Investigation of Pendulum Structures for Rotational Energy Harvesting from Human Motion

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Abstract. Energy Harvesting from human motion as a means of powering body-worn devices has been in the focus of research groups for several years now. This work presents a rotational inductive energy harvester that can generate a sufficient amount of energy during normal walking to power small electronic systems. Three pendulum structures and their geometrical parameters are investigated in detail through a system model and system simulations. Based on these results a prototype device is fabricated. The masses and angles between pendulum arms can be changed for the experiments. The device is tested under real-world conditions and generates an average power of up to 23.39 mW across a resistance equal to the coil resistance of the optimal pendulum configuration. A regulated power output of the total system including power management of 3.3 mW is achieved.

1. Introduction

Body-worn devices are becoming increasingly popular as they can perform a wide range of tasks from fitness and health tracking to ambient assisted living or simply as fashion accessories. The power supply issue however has not been satisfactorily solved to this date as the devices require periodic recharging. Energy harvesting (EH) from human motion offers a potential solution to this problem. EH devices are continuously getting smaller and can thus be integrated more easily into clothing items.

However, previously reported devices generate average powers in the low milliwatt range [1–3] and many devices are not fully characterised under real-world walking conditions [4]. Additionally, previous rotational devices have used a single eccentric mass to couple external motion into the rotating system [4–6]. In contrast this work analyses the influence of the geometrical parameters of the three-armed pendulum on the energy that can be coupled into the system and consequently the energy that can be provided for an electronic system.

The first part of this work focuses on the theoretical analysis of three pendulum structures and their ability to couple human leg motion into the rotational system. Of the three investigated structures the most feasible setup with the highest power output is chosen and a prototype is fabricated. This device consists of three pendulum arms with a proof mass attached to each of them and an adjustable angle between the arms. Different angular positions are characterised experimentally and the proof mass is varied.
2. Theoretical analysis

2.1. External acceleration conditions
Before developing the system model, a range of measurements was performed to obtain the accelerations that occur at different body locations and varying walking speeds. Three subjects walked on a treadmill at speeds of 4, 6, 8 and 10 km/h. This data is used as an excitation source in the simulations.

In order to compare the different body locations (an exemplary acceleration curve is shown in Figure 1 (a)) the RMS acceleration was calculated from the acceleration data. Figure 1 (b) indicates that the lower body locations might be the most suitable positions for energy harvesting from low-frequency, large-amplitude motions. A system model is developed in order to estimate the power output for all body locations.

![Figure 1](image1.jpg)

**Figure 1.** (a) Acceleration along the x-axis at the ankle for subject KY on a treadmill at 6 km/h. (b). RMS accelerations calculated from acceleration measurements on a treadmill at different body locations and walking speeds. The insert shows the axis orientation with the x-axis pointing forward at standstill

2.2. System model
In this work pendulum structures with three pendulum arms are investigated. The length of the pendulum arms, the angle between the arms, as well as the proof mass attached to each arm can be varied. In the first of three configurations, PEH1, the angle between pendulum arms is fixed. In the second configuration PEH2 the arms are connected by springs, thus the angle between arms can change dynamically during operation. Lastly, in PEH3 the angle is fixed, but the proof masses are spring mounted, i.e. the length of the pendulum arms can vary dynamically during operation. The schematic of each configuration is shown in Figure 2.

![Figure 2](image2.jpg)

**Figure 2.** Schematic of the three-armed pendulum. From left to right: PEH1-PEH3. Relevant parameters are shown. The theoretical analysis also includes the dynamic variation of radii and angles during rotation in the case of PEH2 and PEH3 respectively.
The equations of motion are derived for each configuration, based on the moments acting on the pendulum arms. As an example, the equations for PEH1 are given below.

