A vibrating cantilever footfall energy harvesting device

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Abstract

Human footfall is an attractive source of energy for harvesting for low power applications. However, the nature of footfall is poorly matched to electromagnetic generators. Footfall motion is characterised by high forces and low speeds while electromagnetic generators are normally most efficient at relatively high speed. This paper proposes a novel mechanism for converting the low speed motion of footfall to a higher speed oscillating motion suitable for electromagnetic power generation. The conversion is achieved using a cantilever beam which is deflected by the footfall motion using a special 'striker' mechanism which then allows the cantilever to oscillate freely at a relatively high speed. An arrangement of permanent magnets attached to the cantilever cause an alternative magnetic field and a stationary coil converts this to a usable voltage. The paper describes the mechanism and provides a mathematical model of its behaviour which allows the system parameters to be optimised and its performance predicted. The performance of a prototype device is presented and it is shown that this is capable of generating up to 60mJ per step and that the conversion efficiency is up to 55%.

Keywords:

Energy Harvesting, Energy Scavenging, Footfall, Efficiency, Energy Conversion.

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Footfall energy harvesting devices

Various human activities offer the potential for energy harvesting with a wide range of available power levels and ease of conversion. Harvesting of energy from human sources was considered by Starner (1996) who concluded that available energy ranged from around 7mW from finger motion during typing to 67W for lower limb movement. This paper also considered the effect that extracting this energy would have on the subject and concluded that inconvenience to the subject could only be avoided if significantly lower power levels were extracted. A particularly attractive source of energy in this context is foot fall or heel strike since normal walking involves dissipation of significant energy in the shoe and walking surface and so the user might be unaware or unconcerned if some of this energy were converted to electrical energy. It may readily be calculated that a subject weighing 60kg must apply a force of at least 588N through the foot during walking (The peak force is typically 25% above body weight during walking and up to 2.75 - 3 times body weight during running (Trew & Everett, 2001)). If this is accompanied by a 10mm deflection of the floor or shoe, then the available energy is 5.88J and assuming one complete stride per second, an available power of 5.88W per foot.

Footfall occurs at an approximately fixed frequency but is characterised by a series of impacts rather than continuous motion. Given that power delivery during heel strike occurs in a small part of the overall gait period, a significant challenge is to devise mechanically robust devices able to convert the energy in an efficient manner without being large or heavy. Starner and Paradiso (2004) considered a number of shoe insert energy harvesting devices. They predicted that an insert constructed from 40 plies of PVDF positioned to extract energy from the flexing of a shoe sole should be capable of generating 5W when deflected by 5cm by a 52kg user. The device they constructed was smaller than that used as the basis for these predictions and possessed fewer PVDF layer. The measured peak power from this device was 15mW with an average, over the entire gait cycle, of 1.3mW. A second device, based on a PZT unimorph, was developed to capture energy from heel strike. This was found to deliver a peak power of 60mW and an average of 1.8mW. A further development of this device used two unimorphs arranged back-to-back and achieved an average power of 8.4mW. It was noted that this represented an efficiency of mechanical to electrical energy conversion of only around 1%. The efficiency of piezoelectric conversion is improved if the device is operated at its resonant frequency and so consideration has been given to methods to convert the low frequency footfall energy pulses to higher frequencies matched to piezo resonance. Antaki et al (1995) used a passive hydraulic pulse amplifier to effect this frequency conversion and obtained average power of up to 700mW during walking while Hagood et al, (1999) used an active valve to chop the hydraulic flow at the resonant frequency of a PZT resonator.

A heel strike device based on Electro Active Polymers (EAPs) capable of developing 0.8J/step, indicating a power of around 2W at normal walking speed if fitted to both feet has been reported in (SRI International, 2002) and (Pelrine et al, 2001). The durability of EAP materials has been a matter for concern (SRI International, 2002).

Electromagnetic conversion is probably the most well established method of electrical generation and electrical machines can offer a high level of efficiency. Given the design and material constraints imposed on electrical machines, they typically possess a limited range of speeds at which they operate efficiently. The majority of machines are most efficient when operated at high speeds and low force/torque. Thus there is an inherent mismatch with footfall which exhibits relatively high force but low average speed. One method for improving this matching is through the use of gears (Hayashida, 2000) but this introduces significant inefficiency and increasing the gear ratio used typically increases the losses. In addition, since gears do not provide any energy storage capability, the matching must be performed during the footfall impact. This implies that the gears must be capable of transmitting the full impact force. To be capable of handling such forces, gears generally need to be large and typically have associated large frictional losses.

