BROADBAND ENERGY SCAVENGING FROM VIBRATIONS USING AN ECCENTRIC ROTOR ELECTROMAGNETIC GENERATOR

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Abstract: We present the concept of a rotational energy scavenger (ES) called E-Rot, which uses an eccentric rotor to couple with single-axis ambient vibrations. Because the nominal motion of the E-Rot device is continuous rotation, energy conversion to the electrical domain is readily carried out with a conventional rotational electromagnetic generator. In contrast to resonant ES devices, E-Rot is fundamentally capable of operation at any frequency, and thus can operate over an exceptionally wide frequency range of ambient vibrations. Simple controls enable the E-Rot device to self-tune its frequency and phase to match the ambient vibration field. We present theoretical modeling and experimental results, demonstrating the ability of the scavenger to both self-tune and scavenge energy over a large frequency range of input vibrations.

Keywords: Energy Scavenging, Broadband, Electromagnetic, Rotational

INTRODUCTION

With continuous advances in low-power electronics, energy scavenging from ambient vibrations has become a viable method for powering wireless sensor networks [1]. However, vibrational energy scavengers are predominantly implemented with a pre-tuned resonant mechanical energy tank, typically a mass-spring system, resulting in operation tuned for only a narrow frequency range [2]. The major drawback of such resonating systems is that their natural (resonant) frequency has to precisely match the frequency of the ambient vibration field. To overcome this limitation, broadband nonlinear resonant energy scavengers have recently been proposed [3,4]. However, these methods often tend to only modestly (less than a factor of two) broadening of the frequency response of the energy scavenger.

In this work, we present the concept of a *non-resonant* rotational energy scavenger, called E-Rot, that is based on the principle of an eccentric rotor electromagnetic generator. We show that an eccentric mass rotational energy scavenger can couple to an exceptionally wide range of frequency input vibrations. Furthermore, the scavenger can be designed to track vibrations should they change over time. The use of rotational energy scavengers to extract energy from rotational motion has been previously proposed [5]. We show that an eccentric mass electromagnetic generator can be used to scavenge energy from single-axis vibrations.

After introducing the general concept of E-Rot, and contrasting it to a resonant vibrational energy scavenger, a mathematical model of the E-Rot energy scavenging system is shown. Optimal power output of the E-Rot depends on a matching load controller, a concept which is also described. Finally experimental results from an E-Rot prototype, validating its operation over a frequency range of 2x (100%).
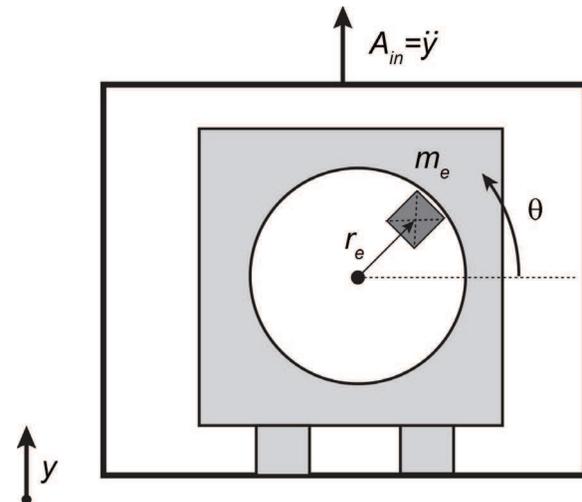
E-ROT CONCEPT

Fig. 1: Schematic diagram of the eccentric rotor electromagnetic generator (E-Rot) as a vibrational energy scavenger.

The diagram of Figure 1 illustrates an eccentric rotor with equivalent eccentric mass m_e at radius r_e, resulting in net eccentricity $r_e m_e$. Input

single-axis vibrations A_{in} are introduced along y-axis to the frame of the system. Using a Lagrangian formulation, one can show that the unloaded rotor dynamics are described by the model:

$$I\ddot{\theta} = -m_e r_e \ddot{y} \cos\theta, \tag{1}$$

where I is the moment of inertia of the entire rotor. With a steady rotation angle $\theta = \omega t + \theta_0$, synchronized to a sinusoidal vibration field with position displacement $y = Y_0 \cos(\omega t)$, the rotor dynamics take the form:

$$I\ddot{\theta} = (m_e r_e)(\omega^2 Y_0)\left[\frac{1}{2}\cos\theta_0 + \frac{1}{2}\cos(2\omega t + \theta_0)\right], \tag{2}$$

