A non-linear 3D printed electromagnetic vibration energy harvester

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Abstract. This paper describes a novel electromagnetic energy harvester that exploits the low flexural modulus of ABS and comprises of a nonlinear mechanism to enhance the generated power and bandwidth. The device is printed using desktop additive manufacturing techniques (3D printing) that use thermoplastics. It has a ‘V’ spring topology and exhibits a softening spring non-linearity introduced through the magnetic arrangement, which introduces a mono-stable potential well. A model is presented and measurements correspond favourably. The produced prototype generates a peak power of approximately 2.5mW at a frame acceleration of 1g and has a power bandwidth of approximately 1.2→1.5Hz and 3.5→3.9Hz during up and down sweeps respectively. The device has a power density of 0.4mW/cm$^3$ at a frame acceleration of 1g and a density of 0.04mW/cm$^3$ from a generated power of 25µW at 0.1g.

1. Introduction
With the advent of the Internet of Things there will be a large quantity of wireless sensor nodes that would be required to operate autonomously. To achieve this, energy harvesting offers an alternative source of energy to traditional battery sources, which have a finite capacity, requiring regular maintenance. This paper presents a topology that can harness mechanical vibrations and is fabricated using a 3D printer exploiting Fused Deposition Modelling (FDM). Additive manufacturing or 3D printing promises to be a disruptive technology and currently, in comparison to traditional (subtractive) manufacturing techniques, it is more cost effective to manufacture a small to medium number of devices and is capable of manufacturing unique and complicated products where traditional techniques cannot. A 3D object is printed as a series of 2D patterns fused on top of each other. Here, a heated plastic is extruded and deposited in thin layers to form the 3D topology sent to the printer. FDM typically uses thermoplastics to construct the object being printed and of the available thermoplastics, ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) are the most common. ABS has a flexural modulus of 2.1GPa and PLA has a higher value of 3.8GPa. However, their material properties can be potentially manipulated with the method of printing. For example, a structure can be printed with a certain fill density or print orientation. For example if an ABS structure is printed in the ZX axis (Cartesian axis) the structure will have a lower flexural modulus (1.65GPa) to when the structure is printed in the XZ axis (2.1GPa) [1]. Better geometric resolution than that achieved using FDM can be achieved using alternative 3D printing technologies, such as stereolithography, however, this may increase the cost of fabrication. Furthermore in [2], where

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microstereolithography is used, it is discussed that it is possible to ‘tune’ the material’s mechanical properties such that devices can be developed to operate at certain frequencies.

In [3] a spring is printed using ABS (FDM (assumed)) and is used as part of an electromagnetic energy harvester that can harness vibrations from an insect. The folded beam structure supports a magnet arrangement and between the magnets coils fabricated on PCB are placed. Through a coil, a load power of 0.9mW is reported for a frame excitation of 0.61g (25.8Hz). Alternative 3D printed technologies such as inkjet printing [4] has been used to fabricate a non-linear energy harvester. The system comprises of two PMMA (Polymethyl methacrylate) folded back cantilevers, with their tips facing each other. At the tips magnets are placed such that as they move they actuate each other. A wide (displacement) bandwidth of approximately 24Hz is demonstrated at frequencies under 40Hz. The transduction mechanism is of the form of piezoelectric patches, and a reported total power of 18.45µW at a frequency of 30Hz is demonstrated. Projection microstereolithography has been used to manufacture energy harvesters [2]. Here a UV curable resin (HDDA – Hexanediol diacrylate) was used to manufacture four helical springs arranged in a 2 x 2 pattern, all supporting a single magnetic mass. Each spring had a diameter of 1010µm and a thickness of 163.5µm. The magnetic mass passed through a coil and a generated power of approximately 2.114µW was generated at a frame acceleration of 0.23g at a resonant frequency of 61Hz.

Of late, though some of the literatures (as discussed above) have described topologies that utilise 3D printing to fabricate vibrational energy harvesters (while one utilises a non-linear mechanism in a piezoelectric transduction) this paper describes a novel electromagnetic vibration energy harvester that exploits the low flexural modulus of ABS, in a non-linear configuration, to increase the system bandwidth and power simultaneously at low acceleration and device volume.

