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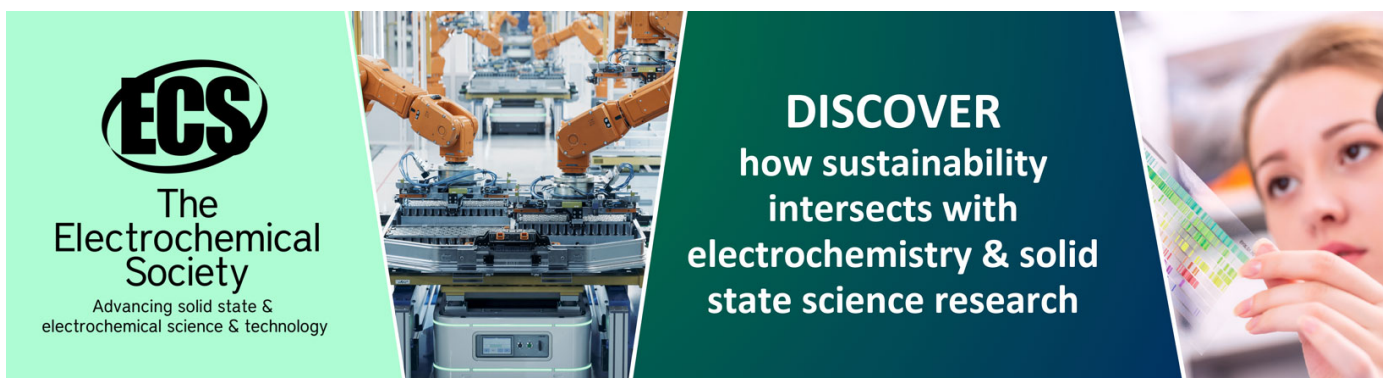
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Stochastic Model of Human Arm Swing Toward Standard Testing for Rotational Energy Harvester

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Abstract. A stochastic model of arm swing is proposed for standard test of rotational energy harvester (EH). Based on the mean values and standard deviation of the frequency and amplitude of arm swing from walking experiment, the output power of rotational electret EH for 95 % coverage is estimated for different parameters of the frequency and amplitude. A multi-link robot is also introduced to mimic the arm swing motion precisely under various conditions. It is found that the output power for the maximum frequency and amplitude is 2.5 times higher than that for the mean values, and the present stochastic model gives 22% higher output power than that with mean values.

1. Introduction

Battery-less wearable devices attached on human body have been strongly desired for healthcare, welfare and entertaining applications [1, 2]. In such applications, rotational energy harvesters (EHs) [3-10] have advantages over resonance-type vibration EHs, because human motion has low-frequency and three-dimensional vibration with 3-axis rotation. Among them, wrist-worn rotational EHs seem the most practical due to easiness of fixing the EH to the human body.

Xue et al. [6] made a series of experiments using actual acceleration obtained for various human motions, and reported that the upper limit for walking is around 200 μW for a 36 mm-diameter generator. They also examined their piezoelectric rotational energy harvester with a pendulum-type testing set-up. Halim et al. [10] investigated an electromagnetic rotational EH with a sprung eccentric rotor, and obtained up to 61.3 μW for their 40 mm-diameter generator with optimum spring. However, it is not a straightforward task to make a standard test of rotational EHs for human walking because of complexity of the arm swing motion. Previously, we proposed a biomechanics-based arm swing model with the two-link model [11]. We found that the instantaneous velocity/acceleration based on the two-link model are different from those based on a pendulum-type model, and examined the effects of different design parameters of rotational electret EH on the output power.

However, in real human walking, even at a nominally-constant walking speed, the frequency and amplitude of arm swing are not constant, but changing in time. Because the dynamics of eccentric rotor is highly-nonlinear and complex, actual mean output power should be different from the output power based on “mean” frequency and amplitude.

