Energy Harvesters for Rotorcraft Wireless Sensor Networks

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Abstract

The goal of this work was to develop and demonstrate energy harvesters capable of powering wireless sensors networks for next generation rotorcraft structural health and usage management systems (SHUMS). Wireless sensors eliminate or reduce cable harness weight and provide access to difficult to monitor locations. The introduction of energy harvesting makes the use of wireless sensors practical by removing the requirement for battery maintenance. The harvesters described here were designed to operate in different locations on different aircraft platforms. They were incorporated into simulated sensing systems measuring pitch link strain, bearing vibration and temperature, gearbox vibration and rotor component strain at various sample rates. Each harvester was evaluated on an appropriate test stand. In all cases, they provided sufficient power to allow the sensor network to successfully measure and transmit component critical data to a wireless sensor data aggregator (WSDA). This demonstration illustrates the flexibility of energy harvesting solutions. It illustrates their potential for inclusion in monitoring applications for a wide variety of machines and structures such as wind turbines, heavy equipment, rotating machinery, and helicopters.

Keywords: Wireless, Sensing, Synchronized Networks, Energy Harvesting, Rotorcraft, SHM, HUMS, SHUMS

Introduction

Recent advances in miniaturized sensors and microelectronics enable a new generation of sensor networks capable of tracking rotorcraft component usage. By gathering critical operational strains, loads, torques, vibrations, and temperatures over a helicopter's operational life, operators can better predict the remaining lifetimes of critical components (Figure 1). This promises to reduce maintenance costs, increase mission readiness, and enhance safety [1,2].

Energy harvesting is an ideal complement to wireless sensor networks. In many applications, energy harvesters can provide the power necessary to run sensors indefinitely. This eliminates the need to connect to a vehicle power bus, or to maintain batteries.

MicroStrain has previously reported on the successful application of strain energy harvesting from rotating components aboard a Bell M412 helicopter [3] and a Sikorsky MH-60S [4]. Those systems supported sampling rates up to 64 samples/sec. In the case of the MH-60, due to power considerations, the data was collected in bursts of one second duration every five seconds.

Figure 1: Examples of applications where energy harvesting combined with wireless sensors can lead to improved understanding of component usage.

In order to implement accurate CBM and PHM, higher data rates may be required, thereby requiring more power. Rotorcraft, due to their predictable vibration profiles, offer favourable conditions for vibration energy harvesting. In addition, the predictable large motions of rotor components offer opportunities for alternative means of electrodynamic energy harvesting. This paper expounds on the application of four specific harvesters on various rotorcraft and the potential they offer for CBM and SHM.

Objectives

The goal of this work was to develop and demonstrate energy harvesters capable of powering wireless sensors for next generation rotorcraft structural health and usage management systems (SHUMS). The target harvesting applications were purposefully selected to include a wide spectrum of vibration and motion inputs requiring the use of a broad range of energy harvesting technologies. Each harvester was to be coupled with a MicroStrain sensor node which would transmit data at rates sufficient for SHUMS. The testing of these systems was to be as realistic as possible by using appropriate test stands, with vibration/motion inputs representative of the target helicopter platforms. The results of this series of tests were expected to further bolster the argument for the viability, reliability and applicability of self-powered, wireless sensor systems onboard helicopters.

We identified four target applications for wireless sensor nodes that would complement existing wired sensors to more fully illuminate the health and usage picture of today's aircraft (Figure 2). Energy harvesting solutions were designed for each. The combination of a harvester with sensor node resulted in a "self-powered" sensor. In all cases, these transmitted the measured sensor data to a wireless sensor data aggregator (WSDA). MicroStrain has previously reported on the ability of the WSDA gateway to collect and synchronize incoming data from multiple sensor nodes operating at differing sample rates [4].

