Manufacture and Characterisation of Piezoelectric Broadband Energy Harvesters Based on Asymmetric Bistable Laminates

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ABSTRACT
Piezoelectric energy harvesters that convert mechanical vibration into electrical energy are potential power sources for systems such as autonomous wireless sensor networks or safety monitoring devices. However, ambient vibrations generally exhibit multiple time-dependent frequencies, which can include components at relatively low frequencies. This can make typical linear systems inefficient or unsuitable; particularly if the resonant frequency of the device differs from the frequency range of the vibrations it is attempting to harvest. To broaden the frequency response of energy harvesters researchers have introduced elastic non-linearities; for example by designing bistable harvesters with two energy wells. Methods employed to induce bistability include magnetic interactions, axial loading, and buckling of hinge-like components. An alternative method has been recently considered where a piezoelectric element is attached to bistable laminate plates with an asymmetric stacking sequence to induce large amplitude oscillations. Such harvesting composite structures have been shown to exhibit high levels of power extraction over a wide range of frequencies. In this paper we manufacture and characterise the energy harvesting capability of bistable asymmetric laminates coupled to piezoelectric materials. Cantilever configurations are explored and harvested power levels as a function of load impedance, vibration frequency and amplitude assessed. Harvested power levels, natural frequencies and mode shapes are compared with linear cantilevers of similar geometry with a symmetrical stacking sequence to assess the benefits of using bistable laminate configurations.

1. INTRODUCTION

Devices for the conversion of vibrational energy to electrical power have received increasing interest in the past decade, with a particular application of autonomous low power devices such as wireless sensor nodes. A variety of methods have been considered including electrostatic generation [1], electromagnetic induction [2] and the piezoelectric effect [3].

The piezoelectric effect has a number of advantages including ease of integration within a system, higher strain energy densities compared to electrostatic and electromagnetic systems and a purely solid-state conversion between electrical and mechanical energy [4]. In many cases piezoelectric energy harvesting devices have been designed to operate close to a resonant frequency to optimise the power generation, for example simple linear cantilevered beam configurations [5]. An alternative approach is to exploit non-linear dynamics, such as bistability, to improve the power harvesting capability. As an example, the dynamic modes of non-linear systems have been observed to produce power across a broadband range of frequencies [6].

A common nonlinear piezoelectric energy harvesting device is a bistable cantilever system where the bistability is induced using an external arrangements of magnets. An alternative method presented by Erturk, et al. employs a piezoelectric element attached to the surface of a composite laminate with an asymmetric stacking sequence [3]. Such an approach is aimed at exploiting the inherent bista-
bility arising from anisotropic thermal properties of laminate composites. Figures 1(a) and 1(b) shows the two stable equilibrium states of a square bistable [0/90], carbon fibre reinforced polymer (CFRP) laminate with a Macro Fibre Composite (MFC) piezoelectric element attached to its centre. Figure 1(c) shows the double-well strain energy profile for the range of curvatures of a bistable composite obtained via an analytical model, where the two minima represent the two stable equilibria, State 1 and State 2 [inset of Figure 1(c)] and the saddle point in the centre shows the unstable equilibrium, [7]. The energy hill that needs to be traversed to ‘snap-through’ from one state to the other is also apparent in Figure 1(c).

Bistable laminates have been extensively studied for morphing or adaptive structure concepts [8–10] since snap-through between stable states can result in a large deflection. For harvesting applications, a conformable piezoelectric element is attached to the laminate surface to generate electrical energy by the direct piezoelectric effect as the structure is repeatedly deformed as a result of mechanical vibrations. The onset of snap-through events is thought to lead to large and rapid variation in strain leading to high power outputs achieved over a broad frequency range [3]. Experimentally, such harvesting devices have been shown to exhibit high levels of power extraction over a wide range of frequencies; for example, approximately 30 mW was achieved for an accel-

Figure 1. (a) First stable state of [0/90], laminate with Macro Fibre Composite (MFC) piezoelectric patch; (b) second state; and (c) corresponding strain energy profile.
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Figure 2. Laminate lay-ups: (a) linear and symmetric [90/0/0/90]; and (b) bistable and asymmetric [0/0/90/90]. The cantilevers were clamped at the left hand side. Bistable states: (c) State I; and (d) State II.

Operation forcing level of 2.0 g [3], and there are opportunities for further optimisation to increase the power output [11] by tuning the laminate lay-up and geometry. However, what is less clear is how the power output compares quantitatively between linear and bistable energy harvesting devices.

