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A Prototype Energy Harvester for Powering a Wireless Acceleration Transducer inside a Rotorcraft Gearbox

Riyazal Hussein, Scott D. Moss, George Jung and Henry J. Kissick

Aircraft Health and Sustainment, Aerospace Division, Defence Science and Technology Group,
506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia

Abstract

This paper describes an energy harvesting approach for use within a rotorcraft main transmission gearbox for powering *Health and Usage Monitoring Systems*, and/or *Condition-Based Maintenance* wireless sensors. The approach uses a wire pancake-coil electromagnetic transducer attached to the planet carrier inside a gearbox that is rotating at 5.8 Hz, and a series of stationary permanent magnets attached to the inside of the casing and adjacent to the circular transducer arrangement. This harvesting approach is being developed for the powering of sensors during long-duration gearbox experiments where replacing batteries within a transmission is both inconvenient and undesirable. When operating at ~350 revolutions-per-minute, the prototype harvester device examined in this work produces an average electrical power of 280 mW, which is sufficient to power a commercial-of-the-shelf acceleration-based sensing system that can be mounted on the planet carrier-plate inside a gearbox.

Keywords: Energy harvesting, *Health and Usage Monitoring System*, HUMS, *Condition-Based Maintenance*, CBM, wireless sensor, electromagnetic.

Introduction

Recently reported Class-A helicopter [1, 2] mishaps have been attributed to faulty planetary bearings/gears in the main transmission gearbox. Potentially, these faults - which lead to catastrophic failure - could have been detected by a *Health and Usage Monitoring System* (HUMS). HUMS sensors attached to the gearbox, mounted outside and/or inside the transmission casing with communication and powering via slip-rings, can arguably detect abnormal vibrations and provide advanced warning to the aircraft operators. HUMS approaches themselves can, however, produce issues such as: certification concerns; increased technical complexity due to the gearbox modifications required; added weight; the introduction of additional maintenance for example the need to replace batteries and the downloading and analyse of data; and may not necessarily have a high probably of detecting the faults associated with planetary bearings/gears due to noise or other mechanical changes.

An experimental HUMS approach being explored by DST involves the utilisation of a commercial-off-the-shelf (COTS) Ridgetop's Rotor Sense ^{TM} wireless acceleration sensor [3]. This sensor is capable of being mounted directly to the planet carrier-plate within the main transmission gearbox, and is capable of providing a continuous time-history of vibration data.

Although the sensor is capable of acquiring HUMS/CBM data in real-time, the as supplied system is powered by a primary battery and hence is restricted to measurements of less than one day. The ability to acquire sensor data over the longer experimental durations, such as months, is required. A robust and continuous source of power is needed in order to operate the Ridgetop's Rotor Sense ^{TM} sensor for these extended experimental periods. Energy harvesting is well suited as a power source for this type of experimental application [4].

The primary objective of this work is to explore, develop and demonstrate an energy harvester prototype capable of powering a wireless transducer for next generation HUMS and CBM applications inside a rotorcraft gearbox. A basic schematic of this concept is shown in Figure 1. A secondary objective is to show that the energy harvester can be used as a power source for a COTS Rotor Sense ^{TM} sensor system employed experimentally inside a rotorcraft gearbox for measuring a complete set of fault vibration data over many months. The vibration data will be analysed to determine whether it can be used to detect the types of gearbox faults reported in references [1, 2]. This work will be under taken by inducing a similar fault in the planet gears inside the Bell 206 gearbox, which will then be subjected to axial and radial load propagating the cracks as reported in the accident investigation reports [1, 2]. The acquired data will be utilised by data scientists to develop algorithms for HUMS and CBM, with the goal of improving safety.