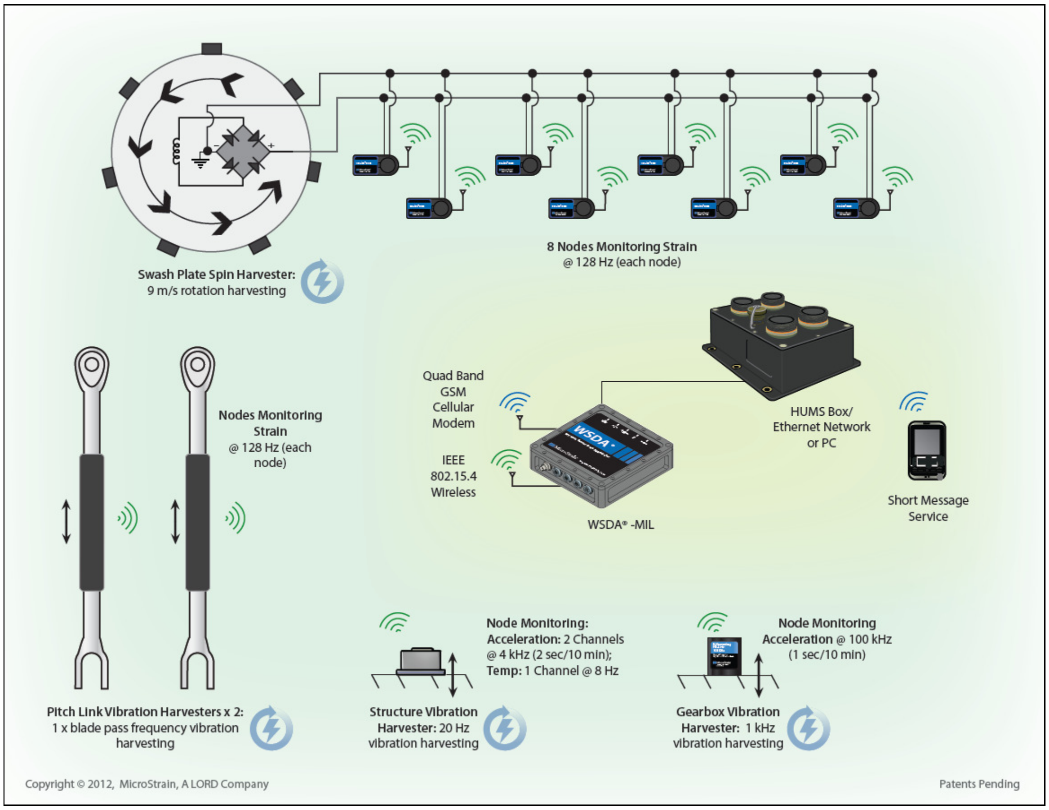

Figure 2: Illustration showing target applications where Energy Harvesters were used to power wireless sensor nodes. All sensor nodes transmitted data to a WSDA gateway.

APPLICATION 1: Pitch Link - Boeing Apache AH-64

Continuously monitoring pitch link loads can potentially provide a means to accurately life that component. More importantly, pitch link loads may also be used to extrapolate load cycles, and therefore fatigue, on many other components in the rotating frame. Measuring pitch link strain is particularly difficult using hard wired sensors due to its remote location, highly dynamic motions. This makes it an ideal candidate for an energy harvesting wireless sensor solution.

Methods – Pitch Link

A magneto-inductive harvester was designed which could mount to the exterior of the pitch link, while still allowing clearance for inspection, maintenance and safety wiring (Figure 3). The harvester was coupled to a MicroStrain SG-Link (Strain Gauge) sensor node. The strain data was transmitted to a WSDA using an adjustable power IEEE 802.15.4 radio in combination with our LXRS "lossless" communications protocol.

Figure 3: Apache Pitch Link Energy Harvester and Sensor Node.

The pitch link harvester consisted of two stacks of opposing magnets enclosed by a moving coil assembly (Figure 4). The vertical motion of the pitch link is primarily at one-per-rev frequency of 4.9 Hz. It is driven by the swashplate's cyclic input with typical amplitudes on the order of 1.2 inches pk-pk. Because of the large motion, it was not necessary to implement a highly resonant system. Instead, a pivot linkage system was implemented utilizing opposing magnets to slightly enhance the motion and provide end stops. Additional over travel protection was provided with hardened stop buttons and spring plungers.

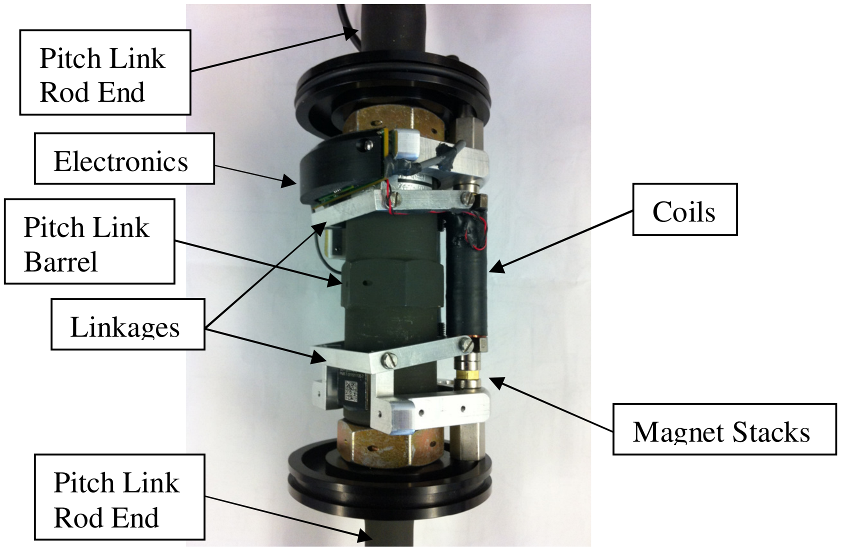

Figure 4: Pitch Link Energy Harvester (Protective Shroud Removed)