2. Topology configuration and model

The topology is as shown in Figure 1. The suspension consists of two ABS printed beams in the form of a ‘V’. The base of the ‘V’ is attached to the base and a support platform is attached to the opposite end. The platform holds two magnets whose magnetization directions (black arrows) are anti-parallel and face two magnets fixed to the frame with the same magnetisation direction. Between the magnets is a coil, attached to the frame and the magnetic flux distribution is shown in figure 2(a).

When the frame is excited the suspended magnets on the platform move (indicated by red arrows) and the coil experiences a change in magnetic flux linkage resulting in an induced current through a load attached to the coil. As a result of the restoring force \( f_{res} \), the system will resonate. The system is modelled through:

\[
m z \ddot{z}(t) + \left( c_m + c_e(z(t)) \right) z(t) + f_{res}(z(t)) = -m y \ddot{t} \quad \text{and} \quad c_e(z(t)) = \frac{(k_e(z(t)))^2}{\sqrt{(k_c + k_d)^2 + (\omega L_c)^2}} \tag{1}
\]
where \( m \) is the equivalent mass of the beam, support and magnets; \( z \) is the relative displacement from the centre position (neutral position); \( c_m \) is the viscous mechanical damping; \( c_e \) is the equivalent electrical damping; \( k_e \) is the electromagnetic coupling coefficient; \( R_L \) is the load resistance; \( R_C \) is the coil resistance; \( L_C \) is the coil inductance; \( \omega \) is the excitation frequency; and \( y \) is the frame excitation displacement.

The restoring force comprises both suspension and magnetic components. As a result of the magnetic components the restoring force is non-linear. This is such that one pair of magnets move relatively to the other, which are fixed to the frame. As a consequence the device exhibits the performance of that with a mono-stable potential well.

**Figure 3:** Restoring force and corresponding potential well profiles.

**Figure 4:** Electromagnetic coupling coefficient.

**Table 1:** Prototype Parameters [mm].

| Property            | Symbol | Value |
|---------------------|--------|-------|
| Beam Height         | \( h_{beam} \) | 17.8  |
| Beam Thickness      | \( t_{beam} \) | 0.8   |
| Beam Width          | \( w_{beam} \) | 4     |
| Coil Outer Diameter | \( d_{coil-o} \) | 6.5   |
| Coil Inner Diameter | \( d_{coil-i} \) | 1.15  |
| Coil Height         | \( h_{coil} \) | 2     |
| Magnet Width        | \( w_{mag} \) | 8     |
| Magnet Thickness    | \( t_{mag} \) | 4     |
| Magnet Height       | \( h_{mag} \) | 2     |
| Separation between magnets | \( S \) | 4     |

The linear component of the restoring force is determined, using FEA, where the mode utilised is the first in-plane mode (figure 2(b)). For the prototypes beam thickness an eigen-frequency of 117 Hz is determined using a flexural modulus of 2.1GPa. However due to the FDM process the beam
thickness can vary, changing the eigen frequency. Figure 3 shows the restoring force profile as a function of displacement and its corresponding potential well profile.

The electromagnetic coupling coefficient determines how well the electrical and mechanical domains of the system are linked and hence how much energy can be transferred between the domains. It is given by Faraday’s law of electromagnetic induction, where the induced voltage, is given by:

\[
v_{oc}(t) = -\dot{z}(t)N \frac{d\phi_{avg}(z(t))}{dz} = -\ddot{z}(t)k_e(z(t))
\]

where \(\phi_{avg}\) is the average flux through the coil and \(N\) is the total number of turns in the coil. The corresponding electromagnetic coupling coefficient for the topology is as shown in Figure 4. Here, the system operates around the neutral position (\(z = 0\)) where the electromagnetic coupling coefficient is at a maximum (and the device is at the bottom of the potential well). A maximum occurs at this point due to the rapid change in magnetic flux direction, due to the anti-parallel configuration.

