Prototype Rotational Energy Harvester for Structural Health Monitoring

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Abstract

This paper reports on a prototype rotational energy harvester capable of generating energy from a rotating drive shaft, without the requirement of a nearby stationary point. The approach uses a rolling magnetic sphere located in a circular track, which is attached to a horizontal drive shaft. At 250 revolutions per minute (rpm), the harvester generated an average peak voltage of 19.8 V across a matched resistive load of 750 Ω, producing an average peak electrical power of 520 mW.

Keywords: energy harvesting, structural health monitoring, electromagnetic

Introduction

With the increasing interest in wireless sensor networks, the powering of sensor nodes becomes an issue. The use of batteries can be problematic, either due to restricted access complicating the replacement of expired batteries, or the excessive maintenance costs associated with having to regularly replace a large number of batteries [1]. Due to the ever reducing power requirements of sensor nodes [2], the harvesting of energy from ambient sources local to the sensors becomes more feasible. There are several sources and methods for harvesting ambient energy [3], and a number of approaches for generating electricity from rotational motion [4] are well recognised and commercially available [5]. A rotary-translational harvesting approach previously reported by the authors used the cycloidal motion of a magnetic pole for mechanical advantage and improved power density [6]. This paper expands upon preliminary work [7] where a similar cycloidal approach was implemented in a purely rotational harvester. The rotational energy harvesting approach uses electro-magnetic transduction, described by Faraday's Law as,

$$EMF = Nl\frac{dB}{dt} = Nl\frac{dB}{dx}\frac{dx}{dt} = Nl\frac{dB}{dx}v \tag{1}$$

where *EMF* is the electro-motive force, *N* is the number of turns contained in a wire coil transducer, *l* is effective length of the coil, *B* is the flux density going through the coil and *x* is the direction of motion. The key distinction of the rotational harvesting approach described in this paper is that it does not need to have one part of it fixed to a stationary structure while the other rotates, such as a stator and a rotor in a standard DC generator. The active part is also designed such that with some repackaging it can be retrofitted to an existing rotating shaft where access to both ends is impossible. The goal of the energy harvesting approach is to power a wireless sensor node that is located on the same rotating shaft. This eliminates the requirement for expensive slip rings that have a limited life-span. One potential application of this technology is the in-situ measurement of torque on a drive shaft with a wireless-connected self-powered torque sensor.

Principles of Operation

Figure 1 shows a schematic of the prototype rotational energy harvester (henceforth, the 'prototype harvester' or simply 'device') described in this paper. The prototype harvester uses a rolling magnetic sphere (henceforth, the 'sphere') mounted inside rotating wheel with horizontal drive shaft, and utilises a cycloidal transduction mechanism developed in previous work [8]. As the wheel rotates the sphere rolls near the bottom of the wheel due to gravity. Using a wheel with a relatively small diameter, a sphere with a large enough mass, and restricting the rotating speed, ensures the sphere will remain rolling near the bottom of the fabricated track, where it acts as a permanent magnet stator. The inside of the track-width is covered by a series of wound copper coil transducers (henceforth called the 'coils'). The relative movement of the sphere past these coils generates an *EMF*, which can then be used to power a sensor collocated near the harvester.

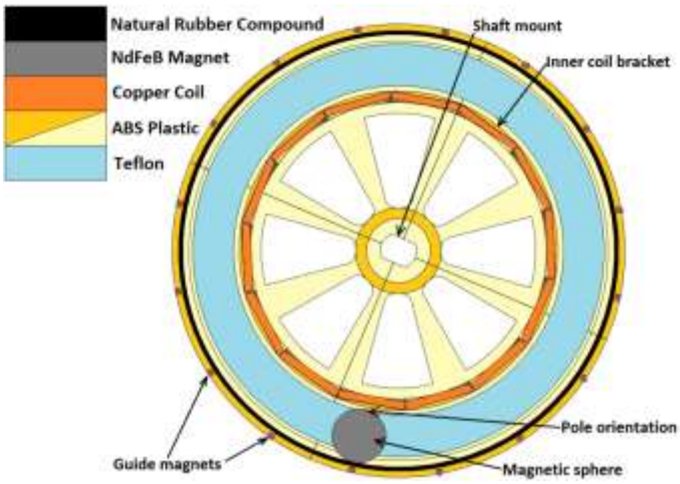

Fig. 1: Showing the prototype rotational energy harvester wheel with key components labelled and materials highlighted.

