Manufacture and characterisation of piezoelectric broadband energy harvesters based on asymmetric bistable cantilever laminates

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Abstract

In this paper a bistable asymmetric laminate is manufactured and coupled to a ferroelectric material for potential energy harvesting applications. The cantilever configuration is explored and the harvester response as a function of vibration frequency, vibration level and electrical load resistance examined. The harvester is characterised at low and high vibration levels where the device exhibits either single well oscillations (at low vibration amplitude) or snap-through events (at high vibration amplitude). As the vibration levels increase the device exhibits snap-through events 'softening' is observed where peak power moves to lower frequencies with differences in power levels during up-sweep and down-sweep of frequencies. Examination of the frequency dependence of power with a variation of the load resistance further emphasise the broadening of the harvester performance at higher vibration levels and during snap-through.

Keywords: piezoelectric, composite, harvesting, bistable, ferroelectric

1.0 Introduction

Piezoelectric based energy harvesting devices are of interest to convert mechanical vibrations into useful electrical energy. Potential applications for vibration harvesting systems include autonomous and 'battery-free' wireless sensor networks, safety monitoring devices or other low-power electronics [1]. In many cases, e.g. transport applications, the ambient vibrations can exhibit multiple time-dependent frequencies, may change with time and can include components at relatively low frequencies [2]. As a result it is often inefficient to employ narrowband harvesting devices that operate at a specific resonant frequency; for example simple linear cantilever configurations. In an attempt to broaden the frequency response of vibration energy harvesters a variety of researchers have introduced elastic non-linearities; this includes the design of bistable harvesters with exhibit two specific energy wells [2,3]. Methods to create bistability include the use of repulsive or attractive magnetic interactions between a cantilever and an external magnet, axial loading and the use of post-buckled beams [3]. An alternative method was reported by Arrieta et al. [4] where a piezoelectric element was attached to an asymmetric bistable laminate plate made from a carbon fibre reinforced polymer (CFRP) with a $[0/90]_T$ layup. Due to the large difference in the coefficient of thermal expansion (CTE) between the carbon fibre (low CTE) and epoxy matrix (high CTE) the thermal residual stress developed on cooling the laminate from an elevated cure temperature leads to it exhibiting two distinct stable states. When subjected to large amplitude oscillations the laminate undergoes 'snap-through' or 'cross-well oscillation' between the two stable states [5,6] leading to a large deformation of any piezoelectric material attached to the laminate. Such harvesting structures have been shown to exhibit high levels of power extraction over a wide range of frequencies [4,5]. The potential advantages of using the intrinsic thermal stress in the laminate to induce bistability, rather than using magnetic configurations [4-6], is that (i) the arrangement can be designed to occupy a smaller space, (ii) there are no stray magnetic fields, (iii) the bistable laminates can be readily combined with piezoelectric materials/fibres and (iv) there is potential to tailor the laminate lay-up, laminate elastic properties and geometry to provide additional control over the harvester response to the vibrations that are being harvested.

Initial research of bistable laminates for vibration harvesting examined centrally mounted laminate plates as the geometry for harvesting [4, 7, 8, 9, 10]. Recently, interest has focussed on cantilever configurations [5, 6, 11] and arbitrary shapes [12]. The cantilever configuration is of interest for broadband energy harvesting since large strains are developed near the clamped end of the structure and 'snap-through' events can be achieved at relatively low vibration levels compared to unconstrained laminate plates [6].

In this paper a bistable asymmetric laminate is manufactured and coupled to a ferroelectric material for energy harvesting applications. The cantilever configuration will be explored and the harvester response as a function of vibration frequency, vibration level and electrical load resistance examined. The harvester will be characterised at low and high vibration levels where the device exhibits either single well oscillations (at low vibration amplitude) or snap-through events (at high vibration amplitude).