In the present study, we propose a stochastic model of the arm swing for rotational EHs in order to examine its effect on the output power. We also introduce a multi-axis robot to mimic precise arm



swing motion for quantitative comparison between the simulation results and the experimental data of rotational EHs.

2. A Dynamic Model of Arm-Equipped Rotational Electret EH

Figure 1a shows the present two-link arm swing model [11], where the arm motion with two rotational joints, i.e., the shoulder and the elbow, is assumed to be confined in the vertical (x - y) plane. A rotational electret EH with an eccentric mass is assumed to be fixed on the wrist. The rotational EH is excited by two-dimensional acceleration as well as the rotational acceleration with the arm swing in the x - y plane. The governing equation of the rotor angle θ is given by

$$I\ddot{\theta} = -Ml \{ \ddot{x}_w \cos(\theta + \theta_{sh} + \theta_{el}) + (\ddot{y}_w + g) \sin(\theta + \theta_{sh} + \theta_{el}) \} + T, \quad (1)$$

where θ , I , M , and l are the rotational angle, the moment of inertia, the mass, and the eccentric distance of the rotor, respectively. $\ddot{x}_w$ and $\ddot{y}_w$ are the external acceleration by the shoulder and elbow motions, while g is the acceleration of gravity. θ_{sh} and θ_{el} are the angles of shoulder and elbow. T is the damping torque for mechanical loss and electrical damping, which corresponds to the energy conversion from the kinetic energy of rotor to electrical energy.

Figure 1b illustrates a schematic of the rotational electret EH using a rotor with patterned electret and a stator with charge extraction electrodes. When external acceleration is applied, the overlapping area between the electrets and the counter electrodes is changed, leading to an external current. Using the Gauss's law, the Kirchhoff's law, and the conservations of charges, a differential equation for the output voltage V is given by

$$(C + C_p) \dot{V} = -\frac{V}{R} \pm CV_s \frac{\dot{\theta}(t)}{\theta_0}, \quad (2)$$

where C is the internal capacitance of the EH, C_p is the parasitic capacitance, R is the external load, V_s is the surface voltage of electret, and θ_0 is the angle of each fan-shaped electrode pattern. In the RHS of Eq. (2), the sign in the second term depends on the rotational direction; whether the overlapping area between the electrets and the counter electrodes is increasing or decreasing. With Eq. (2), the damping torque is described with the viscous damping coefficient D_{mech} as follows:

$$T = -D_{mech} \dot{\theta} - \frac{CV_s}{\theta_0} V. \quad (3)$$

When the frequency and amplitude of shoulder and elbow angles are determined, the output power is estimated for given arm swing excitation by solving Eqs. (1) and (2) simultaneously.

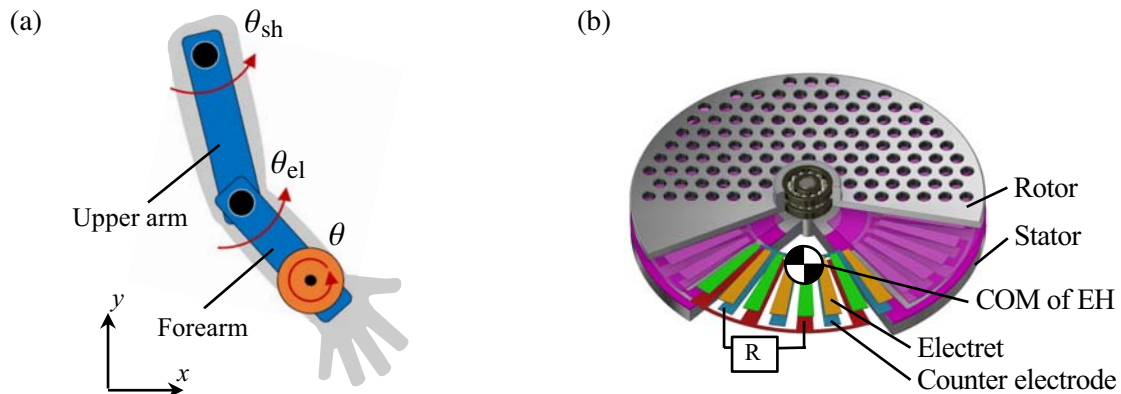


Figure 1. (a) Two-link arm-swing model with rotational energy harvester in the vertical (x - y) plane [11], (b) A schematic of the rotational electret energy harvester [8, 12].