One approach to ameliorate the problems associated with the high impact forces found in footfall is to attempt to store the energy so that the conversion between mechanical and electrical energy can be performed over a longer period, thus making use of physically smaller devices. Mechanical energy may be stored in springs, moving masses, in fluid flow or a fluid pressure vessel. Kymissis et al (1998) demonstrated a system composed of gears, a spring and flywheel used to drive a generator which was able to produce an average of 250mW from a 3cm deflection of the heel during normal walking. It was noted that this device was obtrusive for the user.

In addition to in-shoe energy harvesting devices, a smaller number of floor mounted systems have also been described in the literature, the majority of which are based around piezo conversion. The systems considered include an energy harvesting dance floor (Sustainable Dancefloor, 2013) and 'POWERLeap' which uses energy generated as people walk across a pavement to produce light (Powerleap, 2013).

Japanese Railways and Keio University have developed a ticket gate electricity generation system which relies on a series of piezo elements embedded in the floor under the ticket gates. A total of 90m^2 of piezo power generation mat were laid down in Tokyo station and the device was reported to generate 1mJ per step from a single generator (Takefuji, 2008). The design and performance of these systems is not presented in details in the literature.

A mechanism developed by the authors (Gilbert & Balouchi, 2014) based on mechanical analogues of electrical switched mode power supplies (Gilbert et al, 1996), has been used for harvesting footfall energy. In this device energy supplied during compression is stored in a spring and is transferred through a one-way clutch to a flywheel and generator. Since the impact energy is initially transferred only to the spring, it is not necessary to use such large and robust gears as would be required for direct conversion during the heel strike impact. The device allows a deflection of 10mm and is capable of producing an output energy of 45mJ per step.

The mechanism presented in this paper is based around a vibrating cantilever mechanism with electromagnetic conversion from mechanical to electrical energy. Cantilever based devices have been widely considered for the conversion of mechanical vibration to electrical energy, either using electromagnetic transduction (Glynn-Jones et al, 2004), (Shearwood & Yates, 1997), (Beeby et al, 2006) or piezoelectric materials (Sodano et al, 2004) however the authors are not aware of vibrating cantilever devices being used for footfall energy harvesting.

The aim of the work described in this paper is to achieve higher levels of output power while remaining unobtrusive to the user. The paper is organised as follows: the structure and operation of the device is presented and then a model of its behaviour, relating the input displacement to the output energy, is developed. This model is used as the basis for selecting system parameters to maximise the conversion efficiency. Experimental results for a prototype system, attached to a staircase, are presented. The behaviour of this system is discussed and the potential to increase the output energy outlined.

Proposed system

In order to achieve high conversion efficiency for footfall energy harvesting, a new mechanism is proposed. The proposed system consists of a cantilever beam, which is deflected as a result of the pedestrian footfall and then vibrates. This vibration causes a set of permanent magnets, attached near the end of the cantilever, to move relative to a stationary coil, causing the magnetic field to vary, thus inducing a voltage in the coil.

In order to produce the initial deformation of the cantilever a 'striker' or trigger mechanism, as shown in Figure 1 and Figure 2 is used. The striker is driven in a reciprocating vertical motion by the footfall and the tip of the striker follows an approximately trapezoidal trajectory, initially contacting the cantilever in its neutral position, forcing it downwards and then retracting to allow the cantilever to vibrate freely. Once the pedestrian's foot is lifted and the input moves back up, driven by a return spring, the striker tip bypasses the cantilever and is then re-primed owing to contact with the upper end stop. The cycle can then repeat.

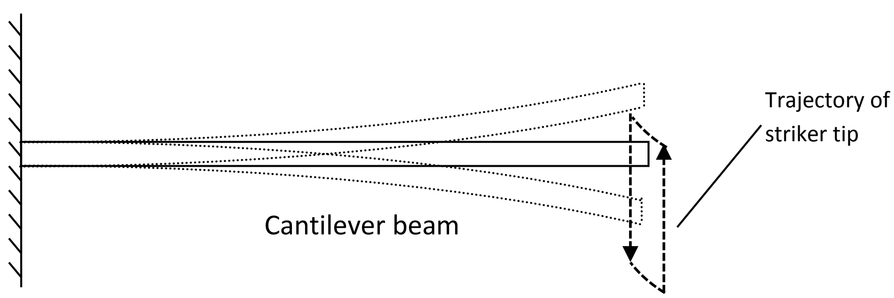

Figure 1 Cantilever and 'Striker' Mechanism Trajectory. The magnet and coil assembly are not included to aid clarity

