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Investigation of a cantilever structured piezoelectric energy harvester used for wearable devices with random vibration input [☆]

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ABSTRACT

The capability of using a linear kinetic energy harvester – A cantilever structured piezoelectric energy harvester – to harvest human motions in the real-life activities is investigated. The whole loop of the design, simulation, fabrication and test of the energy harvester is presented. With the smart wristband/watch sized energy harvester, a root mean square of the output power of 50 μW is obtained from the real-life hand-arm motion in human's daily life. Such a power is enough to make some low power consumption sensors to be self-powered. This paper provides a good and reliable comparison to those with nonlinear structures. It also helps the designers to consider whether to choose a nonlinear structure or not in a particular energy harvester based on different application scenarios.

1. Introduction

Energy harvesting technologies are considered to be able to provide a power source to wearable devices by converting ambient light, heat in the environmental or human body and/or human body motion into electricity [1]. Interestingly, a human body can provide kinetic and thermal energy in daily activities which can be harvested to generate useful electrical energy for low power consumption devices (e.g. biomedical devices and health monitoring sensors) [2]. The wearable electronics powered solely by the biomechanical energy has been developed [3]. Also, the bio-thermal energy has been proved useful for micro-power electricity generation [4]. Among the available energy sources to be converted, the human body motion has drawn a lot of attention, due to the rich kinetic energy source generated by one's body in daily life, e.g. walking, running, working, etc. [5]. For example, a system designed with a plucked piezoelectric bimorphs can be used to harvest the energy in the knee-joint area [6]. An individual resonator with the same structure can also be used to harvest energy in the head area [7]. Recently, a completely self-powered artificial cochlear implant has been developed using the energy harvesting system as the sole power supply [8].

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A number of energy conversion principles, including electromagnetic, piezoelectric, electrostatic, triboelectric, etc., are able to convert kinetic energy into electricity [9]. The structures of the energy harvesters based on these working principles belong to the spring-mass physical model [1]. Therefore, they only work efficiently at or around their resonant frequencies (eigen frequencies). Even a slight change of the input frequency (as small as 5% [10]) which shifts away from the resonant frequency will cause a drastic drop of the output of such an energy harvester. Unfortunately, the kinetic energy in a harmonic vibration with a fixed frequency does not easily exist in practice. The machinery vibrations usually contain secondary frequencies or the frequencies are usually subject to change [11]. The kinetic energy on human bodies are random vibrations in most cases with no stable frequency available. In order to address the issue of the narrow working frequency range of the kinetic energy harvesters, a lot of efforts on the investigation of nonlinearity of electromagnetic and piezoelectric energy harvesting structures have been made [12–15]. The developed nonlinear structures help to widen the working frequency to a large extent, and even make the kinetic energy harvesters to be able to work under a random vibration environment [16]. Meanwhile, the kinetic energy harvesting systems have to be excited by the maximum possible accelerations and amplitudes in order to achieve the largest possible output power [17]. The limbs may have the largest accelerations and amplitudes and thus to generate the largest amount of kinetic energy on the human body when they are moving around [18].

Although in some cases the working frequency range of a kinetic energy harvester can be widened by employing certain nonlinear effect, the design space which can be used for the energy harvester itself in a device to be powered is usually limited (up to 50% of the whole device) [19]. However, the nonlinear approaches may introduce additional components to the energy harvesters, which lead to effectively reduced sizes of the energy harvesting components [15,16]. In fact, when tested using the real data of a machinery vibration, the nonlinear structure does not necessarily outperform its linear counterpart, because of the compromise of the peak output power on the nonlinear structure [11]. Due to such a reason, when researchers are focusing on the development of nonlinearity of the kinetic energy harvesters, it still remains unclear that how in fact a linear kinetic energy harvester may perform and how much energy such a harvester can provide with a human body in the daily life and without the nonlinear supportive structures. It will be interesting to see a comprehensive test in real time in order to answer these questions. Such a test will provide a clear view of the gap existing between the energy harvesting capabilities of the linear and nonlinear energy harvesters. It will also give a judgement of the added value, advantageous and disadvantageous of using a nonlinear structure in a kinetic energy harvesting.

With the purpose presented above, this paper reports a design, simulation, fabrication and testing of a linear kinetic energy harvester used for human motion energy harvesting. A piezoelectric cantilever with a tip mass – the simplest possible structure and smallest possible normalised size a kinetic energy harvester can have – is worn on the wrist and head of a volunteer. The data of the output power generated when the volunteer is doing daily activities are collected and analysed.

It should be noted that, in order to obtain the maximum output power harvested from the common daily activities, the piezoelectric material used in the cantilever has to be specially tuned. The output voltage, output power and energy conversion efficiency of the piezoelectric energy harvesters are usually very sensitive to the compositions of the piezoelectric materials and the processing methods used in the fabrication of the piezoelectric components [20]. Most of the piezoelectric energy harvesting components used in research and commercially available are made from 'soft' PZT (lead zirconate titanate), e.g. PZT-5H [5]. PZT-5H is a composition developed for sensors and transducers [21]. However, it is not considered a composition specially tailored for energy harvesting applications, as it usually has relatively low values of g (piezoelectric voltage coefficient) and/or $d \cdot g$ (figure of merit), which are crucial parameters affecting the output capabilities of piezoelectric energy harvesters [20]. In order to achieve better energy harvesting capabilities, the piezoelectric compositions need to be carefully tailored in order to maximise the values of g, $d{\cdot}g$, k_{eff} (effective coupling coefficient) and Q_M (mechanical quality factor). This is complicated but extremely important when applying piezoelectric energy harvesters in the field of human motion, as the theoretically available input energy will be rather small and unstable, and any energy losses, including those of the energy converting materials, need to be minimised.

2. Experimental and simulation

2.1. Design of the piezoelectric energy harvester

A piezoelectric cantilever with a tip mass provides the simplest design of the mechanical resonator, with the smallest number of influential factors on the output voltage, output power and energy conversion efficiency. This structure was selected in this investigation. Due to such a simple design, the original capability of harvesting the human motion by a linear piezoelectric energy harvester can be revealed. Fig. 1 shows the basic structure of the piezoelectric energy harvester used in this paper, consisting of a beam clamped on one end (a cantilever) or both ends, piezoelectric layers on both sides of the beam (forming a bimorph) and a proof mass attached on the tip of the beam. The piezoelectric layers were poled along the direction perpendicular to the beam, and thus working in the 3–1 mode [22]. The shape of the cantilever is another important factor to be considered in the design. However, although a trapezoidal shape of the cantilever could provide the best mechanical coupling [23], the rectangular shape was still selected in this paper, as it could provide the largest possible area of the piezoelectric layers in a limited size and thus to generate the largest possible peak output power. The harvester was clamped on a base which was fixed on the human body (wrist and head in this paper). The acceleration of the body movement provided a relative displacement to the tip mass and then inducing a deformation of the piezoelectric layers.