A Multi-Directional Piezoelectric Vibration Energy Harvester with Direction-Dependent Dual Resonance

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***Abstract*—A multi-directional base mounted piezoelectric vibration energy harvester with a 2 mm x 2 mm x 20 mm polyurethane resonating beam, an 8.36 g tip mass, and a PZT transducer was designed, fabricated, and tested. The harvester was shown to operate in any direction in a 2D plane and produced as much as 8.2 µW across a 50 MΩ load under harmonic base excitations with peak acceleration of 0.25g at an angle of 45º. Experiments showed that, in some directions, the harvester had two resonant frequencies, one at 36.0 Hz and one at 38.5 Hz. Analysis shows that this phenomenon is caused by deviations in the shape of the polyurethane beam from the intended square cross-section. This analysis is used to propose a method for designing harvesters with any two desired resonant frequencies. The possibility of using this design method to increase the harvester's bandwidth is discussed.**

***Index Terms*— Energy harvesting, piezoelectric transducers, polymer beam, multi-directional, vibration, polyurethane**

I. Introduction

There has been a great deal of interest in remote wireless sensor networks for applications such as infrastructure monitoring, where, due to location or expense, it is often impractical to change batteries in these sensors. It is, therefore, necessary to find alternate sources of energy that can be scavenged to power wireless sensors. Common alternate sources of energy include light, heat, and vibrations [1]. In some environments, such as bridges [2], vibrations may be the most accessible source of energy. To power sensor networks for such applications, numerous energy harvesters that use piezoelectric transducers to convert vibrations into electrical energy have been designed and characterized. The design of a standard piezoelectric vibration energy harvester is a rectangular cantilevered beam with a tip mass and piezoelectric transducers mounted along one (unimorph) [3] or both (bimorph) [4] sides.

The standard piezoelectric vibration energy harvester has several weaknesses. One weakness is energy harvesting bandwidth; these energy harvesters only harvest useful amounts of energy when the beam is resonating. Most such harvesters have a very high Q factor and, as a result, a very narrow bandwidth, whereas naturally occurring vibrations can occur over a large range of frequencies. They might, therefore, not contain much or any energy within the harvester's receptive bandwidth. Many approaches to increasing harvester bandwidth have been proposed, most of which rely on nonlinearity. Some accomplish this by introducing a nonlinearity into the standard system [5-7], while others utilize novel designs to create a nonlinear frequency response [8-10]. Another weakness found in the standard piezoelectric vibration energy harvester is directionality; the rectangular beam will only respond to vibrations with some component in a single direction. Many approaches to extend energy harvesting into two or three dimensions have also been proposed. Some of these utilize some mechanism to translate movement from off-axis vibrations to a standard rectangular cantilevered beam [11, 12]. Still others, however, utilize novel designs such as a dandelion shaped array of cantilevered beams [13], a zigzag structure formed by mounting beams end-to-end [14], a spring

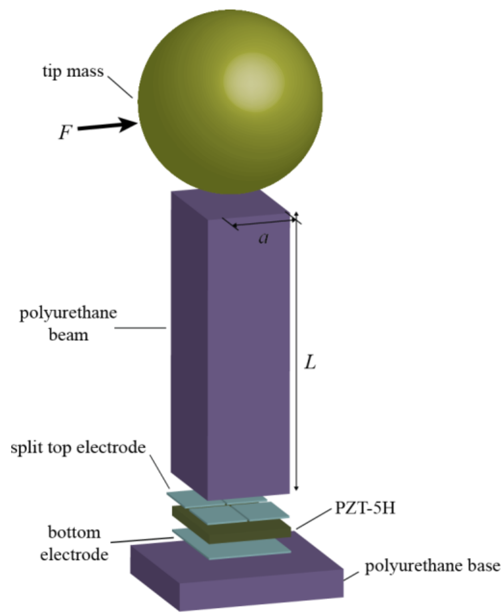

Fig. 1. Design of multi-directional base mounted piezoelectric (mBMP) vibration energy harvester

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pendulum oscillator [15], a spiral-shaped beam [16], four crab-leg beams spiraling inward to a central proof mass [17], or a curved beam [18].

In a previous publication, we showed that energy can be harvested from vibrations using a polyurethane beam with a tip mass and a transducer mounted beneath the base of the beam [19]. We called this design a base mounted piezoelectric (BMP) vibration energy harvester. The device described in that study was restricted to a single direction of motion. There is, however, no physical restriction preventing the design of a BMP vibration energy harvester that can resonate in more than one direction. This paper describes the design, fabrication, and testing of just such a device, shown in Fig. 1, called a multi-directional base mounted piezoelectric vibration energy harvester (mBMP harvester), intended for harvesting energy from motion in any direction in a given plane. Experiments show that the mBMP harvester fabricated for this study can effectively harvest energy from any direction in a given plane. The experiments also show that the mBMP harvester has, in some directions, two closely spaced resonant frequencies which effectively increases its bandwidth. This phenomenon is explained and an approach for designing mBMP harvesters with specific pairs of resonant frequencies is proposed.