Positioning of the coils was determined using theory which will be reported elsewhere. Placing the coils on the inside of the wheel, radially inwards from the sphere, maximised the velocity of the magnetic pole as it rolled underneath the coils. The trajectory of the sphere's magnetic poles is cycloidal, providing a mechanical advantage. Having the coils mounted radially inwards on the wheel means that they are travelling in the opposite tangential direction to the magnetic pole at the point when they pass closest to one another. This results in amplification of the relative velocity, and since the *EMF* generated is proportional to the velocity (equation 1) this induces a larger *EMF*. Guide-magnets are used to ensure the sphere remains optimally aligned as it rolls.

In the sections below, the design, fabrication and testing of the device are discussed. Measured results from the device are examined in detail, the scaled power density of the device is calculated and compared with a previous device.

Experimental

This section describes the construction of the prototype harvester itself, including design decisions and optimisation. The method of testing and characterizing the device is also elucidated.

As shown in Figure 1, the prototype harvester consists of a 2.54 cm diameter spherical magnet (neodymium iron boron, grade N42) rolling along a circular track. The latter is 3D printed (ABS plastic) with an inner track of 20.32 cm diameter which is lined with a 1.8 mm thick low-loss natural rubber (NR). The NR composition has been developed in-house at DSTO [9] to reduce noise and wear whilst minimizing power loss. Teflon sheet with a thickness of 0.5 mm is fixed on both inner vertical sides to reduce friction between the ABS plastic wheel and the sphere. On the radially inner side of this track, a series of fourteen copper wire-wound coils are located. Sixteen small cylindrical neodymium 'guide-magnets' are placed at equal intervals around the outer circumference of the wheel with alternating poles. There are two guide-magnets for each full rotation of the sphere around the track. The guide-magnets are evenly spaced, such that with every half rotation of the sphere the poles of the sphere align with an oppositely poled magnet. The purpose of the guide-magnets is to keep the poles of the sphere rotating end-to-end, as described in full in previous work [7], rather than rolling eccentrically and not generating the maximum possible *EMF*.

To create an optimal transfer of power, the coils have to be wired to the load with some basic analogue circuitry. Were each of the fourteen coils connected in series so that their *EMF* added together, there would be only one or two coils generating electricity at any given point. The remainder of the coils would act as part of the load and so power would be dissipated through these extra coils, rather than just the load. This would severely reduce the power output of the device as a whole. It is for this reason that a simple circuit, shown in Figure 2, has been devised which uses a series of diodes to isolate the coils when they are not generating *EMF*. Low forward voltage diodes (1N5819) with a reverse bias voltage of 40 V were chosen for the individual control diodes as modelling had indicated potentially large open-circuit voltages for the ideal configuration at higher rotational speeds. For the diode bridge, a packaged surface mount diode bridge (ABS10 RG) was used to reduce space usage.

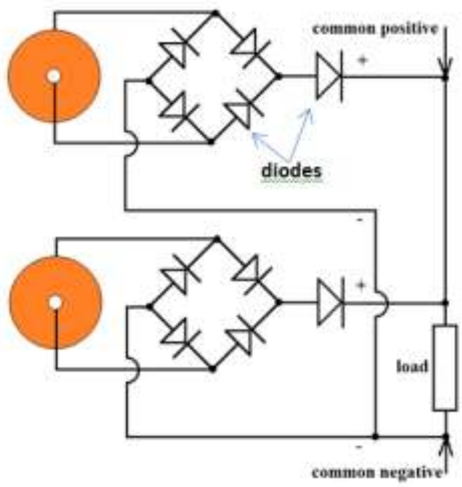

Fig. 2: Showing wiring for two of the fourteen coils. Other coils are connected to the same load at the same common nodes.