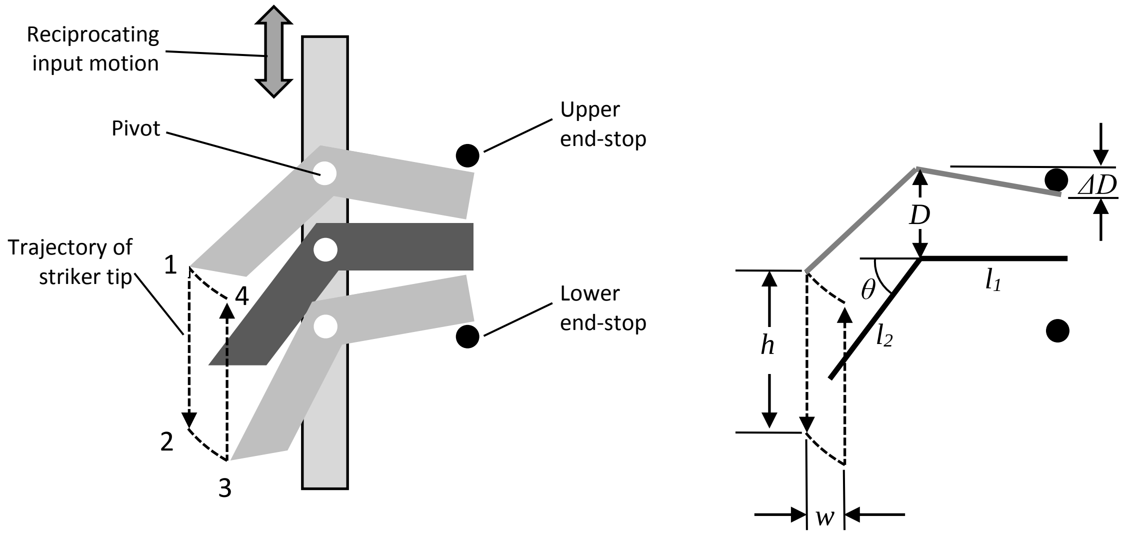

Figure 2 Striker Mechanism Structure and Dimensions

If the striker tip is initially in position 1 and the input is pushed downwards then the tip will move in a straight line to position 2, the lever will then contact the lower end stop and the tip will retract, moving along an arc to point 3. Once the input is allowed to return upwards, the striker tip will move in a straight line to point 4, at which point the lever will contact the upper end stop, forcing the tip back to position 1. Thus the trajectory of the tip is approximately trapezoidal.

To determine the range of movement of the striker tip, consider the dimensions shown in Figure 2, i.e. two links of length l_1 and l_2 offset by an angle θ with an input reciprocating distance of *±D* and end stops set symmetrically a distance *ΔD* less than the reciprocating distance. Also assume that $\Delta D \ll l_1$ so that the striker moves through small angles. The straight line segments of the trajectory (1→2 and 3→4) correspond to the case where the lever is not contacting the end stops. This matches the distance between the end stops, $2(D - \Delta D)$ and so the vertical side length $h = 2(D - \Delta D)$. The arcs (2→3 and 4→1) occur when the lever is in contact with the end stops and the striker is rotating around the pivot. Consideration of the trigonometry of the arrangement allows an expression to be derived for the width, $w \approx 2\Delta D \frac{l_1}{l_2} sin(\theta)$. Using these expressions, it is possible to choose the striker dimensions to maximise the cantilever deflection while producing sufficient horizontal movement, *w*, to ensure clearance between the striker and cantilever.

The generator (not shown in Figure 1) consists of permanent magnets mounted on a ‘U’ shaped bracket attached to the cantilever, with a stationary coil placed between them as shown in cross section in Figure 3. Alternatively, the coil may be mounted on the cantilever and move between stationary magnets.

