Kinetic Energy Harvesting using Improved Eccentric Rotor Architecture for Wearable Sensors

Qian Zhang, Lei Gu, Ken Yang
MEMS Development Group, Analog Devices, Inc.
Wilmington, MA 01887, USA
Email: qian-a.zhang@analog.com

Miah A Halim, Robert Rantz, Shad Roundy
Dept. of Mechanical Engineering, The University of Utah
Salt Lake City, Utah 84112, USA
Email: halim.miah@utah.edu

***Abstract*— This paper presents an energy harvester based on an improved eccentric rotor to generate electrical power from human body motion. An eccentric mass is suspended by a rotational spring to enhance the mechanical energy captured from low and random frequencies. An analytical model of the sprung eccentric rotor is developed to explore the power generation at a volume of 1 cm^3. To compare with the conventional eccentric rotor, the sprung eccentric rotor was simulated with the real walking data measured from five different subjects. The sprung eccentric rotor generates double the average power output compared to the conventional one under optimal electrical damping and spring constant.**

Keywords—energy harvesting; sprung eccentric rotor; spring constant; damping; wearable sensor; electromagnetic transducer

I. INTRODUCTION

Due to improvements in manufacturing technologies, most electronic devices and sensors have become miniaturized in size with low power consumption. Wearable consumer electronics (e.g., smart watch, lifestyle tracker band, smart training shoes etc.) contain a number of sensors to track one's daily activities which are generally powered by electrochemical (e.g., Li-ion, Li-Po) batteries. Although they exhibit high energy density, these batteries have a limited life span and require periodic charging, which is sometimes inconvenient or even impossible. Kinetic energy harvesting from one's body motion can be a good alternative to overcome these power limitations, since significant power can be generated from human body motion [1,2]. When compared to other kinetic energy sources, harvesting power from human body motion is challenging due to its low-frequency (below 5 Hz) and random characteristics [3]. An inertial mechanism is generally employed for human-generated kinetic energy harvesting. A proof mass, mounted in a reference frame attached to the human body, generates electrical power using piezoelectric, electromagnetic, or other transduction mechanisms that convert the relative motion between proof mass and frame while the body is in motion. This transduction has a damping effect on the proof mass. Most inertial devices use linear proof mass motion [3,4] whose power output is limited by the internal travel range of the proof mass. In order to overcome this limitation of linear motion based harvesters, devices with a rotational proof mass have been adopted by researchers [5,6] and the wristwatch industry [7,8]. These devices utilize an eccentric rotor structure that couples the kinetic energy generated by human walking or running into the transduction mechanism. During normal walking motion, the proof mass rotational amplitude of such eccentric rotor structures is quite small. Clearly, larger rotational amplitudes will result in higher power output.

In this study, an improved (sprung) eccentric rotor architecture has been analyzed to evaluate the maximum power output regardless of the transduction mechanism using real walking data from five subjects as input. A mechanical model for both conventional and sprung eccentric rotors has been derived over which an optimization routine is performed. Simulation results show that under optimal electrical damping and spring constant conditions, the sprung eccentric rotor has two times higher average power generation capability over its conventional counterpart.

II. MODELING OF THE ROTOR ARCHITECHTURES

Our analysis starts with a generalized three-dimensional model of a half-moon shaped conventional eccentric rotor rotating freely on a bearing as shown in Fig. 1 (a), reported in previous work [9]. It includes both mechanical and electrical dampers that represent the energy losses due to friction in the bearing (in air, as well) and energy extraction from an ideal energy transducer (regardless of transduction mechanism), respectively. We assume that the power is dissipated through a viscous damper, representing the electromechanical transducer, that allows the system to deliver the highest electrical power [10]. Even though the rotational or linear excitation inputs work on the system in three-dimensions, the rotation of the rotor is constrained to motion in the XY plane. Therefore, the governing equations of the rotor motion in the XY plane are

$$m\begin{bmatrix} -l\cos\phi_z.\dot{\phi}_z^2 - l\sin\phi_z.\ddot{\phi}_z^2 \\ -l\sin\phi_z.\dot{\phi}_z^2 + l\cos\phi_z.\ddot{\phi}_z^2 \end{bmatrix} + m\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} - m\begin{bmatrix} g_x \\ g_y \end{bmatrix} = \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{1}$$

$$I_G\left(\ddot{\theta}_z + \ddot{\phi}_z\right) + \left(D_m + D_e\right)\dot{\phi}_z = F_x l\sin\phi_z - F_y l\cos\phi_z \tag{2}$$

where m, l, and I_G are the mass, eccentric distance and moment of inertia of the rotor, respectively. $\ddot{X}$ and $\ddot{Y}$ are the input accelerations to the system working along X and Y coordinates, respectively. D_m and D_e are the mechanical and electrical damping coefficients, respectively. F_x, F_y and g_x, g_y are the forces from the reference frame and gravity acting on the rotor respectively in the corresponding coordinate. ϕ_z is the angular displacement of the rotor relative to the reference frame.