2. Experimental

2.1 Composite manufacture

The bistable cantilever beam was manufactured using unidirectional carbon fibre reinforced polymer (CFRP), HexPly M21 (Hexcel) with a Young's modulus (E_{11}) of 178GPa and shear modulus (G_{12}) of 5.2GPa [11]. The lay-up of the bistable beam was $[0/0/90/90]_T$, with dimensions 280mm long and 60mm wide and the ply thickness was between 0.185 and 0.195 mm after curing (see Figure 1). To ensure the clamped end of the bistable cantilever remained flat in its two stable states (State I and State II), two additional plies were added to one end to make the clamped region symmetric $[0/0/90/90/0/0]_T$. Figure 2a, b shows the two states of the bistable beam.

To convert mechanical deformation of the bistable beam into electrical energy a Macro Fibre Composite (MFC) piezoelectric element (M8528-P2, Smart Materials) of dimensions 103mm × 31mm was adhesively bonded to the surface of the laminate at a distance of 35mm from the root; the root area is often chosen since it is the area of greatest deformation [6]. The MFC is based on lead zirconate titanate (PZT) ferroelectric ceramic and for harvesting applications a MFC device configuration where the PZT is polarised through its thickness. This type of device was selected for harvesting since this has (i) a more uniform electric field distribution, compared to a conventional inter-digitated electrode (IDE) MFC devices, (ii) a high device capacitance leading to low peak voltages as a result of the piezoelectric charge (Q), since $Q = C_p.V$ and (iii) a low electrical impedance ($Z = 1/i\omega C_p$) due to the high device capacitance. The manufacturer's specified capacitance was 172nF [12] for a M8528-P2 device poled through thickness compared to 5.7nF for a IDE configuration of the same geometry (M8528-P1).

2.2 Energy harvester characterisation

The beam was placed between two aluminium plates to induce the clamped boundary condition at the end, as shown in figure 2c and the energy harvester (i.e. the laminate-MFC combination) was mounted to an electrodynamic shaker (LDS V455). To characterize 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 13mm from the clamped end. Reflective tape was adhered to the harvester to improve the signal return of the scanning laser, as in Figure 2c.

When undertaking frequency sweeps at constant peak acceleration for harvesting characterisation, 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 was achieved by initially measuring the velocity, and then calculating the acceleration of the central shaker attachment for range of drive frequencies (10-200Hz) 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).

To characterise the harvested power it is necessary to attach a resistive load to the piezoelectric element while it is under mechanical vibration. A load resistor was attached across the MFC and the potential difference across it measured using an oscilloscope (Agilent 54835A). The optimal load resistance (R_L) for maximum power at a particular frequency (f) is achieved by matching the load impedance to the capacitative load of the piezoelectric (C_P = 172nF); this is achieved at to the condition $2\pi.f.\,R_L.C_P=1$. For the initial phase of testing a single load resistance was used which for the bistable R_L = 36kΩ (1st bending mode at 26Hz, to be shown later). To examine the influence of the load resistance of harvesting performance the bistable beam was subjected to a range of vibrations at a number of load resistances for low values (1kΩ, approaching short circuit conditions) to high values (10MΩ, approaching open circuit conditions).

Results

3.1 Vibration modes of the bistable cantilever beam

The frequency response function of the energy harvesters were initially characterized to examine the resonant frequencies of the bistable beam. A frequency range from 1Hz to 200Hz which covers a typical frequency range of a bridge with traffic and ground transport was analysed [13]. The beam was subjected to a perturbation input, and its free vibration response recorded in the time domain and transformed into the frequency domain using a Fast Fourier Transform. Snap-through of the bistable beam during chirp characterisation was not observed this testing phase.

Figure 3 shows the Fast Fourier Transform (FFT) of the velocity measurements of the bistable cantilevered beam from 1-200Hz. 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. At 26Hz a first bending mode is observed and a second bending mode at ~170Hz. Since these vibration modes correspond to frequencies of large deformations the power generated was characterised in detail around these frequencies; in particular the first bending mode where deflections at the root are largest [11].