The prototype harvester in its present configuration (as shown in Figure 1) is based on model predictions and optimisation that will be reported in detail elsewhere. The design is centred on the requirement that the sphere make an integer number of rotations for each revolution of the device so that it passes the same point every cycle. This is so that it can align with the guide-magnets. The coils also have to be of such a size that an exact integer quantity fit around the inside of the device to maximise coverage and power generation. An initial series of designs was generated using a simple script which determined which device/coil configurations were geometrically sensible. The script iterated through integer values of number of sphere rotations, coil diameter and coil thickness to determine which combinations produced harvester designs with an integer number of coils. The resulting series of harvester designs were then run through a model (to be described elsewhere) to find the harvester configurations that produced the greatest power. The configurations which produced the most power were further examined to find the configurations which produced a current density less of than 2.8 MA/m^2, the approximate maximum current density of a copper wire prior to it melting due to Joule heating, so as to not fuse the thin 71 µm diameter copper wire used to create the coil transducers. Some efficient harvester designs were simply not practical, such as those containing small coil diameters but large thickness values.

The harvester design chosen for manufacture required the use of 32 mm diameter coils with 3 mm inner diameter and 3 mm thickness. A wheel was built to house these larger coils. However, due to coil availability, existing 27 mm diameter coils, with 3 mm inner diameter and 2 mm thickness (from previous work [6]) were used in the current study. The chosen wheel dimensions, with outer diameter of 21.4 cm and path width of 4.3 cm, resulted in an approximate total volume of 1,730 cm^3 and an active volume of 428 cm^3. Active volume is defined as the volume of the components that transduce energy, including the space that they are required to occupy as they move, for instance, not just the volume of the sphere, but also the volume of its path around the device.

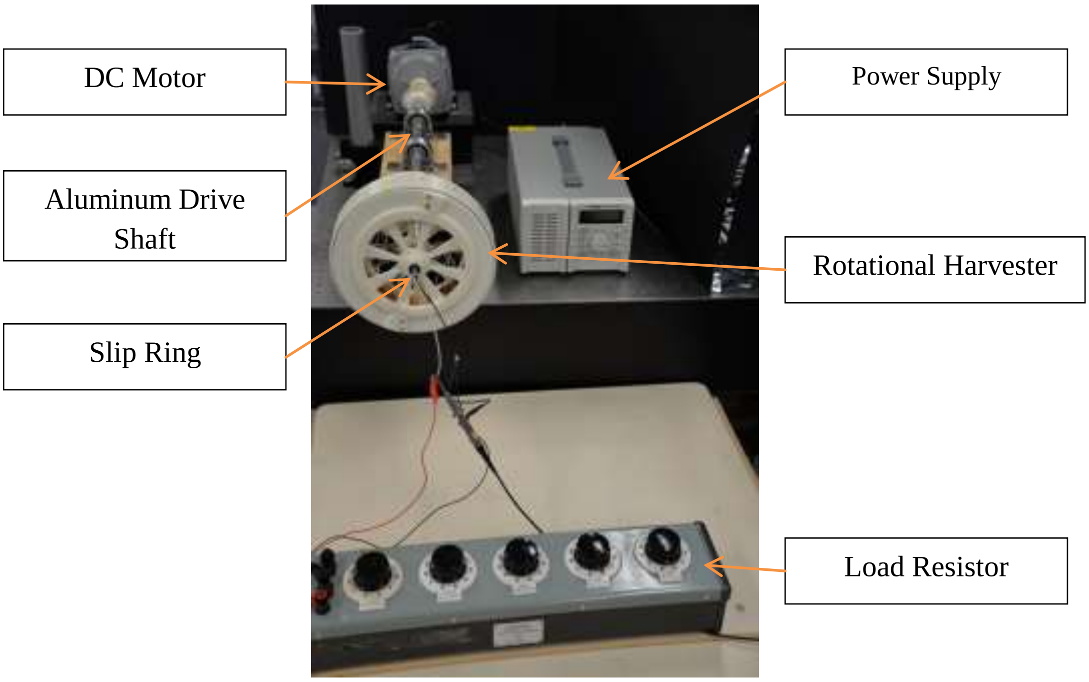

Fig. 3: Experimental setup.