The aim of this paper is to present the comparative investigation of linear and bistable energy harvesters. A cantilevered beam configuration is selected of the same dimensions made from carbon fibre-reinforced polymer (CFRP) laminates. The linear beam has a symmetrical stacking sequence and the bistable beam has an asymmetrical stacking sequence of the same plies. The following sections will outline the further details of the experimental set up and discuss the modal characteristics and the power harvesting capability of the two beam configurations.

2. EXPERIMENTAL

2.1. Composite Manufacture

Two cantilevered beams were made using unidirectional CFRP, HexPly M21 (Hexcel) with a Young’s modulus (E₁₁)
of 178 GPa and shear modulus \((G)\) of 5.2 GPa \([12]\). The ply layup for the linear beam was \([90/0/0/90]\), as shown in Figure 2(a), and the bistable beam was \([0/0/90/0/0/90]\), as shown in Figure 2(b) where 0° is along the span of the beams. The beam dimensions were 280 mm long and 60 mm wide and the ply thickness was between 0.185 and 0.195 mm after curing. To ensure the clamped end of the bistable cantilever remained flat in its two stable states, two additional plies were added at one end to make the clamped region symmetric \([0/0/90/0/0/0/0]\), Figure 2(b). Figures 2(c) and 2(d) shows the two states of the bistable beam.

In order to convert mechanical vibrations of the laminate beams into electrical energy a MFC piezoelectric element (M8528-P2, Smart Materials) of dimensions 105 mm \(\times\) 34 mm was bonded to the surface of the laminate at 35 mm from the root. The MFC is based on a lead zirconate titanate (PZT) ferroelectric ceramic which is polarised through its thickness with a manufacturer’s specified capacitance of 172 nF \([13]\). Figure 3(a) shows a cross section of the MFC bonded onto the CFRP showing the piezoelectric fibre in the MFC, the upper and lower electrodes to collect the harvested charge and the bond layer. Figure 3(b) shows a top-down view of the MFC attached to the CFRP where the piezoelectric fibres and the upper mesh electrode can be observed.

2.2. Composite Characterisation

The first 30 mm of the beams were bolted between two aluminum plates to induce the clamped boundary condition, as shown in Figure 4(a), which also shows the overall dimensions. The energy harvester (i.e. the laminate-MFC combination) was mounted to an electrodynamic shaker (LDS V455) as in Figure 4(b). When undertaking frequency sweeps at constant peak acceleration for power generation, the shaker signal was generated in LabVIEW (National Instruments NI-USB-6211 DAQ) which determines the signal amplitude to achieve a desired g-level at a particular frequency. This is achieved by initially measuring the velocity, and then calculating the acceleration of the central shaker attachment for range of drive frequencies (15–200Hz) and shaker input voltages (0.05–5.0V) and generating a calibration table for any chosen g-level. The shaker input in terms of drive frequency and input voltage is achieved via a power amplifier (Europower EP1500).

In order to characterise the frequency response function of the energy harvester, a mechanical input signal was generated using Polytech’s ‘PSV Acquisition’ software (Ver. 8.82). The structural response of the harvester was monitored by a laser vibrometer (Polytec PSV-400-M4 with VD-09 decoder) to measure the displacement and velocity of one point of the harvester 130 mm from the clamped end. Reflective tape was adhered to the harvester to improve the signal return of the scanning laser, as in Figures 4(a) and 4(b). Figure 4(c) shows a schematic of the experimental arrangement to characterize the frequency response.

In order to characterise harvested power it is necessary to attach a resistive load the to piezoelectric element as it is under vibration. A load resistor is attached across the MFC and the potential difference across it measured using an oscilloscope (Agilent 54835A). The optimal load resistance \((R)\) for maximum power at a particular frequency \((f)\) is achieved by matching the load impedance to the capacitive load of the piezoelectric \((C)\); this is achieved at to the condition \(2\pi \cdot f \cdot R_L \cdot C_P = 1\). For the initial phase of testing a single load resistance was used which for the linear harvester \(R_L = 21 \, k\Omega\) (2nd bending mode at 43 Hz) and for the bistable \(R_L = 36 \, k\Omega\) (1st bending mode at 26 Hz). Figure 4(d) shows a schematic of the experimental arrangement for power characterization and Figure 4(e) shows the harvester electrical circuit diagram. Additional test procedures are also detailed where relevant throughout the paper.
3. RESULTS