3.2 Investigation of harvested power with frequency

To highlight in detail the regions of maximal power output, near the natural frequencies, detailed frequency sweeps with an increment 0.2Hz were undertaken as shown in figures 4a,b at vibration levels of 1g, 2g, 4g and 6g. The lower bound of frequencies when performing sweeps such as these is 15Hz due to the electric current limitations of amplifier powering the shaker system. Measurements were undertaken by both increasing frequency ('up-sweep') and decreasing frequency ('down-sweep') to 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).

$$P = \frac{V_{rms}^2}{R} \quad (1)$$

Figures 4a,b reveal that there is a difference in power output between the upward and downward frequency sweeps at higher g-level. This is particularly apparent for the 1st bending mode at 6g in Figure 4a, where the curve becomes asymmetric and leans towards lower frequencies due to softening at higher excitation levels and is a characteristic of non-linear systems [17]. Snap-through events are shown in Figure 4 by highlighted data points.

At increasing excitation level the structure exhibits non-linear behaviour ('softening') and there is an area of instability underneath the 'overhang' in Figure 4a 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.

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 capacitative 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. Since ferroelectric ceramics are insulating the piezoelectric behaves approximately as a capacitor (C_P = 172nF). 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 load resistor (R_L). 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:

$$R_L = \frac{1}{2.\pi.f.C_p} \tag{2}$$

Thus, a R_L = 36kΩ was used to coincide with the first bending mode at 26Hz (Figure 3). To demonstrate the influence of load resistance on harvested power, additional power characterisation was undertaken at a range of load resistance (1kΩ to 1MΩ).

Figure 5 shows the dependence of the peak power output of the bistable harvester with respect to the load resistance at 1g (Figure 5a) and 6g (Figure 5b) for a down-sweep of frequencies; data for up-sweep are not shown. At 1g the harvester remains in a single state and the peak power is obtained over a narrowband of frequencies; the full width half maximum (FWHM) is 1.6Hz (from Fig 4a). With a low load resistance (1kΩ) the system is approaching short circuit conditions and the piezoelectric discharges rapidly leading to low power generation (see Figure 5a). At a high load resistance (1MΩ), the system is approaching open circuit conditions where the piezoelectric discharges cannot discharge at the frequency range studied. The highest power levels are obtained for 1g at load resistance levels of 30-40kΩ which is in good agreement with the impedance matching calculation from Equation 2. If the vibration level is increased to 6g so that 'snap-through' events are observed, broadening of the power generation can be observed in particular at lower frequencies due to 'softening' of the structure with vibration level (Figure 5b). Again low power levels are observed at low (1kΩ) and high (1MΩ) load resistances with peak powers for resistance levels 30-40 kΩ. Charcterisation below 15Hz would be required to fully characterise the FWHM for the complete range of load resistances but the FWHM is 8.2Hz (from Figure 4a) and in excess of 10Hz in Figure 5b. While the critical vibration level to achieve snap-through was 4.2g for this particular laminate this can be tailored by the addition of an end mass; for example snap-through was achieved at 3.3g by adding a 2gram end mass to the end of the cantilever and was further reduced to 2.9g for a 4gram end mass.

