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A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications☆

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ABSTRACT

Energy harvesting from human motion faces the challenges of low frequency and random excitation. One strategy that has been successful in the past is frequency up-conversion. This paper introduces an inertial device that combines this principle, in the form of piezoelectric beam plucking through magnetic coupling with a rotating proof mass. The advantages rotational systems can have for body movements are discussed. The prototype is described and tested in a real world environment during a running race and later on in a laboratory environment on a custom built linear excitation table. Throughout these tests it is confirmed that such a device can operate over a broad range of frequencies and under varying orientations, making it suitable for this intended application. Across frequencies between 0.5 and 4 Hz and accelerations between 1 and 20 m/s^2 power outputs in the range of tens of microwatts were achieved, with a peak value of 43 µW at 2 Hz and 20 m/s^2 when the rotor went into a continuous rotation.

1. Introduction

The advances in miniaturization of electronic components and devices are opening more applications for the placement of sensors on and inside the human body. Monitoring body functions such as the vital signs, i.e. breathing, heart rate, blood pressure and temperature, or blood oxygenation and glucose levels are highly interesting from a medical point of view for fighting diseases and targeting treatment. Automated drug delivery systems can be combined with sensing devices to optimize the amount of medication administered and reduce adverse effects. Another field for such sensors is athletics, where detailed knowledge about the body's response to training stress can help push athletes to better performance. Measuring the sweat pH, for instance, gives a clear indication on the risk of dehydration and the loss of electrolytes. Furthermore, the worry about increasing obesity and the advent of activity trackers such as the fitbit® or Jawbone Up wristband suggest a general trend for these devices to become more and more part of our lives.

One thing all of these systems have in common is that they rely on battery power. This becomes a problem when the number of sensors increases and can, in the worst case require intrusive surgery for replacement. Energy harvesting is an often discussed alternative that could relieve the maintenance burden. The most available local energy sources for human applications are solar illumination and temperature gradients, which can work well for body mounted devices, and motion, mostly from the limbs. General overviews on energy harvesting can be found in [1–3].

The main challenge that motion harvesters need to address is the low frequency and random movement of the body as discussed in [4,5]. In addition, the motion range is usually much larger than the intended device size, and so resonant designs cannot provide the advantage of dynamic magnification. Different approaches are needed for efficient power generation from human motion.

Rotational devices are promising for this application as they can accept linear and rotational excitations and are less gravity dependent. An example of an electromagnetic harvester with eccentric proof mass is introduced in [6]. Probably the most prominent device in this category is the Seiko "Kinetic" self-powering wristwatch. Seiko built upon their knowledge of mechanical self-winding mechanisms but instead of storing energy in a spring they used an electromagnetic micro generator to convert the mechanical energy from the rotor into electrical energy. The drawback is that this design requires a complex gear train to increase the rotational speed of the generator, otherwise the output voltages would be too small. Based on an assumed power consumption of 1.25 µW for the watch movement and with additional information from the maintenance data sheet [7], an average power output of 5 µW appears to be a reasonable estimate for this system.

In addition, the frequency up-conversion principle has recently seen a lot of interest for harvesting low frequency motion. While

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the proof mass is put in motion by a low frequency external acceleration, the transduction mechanism is actuated at its natural frequency through a catch-and-release or plucking mechanism. The main advantage of this strategy is that the actual energy conversion always happens at an optimal frequency, no matter what the excitation frequency is. This favours an increase in conversion efficiency – crucial when dealing with the low kinetic energy available in these devices. One such device based on piezoelectric beams actuated by teeth with an attached roller can be found in [8]. A magnetic mechanism that latches onto the transducer initially and then releases it was used for an electromagnetic device in [9], and for a piezoelectric version by the same group in [10]. More specific to human motion harvesting, a plucked beam rotational knee joint harvester was presented in [11,12]. This device, however, uses a direct force mechanism and as such needs two attachment points on the body. Most of these devices can cause damage to the piezoelectric material, especially the impact driven designs presented in several different versions in [13–15]. Further examples of this principle have been presented in [16] and in [17] for a MEMS device. The risk of damage to the piezoelectric material has been counteracted by the introduction of magnetic coupling systems with permanent magnets, such as [18,19] and the piezoelectric windmill in [20]. In [21] one of the permanent magnets is replaced by a structured magnetic material. Previously, the authors presented a linear device on the plucking principle in [22].

The purpose of this paper is to introduce experimental results on a rotational piezoelectric harvester for human motion, working on the beam plucking principle. The device uses magnetic coupling with two permanent magnets, as investigated in [23], and the eccentric proof mass has the shape of a half disc. The gravitational and inertial operation modes of this system will be briefly discussed and the results gathered during a test at a half marathon race and on a custom built laboratory shaking set-up presented.