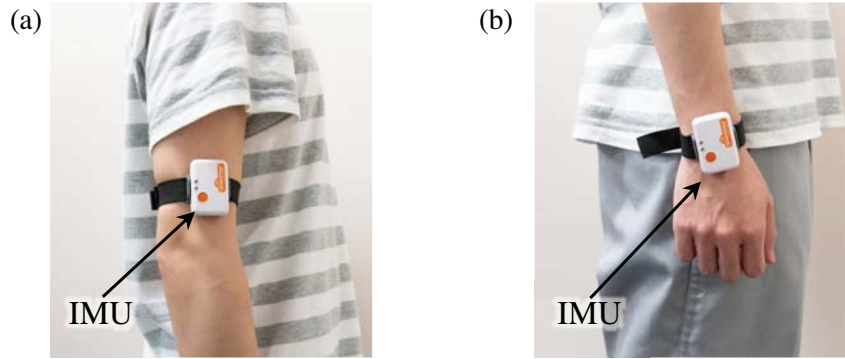


Figure 2. Configuration of experiments to determine the amplitude and frequency of arm swing using Shimmer3 IMU. (a) IMU on the upper arm, (b) IMU on the forearm.

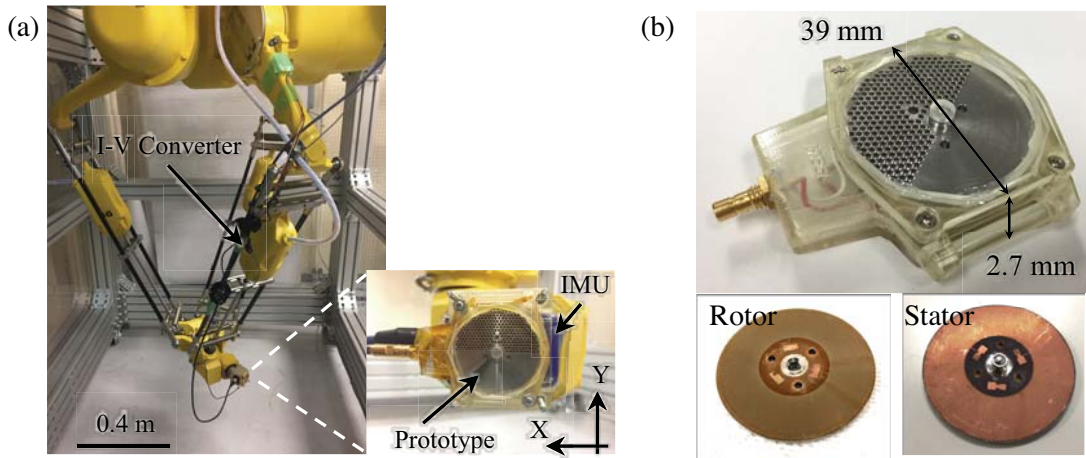


Figure 3. (a) Experimental setup using a multi-axis robot. A 6-axis IMU (CSM-MG100) and the rotational EH are attached to its hand. (b) A prototype of the rotational electret EH [12].