In order to fully test the pitch link energy harvester, we designed a rotating test setup capable of imparting the characteristic 1.2 inch pk-pk vertical displacements at 4.9Hz, while simultaneously inducing the ~38g centripetal acceleration that the pitch links are subject to (Figure 5). This setup consisted of a hydraulic actuator programmed to generate the 4.9Hz vertical motion input. A servo motor was fixed to the hydraulic actuator. The pitch link was mounted to a lever arm which, in turn, was fixed to the shaft of the motor. The motor's rotation speed was adjusted to generate the target 38g centripetal acceleration at the pitch link.

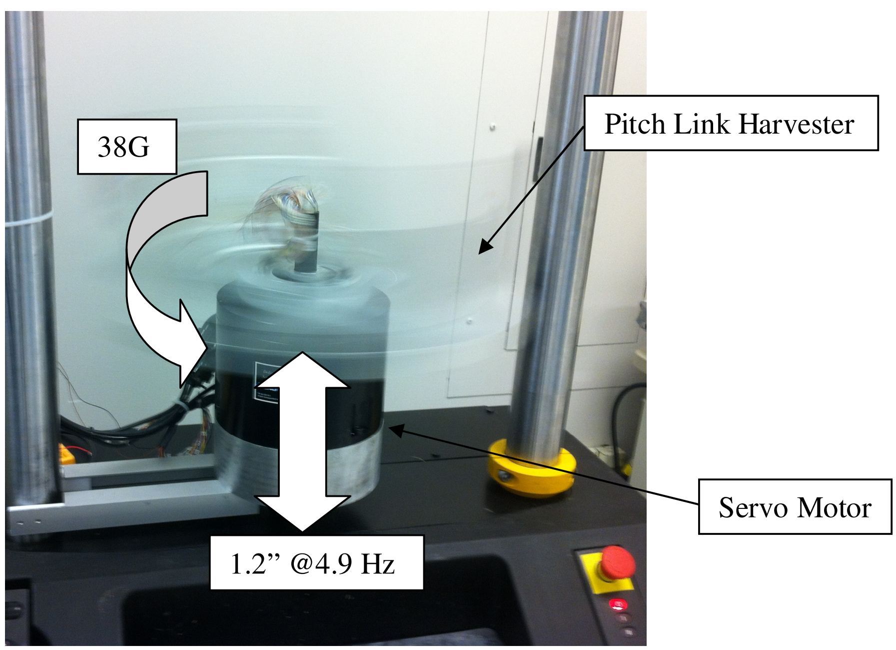

Figure 5: Motion blurred photograph of pitch link Harvester onboard Test Fixture

The SG-Link was configured with a "dummy" strain gage attached to the grade connector. This provided a constant, non-zero strain input level for the sensor to transmit when power conditions permitted. It simulated a strain gauge bridge as would be used in the target application.

Fifteen minute tests were run at 25%, 50%, 75% and 100% of the nominal 1.2 inch pk-pk vertical displacement at 4.9 Hz. The data logged by the WSDA was evaluated to determine if sufficient power was produced by the harvester to allow for continuous data transmission. The time to the first transmission was noted. This represents the time required to charge the internal storage capacitor from 0V up to the minimum voltage required to start the sensor node.

Results – Pitch Link

- No transmission at 25% displacement
- Intermittent transmissions of 128 Hz data at 50% displacement
    - Time to first transmission – 80 seconds
- Continuous transmission of 128 Hz data at 75%
    - Time to first transmission – 54 seconds
- Continuous transmission of 128 Hz data at 100%
    - Time to first transmission – 25 seconds

These results corroborated preliminary power output tests but additionally proved that the power conditioning circuit design was properly configured to support the data collection procedures and radio transmission schedule of the SG-Link sensor on board the pitch link node.

APPLICATION 2: Gearbox

The high frequency vibration data collected from gearboxes can provide vital information to CBM systems regarding gearbox health and operating conditions. Monitoring these vibrations using wireless sensors rather than hardwired sensors may reduce weight, and allow for more convenient retrofit.

Methods – Gearbox

A piezoelectric vibration harvester was designed and tuned to resonate at a typical kHz range gear tooth meshing frequency evident in gearbox vibration spectra. This was used to power MicroStrain's high speed vibration sensor node, the HS-Link.

