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ENERGY HARVESTING FROM ROTATING STRUCTURES

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Abstract: In this paper, we analyze and demonstrate a novel rotational energy harvesting generator using gravitational torque. The electro-mechanical behavior of the generator is presented, alongside experimental results from an implementation based on a conventional DC motor. The off-axis performance is also modeled. Designs for adaptive power processing circuitry for optimal power harvesting are presented, using SPICE simulations.

Key Words: energy-harvesting, rotational generator, adaptive generator, double pendulum

1. INTRODUCTION

Energy harvesting from moving structures has been a topic of much research, particularly for applications in powering wireless sensors [1]. Most motion energy harvesters are inertial, drawing power from the relative motion between an oscillating proof mass and the frame from which it is suspended [2]. For many important applications, including tire pressure sensing and condition monitoring of machinery, the host structure undergoes continuous rotation; in these cases, previous energy harvesters have typically been driven by the associated vibration. In this paper we show that rotational motion can be used directly to harvest power, and that conventional rotating machines can be easily adapted to this purpose.

All mechanical to electrical transducers rely on the relative motion of two generator sections. Inertial generators are valuable because they need only be attached to one moving point; the other section is un-anchored and its inertia is used to restrict motion. For rotational host motion at constant speed, inertia cannot be used. Our device instead uses gravitational acceleration to provide the counter-force (Fig. 1). The housing (stator) of a rotating generator is attached to any point on the rotating structure, and an off-centered mass is attached to the rotor. When power is drawn, magnetic torque initially rotates the rotor along with the stator and host; this creates a gravitational torque $T_g = mgL\sin(\theta)$ which fixes the angle. Stable generation is thus limited to magnetic torques up to mgL, above which the rotor flips over, so the maximum power is

$$P_{max} = mgL\omega \qquad (1)$$

with ω the angular rotation rate of the host.

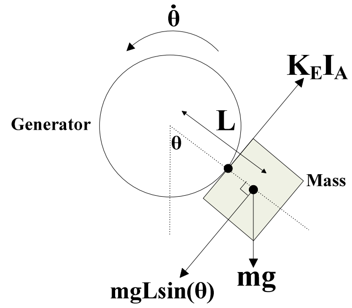

Fig. 1: Schematic of the gravitational torque generator. I_A is the armature current and K_E is the motor constant.

Previously we reported initial experimental results for this device, and circuit simulations based on a buck-boost converter [3]. In this paper we consider a Flyback power conversion circuit, and investigate the device performance when mounted off the rotational axis of the source.

2. EXPERIMENTAL RESULTS

Fig. 2 depicts our experimental setup, where two DC motors were coupled together at their shafts. One motor acts as a rotational source while clamped onto the workbench, and the other as the gravitational torque generator, suspended in air. On the generator's stator, we attached a rectangular mass, while a load resistor, R_L, was connected to its output terminals. We measured the angular velocity of the shaft using an optical tachometer, and the voltage across R_L to derive the output power. For a conventional DC machine driven as a generator, the maximum load power is achieved for R_L matched to the armature resistance, R_A, giving an output electrical power of

$$P_{elec} = \frac{(K_E \omega)^2}{4R_L} \qquad (2)$$

In our case the K_E was 2.6 × 10^{-3} V·s/rad, and the additional mass was 20 g, centered 2 cm from the generator shaft.

