Real World Testing Of A Piezoelectric Rotational Energy Harvester For Human Motion

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Abstract.

Harvesting energy from human motion is challenging because the frequencies are generally low and random compared to industrial machinery that vibrates at much higher frequencies. One of the most promising and popular strategies to overcome this is frequency up-conversion. The transducing element is actuated at its optimal frequency of operation, higher than the source excitation frequency, through some kind of catch and release mechanism. This is beneficial for efficient power generation. Such devices have now been investigated for a few years and this paper takes a previously introduced piezoelectric rotational harvester, relying on beam plucking for the energy conversion, to the next step by testing the device during a half marathon race. The prototype and data acquisition system are described in detail and the experimental results presented. A comparison of the input excitation, based on an accelerometer readout, and the output voltage of the piezoelectric beam, recorded at the same time, confirm the successful implementation of the system. For a device functional volume of \(1.85 \, \text{cm}^3\), a maximum power output of \(7 \, \mu\text{W}\) was achieved when the system was worn on the upper arm. However, degradation of the piezoelectric material meant that the performance dropped rapidly from this initial level; this requires further research. Furthermore, the need for intermediate energy storage solutions is discussed, as human motion harvesters only generate power as long as the wearer is actually moving.

1. Introduction

Energy harvesting from surrounding sources has been a popular area of research in recent years. Some industrially viable solutions have been presented for waste heat and machine vibration harvesting. A general overview of the field can be found in [1], whereas [2] gives a more specific introduction into piezoelectric devices.

Generating energy from human motion is of particular interest to power medical sensors and implants as well as sports devices such as heart rate monitors. Ideally, such systems should operate maintenance free and go unnoticed by the user for the majority of the time and therefore batteries are impractical. However, the main inhibitors are the low and random frequencies that we tend to move in. Frequency up-conversion offers a promising solution – the human excitation acts on a proof mass which then actuates a transducer in a way that it can freely oscillate at its natural frequency. The overall efficiency of conversion is increased because the transducer always operates at its ideal frequency, regardless of external excitation. Piezoelectric devices have been presented in [3] with two piezoelectric springs, in [4] for a direct-force knee joint harvester and in [5] for a linear beam plucking device with magnetic coupling. The device described in this...
article has most recently been discussed in [6], where an experimentally verified simulation model was introduced.

The goal of this paper is to show real world results of a miniaturized prototype worn during a half marathon running race. Testing in such an event gives the opportunity to analyse the performance in a tough environment and to collect data over a long period of time. It is also a significant step in confirming the feasibility of human energy harvesting outside a well controlled laboratory environment.

2. Prototype And Experimental Set-Up

The operation principle can be understood from figure 1. An eccentric proof mass is free to swing around its axis of rotation. The conversion of mechanical to electrical energy is achieved via a piezoelectric beam that is actuated at each pass of the rotor via magnetic coupling and then left to ring down. A photograph of the actual prototype with a £1 coin for size comparison can be seen in figure 2. The dimensions of the rotor match those of a Seiko Kinetic wristwatch and the reader will appreciate the simplicity and small number of parts necessary for this device.

The illustrations in isometric and section view, given in figures 3 and 4 respectively, further clarify the mechanical arrangement of the different components and the device size. The bearings taking the rotor shaft are both housed on the same side of the casing. As a result, the piezoelectric beam can occupy almost the entire diameter on the side of the perspex lid to give a free length of 19.5 mm. With a layer thickness of only 130 µm for each of the piezoceramic sides of the series connected bimorph, and a carbon fibre structural centre of 110 µm, the resulting natural frequency of the beam is around 400 Hz. Based on a measured capacitance of 3.1 nF a load of 150 kΩ was chosen as an impedance match for the power output measurements. The Q-factor of the beam is around 40 and the NdFeB permanent magnets (1 x 1 x 1 mm, strength N45) are in an advantageous repelling arrangement, based on findings in [6]. The total device volume is 5 cm³, at a weight of 10.5 g. However, the functional volume of the components involved in power generation, i.e. without the casing, is only 1.85 cm³.

The measurement system, shown in figure 5, comprises a three axis ADXL335 accelerometer and a Logomatic data logger that records the voltage output of the piezo at 2000 Hz sampling rate. Since, the accelerometer data does not need to be sampled at such a high rate, a separate Ardulog datalogger saves the three channels to a microSD card. This programmable board also controls the Logomatic to ensure that both sets of data are on the same timescale. After packaging and installing the harvester, this set-up was worn in a cell-phone sleeve on the
right upper arm during the race. The device orientation and the coordinate system of the accelerometer are shown in figure 6.

3. Results
Figure 7 shows a sample output of the accelerometer data. The x-axis clearly shows the influence of gravity, whereas the z-axis, being close to the rotational axis of the shoulder, sees very little excitation in comparison. The corresponding FFT in figure 8 confirms that the majority of source motion happens in the x- and y-directions at frequencies around 1 Hz and 2.5 Hz.

Figure 9 depicts the recorded piezo voltage starting at the same time as the accelerometer data but zoomed in further. Three consecutive actuations of the beam with the subsequent ring-down can clearly be recognized. The FFT in figure 10, taken over the middle one of those three actuations, proves that the low frequency excitation, as seen in figure 8, has successfully been converted to a much higher transducer frequency of about 400 Hz.

Finally, two challenges for the feasibility of human motion energy harvesting can also be distinguished from the gathered experimental data. First, the piezo voltage for an entire five minute measurement file of a pre race test is given in figure 11. The data logging system was
designed to make use of the entire ADC range, which causes a slight truncation of data at the top. However, this only affects a negligible portion of the first peak of the decaying waveform after each actuation. More importantly, there are large gaps in the voltage around a time between 100 s and 150 s. This is not a malfunction of the device; the gaps occurred while stopping at a red traffic light to cross the street. Obviously, if the wearer is not moving, no energy can be harvested and this graph clearly illustrates the need for intermediate energy storage solutions to overcome those downtimes, if sensors are required to operate continuously. Second, the average power output for each of the data files is plotted over time in figure 12. Starting from a decent power output of 7 µW, the performance dropped very rapidly to then level out at about 0.5 µW. Examination of the prototype did not show any signs of wear on the mechanics of the device and thus the decrease in power output is a result of degradation of the piezoelectric material. More recent findings suggest that this is due to an excessive initial deflection of the beams before release which can be alleviated by further separating the magnets and consequently weakening the coupling. However, further investigation on this topic is required.
4. Conclusions
This paper reports the first real world experimental data of a rotational piezoelectric energy harvester for human motion. The mechanics of the prototype and the portable data collection system are described. The device uses the principle of frequency up-conversion to transform the random low frequency excitation of a runner into a higher transducer frequency by magnetically plucking a piezoelectric beam. This has the potential for increased efficiency of power generation.

The successful operation of the up-conversion is verified through comparison of an FFT analysis on the output voltage waveform of the harvester and three axis accelerometer data recorded simultaneously.

Identified challenges for successful implementation of human motion energy harvesting in the future are the degradation of device performance over time and the need for intermediate energy storage, e.g. rechargeable batteries or capacitors, to overcome downtimes of the power generation when the wearer is not moving.

Nevertheless, these results are encouraging because the mechanics of the device with its contact-less coupling did not show any signs of wear after the testing and, with a functional volume exactly the same as that of a Seiko Kinetic harvester, a peak power output of 7 µW was achieved – enough to power a wristwatch or other novel sensors for health monitoring.

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