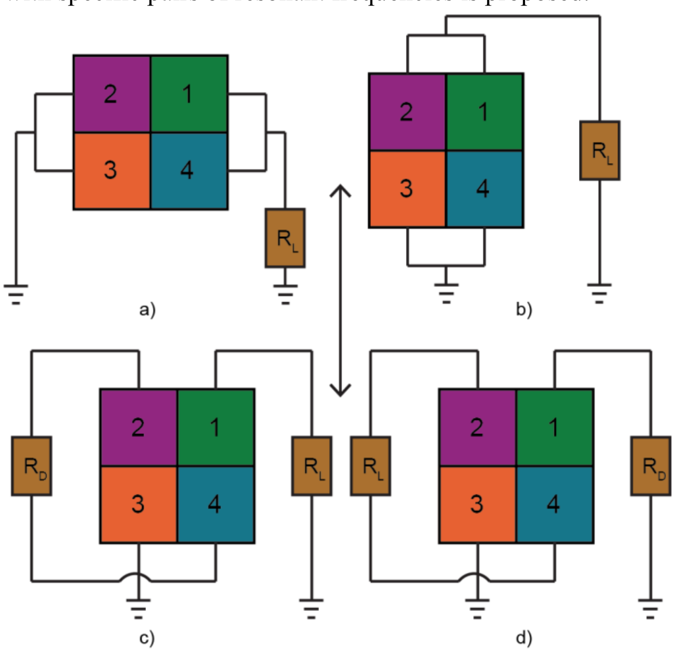

Fig. 2. Electrode pattern and wiring configurations a) side-side b) front-back c) diagonal-13 d) diagonal-24. The arrow in the middle indicates the excitation direction of the beam about the 0° reference axis (i.e horizontal centroidal axis).

II. Design

Thus far, the only BMP vibration energy harvesters studied have had a rectangular cross-section with one side of the rectangle much larger than the other. Such a beam has a much higher area moment of inertia about its short axis and thus, compared to its long axis, a higher resonant frequency in that direction. A square cross-section should allow the beam to resonate at a fixed frequency in any excitation direction since all the axes that go through the centroid are principal axis and all have the same moment of inertia [20].

A BMP vibration energy harvester relies on a split electrode on the transducer to prevent charge cancelation. To do this, the electrodes must be divided along the neutral axis of the beam given the expected bending direction. When the beam cross section is rectangular, there is only one relevant axis, the long axis, and the electrode is simply split in two. However, with two electrodes and a square beam, bending in the direction parallel to the electrode split will always result in charge cancellation and therefore no power output. To remedy this, we designed an mBMP harvester with four square electrodes, each consisting of a quadrant of the beam cross section as seen in Fig. 2. This electrode pattern ensures that there are at least two quadrants that are experiencing no charge cancellation for any given direction the beam may resonate in.

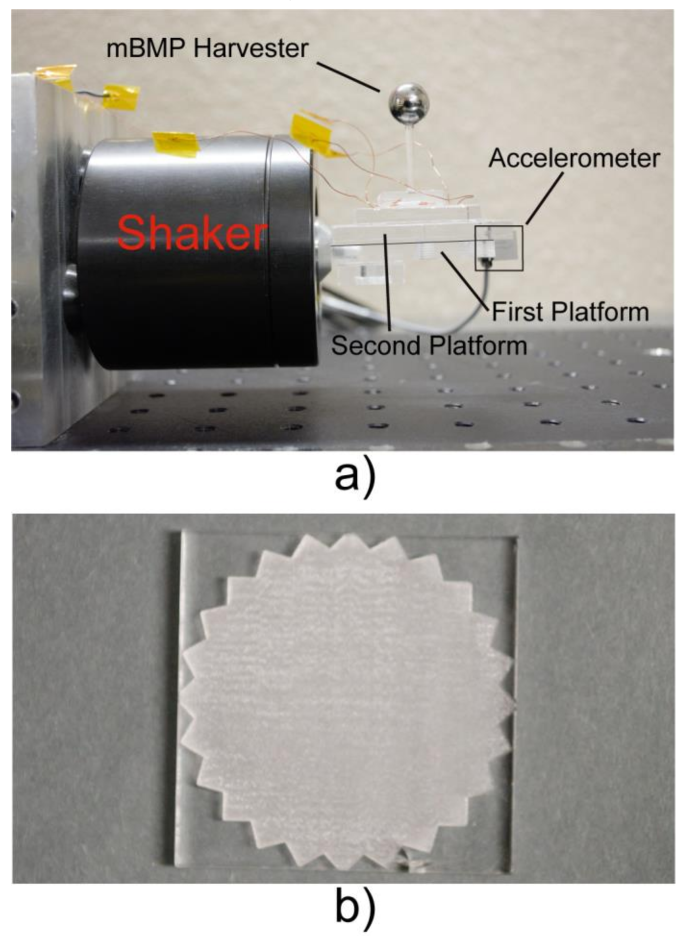

Fig. 3. a) Experimental setup for evaluating the output from the mBMP. b) Second mounting platform with star pattern used to orient the energy harvester with 15 ° increments.