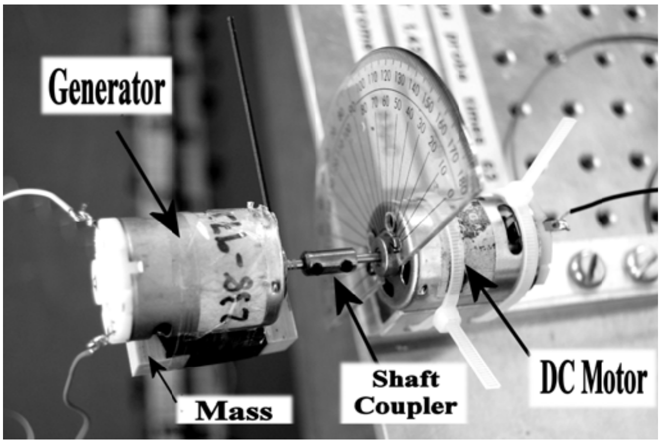

Fig. 2: Experimental setup of the generator and rotational source

Fig. 3 shows the output power measured for this setup, for various values of R_L. The highest power is obtained when R_L is closely matched to R_A, as expected. Output power varies as rotation rate squared, in agreement with (2).

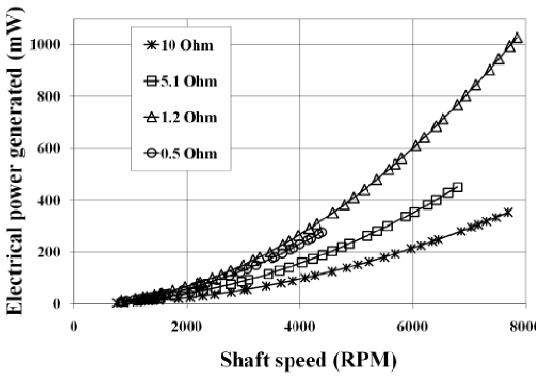

Fig. 3: Measured powers for the specified load resistances when R_A = 1.1Ω

In Fig. 4, the flip-over speed indicates how much we can increase the source rotation before the stator becomes instable and flips over. We have included mechanical drag compensation in our theoretical model using the amount of drag torque present depending on the speed.

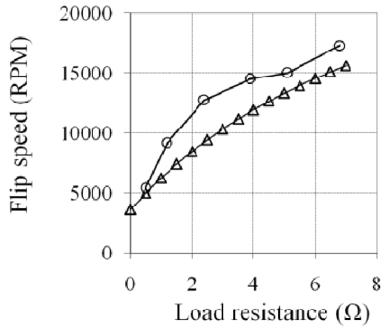

Fig. 4: Flip-over speed vs. load resistances when R_A = 1.1Ω: experimental (circles) and modelled (triangles)

3. ADAPTIVE POWER PROCESSING FOR OPTIMAL POWER TRANSFER

To obtain optimal power transfer from the generator to the load, we require $R_L \approx R_A$. It is very likely that the input impedance of a device being powered by this generator would be higher than R_A. Hence, we have chosen a Boost converter such that R_{IN} can be less than R_L by changing the duty cycle, δ.

$$R_{IN} = R_L (1 - \delta)^2 \qquad (3)$$

A control loop measures the input voltage into the Boost converter to give us the measured current. This is then compared with a current demand and the difference between the two will cause the duty cycle to be adjusted accordingly.

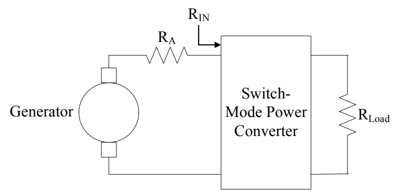

Fig. 5: Using a power converter to get optimal power transfer from the generator

We have constrained the maximum I_A that enters the Boost converter so that the stator does not flip over. The maximum I_A before the stator flips is given by:

$$I_A(\max) = \frac{mgL}{K_E} \qquad (4)$$

The momentum of the mass will cause a flip over if the current demand is set to 100% of *I_A(max)*. Therefore, we have set the current demand to 90% to prevent this instability from occurring. The error between the measured and demand value of I_A will be used to generate a pulse-width modulated (PWM) signal which determines the duty cycle of the Boost converter.

When the generator is used to power up a device, it is essential that the voltage it provides is regulated. Since the Boost converter was used to implement impedance matching, we have designed a Flyback converter which maintains a fixed output rail across R_L. A storage capacitor is connected in parallel between the Boost and Flyback converters (Fig. 6) which has the following function; it stores charge when power is being generated in excess and it discharges when there is insufficient power. This discharge will help regulate the Flyback's output voltage. A voltage control loop measures the voltage across R_L and compares it with a predetermined reference value. The difference in these voltage values will result in a change in the Flyback's duty cycle.

