A compact architecture for passively-switched energy harvesters

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Abstract. This paper presents the design and experimental characterization of a compact parallel-beam architecture for low-frequency energy harvesters that switch passively among dynamical modes to extend their operational range. Two beams interact to generate power; a driving beam couples into low frequency vibrations, and a higher frequency generating beam outputs power upon impact by the driving beam. The system switches between modes in which the driving beam bounces off the generating beam (coupled motion) and modes in which the driving beam passes the generating beam (plucked motion). The compact structure is realized by mounting the generating beam within a U-shaped driving beam on a single support. A flexible tip is mounted inside the driving beam’s U shape to enable robust interactions. This new architecture reduces system volume by 80% compared with an earlier model that has the same resonance frequency, but it also changes the flexible tip’s role in the contact dynamics. The flexible tip is experimentally tailored to optimize performance. The harvester generates power over the measured range of acceleration from 0.2 g to 2 g and driving frequency from 5 Hz to 20 Hz. With one tip design, the harvester offers peak power of 0.267 mW with plucked operation covering 32% of the tested range. With a second tip design, the harvester offers a lower peak power of 0.036 mW with plucked operation covering 73% of the tested range.

1. Introduction
Vibrational energy harvesters output electrical energy from ambient vibration via transduction mechanisms such as magnetics, electrostatics and piezoelectrics [1-2]. Power output and bandwidth are perennial challenges. Resonant operation can increase power output, but resonant harvesters’ powers decline significantly when running off of their resonances. To increase harvesting bandwidth, mechanical tuning methods may be used to tune a harvester’s resonance to match the ambient driving frequency, including active [3-4] and passive tuning [5-7] of harvesters’ resonances. Nonlinear systems also offer increased operational bandwidth [8].

Low frequency energy harvesting, such as for extracting energy from human motions, is another challenge. Frequency up-conversion has proved to be an effective method of coupling low ambient frequencies into higher generating frequencies [9-12]. In frequency up-conversion, a driving element with low resonance frequency interacts with a generating element with high resonance frequency, thereby transferring mechanical energy from lower frequency to higher frequency motions.

Previously we have reported a passively-switched energy harvester with increased operational range that has a measured maximum average power of 1.56 mW under 0.5 g at its resonance of 7 Hz [13]. The harvester comprises a low frequency driving beam and a higher frequency generating beam that are positioned facing each other with overlapping beam tips. The harvester passively switches
between modes of operation in which the driving beam bounces off the generating beam (coupled-motion mode) and modes of operation in which the driving beam plucks the generating beam by moving from above it to below it or vice versa (plucked mode). Each mode has its own resonance frequency. The resulting multiple system resonances enable increased operational range. However, the size of the previous passively-switched, low-frequency harvester is too large for many compact, portable applications. Direct down-scaling does not provide an attractive solution because smaller harvesters typically have higher resonance frequencies.

This paper proposes and experimentally demonstrates a new, 80% smaller, parallel-beam architecture for an energy harvester that allows it to couple robustly into 10 Hz-range vibrations while maintaining passive switching among dynamical modes for increased operational range. As shown in figure 1a, the harvester includes a U-shaped plastic cantilever with a proof mass at the tip as the driving beam. A piezoelectric cantilever identical to that of [13] is mounted inside the driving beam’s U shape to serve as the generating beam. Unlike the harvester of [13], the driving beam and generating beam are mounted together on a single support so that they are in parallel and are in the same plane. The driving beam’s U shape lets the generating beam move freely through the driving beam. A flexible tip mounted inside the driving beam’s U shape overlaps the tip of the generating beam.

For small or off resonance accelerations, the driving beam bounces off the generating beam in coupled motion mode. After the driving beam impacts the generating beam, the two beams move together for about half of an oscillation cycle before separating. The characteristic frequency of this mode reflects a combination of both beams’ resonance frequencies [11]. For large or on resonance accelerations, the driving beam deflects the generating beam until their tips pass and the generating beam is plucked. The characteristic frequency of this mode is dominated by the driving beam’s own resonance. Mixed mode occurs when the beams alternate between coupled-motion and plucked mode.