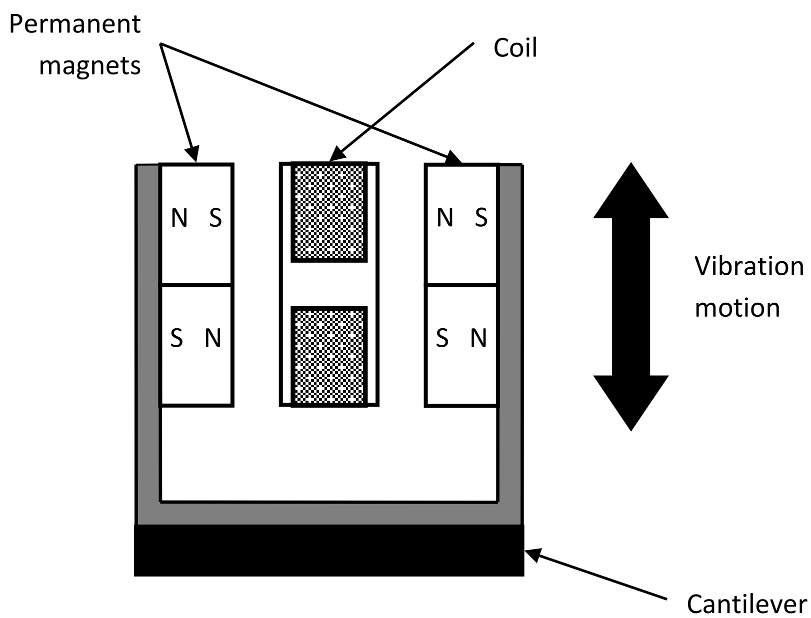

Figure 3 Generator attached to end of cantilever

Modelling and design optimisation

In order to predict the performance of this system and to guide the selection of system parameters, it is necessary to develop a dynamic model of the cantilever and generator. The first mode of vibration in a uniform cross section cantilever subject to small deflections may be described by the equation:

$$m_{eff}\ddot{x} = -kx - b\dot{x} \qquad (1)$$

Where *x* is the displacement of the cantilever tip, the effective mass is $m_{eff} = m_{tip} + {}^{33}/_{140}\, m_{beam}$. (Timoshenko, 1937) in which m_{beam} is the mass of the cantilever beam and m_{tip} the mass at the beam tip, *k* is the effective stiffness of the cantilever and *b* represents the damping.

The damping is composed of mechanical damping and damping due to useful electrical power being supplied to the load. The open circuit voltage induced in the coil is $V = k_e\dot{x}$ where k_e is the emf constant of the generator. Assuming the coil has a resistance R_C and is connected to a load resistance R_L then the current in the coil is:

$$i = \frac{k_e\dot{x}}{R_C+R_L} \qquad (2)$$

This causes a reaction force in the cantilever equal to $k_t i$ where k_t is the force constant of the generator, which is equal to k_e. The damping coefficient is thus:

$$b = b_m + b_e = b_m + \frac{k_e^2}{R_C+R_L} \qquad (3)$$

Where b_m is the mechanical damping coefficient and b_e the electrical damping coefficient. Thus the dynamics of the cantilever beam may be written as:

$$m_{eff}\ddot{x} = -kx - \left(b_m + \frac{k_e^2}{R_C+R_L}\right)\dot{x} \qquad (4)$$

For an initial tip displacement x_0 and zero initial velocity, Equation 4 may be solved for $x(t)$ as:

$$x(t) = \frac{x_0}{\beta} e^{-\omega\xi t} sin(\omega\beta t + \phi) \qquad (5)$$

Where $\omega = \sqrt{\frac{k}{m_{eff}}}, = \frac{\left(b_m+\frac{k_e^2}{R_C+R_L}\right)}{2\omega m_{eff}}$, $\beta = \sqrt{(1-\xi^2)}$, and $\phi = cos^{-1}(\xi)$. The velocity is then:

$$\dot{x}(t) = x_0 \frac{\omega}{\beta} e^{-\omega\xi t}\{-\xi sin(\omega\beta t + \phi) + \beta cos(\omega\beta t + \phi)\} \qquad (6)$$

Thus the velocity, and hence the generated voltage, is a decaying sinusoid.

Using Equations 2 and 6 and the fact that the power delivered to the load is $p(t) = i^2 R_L$, the energy supplied to the load following a single initial displacement is found to be:

$$E_{out} = \int_0^\infty p(t)dt = \frac{kx_0^2}{2} \frac{R_L k_e^2}{b(R_C+R_L)^2} \qquad (7)$$

Given that the mechanical energy initially stored in the cantilever is $E_{in} = \frac{kx_0^2}{2}$ it is straightforward to see that the efficiency of converting this mechanical energy to electrical energy is:

$$\eta = \frac{E_{out}}{E_{in}} = \frac{R_L k_e^2}{b(R_C+R_L)^2} \qquad (8)$$

Or, substituting from Equation (3)

$$\eta = \frac{E_{out}}{E_{in}} = \frac{R_L k_e^2}{\left(b_m+\frac{k_e^2}{R_C+R_L}\right)(R_C+R_L)^2} \qquad (9)$$

The load resistance for maximum efficiency can be determined from $\frac{dE_{out}}{dR_L} = 0$ as

$$\hat{R}_L = \sqrt{\frac{R_C(b_m R_C + k_e^2)}{b_m}} \tag{10}$$

And the peak efficiency is:

$$\hat{\eta} = \frac{\hat{R}_L k_e^2}{\left(b_m + \frac{k_e^2}{R_C + \hat{R}_L}\right)(R_C + \hat{R}_L)^2} \tag{11}$$

It is interesting to note that the optimum load resistance does not correspond to the matched load condition ($R_L = R_C$) used to give maximum power transfer or the matched damping ($b_m = b_e$) used in continuously excited vibration based energy harvesting devices (Beeby et al, 2006).