Conclusions

This paper has examined a bistable asymmetric cantilever CFRP beam coupled to a ferroelectric ceramic material for energy harvesting applications. As the vibration levels increase the device moves from oscillations in a single state (single-well oscillation) to snap-through (cross-well oscillations). When vibrating in a single state the peak power levels are in a narrow range of frequencies and the devices behaves as a linear oscillator with no differences in power during the up-sweep and down-sweep of frequencies. As the vibration levels increase and the device exhibits snap-through events ‘softening’ is observed where peak power moves to lower frequecies and differences in behaviour during upsweep and down-sweep of frequencies. Examination of the frequency dependence of power with a variation of the load resistance further emphasised the broadening of the harvester performance at higher vibration levels, although the optimum load resistance is similar for both low-amplitude (single well) and high-amplitude (snap-through). Tailoring of the laminate lay-up, laminate elastic properties, 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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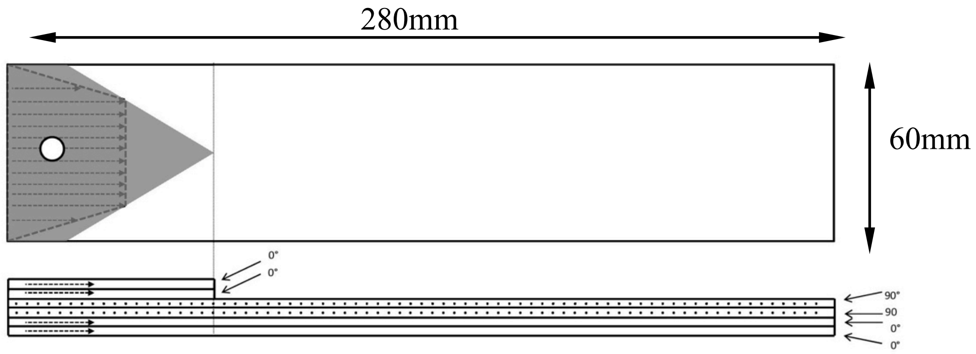
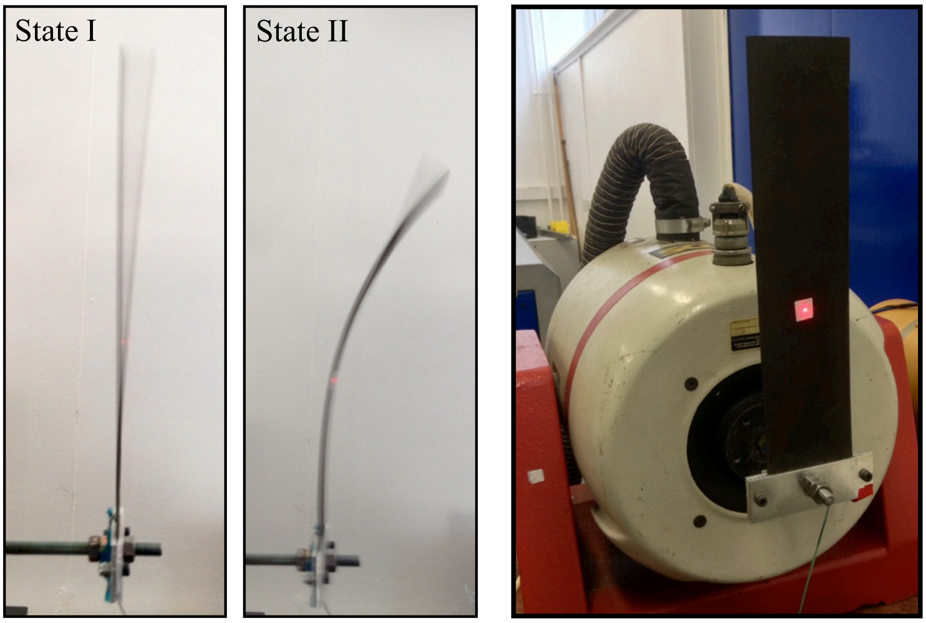


Figure 1. Laminate lay-up of bistable and asymmetric [0/0/90/90]$_T$. The cantilever was clamped at the left hand side.



(a) (b) (c)