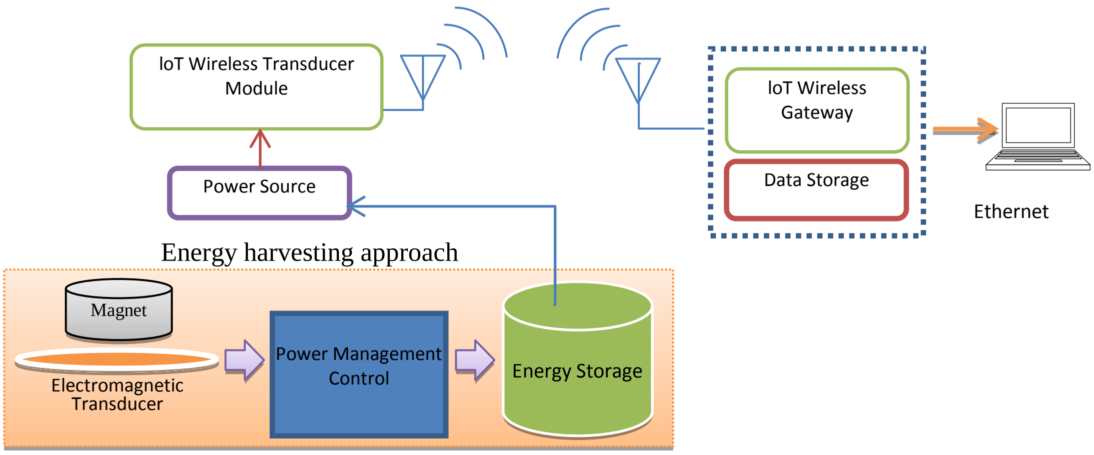

Figure 1: Schematic of the prototype energy harvester to power IoT wireless transducer

Principle and Theory of Energy Harvester Operation

The energy harvesting approach examined uses a wire pancake-coil electromagnetic transducer mounted on a rotating surface along with energy harvesting electronics, and a number of permanent magnets attached to a stationary surface adjacent to the transducer arrangement. As the transducer sweeps past the magnets during rotation, the permanent magnets induce an electro-motive force via Faraday's Law of Induction [5].

$$V_{\text{e.m.f.}} = = Nl\frac{\Delta \Phi_B}{\Delta t} \qquad (1)$$

where $V_{\text{e.m.f.}}$ is the electro-motive force (voltage), N is the number of turns contained in a wire coil, l is effective length of the coil, $\Delta\Phi_B$ is the change of flux density going through the coil and Δt is change in time. The open circuit voltage generated by a pancake-coil transducer, as it rotates beneath a fixed Samarium-Cobalt (SmCo) magnet, was modelled using Faraday's law with a continuum approximation for the coil. The parameters used for the model predictions are given in Table 1. Assuming that the coil is thin, and that the magnetic field is spatially-uniform and time-varying, then it can be shown that the electro-motive force (e.m.f.) generated across the coil is,

$$V_{e.m.f.} = -N\,\frac{\pi}{3}\left(a_2^2 + a_1\,a_2 + a_1^2\right)\frac{\partial B_z}{\partial t} \tag{2}$$

where the effective area of the coil is $A_{eff} = \pi\,\frac{\left(a_2^2+a_1\,a_2+a_1^2\right)}{3}$ and the effective coil radius is $r_{eff}= \left(\frac{a_2^2+a_1\,a_2+a_1^2}{3}\right)^{1/2}$. The variation of the magnitude of the magnetic field with time, averaged over the (thin) coil in the vertical *z* direction, is estimate as,

$$B_z = B_O * Exp\left[-\left(\frac{t-3*(impulseT/2)}{(impulseT/2)}\right)^2\right]. \tag{3}$$

Substituting equation (3), plotted in Figure 2, into equation (2) yields the predicted open circuit coil voltage prediction shown in Figure 3. Assuming a zero gap between the magnet and pancake-coil, the predicted peak open circuit voltage is 111 V. Using the measured coil resistance and inductance shown in Table 1, and assuming half the open circuit voltage across a matched load, the predicted nominal peak power is approximately 3 W. This power prediction will be de-rated by the finite air gap between the SmCo magnets and the coil transducers. The air gap will reduce the peak field B_O in the region of the pancake-coil, hence reducing the flux change in the coil region and lowering the induced e.m.f. The expected gap is ~2 mm, which reduces B_O to ~0.2 T and the predicted average output power to 88 mW per magnet (while the coil is energised). This prediction indicates that an energy harvester design with multiple magnets can generate sufficient power for continuous operation of a Ridgetop Rotor Sense TM sensor.