It may be seen that if $b_m \to 0$ and $\hat{R}_L \to \infty$ then $\eta \to 1$. Unfortunately, we cannot arbitrarily control the mechanical damping but should aim for a cantilever material which has a low loss coefficient such as spring steel (Ashby, 2010). For a given value of b_m it appears that we should aim to make R_C as small as possible and k_e as large as possible. A figure of merit for the generator system may be defined as:

$$\gamma = \frac{R_C}{k_e^2}$$

where we wish γ to be as small as possible. The relationship between γ, b_m and the efficiency is shown in Figure 4. It can be seen that the efficiency increases for decreasing γ and b_m.

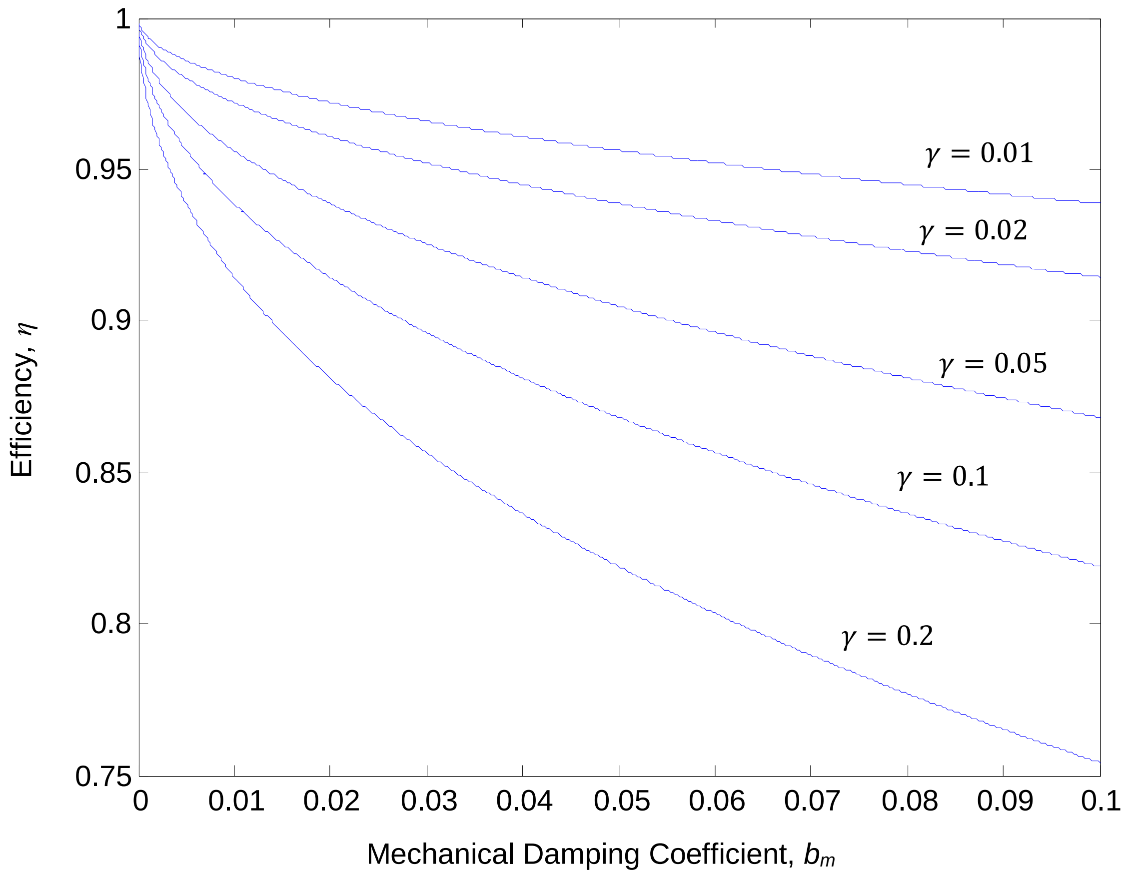

Figure 4 Effect of Mechanical Damping and gamma on Efficiency

Unfortunately, it is not feasible to control R_C and k_e independently since they are both determined by the coil configuration and the wire used. In particular, the value of k_e increases if the number of turns in the coil is increase but to fit a larger number of turns within a given size of coil, it is necessary to reduce the wire diameter and this, in turn, increases the resistance of the coil. For a given size of coil, the coil resistance is minimised if a low resistivity material is used for the wire while k_e is maximised if the coil operates in a strong magnetic field. Alternatively, γ may be reduced by increasing the size of the coil, provided the magnetic field is extended to cover all of the area in which the coil moves.