The harvester utilized a multi-layer piezoelectric stack encased in a resonant frame with a proof mass attached (Figure 6). The frame was configured to amplify the forces generated by the vibrating proof mass, compressing the stack to generate electrical energy. The target resonant frequency was adjustable, within design limits, by altering the size of the proof mass. A one gram change in proof mass resulted in a ~10Hz change in the resonant frequency (Figure 7).

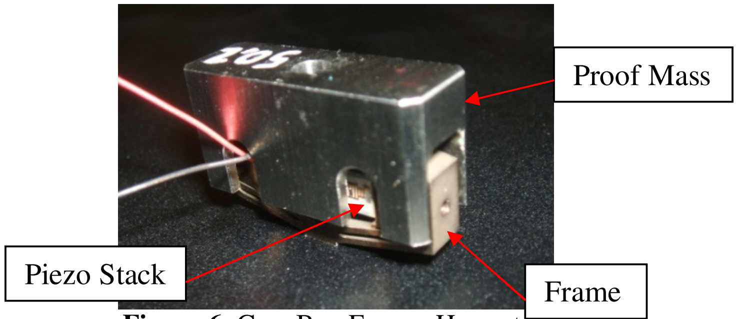

Figure 6: Gear Box Energy Harvester.

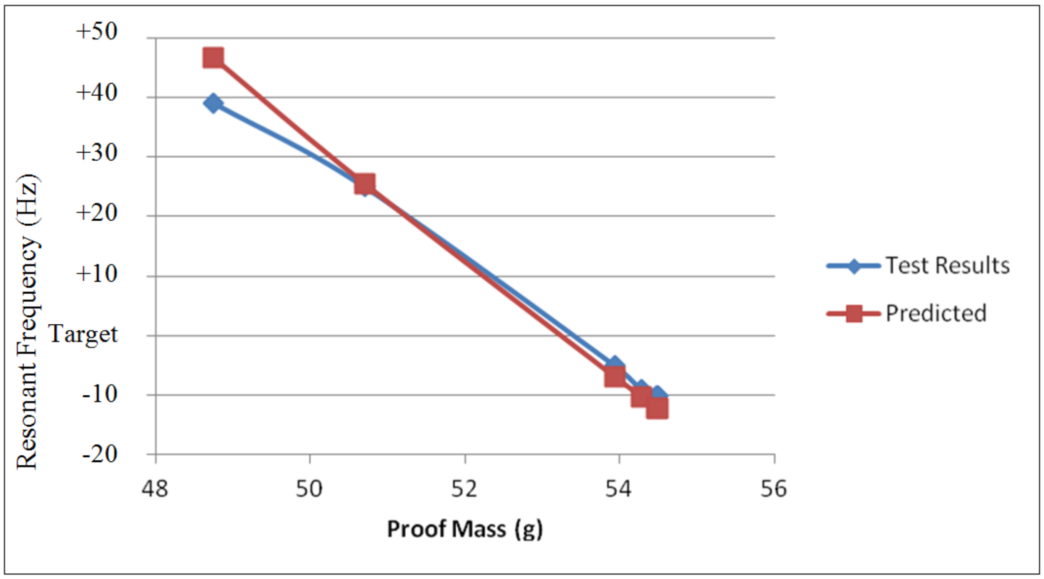

Figure 7: Effects of Proof Mass on Resonant Frequency.

Figure 8: Integrated Gear Box Harvester & HS-Link Sensor Node Assembly.

The high stiffness and low damping required for this application resulted in two unfavorable characteristic. First, the device exhibited a large temperature dependency. Small changes in the dimensions of the mechanical components due to thermal expansion had a significant impact on the resonant frequency (Figure 9).

Second, the low damping (high Q factor) resulted in a sharp resonance peak (Figure 10).