3.1. Dynamic Modes of Linear and Bistable Cantilever Beams

The frequency response function of the energy harvesters were initially characterized to examine the resonant frequencies of the beams. A frequency range from 1–200 Hz which covers a typical frequency range of a bridge with traffic and ground transport was analyzed [14]. To characterise the response of the linear and bistable beams, they were both subjected to the same perturbation input, and their free vibration response recorded in the time domain and then transformed into the frequency domain using a fast Fourier transform. The perturbation was a burst ‘chirp’ signal which swept through frequencies of 310–340 Hz in approximately 0.32s. From the start of the chirp, the scanner was set to delay measurement for 0.55s, giving the laminate 0.23s to transition into a free response and the shaker’s shank to come to a complete stop. From the time measurement began, velocity data was collected for 6.4 seconds with a sampling frequency of 1.28 kHz. The shaker was driven with a constant voltage of 3.5V resulting in an RMS acceleration of 47g and a maximal value of over 70g. Snap-through of the bistable beam during chirp characterisation was not observed this testing phase.

Figure 5 shows the fast Fourier transform (FFT) of the velocity measurements at the scan point of Figures 4(a) and 4(b) of the linear and bistable cantilevered beams from 1–200 Hz. As the velocity measurement is taken in the centre of the width, torsional or rolling modes around the axis along the span of the beam are not identified. Table 1 summarises the resonant modes and Figures 6(a) and 6(b) shows

![Figure 4. Experimental setup: (a) clamped cantilever beam; (b) cantilever energy harvester on the shaker and reflective tape and a load resistor; (c) schematic of the experimental setup for frequency response function; (d) experimental schematic for power versus frequency, g-level and load resistance; (e) energy harvesting circuit.](image)

![Figure 5. Fast Fourier transform (FFT) of the velocity of the linear and bistable cantilevered beams.](image)
Table 1. Mode Shapes and Associated Frequencies for Linear and Bistable Harvester.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode Shape</th>
<th>Linear Beam</th>
<th>Bistable Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st bending</td>
<td></td>
<td>9 Hz</td>
<td>26 Hz</td>
</tr>
<tr>
<td>2nd bending</td>
<td></td>
<td>43 Hz</td>
<td>176 Hz</td>
</tr>
<tr>
<td>3rd bending</td>
<td></td>
<td>129 Hz</td>
<td>&gt; 200 Hz (not observed)</td>
</tr>
</tbody>
</table>

the first and second bending modes; the displacement of the third mode was too small to be observed visually. Within the experimental range of 1–200 Hz, three resonant modes were observed for the linear beam while two modes were observed for the bistable beam. Noting that we measured the velocity at the location just off the centre of the beam, the amplitudes of the modes are consistent with the corresponding mode shapes.

As shown in Figure 5, the frequency at which the bistable encounters the different bending mode orders is consistently higher than those of the linear harvester. This is due to higher stiffness of the bistable cantilever which is attributable to the fact that the bistable harvester has an extra two layers in the clamping region and the asymmetric nature of the bistable layup leads to a curvature of the cantilever about the longitudinal axis, further increasing the bending stiffness.

3.2. Investigation of Harvested Power with Frequency

To demonstrate the differences between high and low excitation for both of the harvesters, sweeps from 15 Hz to 200 Hz were carried out at 1g and 6g acceleration for both the linear and bistable energy harvester. To highlight in detail the regions of maximal power output, near the natural frequencies, more detailed frequency sweeps with an increment 0.2 Hz were undertaken as shown in Figures 7(b), (c) and Figure 8(b), (c) for the linear and bistable system respectively at 1g, 2g, 4g and 6g. The lower bound of frequencies when performing sweeps such as these is 15 Hz due to the electric current limitations of amplifier powering the shaker system. This limits the investigation for the power harvesting characteristics of the linear first mode which is at 9 Hz. We, therefore, focus our power characteristic investigations on the second and third modes of the linear harvester. Measurements were undertaken by both increasing frequency (‘up-sweep’) and decreasing frequency (‘down-sweep’) to further characterise any non-linear behaviour. Upon changing to each frequency, 0.2s was allowed for the harvester to attain a steady-state response before the velocity data was recorded for 4.8 seconds. From the set of data at each frequency, the peak velocity value and a root mean squared (RMS) voltage were measured. The harvesting power for a specific frequency and g-level was calculated using Equation (1).

\[ P = \frac{V^2}{2R} \]  

We see that for the linear harvester, there is a small decrease in the the natural frequency, less than 2 Hz, for the 2nd and 3rd bending modes when the excitation is gradually increased from 1g to 6g [see Figures 7(b) and 7(c)]. The small decrease in natural frequency with increasing excitation is likely due to some softening (non-linearities) inherent to the CFRP material [15,16]. The stiffness of the piezoelectric (PZT ceramic) is also non-linear [17].