Experimental evaluation

A prototype cantilever system has been constructed as shown in Figure 5. In order to aid access, this is mounted on a staircase rather than under a floor. One step of the staircase is able to pivot and the striker mechanism is coupled to the step near its front edge. Thus the mechanism is actuated wherever the pedestrian stands on the step.

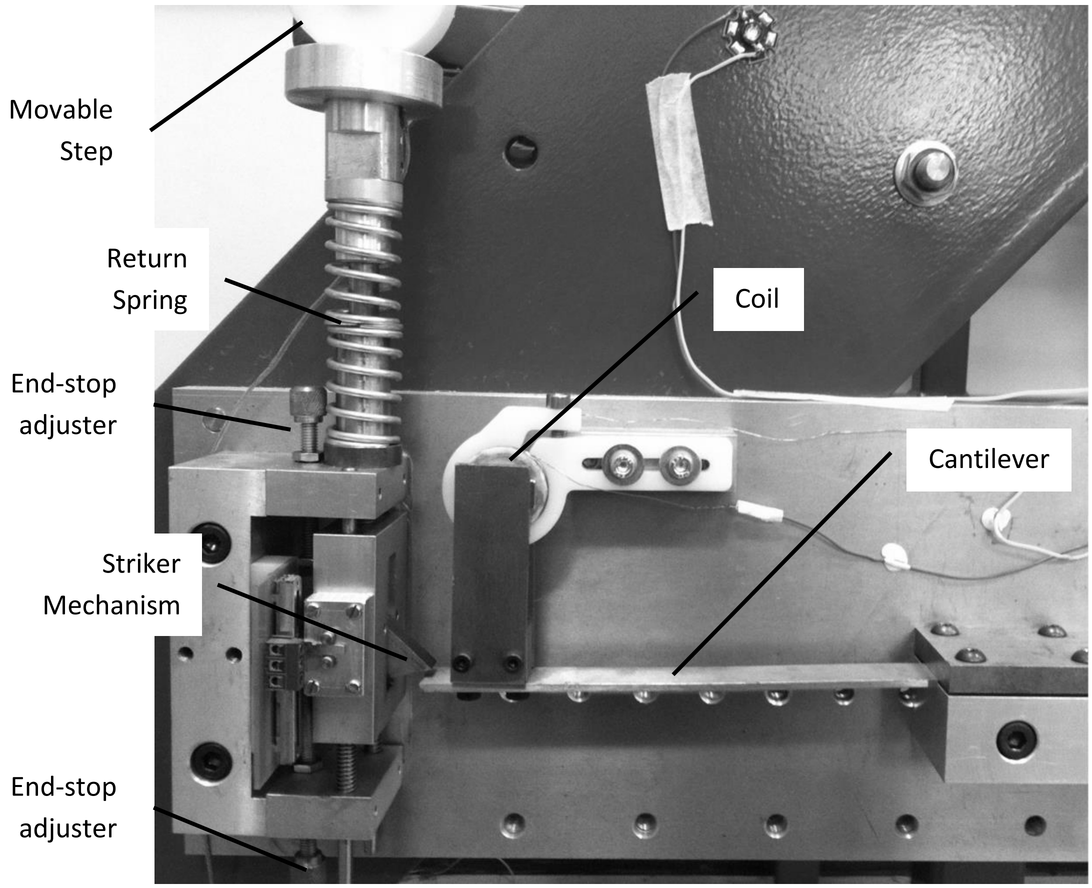

Figure 5 Prototype Cantilever System attached to Staircase

The characteristics of the system may be altered in that the cantilever length, thickness and material may be changed and the magnet and coil arrangement adjusted. The positions of the end stops can also be adjusted. The results discussed here are for the parameter values listed in Table 1. Three lengths of cantilever have been considered, as listed. These parameters have been derived using a mixture of direct measurement and fitting of simulated behaviour to experimental data. In the case of the mechanical damping ratio, a single figure is difficult to determine since, particularly for the shorter cantilevers, the striker causes deflection beyond the elastic region resulting in a large initial damping which then reduces once the deflection returns to the purely elastic region. The figures presented in Table 1 are representative of the overall damping behaviour. The parameters of the electrical generator are given in Table 2.