where θ_0 represents the angular phase shift of the rotor eccentricity with respect to the phase of the vibration field. A value of zero phase shift corresponds to maximal energy extraction from the vibration field, where the eccentric rotor induces a maximum average torque, that scales linearly with the peak value of the acceleration field ($\omega^2 Y_0$) and also with the net eccentricity. Net average power transferred through the rotor is then this average torque multiplied by the angular velocity:

$$P_{avg} = \frac{1}{2}\omega(m_e r_e)(\omega^2 Y_0). \tag{3}$$

The second term on the right-hand side of eq. (2) corresponds to a pulsating torque imparted to the rotor that results in a small velocity ripple at twice the vibration frequency. Over a wide range of frequencies and with additional rotor inertia beyond the eccentricity, this velocity ripple can be shown to be negligible.

Returning to the average torque term of eq. (2), with no load, equilibria corresponding to zero average torque occur at $\theta_0 = +/- \pi/2$. The equilibrium corresponding to $+ \pi/2$ is a stable equilibrium, and corresponds to an initial conceptual operating point. As positive load is applied to the rotor via the generator, this stable equilibrium shifts in phase from $+ \pi/2$ toward zero, until maximum torque is produced. This maximum torque at angle $\theta_0 = 0$ corresponds to a pull-out torque, beyond which, synchronization will be lost.

It is of interest that there is nearly a one-to-one correspondence in the kinematics of the E-Rot eccentric rotational energy harvester and a conventional resonant harvester when the frequencies of the two are matched. It can easily be demonstrated that the maximum available power with a single-axis resonant harvester is given by

$$P_{max} = \frac{1}{2}\omega(Xm)(\omega^2 Y_0), \tag{4}$$

where X is the stroke amplitude, and m is the resonating proof mass. Observe that eq. (4) basically states that derived power in sinusoidal steady state is one-half the product of peak velocity and peak force. There is then a direct analogy between proof mass and equivalent mass eccentricity, and also between linear stroke and radius of eccentricity, resulting in an essentially *identical* formula for available power. Further, the notion of phase shift in the linear resonator (due to slight frequency tuning away from resonance) is also analogous to the introduced notion of phase shift in the rotational harvester.

There are two substantial points of differentiation, which require attention in the design of the control system. First, as noted, the rotational harvester can readily extract maximal power over a wide range of frequencies. Second, the rotational harvester produces zero average power if it is not synchronized with an ambient vibration field. Thus, it requires a synchronization or lock-in scheme, and a control that then avoids pull-out.

CONTROL CIRCUIT

The control system for E-Rot is conceived to operate with a single dominant frequency in the ambient vibration field. With multiple discrete spectral components in the vibration field, the E-Rot system can readily lock onto any one of the discrete frequency components. Maximum available power scales linearly with acceleration field and with frequency, so this product can be viewed as a guide for selecting the lock-in frequency when multiple vibration frequencies are present.

With a single vibration frequency, lock-in is readily achieved by spinning up the rotor to, or beyond this vibration frequency. This is done by operating the electromagnetic machine as a motor, with drive provided by the controller, configured to function as an inverter. During this spin up, energy needs to be momentarily extracted from a local storage resource. Upon synchronization, positive load may be applied by having the controller function as a simple rectifier. One challenge is in adjusting the load to maximize practical power extraction, while avoiding pull-out and subsequent need for re-synchronization. This can

be managed with a sensing system that assesses frequency and amplitude of the vibration field, and translates this into a safe loading level.

EXPERIMENTAL VALIDATION

The E-Rot concept was validated using a prototype rotational motor/generator setup show in Figure 2. The motor/generator consisted of a modified brushless DC fan (a) (RadioShack, catalog #: 273-240) with exposed access to the stator windings, where a digital oscilloscope was connected to measure generated open-circuit voltage. Permanent magnets (b) (K&J Magnetics) were used to induce rotor eccentricity. The mass of the magnets was 1.12 g., and they were attached approximately 15 mm from the center of the rotor to one of the fan-blades. The motor/generator fan was mounted on a commercial shaker table (c) using a custom-fabricated fixture (d). As the motor controller was removed to gain access to the stator windings, airflow directed though the fan-blades was used to accelerate (spin-up) the rotor to a target rotational velocity ω.

corresponding to the extreme points of the 2x bandwidth for the E-Rot scavenger prototype. The prototype was not designed for operation at higher angular velocities due to the interaction of the fan-blades with the surrounding air.