3. Experimental Procedure and Set-up

To determine parameters of the arm swing model, accelerations and angular velocities of the shoulder and elbow motion are measured with a 6-axis inertial measurement unit (Shimmer3 IMU, Shimmer) fixed either on the wrist or the upper arm of a typical subject as shown in Fig. 2. In this specific experiment, the subject (1.65 m of height, 55.0 kg of weight, 0.28 m of upper arm, 0.25 m of forearm, male) walks on the treadmill for 5 min. at a constant speed of 4-6 km/h. In each trial, the acceleration data for 100 s are fitted with sinusoidal functions with intervals of 1.25 s in order to estimate the mean value and standard deviation of the frequency and amplitude of the shoulder and elbow angles. Based on the results, the shoulder and elbow trajectories are determined as follows:

$$\begin{pmatrix} \theta_{sh} \\ \theta_{el} \end{pmatrix} = \begin{pmatrix} A_{sh} \cos(2\pi ft - \pi) + \phi_{0sh} \\ A_{el} \cos(2\pi ft - \pi) + \phi_{0el} \end{pmatrix}, \quad (4)$$

where f is the frequency, A_{sh} and A_{el} are the amplitudes of shoulder and elbow angle respectively. ϕ_{0sh} , ϕ_{0el} are the offset values obtained from Ref. [13].

Figure 3a shows the experimental setup using a multi-link robot (M-3iA/6A, FANUC). A high-precision 6-axis IMU (CSM-MG100, Tokyo Aircraft Inst.) and the rotational electret EH prototype packaged in a 3D-printed plastic housing [12] are attached to the hand of the robot as shown in Fig. 3b. The rotational EH is 39 mm in diameter, 2.7 mm in height, 7 g in mass, and 1.8 mm in eccentric distance. The rotational motion is supported with a miniature ball bearing to keep a 120 μ m air gap. Two print circuit boards are employed for the electret and electrodes, and the number of poles is 120. Other physical parameters are similar with those reported in Ref. [12].

4. Results

Table 1 summarizes the measurement data for frequency and amplitudes. The mean value and standard deviation of each parameters are determined with the assumption that the shoulder and elbow angles follow independent gaussian distributions. It is found that the frequency is increased with the walking speed, and its standard variation is smaller than 10 %. On the other hand, the amplitudes of shoulder and elbow angles do not exhibit clear trend, while the amplitudes at 6 km/h are always larger than 4 km/h. In addition, the standard deviation of the amplitudes are much larger especially for the elbow angle. More experimental data with better accuracy are needed for more precise statistics, but,

Table 1. Measured frequency, and amplitudes of shoulder/elbow angles at each walking speed.

	4 km/h		5 km/h		6 km/h	
	Mean	2SD	Mean	2SD	Mean	2SD
f (Hz)	0.920	0.0927	1.00	0.0590	1.05	0.0429
A_{sh} (deg)	17.03	2.70	15.21	4.61	23.22	3.68
A_{el} (deg)	10.45	6.97	17.17	6.92	15.46	8.31

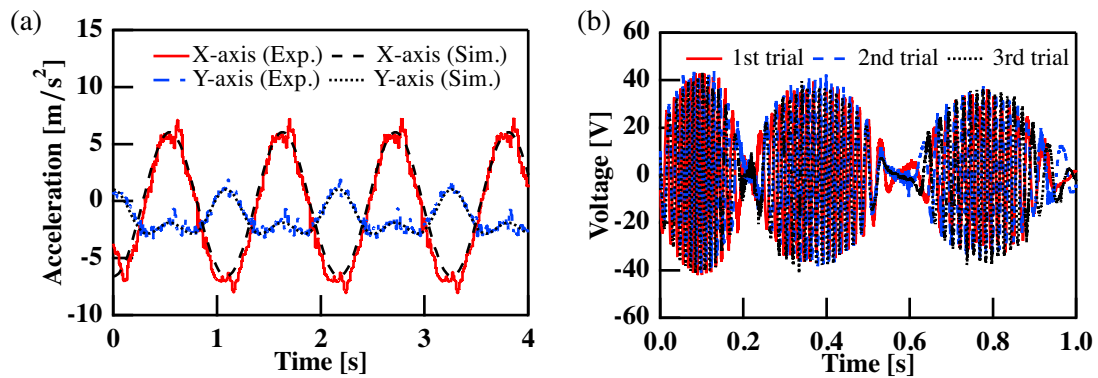


Figure 4. (a) Comparison of accelerations at the hand of robot between the two-link model simulation and the actual motion in experiments. (b) Output voltage of the rotational electret EH for 3 independent trials.