Table 1: Model parameters

Parameter	**Symbol**	**Value**
Coil turns	N	3850
Coil resistance	R	1008 Ω
Coil inductance	L	158 mH
Coil inner diameter	a1	1.5 mm
Coil outer diameter	a2	15.5 mm
Rotational frequency	Rps	5.8 Hz
Period of rotation for coil	p	1/Rps
Radius, center of transmission to the center of the coil	r	85 mm
Coil path length	c	2*π*r m
Coil velocity	v	c/p m/s
Impulse time for coil to pass peak of magnetic field	impulseT	(2*a2)/c s
Effective frequency of the magnetic field change as the coil passes under magnet	ω	(2*π)/(impulseT)
Assumed maximum peak value of SmCo magnetic field	B_O	0.82 T

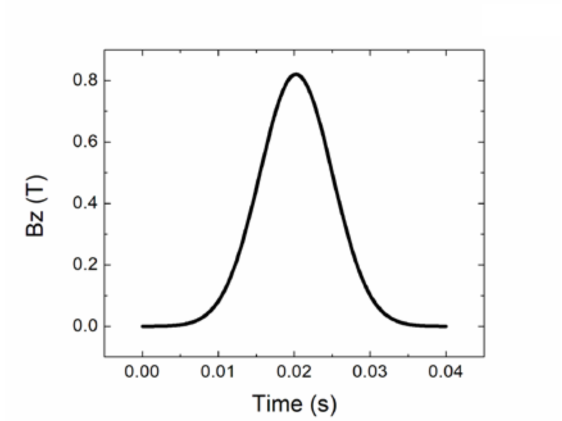

Figure 2: Estimated spatially-constant time-varying magnetic field as the pancake-coil passes under a SmCo magnet (zero gap)

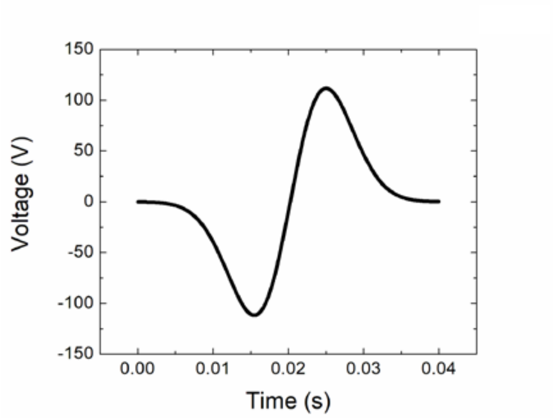

Figure 3: Predicted open circuit voltage as the pancake-coil passes under a SmCo magnet (zero gap)

Experimental

This section describes the construction of the prototype harvester itself and the accompanying power conditioning circuit, and including design decisions and optimisation. The methods for testing and characterizing the device are also elucidated.

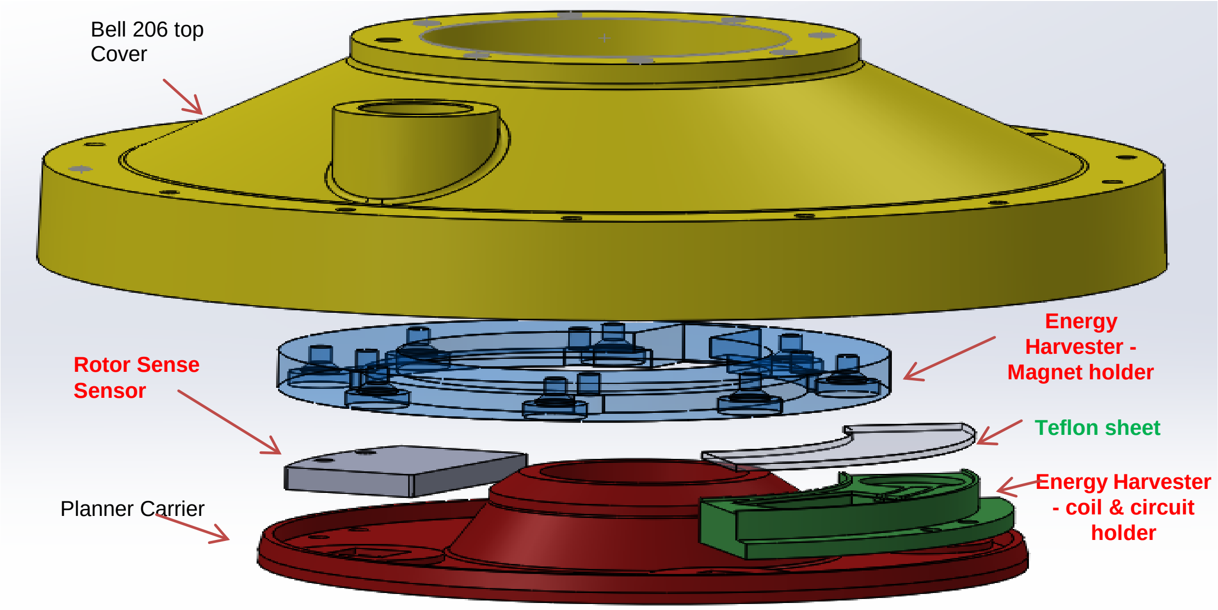

Figure 4: Exploded view designed in Solid works for the components of energy harvester to be 3D printed