Table 1: Open-circuit voltage obtained from the E-Rot scavenger at 10 and 20 Hz, demonstrating a 2x frequency bandwidth.

Frequency [Hz]	10	20
Amplitude of vibartions [G]	0.577	1.4
Output voltage [V]	0.416	0.783

Observed self-tuning behavior of the E-Rot scavenger is shown on Figure 3, which shows the output voltage of the prototype, as the frequency of the driving vibrations is reduced from 20 Hz to 14 Hz. The E-Rot scavenger remained locked-in on the frequency of vibrations without any external interaction.
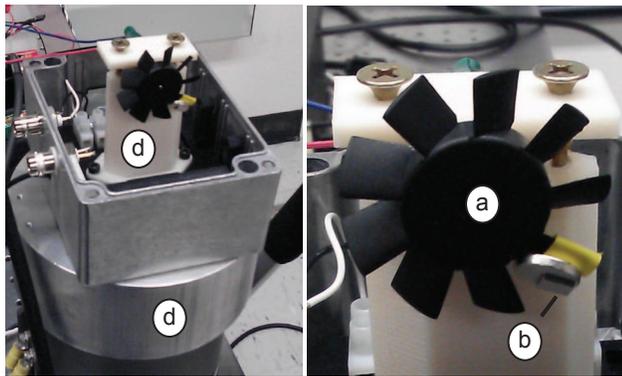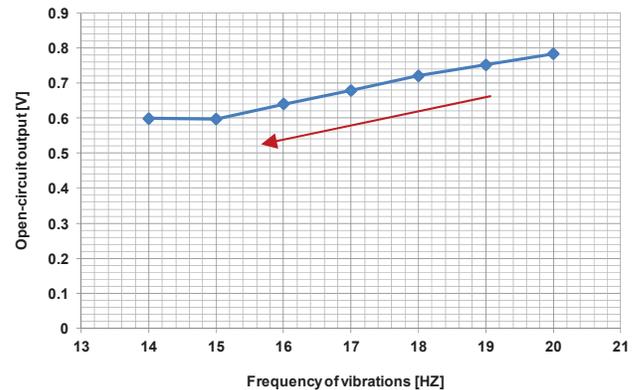

Fig. 2: Prototype of the E-Rot vibration energy scavenger using a commercially available fan. Left: prototype mounted on shaker table. Right: close-up of the fan rotor.

The E-Rot prototype was operated in open-circuit mode, consequently only insignificant amount of energy were extracted from the scavenger. Rather, the experiments were designed to validate the concept of the eccentric rotor electromagnetic generator's viability to scavenge energy from single-axis vibrations. Air-flow was used to spin up the rotor to a rotational speed ω that matched that of the shaker table vibrations. The air-flow was then removed such that lock-in behavior could take place.

Table 1 shows the performance of the prototype after locking in on 10 and 20 Hz shaker frequency,

Fig. 3: Self-tuning of the E-Rot scavenger during a downward frequency sweep (20-14 Hz). The red arrow indicates the direction of the sweep.

The goal of the prototype was to validate the E-Rot concept, and the setup was not optimized for a wide frequency bandwidth. However, simple improvement such as the removal of fan-blades can be made to further extend the 2x bandwidth of the E-Rot prototype.

CONCLUSION

We presented the concept of a rotational energy scavenger (ES) called E-Rot, consisting of an eccentric rotor electromagnetic generator, and demonstrate that E-Rot can be used to scavenge

energy from ambient single-axis vibrations. Mathematical modeling shows that a classical vibrational energy scavenger based on a resonating spring-mass system is similar to E-Rot when it comes to scavenging ambient vibrations. However, a significant advantage of E-Rot is that it is non-resonating, and thus does not rely on a particular frequency of the ambient vibrations to produce significant output. We have shown experimental results validating the E-Rot concept, and have demonstrated 2x frequency bandwidth of a fabricated E-Rot prototype. We have analytically shown that, at least in theory, the available power for a specific acceleration field should be similar to what can be extracted from a resonating proof-mass vibrational energy scavenger.

In contrast with a resonant vibrational energy scavenger, E-rot does require control circuitry to ensure that the rotor ”locks-in” to the frequency of input vibrations, as well as to control the loading of the scavenger to maintain this synchronization. The design and optimization an end-to-end E-Rot system is an exciting area of future work and holds great potential for the development of future broadband energy scavenging systems.

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