The complete design of the mBMP harvester fabricated for this study can be seen in Fig. 1. The device consists of a polyurethane beam of square cross-section with a tip mass on its free end (tip) and a piezoelectric transducer mounted on the fixed end (base). The transducer has four electrodes on the side adjacent to the beam and one electrode on the other. The transducer is, in turn, mounted in a polyurethane base to provide a firm backing. For simplicity and durability, the beam and base are cast around the transducer in a single mold.

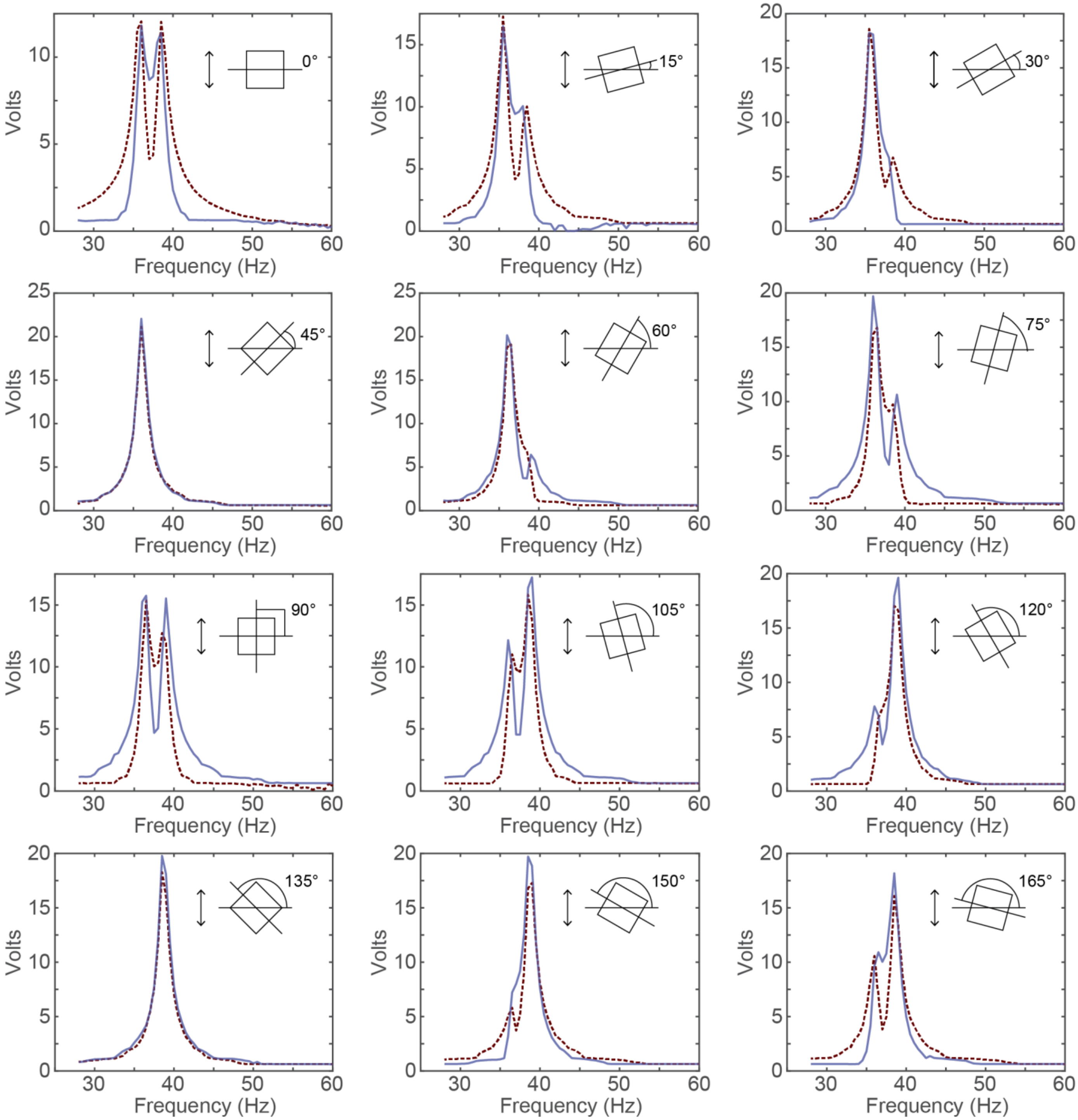

Fig. 4. Voltage output of mBMP harvester for rotations between 0º and 165º by 15º increments for the front-back (solid blue line) and side-side (dashed red line) electrode wiring configurations.

III. Fabrication

The process used to fabricate the multi-directional BMP vibration energy harvester studied in this paper varies somewhat from the process previously discussed in [19], in that most of the mBMP harvester was fabricated in a single mold. The mold consists of two pieces, each shaping a symmetrical portion of the device. It is made of aluminum lined with 500 µm of silicone rubber (Mold Max 30, Smooth On). The silicone rubber eases removal of the device from the mold while the aluminum provides a stiff backing that holds piezoelectric transducers in place throughout the molding process. Cross sections of the mold are illustrated in supplementary Fig. S1.