As depicted in Figure 3, the physical testing was conducted using a test rig with a large DC motor (36V DC, 800 W, 500 rpm output, with large steel planetary 6:1 gearbox) that rotates an aluminium drive shaft. A standard DC power supply was used to power and control the motor. The purpose of the drive shaft is to rotate the prototype harvester, and also provide a significant enough distance between the magnet in the device and any ferrous material nearby, such as the steel bench or the motor. The presence of ferrous material nearby (within ~ 5 cm of the sphere) can significantly hamper the operation of the device by drawing the sphere to point in a direction other than the ideal. The guide-magnets help mitigate this issue. In practice the device would not require a slip ring, however for experimental simplicity a 2-channel slip-ring was attached to the prototype harvester allowing output voltages to be measured using a stationary oscilloscope (PicoScope 6403 PC Oscilloscope).

Several tests were conducted to examine the performance of the device. In order to demonstrate the maximum power provided by the device to a load, the load at which peak power transfer is achieved needed to be discerned. Due to the nature of the load circuit used (Figure 2), it was unclear exactly what the ideal matched load would be, for example, whether the matched load would be equivalent to the resistance of a single coil, two coils in series or two coils in parallel. To determine the matched load, a resistance decade box was connected to the output from the slip ring (Figure 3) and load resistances of 0-3000 Ω were stepped through in 50 Ω steps, with the load voltage recorded at each step. A constant speed of 100 rpm was used to find the matched load, with the speed measured using a hand-held laser tachometer and the speed adjusted by changing the supply voltage to the motor.

The device was tested in the open-circuit and matched-load condition at varying speeds. Voltage levels were recorded for speeds in the range 50-250 rpm, with 50 rpm intervals. DC average voltage, average peak voltage and the highest maximum peak voltage were found for both load conditions, and the corresponding power levels were calculated for the matched load condition.

Results and Discussion

In this section, the results of laboratory testing of the prototype harvester will be shown and discussed. The matched resistive load is experimentally determined. Open circuit voltage, load voltage and output power are reported as a function of rotational speed. The power density of the prototype harvester is calculated, and compared with a previous device.

Figure 4 shows the DC average power delivered to the load for a swept range of resistances. A single coil of the type used is typically 700 – 800 Ω, so expected peak resistance is either approximately 750 Ω to match a single coil, 1500 Ω for two coils in series or 375 Ω for two coils in parallel. Examination of Figure 4 indicates that the peak power transfer does indeed occur when the load resistance is near 750 Ω, suggesting that for the majority of the time each coil is connected to the load individually. It is for this reason that the subsequent tests used 750 Ω as the resistive load.

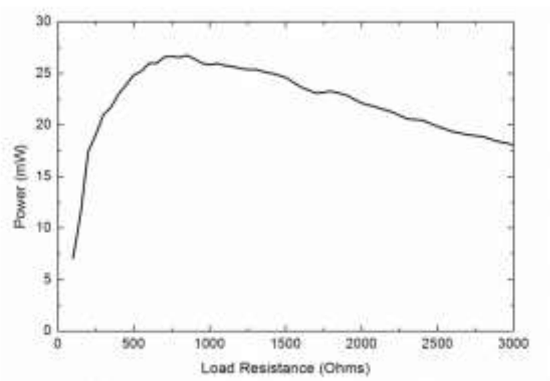

Fig. 4: Measured average power versus load resistance.