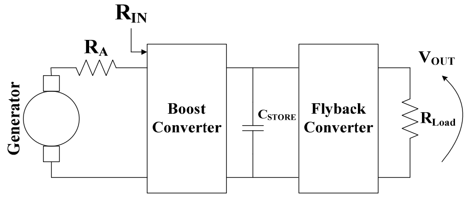

Fig. 6: Using power converters for impedance matching and output voltage regulation

4. SPICE SIMULATIONS

We have modelled the generator using its equivalent electrical circuit as well as the power converters used for optimal power harvesting in SPICE. A 10kΩ output resistor was used to represent the input impedance of an external circuit and 5V was regulated across it. All variables in our model were represented in terms of voltages and their actual units are labelled in Fig. 7 which contains the results of our simulations.

The shaft speed was modelled using a ramp which increases up to 3000 RPM and stays constant for a period of time before immediately decreasing to zero. As the speed increases, the storage capacitor charges up and the current control loop performs impedance matching between the Boost converter and R_A. Once the shaft speed drops to zero, the storage capacitor discharges to maintain a fixed output rail of 5V. However, the impedance at this point is undefined because there is no power transfer from the generator.

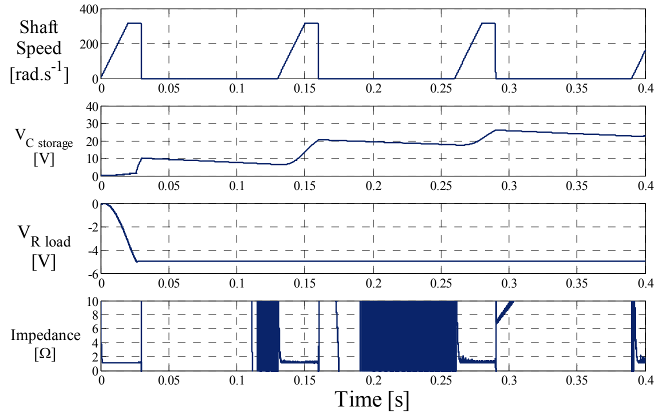

Fig. 7: SPICE simulation results for the model in Fig. 10 with R_{Load} = 10kΩ and R_A = 1.1Ω

5. OFF-AXIS PERFORMANCE

Whilst there are many applications in which the rotational generator could be used with the centre of rotation of the generator aligned with the centre of rotation of the driving source, there are some applications in which this is not possible. In addition, even when this is possible, there will always be some degree of misalignment between these two axes. If the centre of rotation of the generator is misaligned with the centre of rotation of the host structure (increasing l_1 on Fig. 8), the entire generator is subjected to a centripetal force. This has the effect of causing the offset mass, *m*, to be thrown outwards and thus the rate of change of $\theta_1 - \theta_2$ reduces. As it is this rate of change that causes power to be generated, the offset position of the generator will tend to reduce the power generated.

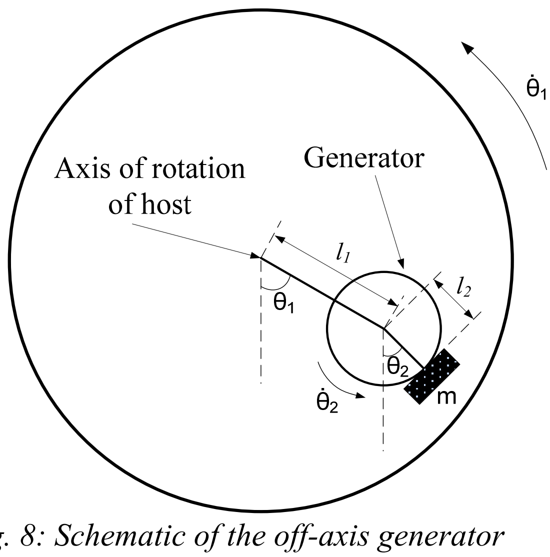

Fig. 8: Schematic of the off-axis generator

As shown in Fig. 8, this mechanical problem is essentially that of the double pendulum, where the first link is driven at constant rotational speed, *i.e.* $\dot{\theta}_1$ is constant. The equation of motion describing the rotation of the mass, *m*, through the angle θ_2 is:

$$\ddot{\theta}_2 = \frac{l_1\dot{\theta}_1^2 \sin(\theta_1-\theta_2) - l_1\ddot{\theta}_1 \cos(\theta_1-\theta_2) - g\sin\theta_2}{l_2} \quad (5)$$

Analytical solutions to the motion of the double pendulum system are not possible even when $\dot{\theta}_1$ is constant, as the system is non-linear and chaotic, and so in order to determine the importance of this centripetal effect on power generation, a Simulink model of a double pendulum system was built to investigate the behaviour numerically. Results from this model are shown in Fig. 9. In the simulation, values of the physical parameters are matched to the actual generator used in the experimental work and the graphs plotted assume a matched load resistance to achieve maximal power generation. With no non-linear effect (i.e. l_1=0), the system is expected to generate power proportional to the square of rotational angular velocity. Fig. 9 shows that this is the general behaviour for the system at low RPM or when the offset, l_1, is small. However, as the rotational speed or the offset, l_1, increases, the results become chaotic. However, some general points can still be noted:

- The power generated tends to decrease as the off axis position, l_1, increases.
- The rotational speed at which the power falls below that predicted by the simple linear system reduces as l_1 increases.
- When the speed is such that the system starts to exhibit chaotic behaviour, the power is generally less than when the system follows the behaviour of the linear system.

6. CONCLUSIONS

We have demonstrated a working concept of a rotational energy harvester using DC generators. This meso-scale generator produced up to 1W of power under matched conditions. The electro-mechanical simulations in SPICE show that it is possible to implement power converters along with control loops to obtain optimal power transfer from the rotational generator. Off axis numerical modelling in Simulink shows that the generator can tolerate a certain amount of misalignment from the axis of source rotation.

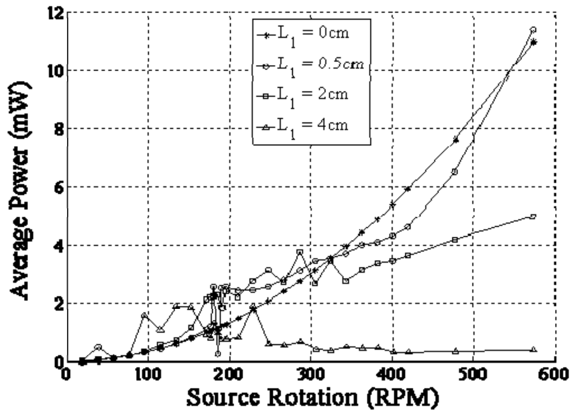

Fig. 9: Average power generated against source rotation at various offset distances, $\boldsymbol{l_1}$

7. FUTURE WORK

We are currently implementing our control circuitry using a PIC microcontroller to optimally harvest power from the microturbine (Fig. 10) detailed in [4].

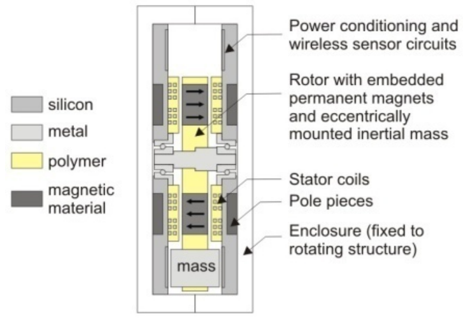

Fig. 10: Schematic of possible microgenerator implementation

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