Fabrication of the multi-directional BMP harvester can be broken down into the five steps illustrated in Fig. S1. First the beam portion of the mold is filled with polyurethane (Crystal Clear 200, Smooth On). There is a lip built into the mold just above the beam, a polyoxymethylene plug is placed on this lip to keep it clear of polyurethane. Next, after the beam has cured, the plug is removed and a thin layer of polyurethane is used to glue a lead zirconium titanate (PZT) transducer to the base of the beam, with the split electrodes facing away from it. The lip above the beam holds the transducer in place while the polyurethane cures. After that, wires are soldered to each of the transducer's outward facing electrodes. The remaining portion of the mold, which forms the base of the device, is then filled with polyurethane, covered with Teflon and a glass slide to create a flat bottom, and allowed to cure. Finally, the device is removed from the mold and Loctite 404 glue is used to both glue a tip mass to the top of the beam and glue the base of the device to an acrylic platform. A 12.7 mm stainless steel ball bearing with a mass of 8.36 g was used as a tip mass.

IV. Experiments

A. Experimental Setup

A diagram of the experimental setup can be seen in Fig. 3a. A shaker (Type 4810 Mini-shaker, Brüel and Kjær) is mounted horizontally using a machined, aluminum plate. An acrylic platform with an accelerometer (Type 4507 Piezoelectric CCLD accelerometer, Brüel and Kjær) is mounted on the shaker. A second acrylic platform is mounted on the first using double-sided tape. As can be seen in Fig. 3b, this second platform has a star pattern etched into it. The star consists of a series of overlapping squares, each rotated by 15º from the last. These squares match the dimensions of the acrylic platform glued to the base of the BMP harvester. This allows the BMP vibration energy harvester to be mounted on the platform with any orientation between 0º and 345º by 15º increments.

The mBMP harvester was connected to a 50 MΩ load. The voltage across the load was measured through a unity-gain buffer made from a Texas Instruments OPA2132P op-amp and powered by a BK Precision 1672 triple output dc power supply. The output of the buffer was read by an oscilloscope (InfiniiVision DSO-X 2014A, Agilent Technologies). The shaker was driven by a power amplifier (Type 2718, Brüel and Kjær) which took its input as a sinewave from a waveform generator (SDG 805 Function/Arbitrary Waveform Generator, Siglent Technologies). The accelerometer was read by the oscilloscope through a signal conditioner (Type 1704 2-channel battery-powered CCLD signal conditioner, Brüel and Kjær). The oscilloscope and signal generator were controlled by LabVIEW software (National Instruments).

B. Experiments

Frequency sweeps from 28 Hz to 60 Hz by 0.5 Hz increments were performed at a 0.25g amplitude acceleration for each orientation of the BMP harvester between 0º and 180º. For each orientation, four frequency sweeps were run, one for each of four ways that the electrodes of the mBMP harvester were connected to the load. Two of these wiring configurations (side-side and front-back, seen in Fig. 2a and Fig. 2b respectively) were selected because they are functionally the same as patterning the transducer with two electrodes instead of four, which would be easier to fabricate should the results prove satisfactory. The other two wiring configurations (diagonal-13 and diagonal-24, seen in Fig. 2c and Fig. 2d, respectively) were selected because, when excited by vibrations from any angle in the plane parallel to the base of the beam, they will, between them, produce current.

V. Results and Discussion

A. Results

Results from the experiments performed are presented in Fig. 4 and Fig. 5. Fig. 4 shows the frequency response of the mBMP harvester for the front-back and side-side wiring configurations as it is rotated counterclockwise between 0º and 165º by 15º increments. Fig. 5 shows the outputs of all four wiring configurations with a rotation of 180º.

At 0º rotation, as can be seen in Fig. 4, the output of the mBMP harvester appears to pass through two resonant peaks in close succession, the first at approximately 36.0 Hz and the second at approximately 38.5 Hz. As the mBMP harvester is rotated between 0º and 45º, the resonant peak at a 38.5 Hz decreases in magnitude until, at 45º, there is only one resonant peak at 36 Hz. As the mBMP harvester is rotated between 45º and 90º, however, the magnitude of the resonant peak at 38.5 Hz increases. By the time the mBMP harvester has been rotated 90º, there are two full resonant peaks again. Between 90º and 180º, the resonant peak at 36 Hz follows the same pattern as the resonant peak at 38.5 Hz followed between 0º and 90º.