3. Experimental and model evaluation

The topology shown in Figure 1 (and Figure 5) was fabricated using a Stratasys Mojo 3D printer, which uses FDM technology. The thermoplastic that was used was ABS and NdFeB permanent magnets (N35, 1.17T) were glued to the frame and support platform. A coil (\(N = 7060\) and gauge is 25\(\mu\)m, Recoil Ltd., UK) was fixed to the frame and placed between the magnets. The coil had a measured resistance and inductance of 3.287k\(\Omega\) and 196mH respectively. Further details of the prototype’s physical properties can be found in Table 1. The prototype was evaluated on an LDS455 dynamic shaker, as depicted in Figure 6. Measurements were in the form of up and down frequency sweeps in the range of 100Hz to 200Hz, at a rate of 1Hz/s.

The measured and calculated open circuit frequency responses, at a frame acceleration of 1g are shown in Figure 7 below and show that quality factors, \(Q\), in the range of \(Q = 100 - 120\), yield good correlation between measured and calculated responses. This Q factor range corresponds to an equivalent mechanical damping ratio of \(\zeta_m = 0.00417 - 0.005\) as \(Q = 1/(2\zeta_m)\). As can be seen from the figure, it is clear that the frequency response is of a softening spring type, and the bandwidth of the device increases between the up and down sweeps and demonstrates hysteresis. The measured peak frequencies (at which maximum occurs) of both the up and down sweeps correspond to that determined by the model and differ slightly, possibly due to the variability in the printed beam thickness. Table 2 below lists both the calculated and measured peak frequencies of the topology at different frame accelerations. As is evident, the peak frequencies decrease with the frame acceleration, however, the downward sweep peak frequency generally occurs at a lower value than that of the upward sweep. The open circuit measured/calculated bandwidths for the up and down sweeps are respectively 2.6/2.4 Hz and 6.5/4Hz.

| Frame Acceleration | 0.1g | 0.5g | 1g         |
|--------------------|------|------|------------|
| Up – calculated    | 153.3| 152.7| 151.7-151.8|
| Up – measured      | 150  | 150  | 149        |
| Down – calculated  | 152.3| 151.4| 148        |
| Down – measured    | 152.4| 151.7| 149.4      |

Figure 8 shows the peak power determined from frequency sweeps for both the model and that generated from the prototype at frame acceleration of 1g. Similar curves are seen for frame
accelerations of 0.1g and 0.5g. Under these conditions, the generated peak powers for the up and down sweeps (average of up and down values) are: 25µW, 0.7mW and 2.5mW for frame accelerations of 0.1g, 0.5g and 1g respectively. These correspond to power densities of 0.04mW/cm$^3$, 0.12mW/cm$^3$, and 0.4mW/cm$^3$ respectively from a device with an active volume of 6cm$^3$. The power bandwidth was determined from the measurements as between 1.2→1.5Hz and 3.5→3.9Hz for the up and down sweeps respectively, for the maximum power points in figure 8 below. The corresponding peak frequencies were determined from the measurements as approximately 146-149Hz, with that of the down sweep slightly lower than that of the up sweep. From the simulations it is observed that the peak frequency, at which the generated power frequency response occurs at a maximum changes with the load. At 1g it varies by 1-2Hz (depending on Q factor) and varies by a lower amount (~<0.5Hz) at lower frame accelerations.

Figure 7: Open Circuit Frequency Response at 1g.  
Figure 8: Peak power for different loads at 1g.

4. Summary
This paper reports a non-linear vibration energy harvester that has successfully been fabricated using ‘desktop’ 3D printing, demonstrating its potential to be exploited with the advent of the Internet of Things. The topology comprises an electromagnetic vibration energy harvester that exploits the low flexural modulus of ABS, in a non-linear configuration, to increase the bandwidth and power at low acceleration (25µW observed at 0.1g) and device volume. It has a mono-stable non-linearity and a softening spring response. The model and measurements are in agreement and demonstrate a peak power of 2.5mW at 1g. The up/down sweep maximum peak power frequencies lie in the range of 146-149Hz and a power bandwidth of 1.2→1.5Hz and 3.5→3.9Hz respectively are observed at 1g. This yields a power density of approximately 0.4mW/cm$^3$ at 1g.

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