Figure 2. (a) State I, (b) State II, (c) cantilever attached to shaker system

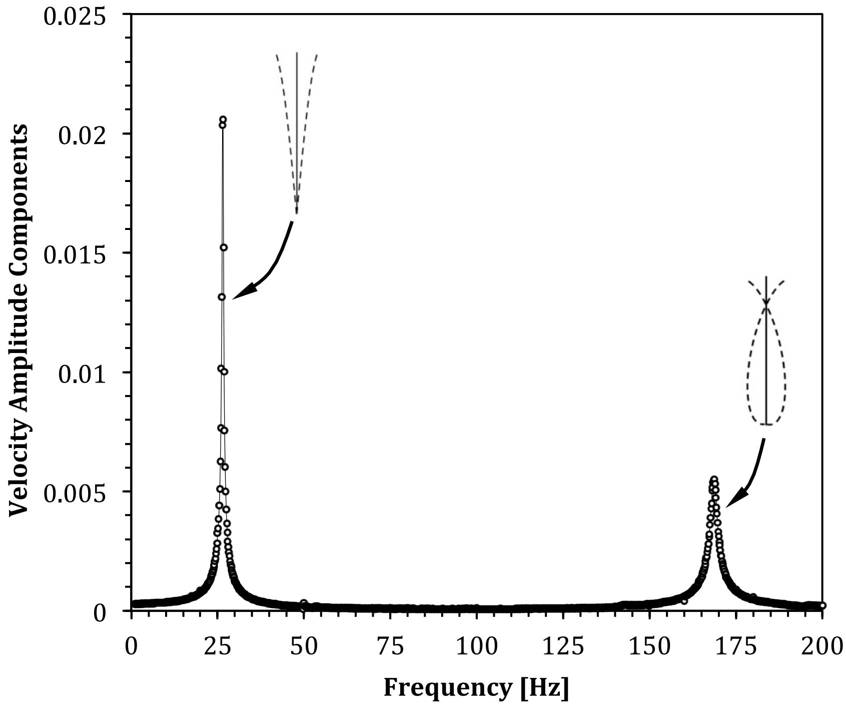
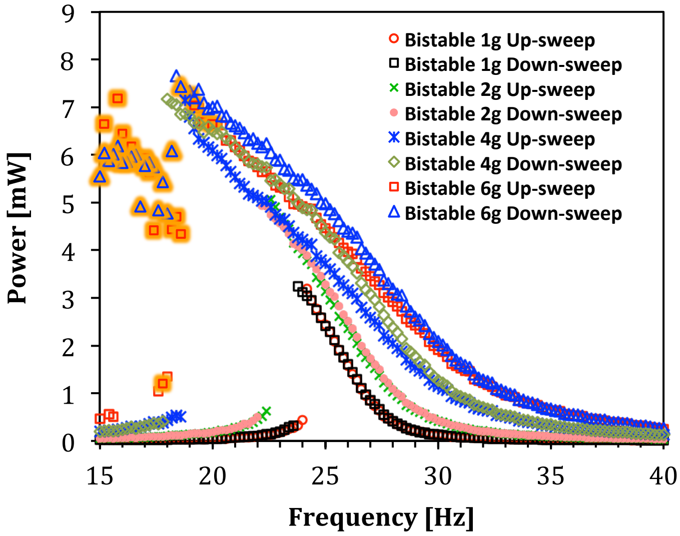


Figure 3. Fast Fourier transform (FFT) of the velocity of bistable cantilever beams.



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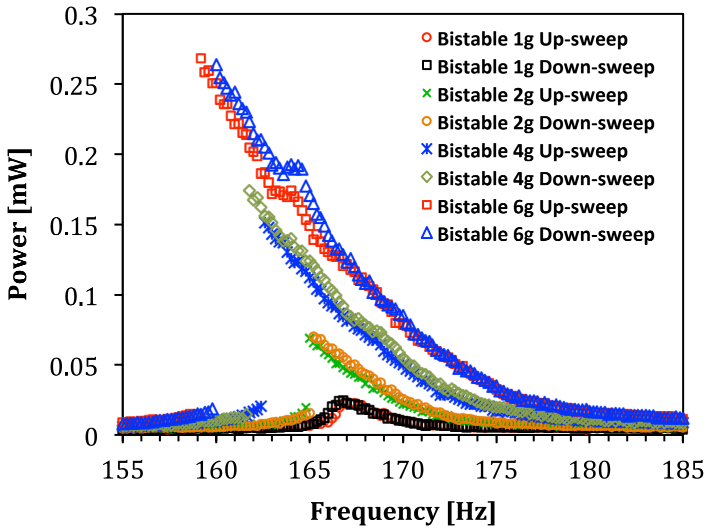
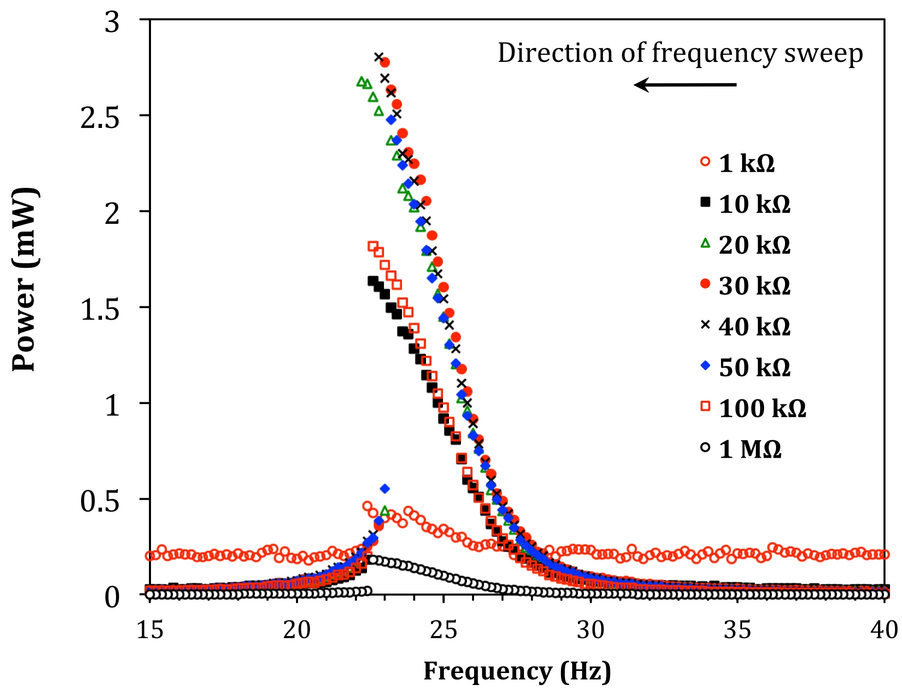