The parallel-beam architecture fundamentally changes the flexible tip’s role in the dynamics. For facing beams as in [13], the lengthwise overlap between the driving and generating beams decreases as the beams deflect. If the initial overlap is small enough, the tip of the driving beam eventually passes the generating beam. For the parallel architecture, deflecting the beams increases their lengthwise overlap, making it harder for the driving beam to pass the generating beam. The design of the flexible tip is therefore critical for the new architecture to undergo plucked harvesting as well as coupled motion harvesting.

2. Experiment

2.1. Experimental Setup
Figure 1b shows the experimentally-implemented harvester. Two bronze half-cylinders comprise the 8.76 g proof mass at the tip of the U-shaped ABS driving beam. A PZT bimorph cantilever (Piezo System, Inc.) inside the driving beam’s U shape serves as the generating beam. The harvester’s
dimensions and parameters are listed in table 1. The generating and driving beams are epoxied on a common 3D printed support.

Unlike the rectangular flexible tip in the previous passively-switched harvester [13], the present tips are shaped as isosceles triangles. The tips have two thirds of the stiffness of a rectangular cantilever with the same base and length dimensions and material, but the triangular shape reduces the actual impact area between the flexible tip and the generating beam by more than 90%.

| Table 2. Mechanical and electrical specifications of the driving beam and generating beam. |
|-------------------------------------------------------------|
| Driving beam | Generating beam |
| Material | ABS plastic with proof mass | PZT-5A |
| Length (mm) | 36 | 28.5 |
| Width (mm) | 6 on each side, 12 total | 6.4 |
| Thickness (mm) | 0.53 | 0.51 |
| Effective mass (g) | 8.76 | 0.174 |
| Young’s modulus (GPa) | 2.24 | 66 |
| Measured stiffness (N/m) | 17.2 | 578 |
| Capacitance C (nF) | Not applicable | 7.4 |

Two variations of the triangular tip design are used, in each case with the same driving beam and generating beam. Both tips are isosceles triangles with a base of 6.8 mm and a length of 5.7 mm. One flexible tip is made of two layers of VWR labelling tape (0.29 mm thick total), and the other is made of three layers of the same tape (0.43 mm thick total). The experimentally-estimated stiffness values of the two flexible tips are 20 N m-1 (two-layer) and 37.5 N m-1 (three-layer). Because the driving beam and generating beam are mounted in the same plane, the flexible tip initially touches the generating beam and is deflected by generating beam’s thickness. The overlap between the flexible tip and the generating beam can be adjusted to vary the distribution of dynamical modes.

The energy harvester is mounted on a vibration testing system (LW139.151-30, Labworks Inc.) and tested under sinusoidal excitation. The acceleration is displayed in real time by the system’s integrated accelerometer. A second accelerometer (ADXL203CE, Analog Devices) mounted on the harvester’s base measures the acceleration output. The synchronized generating beam voltage and acceleration are recorded. For both tips, the harvester’s dynamics and power output are measured from 0.2 g to 2 g and from 5 Hz from 20 Hz with a load resistance matched to the coupled-motion mode. Coupled-motion dynamics are identified when the driving beam always bounces off the generating beam on one side in steady state. Plucked dynamics are identified when the driving beam repeatedly plucks the generating beam in steady state. Mixed dynamics are identified when coupled-motion and plucked dynamics coexist in steady state. When the driving beam undergoes large deflections greater than about 30 mm, the generating beam has the potential to break; these conditions are avoided and no data are recorded. The inclusion of motion stops in future harvesters may reduce the risk of breakage.