2. Rotational devices for human motion

Based on experience with the linear device presented in [22], the authors believe that rotational structures do have advantages for human motion. The first device used a rolling rod as a proof mass and actuator, plucking piezoelectric beams. While the results were promising, this system can only work well in environments where the device orientation is known, for example for bridge monitoring. In the human body this is not the case and if the device is tilted too far, the rolling rod will simply remain at the lowest point, and no energy will be harvested at all.

Fig. 1 shows a basic model of the operating principle of the current device. An eccentric proof mass is free to rotate around its axis and carries a permanent magnet. A piezoelectric beam is fixed on the outer casing (not shown in this figure) such that its tip, with a second permanent magnet, is facing the magnet on the rotor. Under external excitation the rotor will move and swing its magnet past the tip magnet on the beam, which causes an initial deflection of the beam tip. After release, the beam rings down at its natural frequency and electrical energy can be extracted.

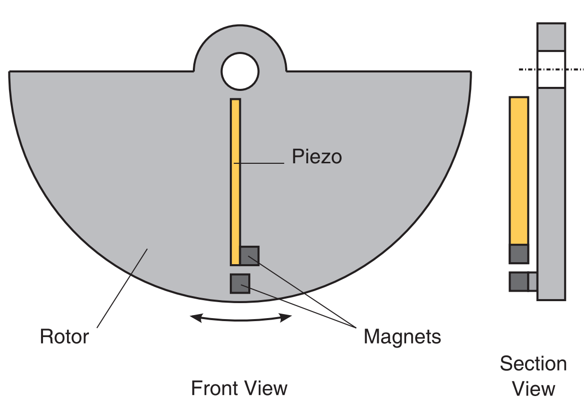

Fig. 1. Principle of operation of the rotational beam-plucking energy harvester.

A further advantage of this rotational set-up is that the proof mass has no inherent motion limit, it can continuously rotate depending on the excitation. An investigation on rotational and gyroscopic proof masses for energy harvesting was introduced in [24] and the absolute maximum power for such a device, based on the kinetic energy stored in the proof mass, was found to be:

$$P_{max} = \frac{\omega^3 \Omega_0^2}{4} I \quad (1)$$

with ω the angular excitation frequency, Ω_0 the excitation amplitude and I the mass moment of inertia of the rotor. For a semi-circular proof mass of constant thickness and density, $I = mR^2/4$, with m being the total mass and R the radius. As discussed for the very similar linear case in [2], this equation assumes that the rotational acceleration is constant and maximal over the whole travelled angle. This is why (1) represents an absolute maximum and the achievable power in practical terms will be lower.

To further the understanding of the dynamic behaviour of this system, the configuration depicted in Fig. 2 was studied. Essentially, a point mass at a distance r from its axis of rotation (the z-axis in this figure) is considered under gravity and external excitation. The distances r_x and r_y describe the proof mass position and F_x and F_y are the corresponding inertial reaction forces caused by linear external excitation. Gravity g acts in the negative y-direction. The angle γ is the angular deflection of the proof mass in relation to the y-axis. The angle α represents rotational base excitation, i.e. rotation of the device enclosure, and β is the resulting angle between the mass and the inertial frame, i.e. the one that determines the capability of harvesting energy from the relative motion, with $\gamma = \alpha + \beta$.

In a first analysis, ignoring the effects of damping and the transduction mechanism, the basic equation of motion for rotation states that the angular acceleration $\ddot{\gamma}$ multiplied by the mass moment of inertia I equals the sum of all n external moments M_i acting on the mass:

$$\ddot{\gamma} I = \sum_{i=1}^{n} M_i \quad (2)$$

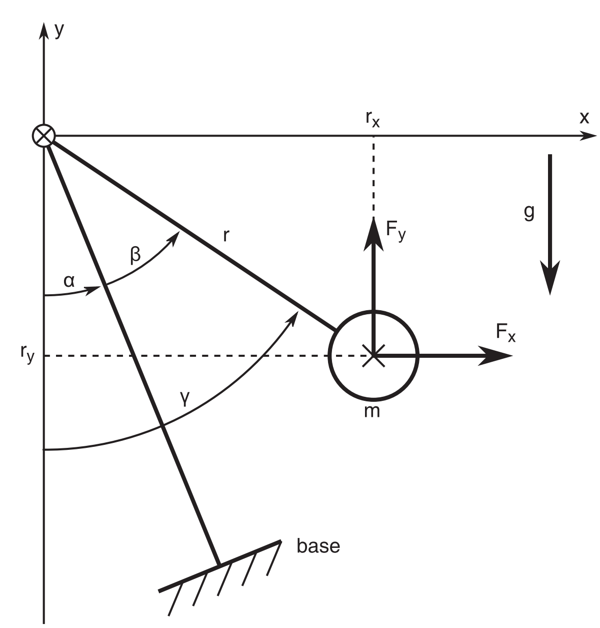

Fig. 2. Schematic view of an eccentric proof mass under external excitation.