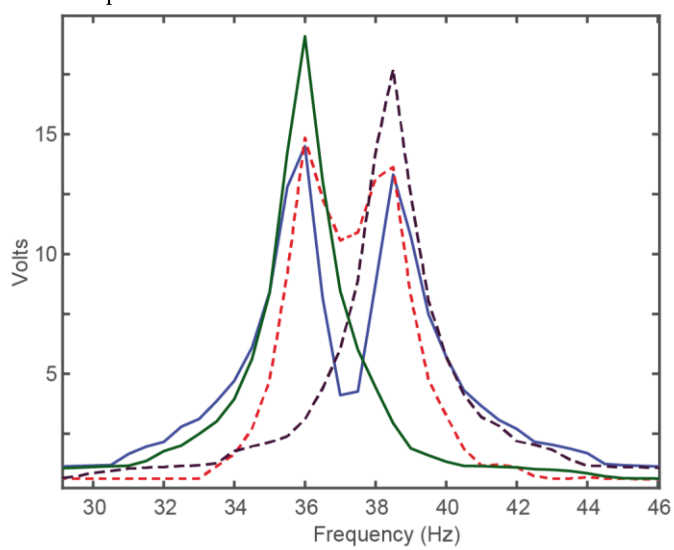

Fig. 5. Voltage output of mBMP harvester at a rotation of 180º for the front-back (dashed red line), side-side (solid blue line), diagonal-13 (solid green line), and diagonal-24 (dashed purple line) electrode wiring configurations.

The shapes of the frequency responses of the front-back and side-side wiring configurations of the mBMP harvester also change as it is rotated. At 0º, and as the mBMP harvester is rotated between 0º and 45º. The side-side wiring configuration presents a more dramatic voltage drop between resonant peaks and its individual peaks appear to have a greater bandwidth than those of the front-back wiring configuration. At 45º, the frequency responses of both wiring configurations are identical. Between 0º and 90º, the front-back wiring configuration begins to experience a greater voltage drop between resonant peaks than the side-side wiring configuration, while maintaining a greater apparent bandwidth for each individual peak. At 90º, the two wiring configurations have each adopted the shape of the frequency response of the other at 0º. Between 90º and 135º, the wiring configurations maintain these relative shapes. At 135º, the frequency responses of both wiring configurations are identical again. Between 135º and 180º, the relative shapes of both wiring configurations' frequency responses resemble those seen between 0º and 45º. In fact, as can be seen in Fig. 4 and Fig. 5, the shapes of the frequency responses of both wiring configurations at 0º rotation and 180º rotation are virtually identical.

Fig. 5 demonstrates the relationship between the diagonal wiring configurations and the front-back and side-side wiring configurations. The diagonal-13 wiring configuration only resonates at 36 Hz while the diagonal-24 configuration only resonates at 38.5 Hz. The outputs of the front-back and side-side wiring configurations both resemble a scaled sum of the diagonal wiring configurations. This relationship holds true at all angles of rotation and makes sense, given that the front-back and side-side wiring configurations can be made by connecting the diagonal wiring configurations.

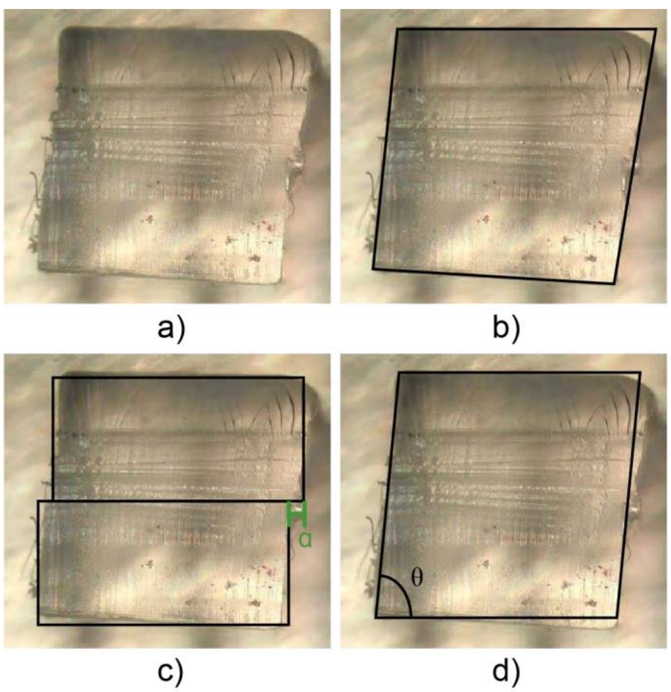

Fig. 6. a) mBMP harvester beam cross section b) Actual mBMP harvester cross section as a quadrilateral c) mBMP harvester cross section as mismatched rectangles d) mBMP harvester cross section as a rhombus

B. Discussion

An analysis of the mBMP harvester described in this paper leads to the expectation that it will resonate at only one frequency in any direction. However, the experimental results indicate otherwise. The most likely explanation is that the fabricated harvester does not exactly match the design, in that its cross-section is not a perfect square. In fact, we have concluded that the cross section of the beam of the fabricated device is some non-specific variety of quadrilateral. The following analysis compares the expected behavior of the beam with its observed behavior and demonstrates how the deviation of the cross-section, from a perfect square, accounts for the difference.