Figure 5 shows the open circuit voltage, and the voltage read across a matched 750 Ω load, as a function of rotational speeds. In both figures, the DC average voltage, maximum peak voltage and averaged peak voltage are plotted. It can be seen in both figures that the DC average voltage maintains a linear relationship to speed across the entire sample range. This is also true of the average peak voltage. This is in agreement with equation (1) where *EMF* is proportional to velocity and shows that the device is well behaved for the rotational speeds tested. The maximum peak voltage, being the absolute highest value read shows disproportionate values at higher revolutions. The authors believe that this is due to eccentricities in the motion of the sphere relative to its intended line of travel.

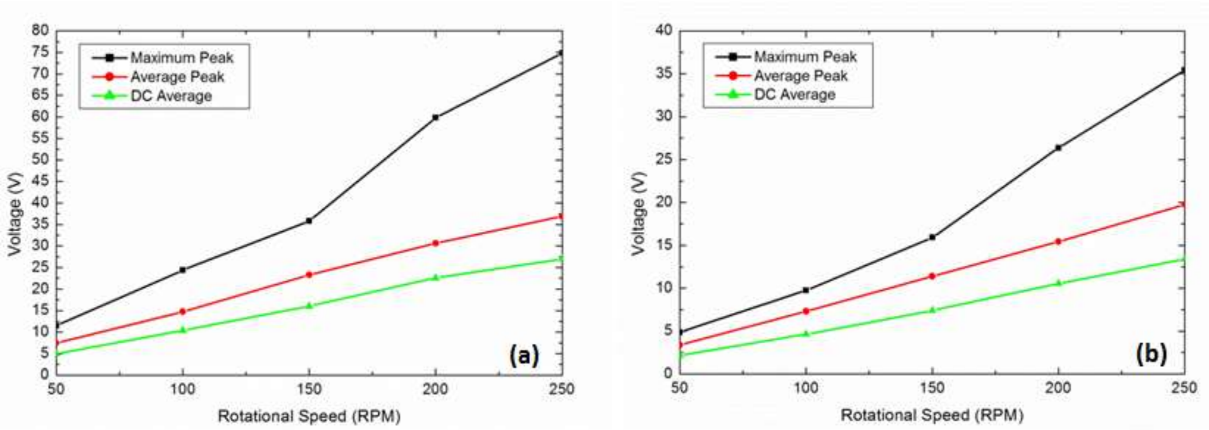

Fig. 5: a) Measured open circuit voltage, and b) measured load voltage across a 750Ω load, versus rotational speed.

Figure 6 compares the power delivered to the load as a function of rotational speed. It shows a steady increase in power with rotational speed, to a maximum DC average power output of 239 mW at 250 rpm. Even at low speeds of 100 rpm the device can deliver 28 mW, which is more than sufficient continuously power a wireless sensor.

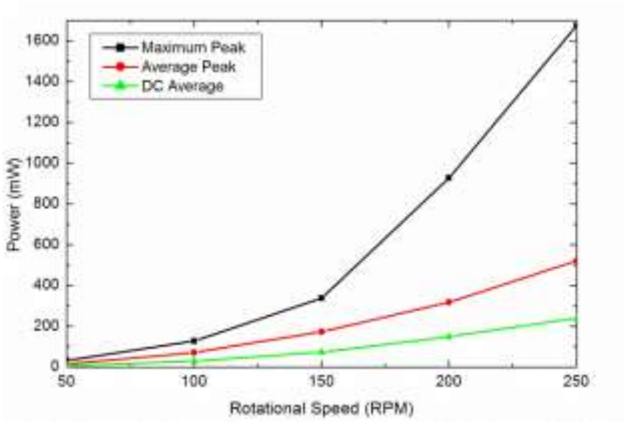

Fig. 6: Measured power versus rotational speed.

To provide a more direct comparison with other energy harvesting devices, it is useful to calculate some comparable metrics. As a rotational design naturally provides greater power with greater speed and size, scaling for these factors is necessary. As mentioned, the prototype harvester described in this paper has a total active volume of 428 cm^3, yielding the power densities shown in Table 1.