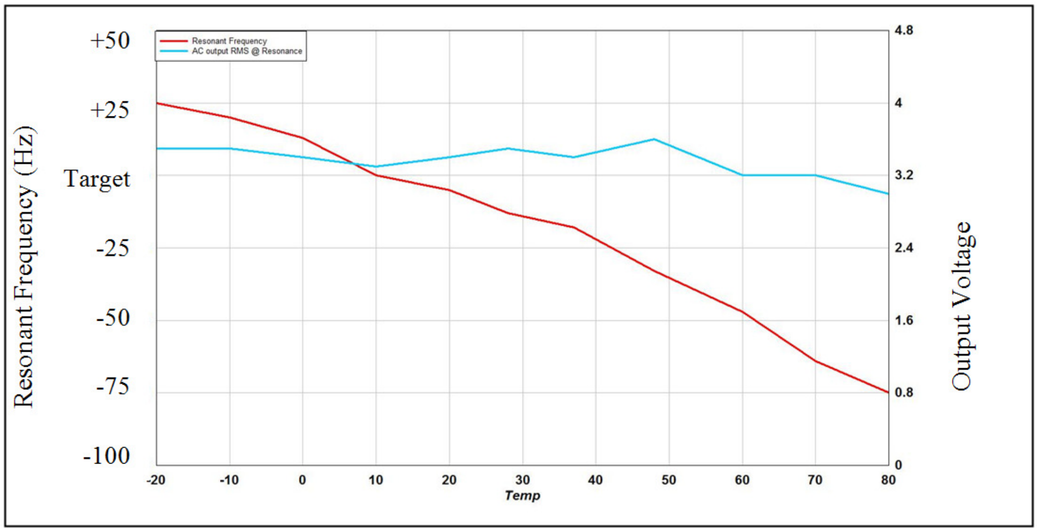

Figure 9: Effect of temperature on resonant frequency of the gearbox energy harvester.

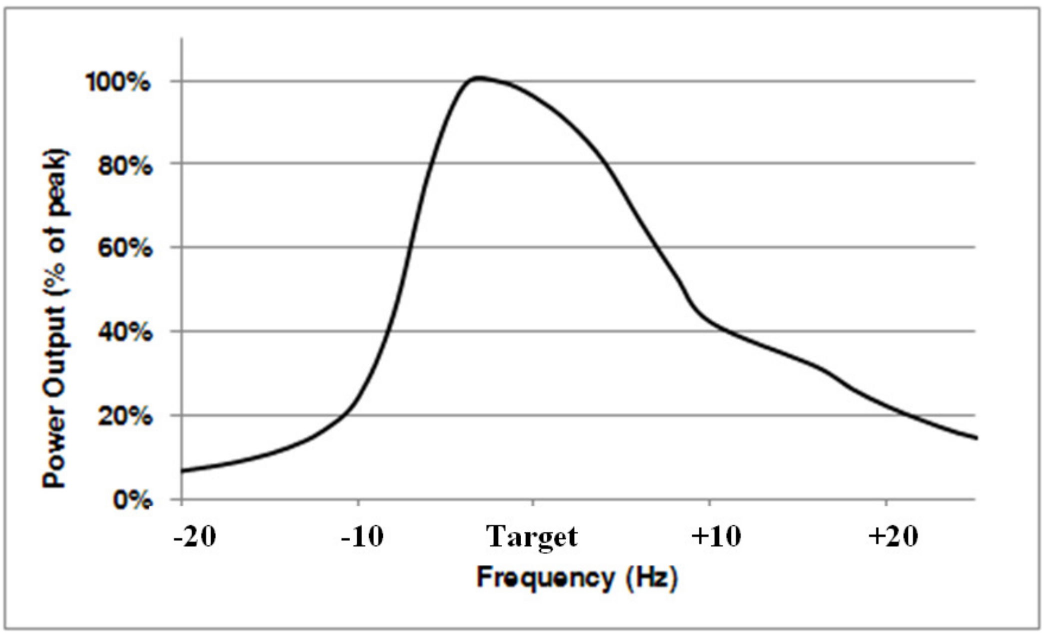

Figure 10: Gearbox energy harvester output power vs. input vibration frequency

The temperature effect, in combination with the narrow resonance peak, result in a operating temperature range of ±10˚C from design temperature. Despite these limitations, we believe that this can be a viable solution due to the relatively constant temperatures experienced on the gearbox while in operation, and the high power peak power output (35mW).

Initial testing was carried out using field recorded vibration data provided by a helicopter manufacturer. That data was replayed by our shaker table to excite the harvester and consequently power the HS-Link node. The sensor node was configured to collect burst samples of acceleration data at 100 kHz, for a one second duration. This was repeated every ten minutes.

Final field test was carried out on a gearbox test stand at the aircraft manufacturer's site (Figure 11). The gearbox was run at a range of operational torques.

