frequency and thus effectively ignores a large portion of the input power.

A variety of environments produce considerable vibrational energy which can potentially be harvested; furthermore, many mechanical and electronic systems such as sensor networks require bulky batteries and/or power supplies for their operation. We believe that energy harvesters

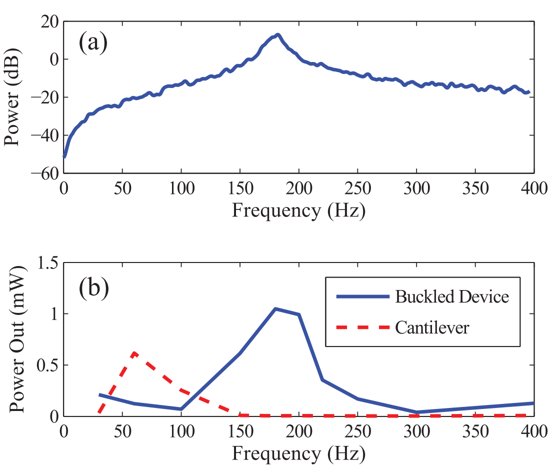

FIG. 5. (a) Example of broadband frequency input. (b) Power output from broadband input at different frequencies.

based on the design presented in this paper, which operate in nonlinear and chaotic regimes, could prove to be very useful for such environments.

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