1) Cross Section Shape and Dimensions

The only BMP vibration energy harvesters studied prior to this one had rectangular beams. Such a beam is very stiff along the length of its cross section, resulting in a high resonant frequency in that direction. This resonant frequency is far too high to be useful and has, therefore, been ignored. However, reducing that length, so that the beam's cross section becomes a square, should allow it to resonate at a single frequency in any direction of excitation. This is because the moment of inertia of a square, monolithic beam is constant about any axis going through its centroid [20]. Other quadrilateral cross sections, however, only have two, orthogonal, principal axes of inertia. The existence of two peaks in the experimental results indicate that the beam's cross-section is not a perfect square. Indeed, images of the cross-section obtained by an optical microscope show that the cross-section deviates from a perfect square (Fig. 6).

Examination of the beam cross section seen in Fig. 6 shows that its angles and sides are non-uniform in magnitude (Fig. 6b). However, for the sake of modeling the behavior of the beam, and for future design applications, a simpler cross section is preferable. As can be seen in Fig. 6c, the actual beam cross section seems to have been the result of a misalignment between the two halves of the mold used in fabrication, resulting in two adjacent, and slightly distorted, rectangles with a slight misalignment α between them. As can be seen in Fig. 6d, the cross section also closely resembles a rhombus with a characteristic acute angle θ. Adjacent, misaligned rectangles and a rhombus both have approximately the same principal axes of inertia, running diagonally from corner to corner of the cross section. Thus, the two resonances are expected to be in the diagonal directions. As can be seen in supplemental movie 1, the device fabricated for this study resonates strongly in the two diagonal directions when the driving force is parallel to one side. Note that a beam with either of these cross sections is expected to have two different resonant frequencies as the area moments of inertia about its principal axes of inertia are different from one another.

The dependence of resonant peaks on the excitation direction, as shown in the experimental results, can be explained by the relative ratios of excitation corresponding to each resonant direction. If the excitation is parallel to one side, then the resulting excitation in the two resonant directions will be approximately equal. As the excitation direction gets closer to one of the resonant directions, the other resonant peak will start to diminish in size and eventually disappear at perfect alignment. This resonant behavior, along with the electrode configuration, will determine the relative magnitude of voltage at a given excitation direction (see Fig. 7).

Since they determine the directions in which it will resonate, it is useful to view the movement of the mBMP vibration energy harvester in terms of the beam's principal axes of inertia. Here, we present an analysis for a rhomboid cross-section in an attempt to explain the experimental results. Additionally, a rhombus is an easy shape to analyze and fabricate, so an approach to designing an mBMP harvester beam with a rhombus cross section that resonates at two desired frequencies is proposed here.

As can be seen Fig. 7, the principal axes of inertia of a rhombus run from corner-to-corner. The resonant frequency ω_d of a beam vibrating about a given principal axis of inertia with a rhombus cross section and a tip mass m can be determined by the standard formula

$$\omega_d = \sqrt{\frac{k_d}{m}}, \tag{1}$$

where k_d is the beam's stiffness in that direction. The stiffness can, in turn, be calculated for a cantilevered beam of fixed-free ends using

$$k_d = \frac{3YI_d}{L^3} \tag{2}$$

where Y is the elastic modulus of the beam, I_d is the beam's area moment of inertia about the axis perpendicular to the tip displacement, and L is the beam's length.

To design a beam with two desired resonant frequencies, ω_1 and ω_2, one for each direction along a principal axis of inertia, start with the ratio of the resonant frequencies

$$\frac{\omega_1}{\omega_2} = \sqrt{\frac{\frac{k_1}{m}}{\frac{k_2}{m}}} = \sqrt{\frac{k_1}{k_2}} = \sqrt{\frac{\frac{3EI_1}{L^3}}{\frac{3EI_2}{L^3}}} = \sqrt{\frac{I_1}{I_2}}. \tag{3}$$

Next, consider the beam's area moment of inertia. For direction 1, which is parallel to the principal axis of inertia that bisects the acute angle θ of the rhombus, this is

$$I_1 = \frac{a^4 \cos\frac{\theta}{2} \sin^3\frac{\theta}{2}}{6}, \tag{4}$$

where a is the length of one side of the beam. For direction 2, which is parallel to the principal axis of inertia that bisects the obtuse angle of the rhombus, the area moment of inertia is

$$I_2 = \frac{a^4 \sin\frac{\theta}{2} \cos^3\frac{\theta}{2}}{6}. \tag{5}$$

Once again revisiting the ratio of the resonant frequencies, and substituting for the area moment of inertias, gives

$$\frac{\omega_1}{\omega_2} = \sqrt{\frac{I_1}{I_2}} = \sqrt{\frac{\sin^2\frac{\theta}{2}}{\cos^2\frac{\theta}{2}}} = \tan\frac{\theta}{2}. \tag{6}$$

So, θ can be calculated using

$$\theta = 2\tan^{-1}\frac{\omega_1}{\omega_2}. \tag{7}$$

With θ known, the obtuse angle of the rhombus can easily be found by using geometry.