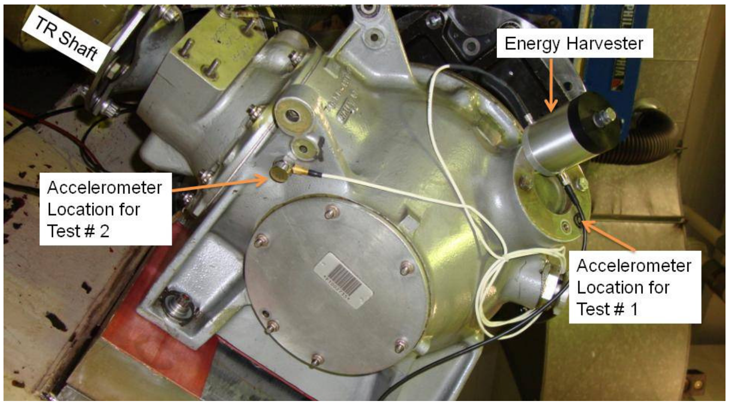

Figure 11: Energy Harvester/HS-Link Sensor Node Mounted on Gearbox Test Stand.

Results – Gearbox

Sufficient power was produced at all operational torque levels to collect and transmit the target acceleration data (Figure 12, Figure 13 & Figure 14). Excess power was produced in all cases, with much higher than anticipated power at the highest torque levels.

Time	Action	Harvester Output	Approx. Power Output
00:00	Node Started	NA	NA
03:00	TGB Ph I: 130 ft-lbs/4116 RMP	2.5 Vrms	31.25 mW
09:00	Ph II: 360 ft-lbs/4116 RPM	3.5 Vrms	61.25 mW
15:00	Ph III: 540 ft-lbs/4116 RPM	4.7 Vrms	110.45 mW
21:00	TGB Stopped	NA	NA
24:00	Node Stopped	NA	NA

Figure 12: Gearbox Energy Harvester Performance on Test Stand.

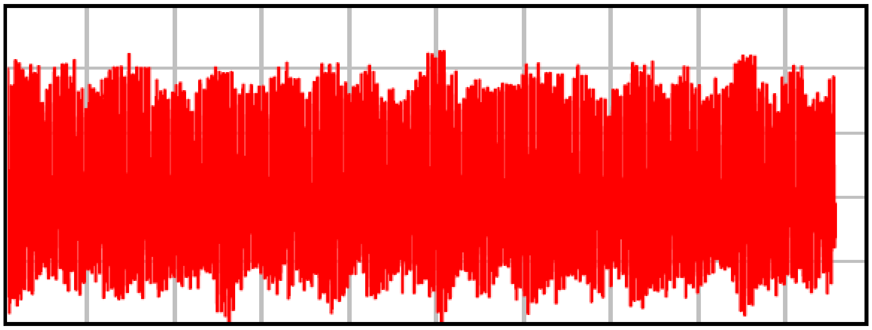

Figure 13: Example of 100kHz acceleration data vs. time collected by the HS-Link on the gearbox test stand. (Axis information obscured for Confidentiality.)

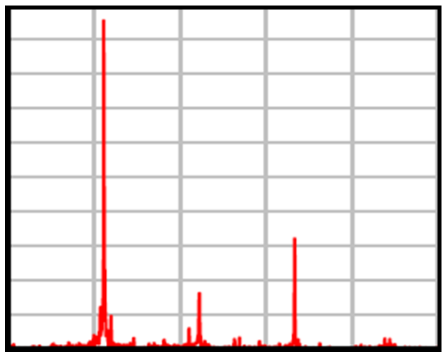

Figure 14: Segment of FFT of Raw Data from Figure 13.
(Axis information obscured for Confidentiality.

APPLICATION 3: Structural Vibration

Low amplitude vibrations centered on the blade passing frequency are found throughout helicopter airframes. This provides an opportunity to power low to medium duty cycle wireless sensors in a variety of locations.

Methods – Structural

We designed a resonant magneto-inductive vibration energy harvester tuned to the blade passing frequency of a target helicopter platform. This powered a wireless sensor node capable of collecting two axes of acceleration data at 4 kHz in two seconds bursts every ten minutes. In addition, it collected one temperature channel at 1 Hz continuously.

The energy harvester utilized a resonant spring-mass architecture with a magneto inductive energy generating element (Figure 15). The magnets were located on the stationary side to avoid damping due to nearby ferrous materials and to lessen dampening due to eddy currents.

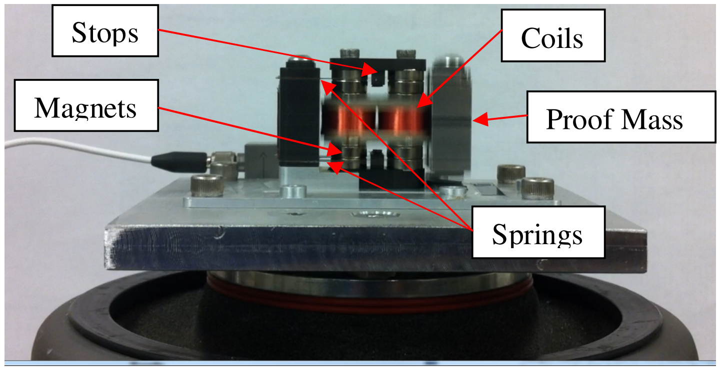

Figure 15: Structural vibration energy harvester shown during preliminary testing on shaker.