Parameter	**Symbol**	**Value**		
Cantilever Breadth	b	20mm		
Cantilever Height	h	3mm		
Cantilever Length	l	l_1 =127mm	l_2 =178mm	l_3=254mm
Initial deflection	x_0	5mm	10mm	11mm
Beam Input Energy	E_{in}	0.21 J	0.30 J	0.098 J

Resonant Frequency	ω	$\omega_1 = 299.2$	$\omega_1 = 174.5$	$\omega_1 = 89.2$
Mechanical Damping	ξ	$\xi_1 = 0.0227$	$\xi_2 = 0.0198$	$\xi_3 = 0.0049$
Spring Constant	k	17050 N/m	5980 N/m	1620 N/m

Table 1 Prototype System Parameters

Parameter	**Value**
Coil Diameter	30mm
Coil Length	12.5mm
Wire Diameter	0.35mm
Number of Turns	1100
Coil Resistance	11Ω
Effective Magnetic Field Strength	0.16T

Table 2 Generator Parameters

It can be seen that the shorter cantilever is stiffer and has a higher resonant frequency but also has higher damping. The initial displacement for the shorter cantilever is limited to avoid plastic deformation. The peak voltage generated is different for each cantilever due to the different resonant frequencies and displacements but is in the range 4-8V.

The electrical energy delivered to the load as a function of load resistance is shown in Figure 6. It can be seen that there is good agreement between the experimental and simulated behaviour. It can also be seen that the load resistance for maximum output energy is higher for the longer cantilevers which have lower mechanical damping, as predicted from Equation 11. The maximum output energy is approximately 60mJ for the 178mm long cantilever. If it is assumed that the stair is deflected once per second then the average power would be 60mW. Considering the volume of the cantilever and the generator, but excluding the striker, this corresponds to a power density of approximately 1000W/m^3 which is comparable to the estimated power density of other footfall harvesters described in the literature (Gilbert & Balouchi, 2008).

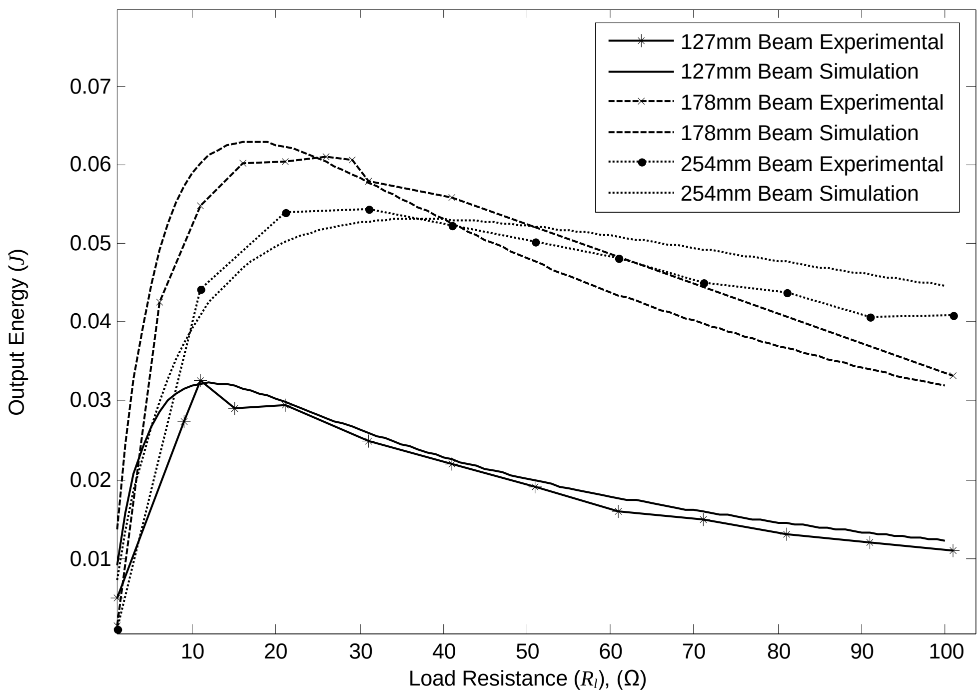

Figure 6 Experimental and Simulated Output Energy for Differing Length Cantilevers and Varying Load Resistance

Figure 6 shows the output energy for different cantilevers but, owing to the different cantilever lengths, and hence stiffness, the input energy in each case is different, as shown in Table 1. A more consistent comparison is provided by the efficiency plots shown in Figure 7.

