An Energy Harvester for Broadband Vibrations

Louis Van Blarigan[1], Per Danzl[1], Jeff Moehlis[1]
[1]*Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA*
moehlis@engineering.ucsb.edu

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, 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 electrical 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.

Improving the range of frequencies for which vibrational energy harvesters have large response is crucial for increasing their efficiency and functionality. There have been attempts to overcome bandwidth limitations while staying within the linear mechanical system framework, and recently attempts have been made to exploit nonlinearities for energy harvesting; see, e.g., [2] and references therein. Here we report on a new design for an energy harvester which operates in a nonlinear regime and that has the potential to harvest vibrational energy over a broad range of ambient frequencies. The data indicates that this harvester design gives peak energy generation when driven at frequencies at which it responds with chaotic vibrations.

Our harvester uses two flexible ceramic piezoelectric elements from Advanced Cerametrics, Inc. [3] 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 stiffness of the single layer element is much less than the stiffness of the bimorph element. The elements are bonded together as shown in Figure 1(b) with a $B \equiv 6$ mm overlap, and the other ends are fixed to an aluminum mount so that at equilibrium the single layer element is slightly buckled, as shown in Figure 1(a). The mount is shaken vertically, with the instantaneous acceleration measured by an accelerometer.

The output from the piezo elements is connected to a linear load resistance of 10 kΩ. It was found that, depending on the shaker amplitude and frequency, the voltage across this resistor can be periodic or chaotic in time, and different vibrational modes can be excited. An example of chaotic output for the bimorph element for a shaker frequency of 150 Hz is shown in Figure 2 (a,b). Here the peak acceleration is ± 5.9 g. The average power generated by the single layer and bimorph element is 0.066 mW and 2.33 mW, respectively, giving an RMS total power of 2.33 mW.

We have investigated the performance of this energy harvester for a range of forcing frequencies, as shown in Figure 2(c). The vertical axis shows the total RMS power from the harvester divided by the RMS power associated with the shaking, the latter being proportional to the product of the RMS velocity and RMS acceleration of the shaker. We present our results in this way to account for the variation of the impedance of the shaker with frequency. Our data shows that the maximum RMS power output for this device occurs when the device responds chaotically to the periodic shaking, as is the case near a forcing frequency of 150 Hz. We also see that the harvester outputs appreciable power over a broad range of forcing frequencies, especially relative to the power generated by a bimorph element in a cantilever configuration, which behaves linearly for the forcing amplitudes used, as seen in Figure 2(c).

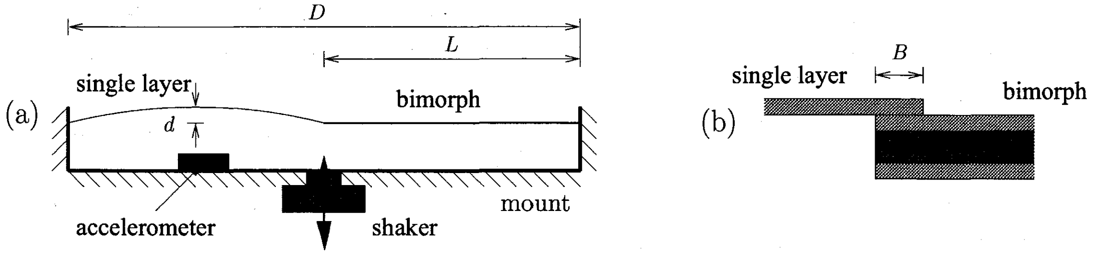

Figure 1: (a) Sketch of experimental device. (b) Zoom-in on bond, not drawn to scale. Here $D = 235$ mm, $d \approx 6.3$ mm, $L = 116$ mm, and $B = 6$ mm. A short length of each piezo is used to clamp it to the mount.

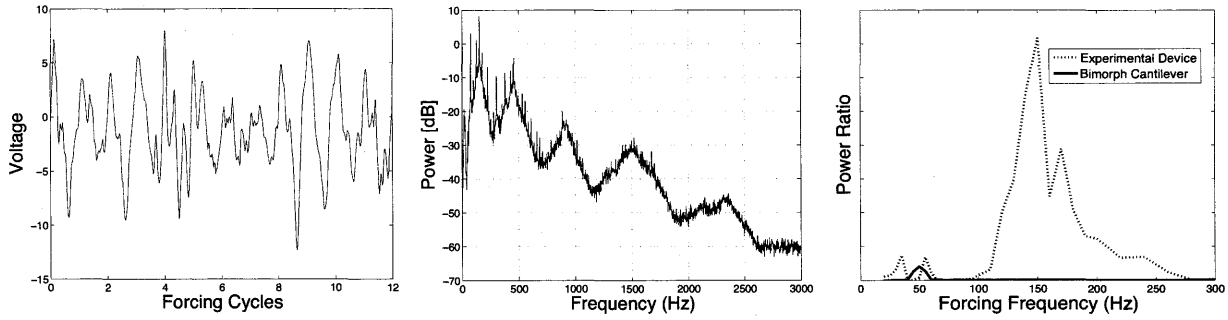

Figure 2: (a) Example chaotic time series for bimorph output voltage for forcing frequency of 150 Hz. (b) Power spectrum for time series shown in (a); the broad spectrum is characteristic of chaotic behavior. (c) RMS mean power from energy harvester divided by RMS power associated with shaking, with arbitrary scaling on the vertical axis. The solid line is for a bimorph cantilever, and the dotted line is for the device shown in Figure 1.

An interesting viewpoint for understanding the large response over a broad range of forcing frequencies 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 [4]. 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 chaotic signal is broadband [5]. The response of oscillators in the chaotic regime might be related to resonances between the forcing frequency and the unstable periodic orbits embedded in the chaotic set.

Our study of this energy harvester is ongoing. We will use a mathematical model to investigate how the results depend on parameters, such as the stiffness of the piezo elements. We will also develop a feedback controller for the shaker so that we can more carefully characterize the ratio of harvested power to the input power over a range of frequencies. Finally, we will characterize the response of this device to noisy shaking.

Many environments produce considerable vibrational energy which can potentially be harvested, such as automobiles, trains, aircraft, watercraft, machinery, and buildings. Furthermore, many mechanical and electronic systems such as autonomous vehicles and sensor networks require bulky batteries and/or power supplies for their operation. We believe that energy harvesters based on the design presented in this paper, which operate in nonlinear and possibly chaotic regimes and respond to a broad range of ambient frequencies, could prove to be very useful for such environments.

Acknowledgments

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