978-1-4799-8287-5/16/$31.00

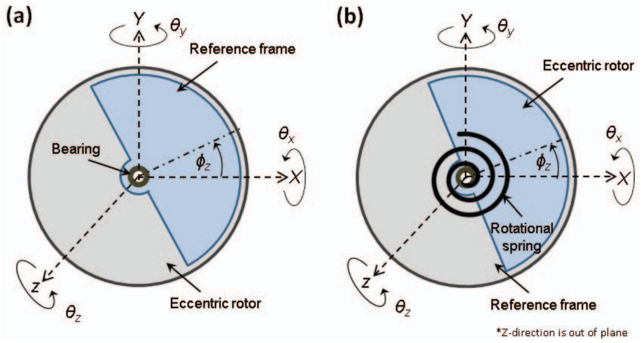

Fig. 1: Schematic representation of the eccentric rotor: (a) conventional rotor and (b) sprung rotor. θ_x, θ_y and θ_z are the rotational inputs to the reference frame whereas the linear accelerations work on X, Y and Z directions.

In order to investigate the performance improvement from the eccentric rotor, we have added a rotational spring, with constant k_{sp}, that couples the rotor mass to the reference frame, as shown in Fig. 1(b). Note that the neutral position of the sprung rotor is considered to be vertically up at π/2 radians. Since the other parameters and the operating conditions for both unsprung and sprung rotor structures are same, the sprung rotor will have the same force matrix as the conventional rotor, as presented in Eq. (1). However, the rotational displacement of the sprung rotor will be

$$I_G\left(\ddot{\theta}_z+\ddot{\phi}_z\right)+\left(D_m+D_e\right)\dot{\phi}_z+K_{sp}\left(\phi_z-\frac{\pi}{2}\right)=F_x l\sin\phi_z-F_y l\cos\phi_z \quad (3)$$

The relative angular displacement/velocity of the eccentric rotor (for both unsprung and sprung) can be obtained by solving the governing equations, which determines the instantaneous power output as

$$P_{out}=D_e\dot{\phi}_z^2 \quad (4)$$

III. RESULTS AND DISCUSSION

A custom, Arduino based, inertial measurement platform was used to measure the input data (linear acceleration and rotational rate) from five subjects during walking, wearing the platform on their wrists (right hand). Gyroscopic data were used to determine the gravitational force in the X-Y plane by the orientation calculated.

A Pattern Search (PS) optimization routine was employed in order to determine the values of the harvester design parameters that were most likely to produce high levels of power. The objective function was formed by virtue of the output of an ordinary differential equations solver, which solved Eqs. (2) and (3) using candidate solution values, returning the power dissipated in the electrical damper. Candidate solutions were two-dimensional, comprised of the design variables: the electrical damping coefficient and the rotational spring constant. All other design parameters, including rotor geometry, were considered fixed. The size of the feasible set was reduced by applying practical upper and lower bounds on the design parameters. A Latin Hypercube Search of 200 design points was utilized to inform the initial point for the PS routine. This process was repeated for each user's signal in the study.

Figure 2a shows that a generalized harvester coupled to a sprung eccentric rotor is capable generating 86.4% higher power (313.9 µW) than the power (168.4 µW) generated by the harvester coupled to an unsprung eccentric rotor. The rotor was considered to be made of tungsten having 12.6 mm radius and 2 mm thickness. To achieve these maximum power values, an optimum level of electrical damping coefficient is required which was found to be 0.26×10^{-5} N·m·s/rad and 1×10^{-5} N·m·s/rad for the unsprung and sprung rotor, respectively, using the PS routine. The spring constant of the sprung rotor is set to an optimum value. Figure 2b shows that the maximum power is generated when the optimal spring constant of the sprung rotor is 2.78×10^{-4} N·m/rad. In order to determine the optimal spring constant to achieve maximum power, we held the optimal electrical damping coefficient constant for the representative subject (Subject 2).