(b)

Figure 4. Power versus frequency and 1g, 2g, 4g and 6g for bistable beam (a) detailed view of 1st mode (b) detailed view of 2nd mode. R_L*=36 kΩ.*



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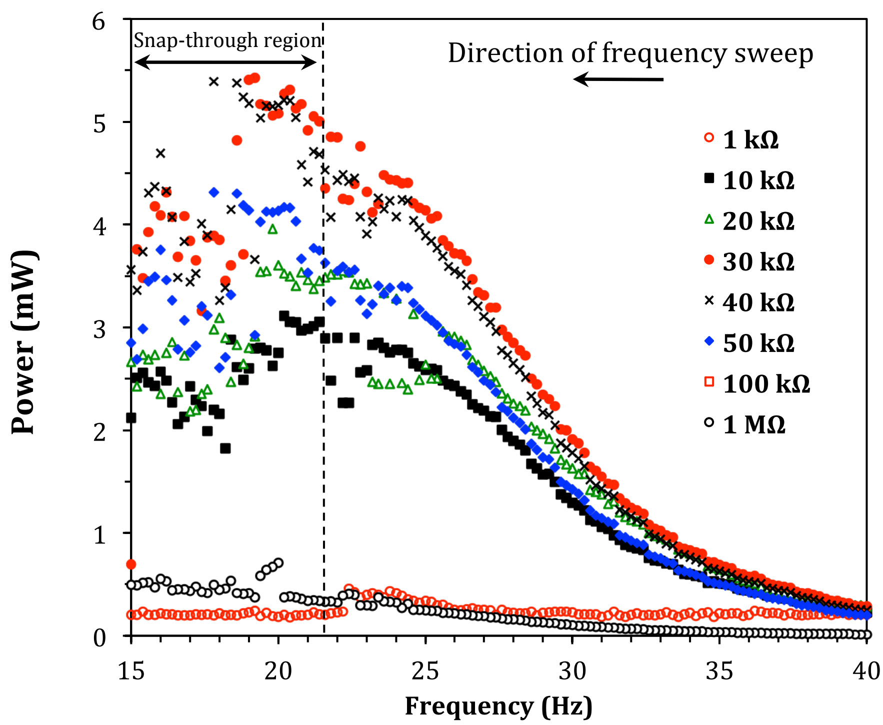

(b)

Figure 5: Vibration harvester at (a) 1 g excitation with various resistances sweeping downwards through a range of frequencies (b) at 6 g excitation with various resistances sweeping downwards through a range of frequencies.