\[ J\ddot{\varphi} = -c\dot{\varphi} + \sum M_g + \sum M_{Ax} + \sum M_{Az} \quad (1) \]

\[ \sum M_g = -g m_1 r_1 \cos(\varphi - \alpha_1) - g m_2 r_2 \cos(\varphi) - g m_3 r_3 \cos(\varphi + \alpha_2) \quad (2) \]

\[ \sum M_{Ax} = A_x m_1 r_1 \cos(\varphi - \alpha_1) + A_x m_2 r_2 \cos(\varphi) + A_x m_3 r_3 \cos(\varphi + \alpha_2) \quad (3) \]

\[ \sum M_{Az} = -A_z m_1 r_1 \sin(\varphi - \alpha_1) - A_z m_2 r_2 \sin(\varphi) - A_z m_3 r_3 \sin(\varphi + \alpha_2) \quad (4) \]

\[ J = m_1 r_1^2 + m_2 r_2^2 + m_3 r_3^2 \quad (5) \]

2.3. Simulation results

In order to find the optimal geometry for each PEH, the RMS number of rotations per second “OmegaRMS” is introduced. It is used as a measure of how much motion is coupled into the rotational system and serves as the target function of an optimisation algorithm before the transduction mechanism is modelled.

Using the system model for each PEH, an optimization is performed with the following boundary conditions: The radii are limited from 5 mm to 25 mm and the proof masses from 5 g to 25 g per pendulum arm with a step size of 1 mm and 1 g respectively. The angles \( \alpha_1 \) and \( \alpha_2 \) are static in the case of PEH1 and PEH3 and can range from 0° to 180° in steps of 5°. Hence, in the case of \( \alpha_1 = \alpha_2 = 0° \), a single-arm pendulum is calculated. Figure 3 (a) shows the optimal design for one particular motion speed of PEH1 and it can be seen that each design is only optimal for one motion speed (each line is above all other lines at only one speed). Figure 3 (b) compares the optimal design of PEH1 and PEH3 for the second runner: DH. It can be noticed, that PEH3 shows a minor advantage in the average number of rotations over PEH1. However, the PEH3 optimal design found by the optimisation algorithm is “unfeasible” with respect to the spring expansion which reached values larger than 50 cm from the starting point of 2.5 cm. The optimal design of PEH2 was identified as an unfeasible design, because the angle between pendulum arms reached large values (effectively winding the spring around the rotational axis). Consequently, the spring-less pendulum PEH1, is found to be the most feasible design with the highest power output that can be implemented as a human motion harvester.

![Figure 3](image_url)

**Figure 3.** (a) Comparison of the optimum designs calculated for each particular motion speed for subject KY. Each line represents one design. (b) Comparison of the average number of rotations per second for PEH1 and PEH3 and subject DH.

Focusing on PEH1, an electro-magnetic transduction mechanism is modelled according to Figure 4. It consists of 8 segment magnets with a 45° arc each, which when placed next to each other (in alternating polarisation) form a ring. The magnets are linked to the pendulum and perform the same rotation. A total of 8 coils are placed in a way that all coils observe a change in flux density at the same time, as the magnets pass across them. Table 1 shows the simulated maximum average power output at the most suitable location on the lower body (ankle) and upper body (wrist). The geometrical boundaries used to find the designs that generate the shown power output are: pendulum arm lengths no longer than 25 mm and a combined proof mass of 75 g. For both test subjects the highest power
output is simulated with acceleration data obtained from the ankle which is the only body location considered henceforth. Although each power output in Table 1 is based on a separate optimal design calculated for that particular walking condition, the tendency of the system parameters remains constant throughout the simulations. The best designs tend to have the maximum proof mass of 25 g per pendulum arm and the maximum allowed arm length of 25 mm. The optimum magnet height is calculated to be 5 mm and the optimal coil height ranges between 3 and 3.5 mm. The angles between pendulum arms range between 0° and 10°, indicating that the largest power output can be achieved when the three pendulum arms and thus the three masses are overlaid to effectively form a classic single-armed pendulum. This can be explained by the fact that in this case, the system's centre of gravity is the furthest from the rotational axis and consequently the external acceleration can act on the largest possible lever.