As mentioned earlier, the Ridgetop's Rotor Sense ${}^{\text{TM}}$ sensor system is a COTS wireless rotational and acceleration sensor (3-axis) designed to extract high-resolution vibration signatures caused by gear faults. Figure 4 shows the positioning of the Rotor Sense ${}^{\text{TM}}$ sensor on the planet carrier gear. The energy harvester itself consists of two parts: (i) a magnet holder, and (ii) a coil and circuit holder. The magnet holder is attached to the inner casing of the Bell 206 gearbox top cover using four out of its eight studs, and contains up to eight equally spaced SmCo rare earth magnets along its circumference. SmCo magnets can operate up to its base temperature of 260°C without significant demagnetisation, more than sufficient for the expected 100°C gearbox internal operating temperature. The circuit holder contains a single pancake-coil and the energy harvester power conditioning circuit. The coil consists of a 31 mm outer diameter coil wound from 33.5 µm diameter enameled copper wire to a thickness of 3 mm with approximately 3850 turns. Coil resistance is 1 kΩ with an inductance of 160 mH. The rotating coil is positioned such that there is a gap of 2 mm to the lower face of the magnets. Located next to the coil is the power conditioning circuit to regulate the harvested electrical power, which was designed and built in-house. The voltage pulses are first rectified using a diode bridge and used to charge a small high voltage storage capacitor. A buck regulator converts the high voltage to approximately 4 V with high efficiency. This is followed by a low dropout linear regulator for filtering and final regulation to a sufficiently clean, constant output of approximately 3.5 V (Figure 5). The power conditioning circuit also features overvoltage protection at both the input and output stage to protect itself and the attached sensor. Any excess power produced during operation is safely dissipated. All components have been carefully selected to withstand operating temperatures of up to 125 °C over extended periods with, as mentioned, the maximum expected temperature during operation is expected to be just below 100 °C.

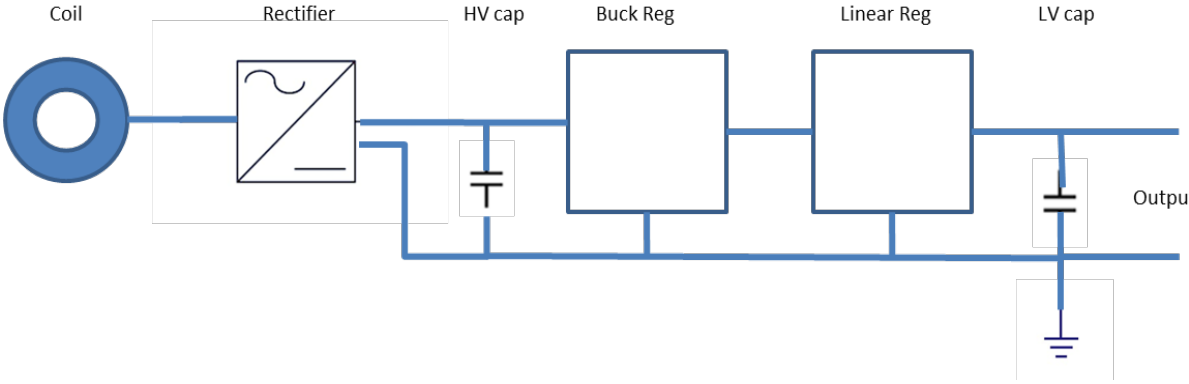

Figure 5: Energy harvester functional block diagram

The two energy harvester carrier parts were designed using computer aided design (Solidworks) and were three-dimensionally (3D) printed using polycarbonate (PC). PC was chosen due to its ability to withstand high temperatures since the oil temperature in the gearbox is expected to reach up to 100°C. PC has a tensile strength of 59 MPa with flexural strength of 93 MPa. It also is non-magnetic and exhibits a high resistance to synthetic gearbox oil.

Several bench tests were conducted using a custom build rotary lathe test rig to examine the performance of the energy harvester. A lathe gearhead with electronic speed control was vertically mounted on a test bed. An aluminum replica full scale Bell 206 top plate planet carrier was machined to be mounted on this lathe. Adjacent to this attachment, a stationary holder for the energy harvester was mounted.