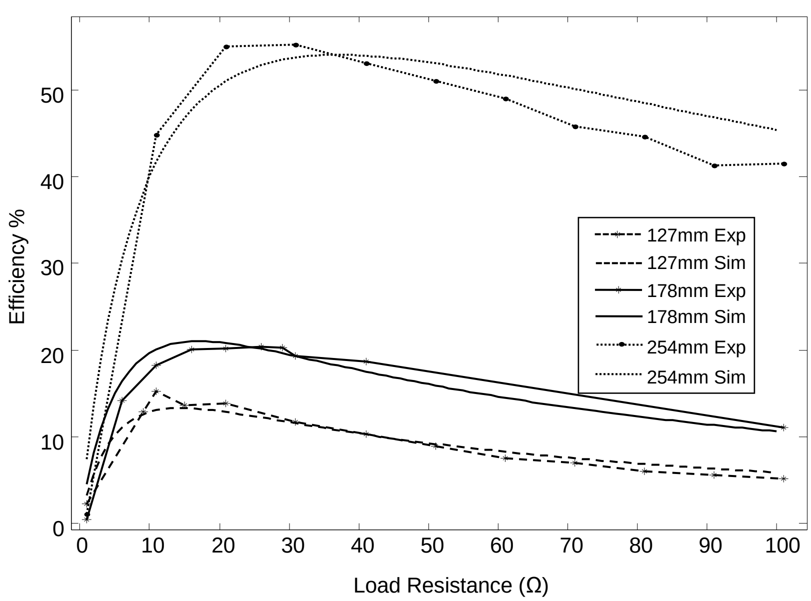

Figure 7 Efficiency for Differing Length Cantilevers and Varying Load Resistance

It can be seen that the longer cantilever provides significantly greater efficiency, up to a maximum of approximately 55%. It should be noted that this is the efficiency of the cantilever converter alone and does not include any losses in the mechanism coupling the striker to the floor/staircase. In the case of the prototype system described here, the losses in this coupling are significantly higher than losses in the cantilever itself and so the overall efficiency is poorer. However, the prototype was not designed to extract the maximum energy from users but re-design of the cantilever (as discussed in the next section) would allow greater energy capture and greater overall efficiency.

Discussion

Human footfall offers a significant amount of energy available for harvesting. If a pedestrian is assumed to weigh 60kg and the harvesting device undergoes a deflection of 10mm then the energy available in each step is approximately 6J, assuming a constant 60N is applied during the deflection stage. A more realistic situation is that the reaction force increases in proportion to the deflection and so the stored energy would be half of this value $\left(E = \frac{1}{2} force \times displacement\right)$ hence 3J. This is approximately 50 times greater than the maximum output energy achieved in the prototype device. There are two reasons for this disparity. Firstly, there are significant losses due to friction in the striker mechanism, however, the second reason is that the cantilever used was not designed to store this amount of energy and since storing potential energy is the first stage in the conversion process, if the cantilever cannot store the required energy, it will not be able to convert it.

The potential energy storage capacity of a cantilever beam depends on the volume of material and its yield strength. For a cantilever with uniform cross section, subject to a force applied at the free end, the maximum stored energy density is $\frac{Energy}{Volume} = \frac{\sigma_f^2}{18E}$ where σ_f is the yield stress of the cantilever material and E is it's Young's modulus (Ashby, 2010). In the case of spring steel, $\frac{\sigma_f^2}{E} \approx 10MJ/m^3$ (Ashby, 2010) and so a steel cantilever is capable of storing approximately *550kJ/m*^{3}. Thus, to store the 3J available for a typical pedestrian would require a cantilever volume of $5.5 \times 10^{-6} m^3$. This figure may be compared to the volume of the longest cantilever used in the prototype which has dimensions of $3mm \times 20mm \times 254mm$ giving a volume of $15 \times 10^{-6} m^3$. In the prototype, this beam receives approximately 100mJ and delivers 55mJ to the load. Given that it is easily capable of storing 3J, it may be inferred that it could deliver approximately 1.65J. Again, assuming a footfall rate of 1 step per second and considering only the cantilever and generator volume, this would correspond to a power density of 27500W/m^3, a figure which is well above any figure in the published literature (Gilbert & Balouchi, 2008). It may be that achieving such a high power density would not be possible since a greater power output would be require larger components in the generator but these figures indicate that further development of the device is worthwhile.

An interesting point to note is that in this device, the material of the cantilever performs a dual role: as a potential energy store (in the form of elastic deformation of the material) and as a kinetic energy store (in the form of a moving mass). This may be compared with the device described in Gilbert and Balouchi (2013), in which a spring is used as a potential energy store and a separate flywheel is used as a kinetic energy store. Using the same material to perform both functions suggests that the device described in this paper could achieve a higher energy density.

Conclusions

A novel device has been presented which is capable of converting human footfall into electrical energy in a simple and efficient manner. The system is composed of a cantilever beam which is made to vibrate by a striker mechanism. This striker mechanism is coupled to a movable stair as part of a staircase but could also be connected to a movable floor panel. The vibration of the cantilever causes movement of permanent magnets around a coil, thus generating electrical power. It has been shown that it is possible to model the behaviour of the system and identify parameters to maximise the efficiency of the energy conversion. Experimental results for the prototype system demonstrate that the device is capable of delivering an average power of 60mW and that the conversion efficiency of the cantilever mechanism can be as high as 55%. Analysis of the energy storage capacity of the cantilever indicates that this approach could offer significantly higher output power and power density than other footfall energy harvesters described in the literature.

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