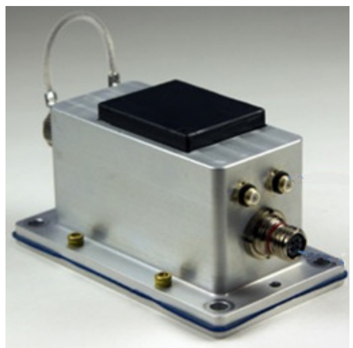

Figure 16: Structural energy harvester integrated with wireless sensor node capable of burst sampling two accelerometer axes at 4kHz, and continuously sampling one temperature channel at 1Hz.

Vibration surveys provided by the target platform manufacturer showed that, at the selected installation location, a vibration component at the blade passing frequency and 0.3g amplitude would typically be present. Preliminary testing of the harvester on our shaker table under these conditions showed a peak output power of 6mW, a bandwidth of ±1 Hz (Figure 17) and resonance shift across the temperature range of interest of 2% (Figure 18). The sensor node consumes an average of 1.5 mW when operating as configured.

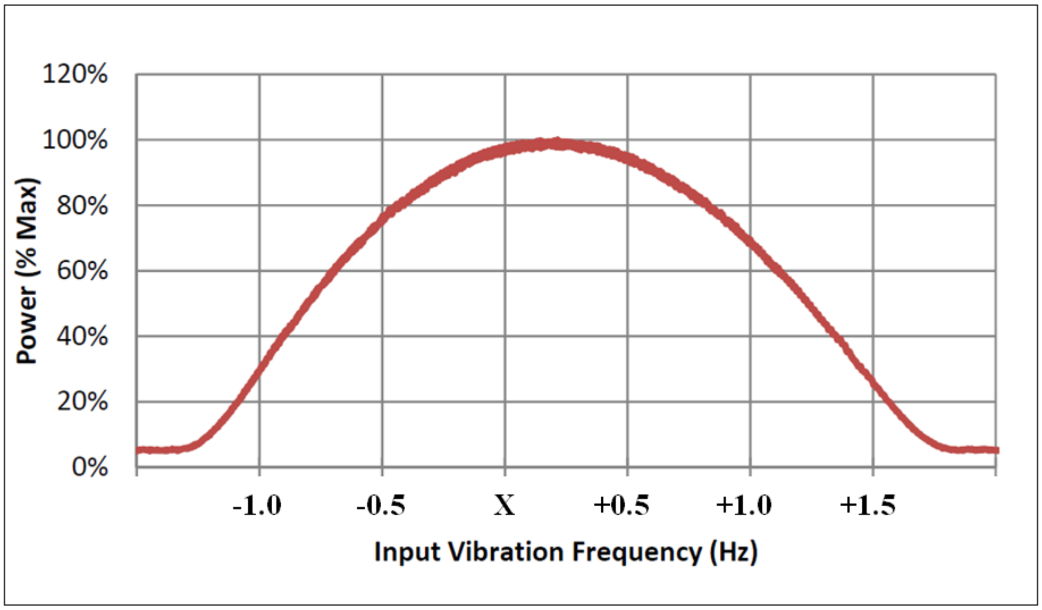

Figure 17: Structural vibration energy harvester output power vs. input vibration frequency. Peak power output with 0.3g input amplitude is 6mW. The usable input frequency bandwidth is +/-1 Hz.