For the bistable harvester, there is a difference in power output between the upward and downward frequency sweeps at higher g-level (see Figure 8). This is particularly apparent for the 1st bending mode at 6g in Figure 8(b), where the curve becomes asymmetric and leans towards lower frequencies ('horming') due to softening at higher excitation levels and is a characteristic of non-linear systems [18]. Snap-through events are shown in Figure 8 by highlighted data points.

Figures 9(a), and 9(b) show the increase of peak power for
Figure 7. Power versus frequency for 1g, 2g, 4g and 6g for linear beam: (a) frequency range 15–200 Hz; (b) detailed view of 2nd mode; and (c) detailed view of 3rd mode.

Figure 8. Power versus frequency and 1g, 2g, 4g and 6g for bistable beam: (a) frequency range 15–200 Hz; (b) detailed view of 1st mode; and (c) detailed view of 2nd mode.
the 2nd and 3rd modes of the linear harvesting beam respectively. The relationship between peak power and excitation level is approximately linear. A small degree of nonlinear behavior in the power versus excitation level is observed; this may be due to the fact that both CFRP and PZT exhibits a small degree of non-linear behavior [15–17]. Based on a linear relationship of peak power against the excitation level for the data in Figures 9(a) and 9(b), the $R^2$ is 0.992 and 0.981 for the second and third bending modes respectively. However, a quadratic relationship leads to $R^2$ values of 0.999 for both cases. Thus, the power increase over the range is slightly greater than expected by a linear approximation and any softening of the harvester leads to higher strain in the MFC, resulting in higher power output.

Figures 9(c) and 9(d) show the increase of peak power for the 1st and 2nd modes of the bistable harvester respectively at increasing excitation (g-level). The relationship between the excitation level, the degree of softening and the hysteretic behaviour of the power output of the harvester is more complex than the linear system. With reference to the first bending mode, at 1g the ‘up-sweep’ and ‘down-sweep’ power levels are almost coincident since at low excitation levels
the bistable harvester exhibits almost linear behaviour. At increasing excitation level the structure exhibits non-linear behaviour (‘softening’), as seen in Figure 8(b). In this case there is an area of instability underneath the ‘overhang’ in Figure 8(b) where limited power data are recorded. The is due to the fact that on the up-sweep, the state of the system tends to stay on the lower fold until sufficient energy is achieved for the system to switch to the upper fold. During the down-sweep the system tends to stay on the higher of the two folds and stays at a higher state of excitation for a greater duration until energy dissipation causes a jump down to the lower fold. The increase of the degree of softening at higher excitation explains why the peak power outputs diverge for both the up-sweep and down-sweep. At high levels of excitation, especially when there are ‘snap-through’ events as in Figure 8(b), the position and tendency of the system to jump from one fold to another is highly sensitive which combine to bring the peak powers closer together; see for example data for 5g and above in Figure 9(a).

3.3. Investigation of Harvested Power and Load Resistance

The measurements in the previous sections were undertaken for a fixed load resistance corresponding to impedance matching of the capacitive impedance of the piezoelectric MFC to the load resistance. In this section the load resistance is varied to examine the change in optimal resistance with excitation level due to the shift of peak power frequency [e.g. as in Figure 8(b)]. For measurement of the harvested power both harvesters were connected to an electrical circuit with a range of load resistors as in Figure 4(e).

Since ferroelectric ceramics are highly insulating the piezoelectric patch behaves approximately as a capacitor \( C_p \) and has a capacitance of 172 nF. During vibration of the harvester the resulting deformation in alternating directions leads to charges of alternating polarity accumulating on the electrodes with each reversal of curvature of the beam. This accumulation of alternate charges translates to an AC voltage signal, dissipating the energy across the resistor \( R_i \). This resistor represents the load of the electrical system which could be a sensor, or other such electrical component receiving the harvested energy. To maximise the power output, the value of the resistor is chosen to accommodate the harvester’s natural frequency, and the value of the capacitance within the circuit. The power output is at a maximum when:

\[
R_L = \frac{1}{2\pi f C_p}
\]

Thus, for the linear harvester a value of 21 kΩ was chosen in the previous section to coincide with the 2nd bending mode at 43 Hz, and for the bistable, and 36 kΩ to coincide with the first bending mode at 26 Hz. To demonstrate the influence of load resistance on harvested power, additional power characterisation was undertaken at a range of load resistance (1 kΩ to 1000 kΩ).