Table 1. Simulated maximum average power output for different conditions and maximum pendulum arm lengths of 25 mm and a total proof mass of 75 g.

|                | Runner KY | Runner DH |
|----------------|-----------|-----------|
|                | 4 km/h    | 6 km/h    | 4 km/h    | 6 km/h    |
| Ankle \(P_{RMS} [mW]\) | 10.46     | 16.4      | 6.62      | 9.11      |
| Wrist \(P_{RMS} [mW]\)    | 0.36      | 2.51      | 0.16      | 0.19      |
| Ankle \(\omega_{RMS} [1/s]\) | 3.55      | 4.37      | 2.77      | 3.26      |
| Wrist \(\omega_{RMS} [1/s]\) | 0.63      | 1.73      | 0.4       | 1.06      |

3. Experimental evaluation

An adjustable prototype was fabricated for the experimental verification of the previously calculated best theoretical designs for PEH1 (Figure 5 (a)). The device consists of three pendulum arms with proof masses of 26 g each (high-density wolfram alloy, 18 g/cm³). The angle between pendulum arms can be adjusted in steps of 15° and the proof masses are removable. Segment magnets with an inner radius of 5 mm, outer radius of 19 mm, height of 5 mm and arc of 45° according to Figure 4 were used. The coils have inner and outer diameters of 3 and 10 mm and a height of 3 mm (~80 Ω/coil).

A total of 7 setups was characterised with two test subjects on a treadmill. The parameters of each setup as well as the average power output across a resistance equal to the total coil resistance are shown in Table 2. The pendulum arm length is 25 mm for all setups.

Table 2. Average power output for the prototype device based on PEH1 and seven different configurations as measured during treadmill runs with two subjects.

| Setup | Geometrical Parameters | \(P_{RMS} [mW]\), Runner: DH | \(P_{RMS} [mW]\), Runner: KY |
|-------|------------------------|-----------------------------|-----------------------------|
|       | \(\alpha_1\), \(\alpha_2\), \(m_1\), \(m_2\), \(m_3\) | 4 km/h | 6 km/h | 4 km/h | 6 km/h |
| 1     | 0°, 0°, 26 g, 26 g, 26 g | 8.47 | 23.39 | 9.04 | 22.16 |
| 2     | 0°, 180°, 26 g, 26 g, 26 g | 3.55 | 5.04 | 2.91 | 4.54 |
| 3     | 90°, 90°, 26 g, 26 g, 26 g | 3.84 | 5.09 | 6.16 | 8.41 |
| 4     | 15°, 15°, 26 g, 26 g, 26 g | 9.11 | 16.92 | 9.09 | 19.79 |
| 5     | 0°, 0°, 26 g, 26 g, 0 g | 10.77 | 10.87 | 7.19 | 12.87 |
| 6     | 0°, 0°, 26 g, 0 g, 0 g | 8.92 | 11.13 | 5.98 | 11.8 |
| 7     | 90°, 0°, 26 g, 26 g, 0 g | 7.34 | 9.14 | 10.24 | 12.88 |
Additional measurements were performed to determine the net average power into a supercapacitor by using a power management circuit consisting of a full-bridge rectifying circuit, an overvoltage protection, a 0.25 F supercapacitor and hysteresis regulation as presented in [7]. A total of 213 s was required to charge the capacitor from 0 V up to 3 V where the regulated voltage output is enabled by the hysteresis control and the consumer system can start operating. The voltage at the capacitor (measured during fast outdoor walking) is shown in Figure 5 (b). The average consumed power at which a regulated voltage output of 3V can be maintained is 3.3 mW.

Figure 5. (a) Prototype device attached at the ankle with two of three proof masses mounted on the pendulum arms. (b) Voltage at a 0.25 F supercapacitor being charged during fast outdoor walking (approximately 6 km/h, runner: DH)

4. Conclusion
The previous sections confirmed that the classic one-armed pendulum is the most suitable of the three investigated pendulum structures. The analysed prototype pendulum harvester can easily be attached to the ankle using a Velcro strip and the housing is of a size that can easily be worn hidden under the pants with its external dimensions of 60x60x40 mm³ (HxLxW). The net average power of 3.3 mW that is provided is sufficient for wearables like a fitness tracker or an indoor-navigation system.

Currently ongoing improvements focus on a smaller device size and particularly a smaller width. In addition, modifications to the magnetic circuit are expected to allow a reduction of the device weight, while maintaining the current high power output level. This is advantageous in terms of wearing comfort as the user is less likely to be disturbed by a reduced eccentric proof mass.

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