Three series of test measurements were performed. The first tests measured the power required to run Ridgetop ^{TM} sensor at different sampling rates. This was done by measuring the voltage across a known (10 Ω) series resistor using an oscilloscope. The second tests measured the output of the harvester with a single SmCo mounted in the magnet holder and rotating at 350 rpm. This measurement was used to determine the number of SmCo magnets required to power the Ridgetop ^{TM} sensor. The third set of tests determined the power output of the energy harvester with all eight SmCo magnets installed.

Results and Discussion

In this section, the power requirements of the Ridgetop’s Rotor Sense $^{\text{TM}}$ sensor system will be examined, measurements of the performance of the prototype energy harvester will be reported and discussed, and the future work will be outlined.

Ridgetop’s Rotor Sense $^{\text{TM}}$ sensor system was examined to determine its average power requirements. During operation the sensor system transmits its accelerometer data to a wireless gateway, which in turn communicates with a personal computer via Ethernet or Wi-Fi. The measured electrical inputs for a sensor acquiring samples in streaming mode and transferring data to the gateway were 3.6 V and 45 mA (maximum current) equating to 162 mW. The measurements indicated a peak current requirement of 40 mA while transmitting, and an average current of 46 mA in data streaming mode (all at 3.6 V), broadly agreeing with Ridgetop’s specified 50 mA. Power consumption is not constant, as data is transmitted in discrete bursts; however these measurements showed that the power requirements between streaming and fast sampling modes did not vary widely. The harvester was therefore designed to satisfy the peak power requirement plus an additional power margin to account for additional losses under high temperature operation.

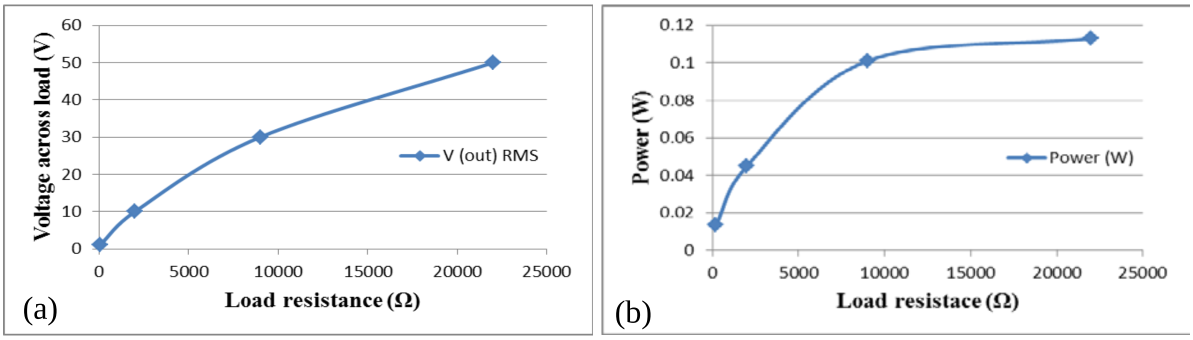

Figure 6: (a) Coil output voltage, and (b) harvested power, as a function of load resistance for a 31 mm pancake-coil, 2 mm air gap, and 350 rpm.

A single coil/magnet combination was used to determine the power output from the coil under various electrical loads. The coil transducer used has high internal impedance (approximately 1000 Ω) and is not an ideal power source. The output of the coil was rectified using a diode bridge and dumped into a small (220 uF) storage capacitor so that the output could be measured with a DC voltmeter. From Figure 6, the single coil/magnet combination at 350 rpm produced more than 40 V and a maximum power of 110 mW for load resistances exceeding 15 kΩ, and below 25 mW at low load resistances less than 1 kΩ. Hence, it was decided to use the maximum number of magnets practicable in the magnet holder (Figure 4). Due to geometrical constraints the maximum number of magnets was eight. The harvesters maximum output power using eight magnets is expected to be 8 * 25 mW = 200 mW which is more than adequate to power Ridgetop’s Rotor Sense $^{\text{TM}}$ sensor system. However, it required power conversion, conditioning and storage to output ‘clean’ DC power to the sensor.

The final sets of tests were performed to validate the design and construction of a power conditioning circuit. At the very least, the coil output had to be regulated and filtered to a steady 3.5-3.8 V for the sensor. As linear regulators are too inefficient for this task, it was decided to utilise a high efficiency, low power buck converter (Texas Instruments LMR16010), followed by a low dropout linear regulator (for output filtering) to keep the overall efficiency of the circuit, including its own power consumption, to above 50%. In addition, overvoltage protection was added for the coil and output storage, and filtering capacitors were included to present the sensor with low impedance, stable DC source. The entire circuit was assembled on a double-sided printed circuit board (PCB) of dimensions 49 mm (L) x 25 mm (W) x 14 mm (H) and was mounted into a recessed slot adjacent to the coil.