The second step to designing a beam with two specific resonant frequencies is to find the length a of a side of the rhombus cross section of the beam. To do this, (1),(2), and (4) are combined to find

$$\omega_1 = \sqrt{\frac{Ya^4 \cos\frac{\theta}{2}\sin^3\frac{\theta}{2}}{2mL^3}}, \tag{8}$$

which can be rewritten as

$$a = \sqrt[4]{\frac{2m\omega_1^2 L^3}{Y\cos\frac{\theta}{2}\sin^3\frac{\theta}{2}}}. \tag{9}$$

Using (7), the angle θ of the cross section of the beam of the mBMP harvester fabricated for this paper, when it is presumed to be a rhombus, is calculated to be 86.2º. Using (9), and using the known values of m = 8.36 g, ω_1 = 72π, L = 2 cm, Y = 2.39 GPa (found in [19] using COMSOL FEM analysis software), and θ = 86.2º, the length a of a side of the beam is calculated to be 1.87 mm, very close to the 2 mm intended side length. In fact, slightly lowering the elastic modulus to 2.0 GPa, a very possible value given the potential variability in elastic modulus of the polyurethane used, results in a side length a of 1.96 mm, which is an even better match. Measurements taken using calipers show two sides with length 1.96 mm and two sides with length 2.02 mm, so the intended, predicted, and measured values are all in close agreement.

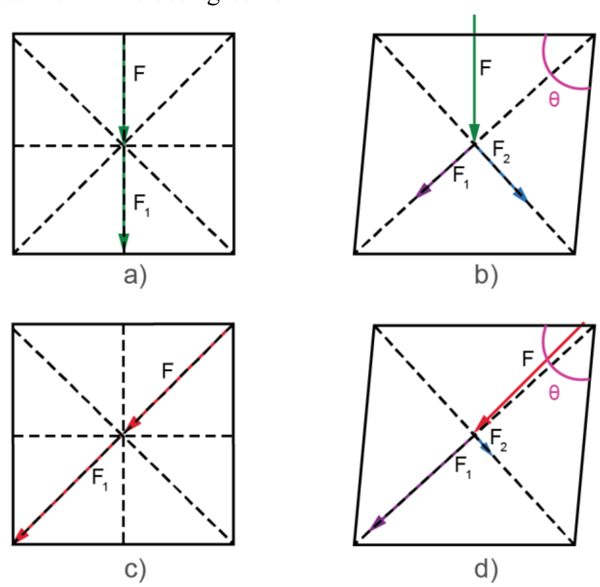

Fig. 7. Projection of driving force from 0º (a and b) and 45º (c and d) clockwise rotation on principal axes of inertia for square (a and c) and rhombus (b and d) beam cross sections.

2) Electrodes and Charge Cancellation

As was previously mentioned, Fig. 5 demonstrates the relationship between the output of the diagonal electrode wiring configurations and the front-back and side-side electrode wiring configurations. However, while the front-back and side-side wiring configurations resemble a scaled summation of the diagonal wiring configurations, there are some distinct differences. The side-side wiring configuration has an exaggerated dip between the resonant peaks and the front-back wiring configuration has an exaggerated roll-off on the outside of the resonant peaks.

The exaggerated dip between resonant peaks seen in the side-side wiring configuration in Fig. 5 is the result of charge cancellation. Since the two resonant frequencies are close together, as the driving frequency of the tip mass moves between them, two things happen: First, because the movement of the tip mass is being amplified in two directions, the direction of the net movement changes. Second, because the beam is on different sides of resonance for each direction, resulting in a phase difference between directions of movement, the movement of the tip mass takes on an elliptical shape. This first effect results in the bending direction of the beam sweeping across the division between connected electrodes, which causes charge cancellation to first increase, then decrease. Maximum charge cancellation takes place when the net movement of the tip mass is parallel to split between connected electrodes. This happens halfway between resonant peaks. The fact that current output does not drop to zero at this point seems to be because of the elliptical path travelled by the tip mass.

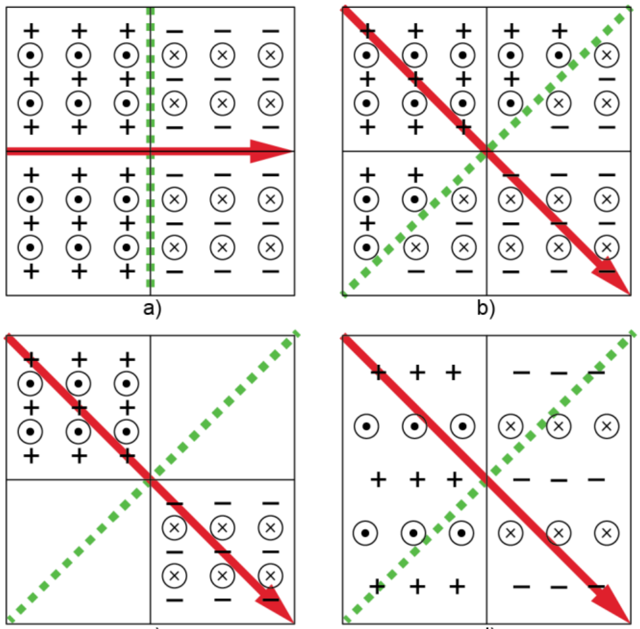

Fig. 8. Stress on, and charge distribution in, the transducer's electrodes for a) four electrodes and driving force perpendicular to one division between electrodes b) four electrodes and driving force at 45º angle with respect to electrode divisions c) four electrodes and driving force at 45º angle with respect to electrode divisions, showing net charge in electrodes d) two electrodes and driving force at 45º angle with respect to electrode division