2.2. Experimental results

Figure 2 shows the experimentally-observed dynamics vs. frequency and acceleration for harvesters with the two tip designs. The lengthwise overlap of the tip on the generating beam is similar for the two harvesters. For the more flexible, two-layer tip, plucked dynamics initiate at 0.1 g when the driving frequency is near the driving beam’s resonance of 7 Hz. For the stiffer, three-layer tip, plucked dynamics initiate at 0.5 g when the driving frequency is near the driving beam’s resonance. Under all measured operating conditions, the system exhibits either coupled-motion, plucked, or mixed dynamics. Unlike in [13], there are no conditions under which the driving beam fails to impact the generating beam. The successful production of power across the entire measured range reflects the coplanar (zero-gap) mounting of the driving and generating beams. For both tips, the system passively switches between coupled-motion and plucked harvesting with mixed mode between them.
The harvester with the stiffer, three-layer tip has a much smaller range of plucked dynamics (32% of the tested range) than the harvester with the two-layer tip (73% of the tested range). The stiffer tip deforms less under a given load, making it harder for the driving beam to pass the generating beam. For the two-layer tip, plucked and mixed modes appear at lower accelerations near the system’s characteristic frequencies than they do off of the system’s characteristic frequencies. These frequencies reflect the driving beam’s resonance (7 Hz), the coupled-motion resonance (11 Hz), and the first harmonic of the driving beam’s resonance (14 Hz). For the three-layer tip, plucked and mixed modes only appear near the driving beam’s resonance because the other characteristic frequencies are not powerful enough to drive plucked modes with the stiffer tip in the tested acceleration range.

Average power outputs from harvesters with two-layer and three-layer tips are compared in figure 3. Power output is calculated by averaging instantaneous power from stable dynamics over time. Figures 3(a) and 3(b) plot average power vs. driving frequency for harvesters with two-layer and three-layer flexible tips at accelerations of 0.6 g, 1 g, and 1.5 g. Under 0.6 g, power outputs from both harvesters peak at the driving beam’s 7 Hz resonance; output at other frequencies is small. Under 1 g and 1.5 g, the frequencies near the driving beam’s resonance are omitted to avoid breakage, but peak broadening and the emergence of subsidiary peaks at other frequencies are evident. For the two-layer tip, additional power peaks appear near the coupled-motion and second harmonic frequencies, albeit at reduced amplitude because coupled-motion and mixed dynamics output less power than plucked dynamics. For the stiffer three-layer tip, the consistent coupled-motion dynamics at higher frequencies prevents the appearance of significant power peaks at the secondary resonances. Figure 3(c) compares
the overall power level of the two- and three-layer tips at 0.6 g. The harvester with the stiffer tip generates higher power in both plucking and coupled-motion modes because it transfers more energy from the driving beam to the generating beam. However, the stiffer tip also suffers a narrower range of plucked harvesting and a larger chance of the tip becoming wedged with the generating beam.

3. Conclusion
The new, parallel-beam architecture presented here for passively-switched energy harvesters enables harvesters that are 5X more compact than their predecessors [13] to convert human-scale low frequency accelerations into effective power generation across a wide range of frequencies and accelerations. The wide operational range is achieved by the same kind of passive switching among dynamical modes that is used in [13], but the present unique architecture of a generating beam embedded with a co-planar U-shaped driving beam enables the harvester’s dramatic reduction in size. The detailed design of the flexible tips by which the driving and generating beams interact is a key consideration for the parallel-beam design. A triangular tip minimizes the opportunity for the driving and generating beams to become wedged together, and the system’s dynamics and power output vary enormously with tip stiffness. The harvester with a stiffer tip produces higher powers of up to 0.267 mW; the harvester with the more flexible tip outputs a peak power of 0.036 mW. The harvester with a stiffer tip requires higher accelerations to switch from coupled-motion to plucked harvesting, so that only 32% of the operating range is in the plucked harvesting region. In contrast, the harvester with a flexible tip undergoes plucked harvesting over 73% of its operational range. In the future, motion-stops may deter breakage under the driving beam’s large resonant deflection.

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