The scaled power density of the prototype harvester is significantly improved to 19.5 $mW/cm^3 krpm^2$ at only 250 rpm, compared with the previous device reported by the authors [7], which had an average peak power density of 661 $\mu W/cm^3$ and a scaled average peak power density of 7.4 mW/cm^3 krpm^2 at 300 rpm. The prototype harvester described in this paper compares well with the fourteen rotational generators tabled by Arnold [10], which have scaled power densities in the range 3.5 µW/cm^3 krpm^2 to 14 mW/cm^3 krpm^2.

Table 1: Power densities for varying speeds.

Speed (rpm)	Power Density (µW/cm^3)			Scaled Power Density (mW/cm^3 krpm^2)		
	Maximum Peak	Average Peak	DC Average	Maximum Peak	Average Peak	DC Average
50	74.3	36.0	14.5	29.7	14.4	5.8
100	297.1	166.5	66.9	29.7	16.6	6.7
150	788.7	404.9	171.1	35.1	18.0	7.6
200	2,168.3	741.8	347.5	54.2	18.5	8.7
250	3,911.3	1,216.6	559.5	62.6	19.5	9.0

Conclusion

This paper has presented a prototype rotational energy harvesting device with an optimised configuration using a novel method for harvesting rotational energy. The key distinction of this device is that, unlike many generators, it does not require a relative stationary point of reference and so can be co-located on the shaft being monitored. The DC average power output from the device is 239 mW at 250 rpm, with instantaneous peaks of up to 1.6 W. This power harvesting was achieved through the use of mechanical advantage provided by the rolling sphere, which increases the relative velocity between the moving magnetic pole and the coil transducer above it, hence increasing the *EMF* generated across the coil. The prototype harvester is optimised with an average peak power density to 19.5 mW/cm^3 krpm^2 at 250 rpm, a significantly improvement when compared to a previously reported device.

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References

1. M. Halgamuge, "An Estimation of Sensor Energy Consumption," Progress In Electromagnetics Research B, vol. 12, pp. 259-295, 2009.

2. W.-C. Yeh, "Novel TPMS Sensing Chip with Pressure Sensor Embedded in Accelerometer," in Transducers, Barcelona, Spain, 2013.

3. S. Roundy, "On the Effectiveness of Vibration-based Energy Harvesting," Journal of Intelligent Material Systems and Structures, vol. 16, pp. 809-823, 2005.

4. M. Amin Karami and D. J. Inman, "Hybrid-Rotary Translational Energy Harvester for Multi-Axis Ambient Vibrations," in Proceedings of the ASME 2012 Conference on Smart

Materials, Adaptive Structures and Intelligent Systems, Stone Mountain, Georgia, USA, 2012.

5. H. Moradi, M. Seyed Yazdi and E. Afjei, "Brushless dc Generator without Permanent Magnet," in International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Pisa, 2010.

6. S. Moss, G. Hart, S. K. Burke and G. P. Carman, "Hybrid rotary-translational vibration energy harvester using cycloidal motion as a mechanical amplifier," Applied Physics Letters, vol. 104, no. 3, pp. 1-12, 2014.

7. O. R. Payne and S. D. Moss, "Rotational Energy Harvesting from a Drive Shaft for Structural Health Monitoring," in 8th Australasian Congress on Applied Mechanics, ACAM 8, Melbourne, 2014.

8. S. D. Moss, G. A. Hart, S. K. Burke, S. C. Galea and P. G. Carman, "Vibration energy harvesting using a spherical permanent-magnet," Proc. SPIE, vol. 9057, p. 90570S , 2014.

9. G. A. Hart, S. D. Moss, D. J. Nagle and S. C. Galea, "Endurance Testing of a Vibration Energy Harvester for Structural Health Monitoring," Advanced Materials Research , Vols. 891 - 892, pp. 1261 - 1267, 2014.

10. D. P. Arnold, "Review of Microscale Magnetic Power Generation," IEEE Transactions on Magnetics, vol. 43, no. 11, pp. 3940-3951, 2007.