Energy Harvesting, Wireless, Non-Contacting Slip Ring for Rotorcraft

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ABSTRACT

This work demonstrated a magneto-inductive energy harvester for use as the energy source for a wireless, non-contacting “slip ring” capable of communicating digital data to/from a rotating shaft while simultaneously providing power to a wireless structural health monitoring (SHM) system for helicopter rotor components.

The energy harvester used the relative spinning motion of the rotor head swash plate to rotate small coils past permanent magnets, which generated an alternating (AC) current within the coils. A rectifier and DC-DC converter was used to convert these AC currents to DC currents at the voltage levels needed to power a SHM sensor network. The rectifier and DC-DC converter provided a constant 3.6 VDC output in the face of widely varying input AC voltages and spinning magnet frequencies in order to facilitate start-up from a rotor stopped condition. The system included protection from high voltage transients such as those from static discharge or lightning.

The spin energy harvester (0.5 kg), with one 13cc magnet, four 34cc coils, and with a 5mm gap, produced ~9Watts DC output at relative velocities of 9m/s. The harvester can be mounted to a swash plate to continuously power a scalable network of wireless sensor nodes in the rotating frame.

INTRODUCTION

Current practice for helicopter rotor systems maintenance does not provide for the direct measurement of rotor system loads. Installed heath and usage monitoring systems (HUMS) typically include drive train and gearbox monitoring with hard wired vibration sensors, but HUMS does not measure the loads on the rotating structure [1]. The continuous and automatic monitoring of the loads borne

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by each individual aircraft's critical components would allow tracking of the rate of fatigue damage. For rotorcraft, this capability would enable improved condition based maintenance (CBM), resulting in enhanced safety, reduced downtime, and increased mission readiness.

In our previous work, we have demonstrated wireless sensors for the direct measurement of strains and loads from helicopter rotor components [2]. Each wireless sensor node included its own integral energy harvester, power conditioning circuit, and energy storage element to eliminate the need to maintain batteries. Another approach to energy harvesting is to harvest the energy at one location and then distribute that energy to the sensor network as needed by the application.

The ability to distribute power to a network of wired/wireless sensor nodes provides for greater flexibility in the distribution of sensors and in deploying sensors that may require more power than a small vibration harvester can deliver. This is particularly important for optical fiber strain sensor demodulators, which may require several watts of power; and for impact detection sensors, which may require high continuous sampling at relatively high sample rates (20 KHz).

Providing a power and data interface to sensors on the rotor has presented significant challenges. Conventional slip rings weigh up to 11 pounds, suffer from data dropouts and noise, and require frequent cleaning and brush replacement [3]. Straub et al. discussed the idea of power generation on the rotor hub using both radio frequency (RF) power transfer as well as an alternator to overcome the limitations of slip rings [4]. These authors did not select RF power transfer because of its relatively low efficiency (10-30%). They also did not select an alternator because it could not provide power when the system stopped rotating. They compared a "roll ring" methodology to a rotating transformer assembly. Roll rings provided the same functionality as slip rings, but with a rolling electrical contact, which resulted in greatly reduced wear. The transformer provided a non-contact solution, which the authors identified as important for long-term use.

Arms et al. [5] described an energy harvester for wireless sensor operation from rotating shafts by mounting coils on the shaft that rotated relative to permanent magnets mounted adjacent to the shaft. Andrews and Augustin [1] used a "permanent magnet alternator" (PMA) to supply autonomous power to a hub-mounted digital communications interface on a full scale Bell Model 407 in a whirl stand. The prototype PMA had a mass of 3.6 kg (8 pounds) and consisted of 36 magnets mounted on the swashplate's non-rotating ring and 18 coils on the rotating ring. The PMA produced 68 watts, clearly demonstrating the feasibility of using the rotational motion of the rotor to generate energy.

For many applications, the power requirements for a network of wireless strain and load sensors may require much less than 1 Watt [6]. The optimum energy harvesting solution for given application would use a minimal number of components to power the appropriate number of wireless sensor nodes. Because each wireless sensor provides its own RF communications interface to a wireless sensor data aggregator (WSDA), the requirements for a hub-mounted digital communications interface are eliminated. The cabin-mounted WSDA supports beaconing protocols to enable time-synchronization, which avoids RF collisions by using time division multiple access (TDMA), and ensures all wireless sensor data are time-stamped accurately to +/- 32 microseconds [2,6]. A two-wire bus can be used to carry DC power and ground to each of the wireless sensor nodes in the network, which eliminates long wire runs for the sensor connections, and may be distributed using flat circuitry. The resulting system would be lightweight, compact, and scalable in design, so that it could be tailored for a given structural health monitoring (SHM) application.