The exaggerated roll off seen on the outside of the resonant peaks of the output of the front-back wiring configuration in Fig. 5 can also be explained by charge cancellation. Once again, it is a matter of considering the direction of tip mass movement. The resonant frequencies of the beam are close enough that there is amplified movement along both principal axes at frequencies moving into the first lower resonant frequency and frequencies moving out of the second higher resonant frequency. In both scenarios, this shifts the direction of movement past the corners of the transducer's electrodes. For the side-side electrode wiring configuration, this reduces charge cancelation. However, for the front-back electrode wiring configuration, this increases charge cancelation. Between 45º and 135º, the shapes of the frequency responses are switched because each wiring configuration experiences the cause of charge cancelation the other does at other angles.

3) Power

The power output of the mBMP vibration energy harvester fabricated for this paper is dependent on the electrode wiring configuration. As is demonstrated in Fig. 8, the corner-to-corner wiring configurations each minimize charge cancelation in one resonant direction and maximize it in the other. The result is that each corner-to-corner wiring configuration responds only to one resonant frequency. As is illustrated in Fig. 8, the net charge between electrodes, when two electrodes shorted together count as a single electrode, of the front-back and side-side (Fig. 8d) wiring configurations is the same as the sum of the two diagonal (Fig. 8b and Fig. 8c) wiring configurations. However, for each of the diagonal wiring configurations, the charge is collected in a smaller area. The reduced area means that the capacitance between electrodes is reduced and more electrical energy is stored in the transducer. This, in turn, results in a higher power output. For example, the highest average power output by the mBMP harvester was 8.2 μW, measured from the diagonal-13 wiring configuration across the 50 MΩ load at a 45º rotation. Compared to the power output that can be calculated from Fig. 4, where the side-side wiring configuration outputs a peak voltage amplitude of 22 V across the 50 MΩ load at a rotation of 45º, which amounts to an average power output of 4.8 μW.

Fig. 5 shows that the diagonal wiring configurations have a higher voltage amplitude, and therefore output a higher average power, than the front-back and side-side wiring configurations at the mBMP harvester's resonant frequencies. This indicates that a superposition of both diagonal wiring configurations would be expected to yield the highest possible power output at the most frequencies and angles of excitation.

4) Bandwidth

While it can, because of their different shapes, be hard to compare the operating bandwidths of the outputs of the various electrode wiring configurations, the dual resonant peaks seen in Fig. 4 and Fig. 5 clearly represent a bandwidth increase over that of the single peaks in Fig. 5, which is approximately 1.5 Hz. They are also a clear increase over the bandwidth of the original BMP harvester design, which was estimated in [19] to be 1.5 Hz. It is to be expected that a superposition of the two diagonal wiring configurations that would have the greatest operating bandwidth of all, since there would be no significant charge cancelation and, therefore, a minimal voltage decrease between resonant frequencies and a shallow role off on the outsides of the resonant frequencies. It would have the best qualities of the front-back and side-side wiring configurations with the power output of the diagonal wiring configurations. The best way to combine outputs of the diagonal wiring configurations so as to achieve this result is being investigated.

VI. Conclusion

A multi-directional piezoelectric vibration energy harvester with a base-mounted piezoelectric transducer, called an mBMP vibration energy harvester, was fabricated. The transducer had four output electrodes and four ways of wiring those electrodes to a load were tested. Experiments were performed in which the output of each electrode wiring configuration was measured while a frequency sweep of driving accelerations was conducted. These experiments were repeated after rotating the mBMP vibration energy harvester, and thus the direction of the driving acceleration, between 0º and 180º in 15º increments. While the frequency response of the mBMP vibration energy harvester varied with electrode configuration, significant power output was recorded in each direction. Experiments also showed that, when the driving acceleration was applied from certain directions, the mBMP vibration energy harvester had two closely spaced resonant frequencies, resulting in an increased operating frequency bandwidth. The phenomenon was found to be a result of the slight deviation of the beam cross-section from a square. In light of the experimental observations, an approach to designing an mBMP vibration energy harvester with two specified resonant frequencies was proposed.

The mBMP vibration energy harvester will be further developed in future work. Based on the experimental results presented in this paper, for example, two mBMP vibration energy harvesters with identical beams and one rotated 90º with respect to the other should, between them, maintain a consistent frequency response with two resonant frequencies when driven by vibrations in any direction. Approaches for extracting the maximum possible power from the mBMP vibration energy harvester in any direction will be tested. Finally, we plan to see how well the resonant frequencies of mBMP vibration energy harvesters can be controlled when using our mold-based fabrication technique and if any natural variation can be exploited by fabricating arrays of mBMP vibration energy harvesters for broadband vibration energy harvesting.

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