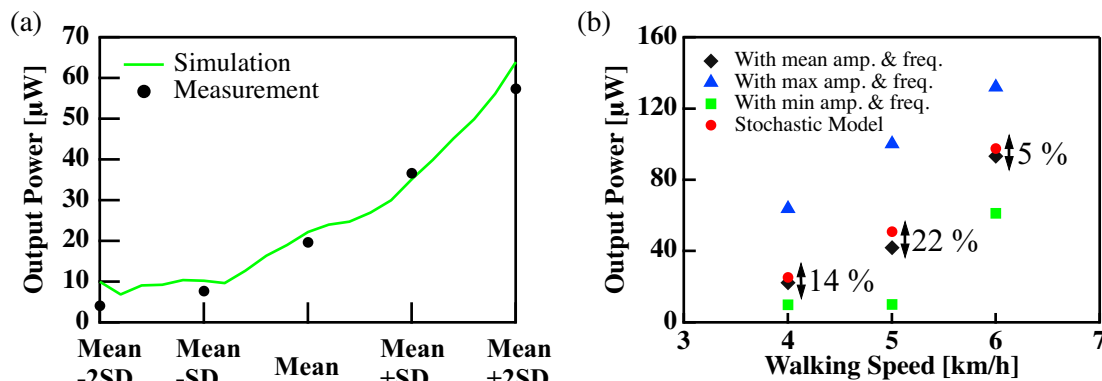


Figure 5. (a) Simulation and measurement results of the output power in the range of 95 % coverage of the frequency and the shoulder and elbow amplitudes at 4 km/h. (b) Simulation results of output power with maximum, mean and minimum values of the shoulder and elbow amplitudes and the frequency in comparison with the results using the present stochastic model.

at least, the effect of the statistical motion can be estimated with the present results.

Figure 4a shows accelerations in the x - and y -directions reproduced by the multi-axis robot at 4 km/h. Although some mechanical noises can be seen, the experimental data are in reasonable agreement with the response of the two-link model. As shown in Fig. 4b, unlike power generation experiments by actual walking with specific subjects, the output voltage data for 3 independent trials with the present robot are almost overlapped with each other, showing excellent reproducibility of the present experimental set-up with the multi-link robot.

Figure 5a shows the output power at 4 km/h in the range of 95 % coverage. In this plot, all three parameters are simultaneously changed from (Mean-2SD) to (Mean+2SD). As expected, the output power is a nonlinear function of those parameters. The maximum output power is about 8-10 times higher than the minimum value, and this trend is in good agreement with the present experiment with the multi-link robot. Therefore, the output power for the mean values are not necessary the same as the ensemble-averaged output power assuming three parameters with statistical distributions. Figure 5b shows the simulation results of output power for the stochastic arm motion at different walking speeds. At 5 km/h, the output power for the maximum amplitudes of shoulder and elbow angle and the frequency is 2.5 times higher than that for the mean values. The output power based on the present stochastic model is 22 % higher than that with mean values of amplitudes and frequency, while such deviation is smaller at the walking speeds of 4 and 6 km/h.

5. Conclusion

We have proposed a stochastic model of arm swing of the rotational EH. Using the multi-axis robot, typical arm swing motion can be well reproduced with good repeatability. The output power by arm swing motion in the 95 % coverage exhibit large difference even at the constant walking speed, showing the significance of the present model. Based on the present model, it is possible to estimate the minimum/mean/maximum output power during walking under various conditions. Also, it is shown that the stochastic model is required for accurate estimation of the mean output power of rotational EH, although more walking data sets with better measurement accuracy should be used for quantitative discussion.

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