Figure 10 shows the dependence of the peak power output of the bistable harvester with respect to the load resistance at 1g and 6g. Data for the linear harvester are not shown since it is the bistable system that exhibits the largest degree of softening. The resistances were varied from 1 kΩ, approaching short circuit conditions where the piezoelectric discharges rapidly, to 1 MΩ, approaching open circuit conditions where the piezoelectric discharges slowly. It can be clearly observed that the power generation is highly dependent on load resistance.

![Figure 10. Bistable harvester peak power output over range of load impedance at: (a) 1g peak acceleration; and (b) 6g peak acceleration.](attachment:image.png)
With increasing excitation, there is a softening of the bistable, [Figure 8(b)] causing the natural frequency to shift lower, in accordance to $\omega_n = \sqrt{k/m}$. where $k$ relates to the stiffness of the mechanical system, $m$ to its mass, and $\omega_n$ to the natural frequency. Figure 10(a) shows that at 1 g, the optimal resistance is 40 kΩ. At 6 g excitation input, Figure 10(b) shows that the optimal resistance value has changed to 36 kΩ. Thus, it is seen that ideally, the resistance of the harvesting system would be changed actively depending on the input characteristics. For a purely linear harvester a strong dependence of the peak power with respect to load resistance, as in Figure 10, would also be expected since it originates from an impedance mismatch between the piezoelectric element and the load resistance. Compared to a bistable system, the main difference would be that the natural frequency of a linear harvester is not dependent on vibration level, as in Figure 7, and the load resistance would not have to be changed with vibration to achieve peak power.

4. COMPARISON OF BROAD-BAND RESPONSE

In practical applications the frequency of the excitation can change significantly with respect to time, meaning that a meaningful comparison requires more than just a comparison of peak power outputs and that the broadness of the power generation capability must be quantified. The frequencies on either side of the maximum at which the power output level reduces to half the maximum value, Full Width Half Maximum (FWHM) is often used to evaluate the broadband nature of harvesters [19,20], an example is indicated in Figure 7(c). Table 2 summarises these three measures for the different modes at excitation levels of 1 g and 6 g.

Table 2 shows that at an excitation level of 1 g, the bistable harvester in Mode 1 generates higher power, at greater bandwidth than the linear harvester. While the power of Mode 2 of the bistable is small, it is a relatively broad response; also shown in Figure 8(c). At a 6 g excitation level, the peak power for the Mode 2 and Mode 3 of the linear harvester is highest and exceeds the power for the Mode 1 and Mode 2 of the bistable harvester, but only over a narrow frequency range [see FWHM bandwidth in Table 2 and Figure 7(a)]. As the excitation level increases the FWHM increases and at a 6 g excitation, Mode 1 of the bistable produces the widest FWHM [see Table 2 and figure 8(a)] indicating the potential for such an approach for increase the broadband response.

5. CONCLUSIONS

This paper has examined both linear and bistable cantilever CFRP beams coupled to piezoelectric materials for energy harvesting applications. In comparing the energy harvesting performance of a linear harvester against that of a bistable nonlinear harvester, it has been seen that at low frequency and low excitation, the bistable has higher power output over a broader range of frequencies. The linear harvester has the potential to produce a higher peak power, but at a comparatively narrow bandwidth with respect to the bistable system. The similarity of the harvesters was imposed by matching the physical characteristics of dimension and piezoelectric patch placement as closely as possible, but further testing where the dynamic responses are matched could prove useful. The load resistance should be matched with the capacitive load of the piezoelectric element to produce peak power levels. With increasing excitation levels, softening of the bistable system leads to the peak power being produced at lower levels of frequency, necessitating some form of active tuning of the load resistance. It was also observed that the maximum power output of the linear harvesters increased quadratically with the excitation amplitude in the range we tested. The trend for the bistable harvesters was not as clear due to complex interaction of nonlinearity and difference between up- and down-sweeps at high excitation levels.

In this paper the change from a linear to a bistable harvester has been achieved by simply changing from a symmetric layup of [90/0/0/90]t to an unsymmetric layup [0/0/90/90]t to enable a comparison between the two cases. Tailoring of the laminate lay-up, cantilever geometry and materials employed (CFRP and piezoelectric) provides a variety of routes to tailor the non-linear characteristics to harvest specific vibration energies.

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7. REFERENCES