OBJECTIVES

Our goal was to design, build, and test a robust, lightweight, energy harvester for use as the energy source for a wireless, non-contacting "slip ring" capable of communicating digital data to/from a rotating shaft while simultaneously providing power to a wireless structural health monitoring (SHM) system for helicopter rotor components.

METHODS

To accomplish this, we elected to use a magneto-inductive energy harvester in the form of a rotating energy generator. The energy generator used permanent magnets located on the vehicle (fixed) reference frame, and an array of coils located on the shaft (rotating) reference frame.

The design criteria for the energy harvester were:

- Energy harvester should be relatively light in weight and small in size
- Magnet/coil pair gap to range from 5-18mm (0.2-0.7 inches) to minimize installation alignment requirements and to avoid potential wear problems from debris
- System protection from high voltage transients such as from lightning strikes
- Energy harvester should produce 1.0 Watt (4.0 VDC at 250 mA) power output while rotating at ~4 revolutions/second on the H-60 swash plate.

A rotating testing machine with optical rate control was used to simulate the motion of a Sikorsky H-60 rotor swash plate. This allowed spin testing to be performed at range of known angular velocities. The fixture rigidly supported permanent magnets, which were mounted to the stationary portion, as well as arrays of small pickup coils, which were mounted to the rotating portion. The test fixture allowed the gap and the relative velocities between the magnets and coils to be well controlled. The positioning of each coil was such that each magnet passed one end of the coil core first, inducing a voltage in one polarity across the coil. As the magnet passed by the other end of the coil, a voltage of opposite polarity was induced.

Wireless sensing electronics require direct current (DC) for power; therefore, in order to use the alternating current (AC) generated in the rotating coils, a rectification circuit was designed and tested. Figure 1 provides a block diagram of the rectification and power conditioning circuit. AC voltage was rectified using an efficient Schottky bridge rectifier along with a relatively large capacitor to remove AC ripple from the resulting DC voltage output. Relatively high AC currents were demonstrated from the spin energy generator due to the construction and number of pickup coils, the high strength of the spinning permanent magnets, the close spacing of the coil/magnets, and their high relative velocities.

To condition this AC power for DC operated wireless and wired sensors, a wide input range buck-boost type DC-DC converter was used. The converter provided a constant DC voltage output over a wide input voltage range of 2.5V to 40V. This wide range can accommodate a number of different coil configurations, magnetic field strengths, and magnet/coil gap distances. Therefore it serves to make mechanical design tolerances less critical. Additionally, the use of the buck boost converter increases efficiency and greatly reduces the large ripple voltages that are present at low magnet pass frequencies. This design approach ensured that our spin energy harvester would generate energy very quickly from a rotor stopped condition, thereby enabling the harvester to provide power to the SHM sensor network before the rotor had reached its full rotational speed. This enables sensor data to be gathered from the rotor during start-up operational conditions.

The DC-DC converter stage was protected from large electrical transients that may occur in flight due to static discharge or lightning, through the use of a fast acting transient suppressor diode rated at 1500 Watts for fast (20uS) transient pulses, and was made fault tolerant through use of a series auto-resetting fuse. A signal indicating power status was also included, which tapped into the output from the DC-DC converter, and was used to notify the wireless sensor system when the power has attained an output level appropriate to support sustained operation.

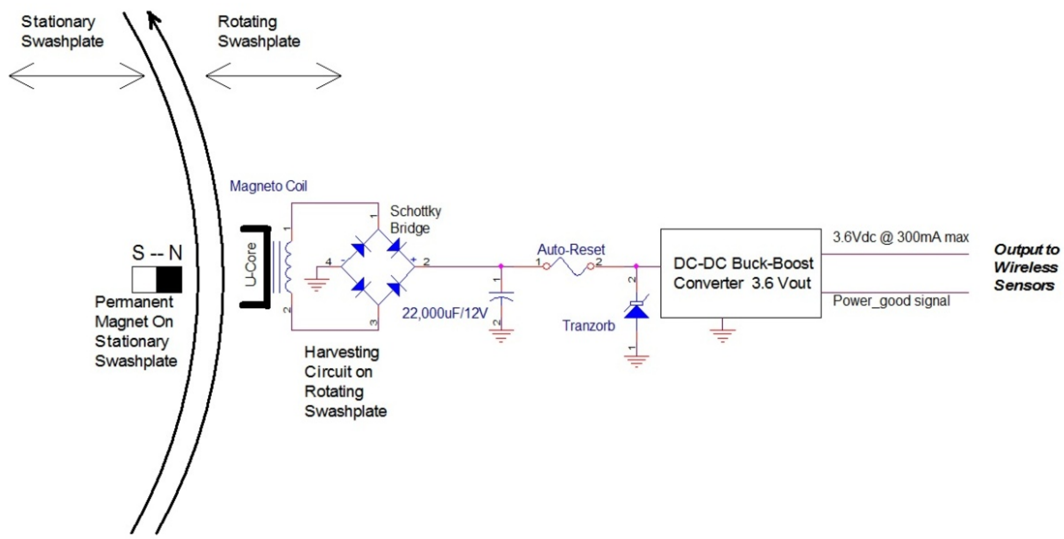

Figure 1. Functional block diagram of magneto-inductive spin energy harvester.