As the energy harvester impedance presented to the coil was not known (the buck regulator effectively chops the input current at approximately 1 MHz), the maximum output power of the harvester circuit was determined experimentally by placing a variable load resistor at its output and slowly decreasing the resistance until output regulation could just be maintained. For eight magnets at 350 rpm and 3.49 V output the 'critical' load resistance was 43 Ω. Hence, maximum power output of the energy harvester is $P=V^2/R$ = 283 mW. The harvester thus has a power margin in excess of 50% over the sensor requirement. This is expected to decrease somewhat at high temperatures due to increased current leakage of electronic components (especially diodes and other semiconductors).

The next phase of this work program involves the installation of the energy harvester and the Ridgetop's Rotor Sense ^{TM} sensor inside a Bell 206 gearbox (Figure 7a), with experiments to be performed within the DST Helicopter Transmission Test Facility (Figure 7b) to extract fault vibration data from the gearbox.

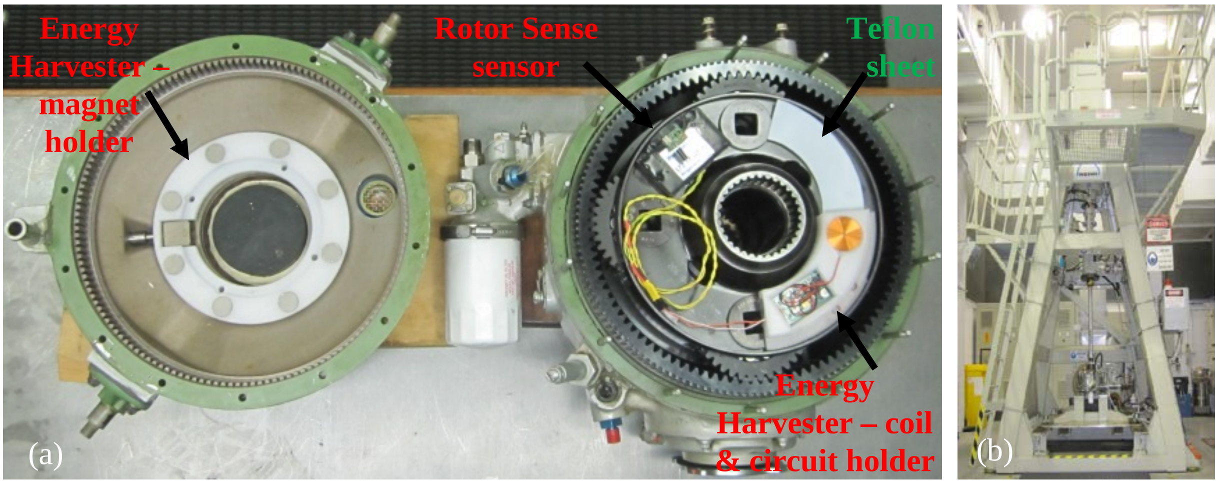

Figure 7: (a) Energy Harvester setup inside Bell 206 Gearbox, and (b) DST's Helicopter Transmission Test Facility

Conclusion

This study has demonstrated that a prototype energy harvester is able to generate sufficient power to supply a COTS wireless accelerometer (Ridgetop's Rotor Sense ^{TM} sensor system) located inside a Bell 206 gearbox. The prototype harvester uses a single pancake-coil mounted on a rotating planet gear (~350 rpm) with eight stationary SmCo magnets attached to the outer casing. The energy produced by this arrangement is in the form of discrete voltage impulses of up to 30 V amplitude and not suitable for powering electronics directly. An energy conditioning circuit was constructed that converts the high voltage pulses into a steady, regulated DC voltage source that is used to power the wireless sensor. The conditioning circuit is designed for operation in the high temperature ~100°C gearbox environment. The prototype harvester was evaluated on a bench test rig and energy consumption was measured, and compared with the measured power requirements of the wireless sensor system. The next phase of the study will be performed within DST's Helicopter Transmission Test Facility. This energy harvesting approach is expected to be useful for the next generation of long-duration HUMS experiments, powering wireless transducers in-situ within rotorcraft gearboxes.

Acknowledgements

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