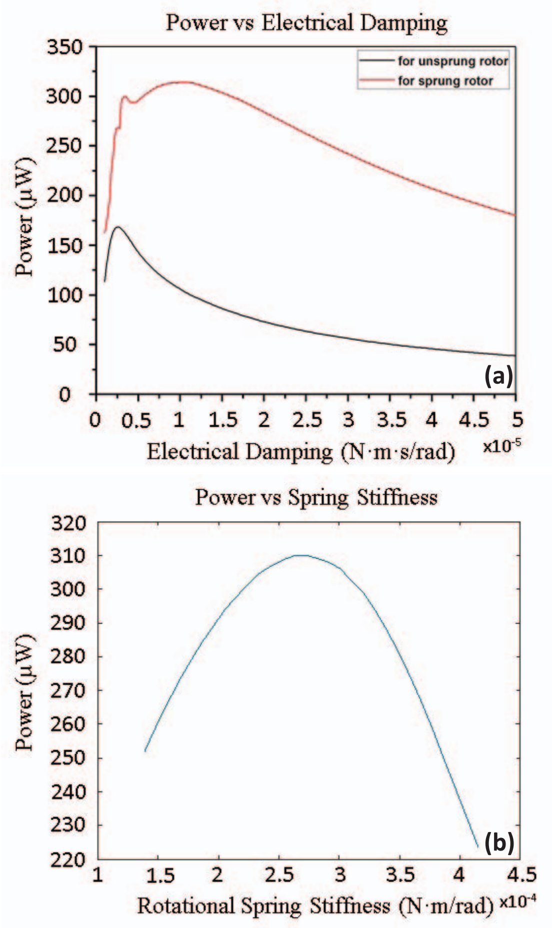

Fig. 2: (a) Power output vs. electrical damping coefficient and (b) power output vs. spring constant from a generalized rotational harvester coupled to a sprung eccentric rotor during walking for a representative subject (Subject 2).

Figure 3 shows the power outputs from five different subjects, generated by the generalized harvester coupled to both unsprung and sprung rotors having both the electrical damping and spring constant (for sprung rotor) values optimal. The power outputs are different for different subjects due to unique walking pattern for each subject, such as swing amplitude, frequency, and bias angle. In addition, the results show that the output power can be significantly increased (87% on average) by a generalized wrist-worn rotational harvester coupled to a sprung rotor (478.4 µW on average) than that coupled to a conventional unsprung rotor (255 μW on average).

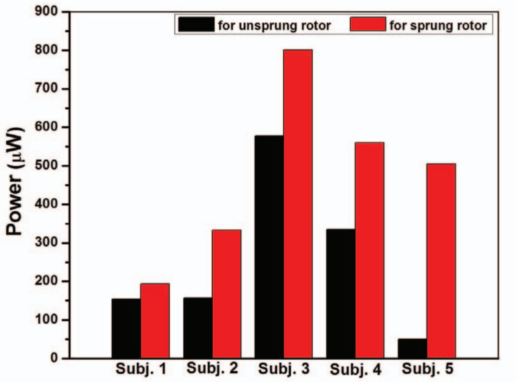

Fig. 3: Power outputs from a generalized rotational harvester coupled to both unsprung and sprung eccentric rotors during walking for five subjects.

IV. CONCLUSION

This paper presents an improved (sprung) eccentric rotor architecture to provide an evaluation on maximum power output from wrist motion during normal walking conditions, regardless of the transduction mechanism. Estimates have been done using the measured 6-axis inertial data from five subjects as inputs to a three-dimensional rotor model. Simulation results indicate that the generalized harvester coupled to a sprung rotor is capable of generating at least 25% (87% average over all subjects) higher power than its conventional rotor counterpart.

REFERENCES

[1] R. Riemer and A. Shapiro, “Biomechanical energy harvesting from human motion: theory, state of the art, design guidelines, and future directions”, J. Neuroeng. Rehabil., vol. 8, pp. 1-13, April 2011.

[2] T. Starner and J. Paradiso, “Human-generated power for mobile electronics,” in Low-Power Electronics Design, Chp. 45, C. Piguet, Ed. New York: CRC Press, 2004, pp. 1–30.

[3] K. Ylli, D. Hoffmann, A. Willmann, P. Becker, B. Folkmer, and Y. Manoli, “Energy harvesting from human motion: exploiting swing and shock excitations,” Smart Mater. Struct., vol. 24, p. 025029, January 2015.

[4] C. R. Saha, T. O’Donnell, N. Wang, and P. McCloskey, “Electromagnetic generator for harvesting energy from human motion,” Sens. Actuators A, vol. 147, pp. 248–253, September 2008.

[5] P. Pillatsch, E. M. Yeatman, and A. S. Holmes, “A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications,” Sens. Actuators A, vol. 206, pp. 178–185, February 2014.

[6] E. Romero, M. R. Neuman, and R. O. Warrington, “Rotational energy harvester for body motion”, MEMS Conference '11, Mexico, pp. 23-27, January 2011.

[7] M. Hayakawa, “Electronic Wristwatch with Generator”, US Patent 5,001,685, 19 Mar., 1991.

[8] Kinetron, “Micro Generator System ’26.4’”, MGS 26.4 datasheet, Dec. 2014.

[9] T. Xue, X. Ma, C. Rahn, and S. Roundy, “Analysis of upper bound power output for a wrist-worn rotational energy harvester from real-world measured inputs,” J. Phys. Conf. Ser., vol. 557, p. 012010, December 2014.

[10] P. D. Mitcheson, E. M. Yeatman, G. K. Rao, A. S. Holmes, and T. C. Green, “Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices,” Proc. IEEE, vol. 96, pp. 1457–86, September 2008.