Several different coil and magnetic core configurations were built and tested. The configuration chosen was one that provided the best trade-off between weight and output power. Each coil's inductance was 20 mH with a magnetic core of laminated cold rolled grain oriented electrical steel, typical of those used in 50 and 60 Hz AC power transformer core laminations. The core extended around the sides of the windings to enhance the magnetic coupling. Each core measured

27mm x 42mm x 30mm (34 cc volume). The magnetic core and wound coil's mass totaled 96 grams. Cylindrical neodymium iron boron magnets were chosen, these had a mass of 97 grams each and were 25.4 mm in diameter and 25.4 mm in length (13cc volume). Figure 2 provides photographs of the coil/magnetic core and permanent magnet used in the selected design.

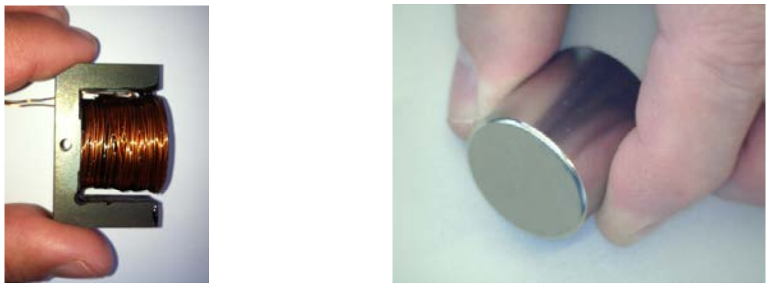

Figure 2. Components for spin energy harvester: Coil and laminated transformer core (at left), neodymium iron boron magnet (right).

Mounting to a Rotorcraft Swash Plate

A mechanical design for the spin energy harvester to be mounted on the Sikorsky H-60 swash plate is provided below in Figure 3. The mass of the aluminum housing and fasteners for this design is 950 grams. Including four coils with laminated transformer cores and four neodymium magnets, the total mass of the energy harvester is ~1.7 kg. One advantage to placing the harvester at this location is that the air gap between the rotating and stationary elements is well controlled by the main rotor bearing. The other advantage is that at the H-60's main rotor rotational rate of 4.3 Hz (27 radians/sec), and with the swashplate diameter of 0.7 meters, the relative velocity of coils/magnets is ~9.5 meters/second.

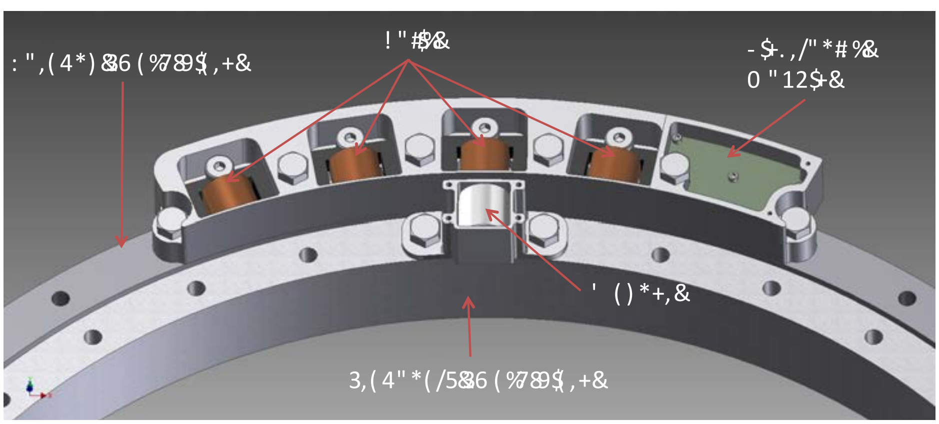

Figure 3. Design for spin energy harvester mounted to a Sikorsky H-60 swash plate.

RESULTS

The spin energy harvester's power output was proportional to the square of the relative velocity of the magnet to the coils, and power output decreased exponentially with increasing gap size. Matching the load impedance produced a maximum power output, this load impedance was determined to be ~13 ohms for a spin harvester comprised of four coils. With one magnet & four coils, and 3m/sec relative velocity, continuous power output ranged from 1.0W to .06W for coil/magnet gaps of 5 to 18 mm. At 9m/sec velocity, power output was significantly increased and ranged from 9.2W to 0.5W for coil/magnet gaps of 5 to 18 mm. Figure 4 provides continuous power output as a function of gap at these two relative velocities, with a matched load impedance on the four coils.

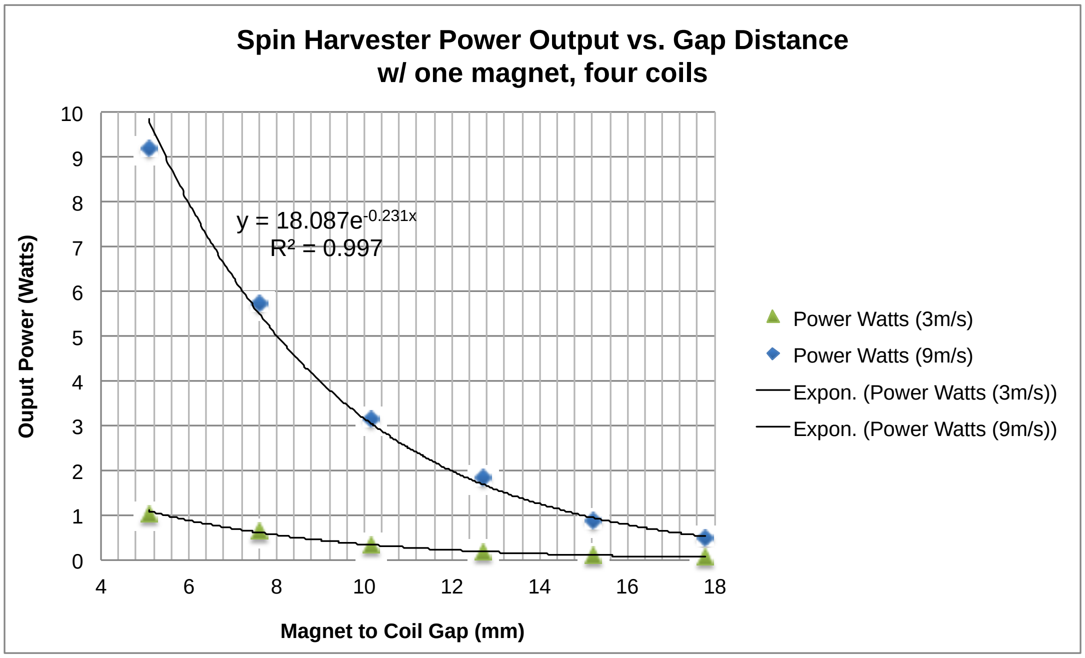

Figure 4. Spin energy harvester's output power versus magnet/coil gap for two relative velocities: 3m/s and 9m/s. An exponential curve was fit to the 9m/s velocity data, representative of the H-60 swashplate application.

With four magnets and four coils, and at 9 meters/second relative velocities, the spin energy harvester's power output would be quadrupled to produce ~37W at 5mm gap. The specific power output for our spin energy harvester in that configuration, which would feature a total mass of 1.75 kg (800 grams for the coils and magnets plus 950 grams for the aluminum mounting hardware) may be calculated at 21 Watts/kg. This result compares favorably with the more complex PMA design of Andrews and Augustin [1], which produced 68W (for a 3.6 kg mass) to provide a specific power output of 19 Watts/kg.

A laboratory SHM demonstration was made that was powered exclusively from the permanent magnet generator. Power was distributed along the rotor system using a two-wire power bus. The spin energy harvester generated power at eight separate and distinct rotor head strain measurement locations (using half bridge, 4000 ohm resistance strain gauges) in the rotating frame. Each of the eight distinct wireless strain sensor nodes sampled strain at 128 samples per second simultaneously (within +/- 32 microseconds of each other). Data were transmitted from each sensor node using an IEEE 802.15.4 radio with a transmitted output power of +15 dBm. The time-synchronized data were transmitted to a Wireless Sensor Data Aggregator (WSDA, MicroStrain, Inc., Williston, VT, USA) from the rotating frame to the fixed frame continuously, with a measured bit error rate of less than 1%.

CONCLUSIONS

This work has demonstrated that a relatively lightweight and small non-contacting magneto-inductive generator can power a wireless rotorcraft SHM system. The system can be tailored to meet the requirements of a given strain or loads monitoring application, and has the potential to provide enough energy for a wide variety of measurement systems that may require high data rates, including: conventional foil strain gauges for loads monitoring, piezoelectric strain gauges for impact detection, and accelerometers for vibration monitoring. The two-wire DC power bus may conform to a complex structural geometry by using flexible circuits, highly conductive inks, or plasma deposition processes.

Further work is planned to enhance the harvester's permanent magnet configuration, to harden the system, and to test the packaging to military environmental standards (MIL-STD-810F) in order to support full scale (whirl tower) and flight tests in the future.

ACKNOWLEDGEMENTS

MicroStrain, Inc. gratefully acknowledges the support of the US Navy's SBIR & BAA programs. Note that the US Navy does not endorse any specific product or process by supporting this work.

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