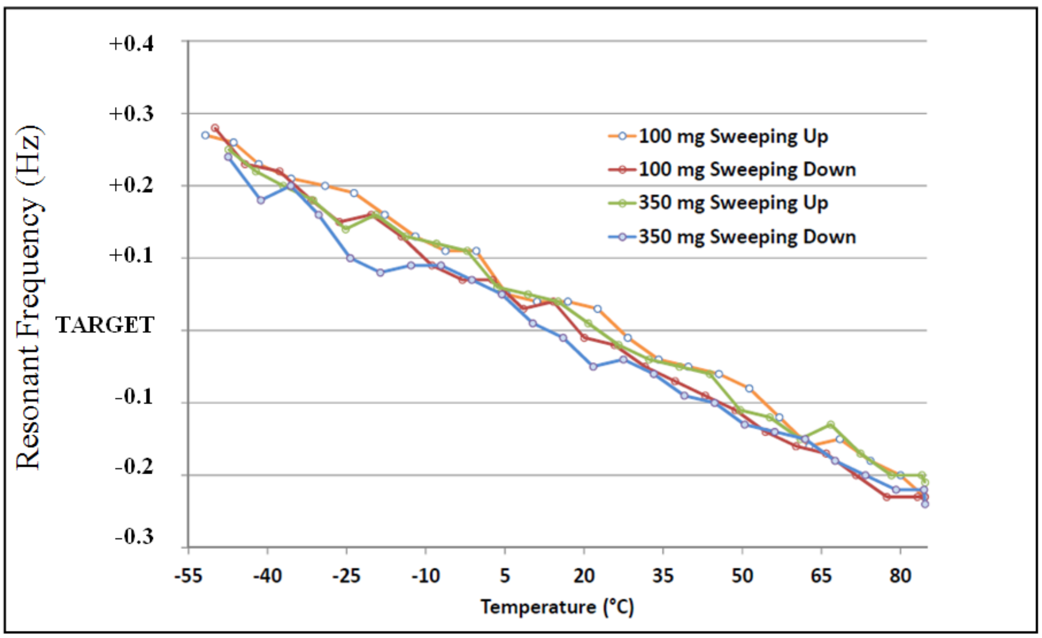

Figure 18: Effects of temperature on the resonant frequency of the structural vibration energy harvester.

The integrated harvester/sensor node was tested as a system in our laboratory using a shaker to generate the input vibrations. The platform manufacturer provided us with a series of vibration recordings taken from the target installation location under different flight conditions. We selected the recording with the lowest vibration amplitude. Our shaker was configured to reproduce this vibration dataset continuously for 6 hours. During that time, all data collected and transmitted by the sensor node was logged in the WSDA for later analysis.

Results – Structural

Figure 19 shows the sample data collected during the 6 hour test run. No missing data was observed due to a lack of power. All bursts of 4kHz data at 10 minute intervals is present. The several dropped temperature measurements were due to radio interference, not due to lack of available power. This data demonstrates that the energy harvester supplied sufficient power for the sensor node to operate throughout the test.

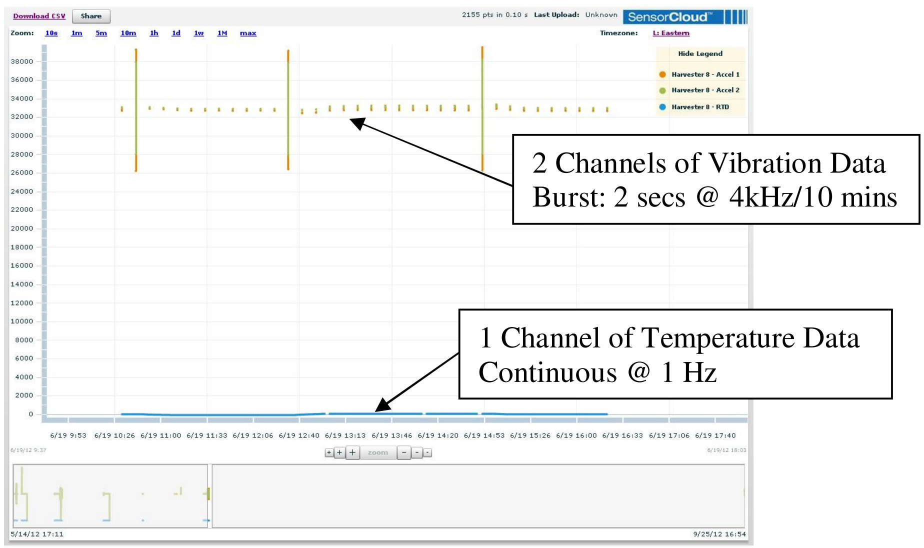

Figure 19: Screen shot showing data logged by WSDA during a 6 hour test of the Structural Harvester/ Sensor Node.

APPLICATION 4: Spin Harvester

The rotor head contains many flight critical components. Ideally, a number of these could be monitored simultaneously. Wireless sensors are well suited to this task. A single, high output energy harvester located on the rotor head and capable of powering a number of wireless sensors would simplify this application.

Methods – Spin Harvester

We developed a high output magneto-inductive energy harvester targeting the UH60 platform. It takes advantage of the relative motion between the fixed and rotating sides of the swashplate. Permanent magnets are mounted on the fixed swashplate and power generating pickup coils, along with power conditioning electronics, are mounted on the rotating side of the swashplate as depicted in Figure 20. The relative motion between the magnets and coils generates energy in the coils. Due to the high mechanical power and high speeds available at this interface, a great deal of electrical energy (from a microelectronics standpoint) can be generated locally on the rotating side of the swashplate. Short leadwires can communicate this power to any number of wireless sensors located around the rotor head.

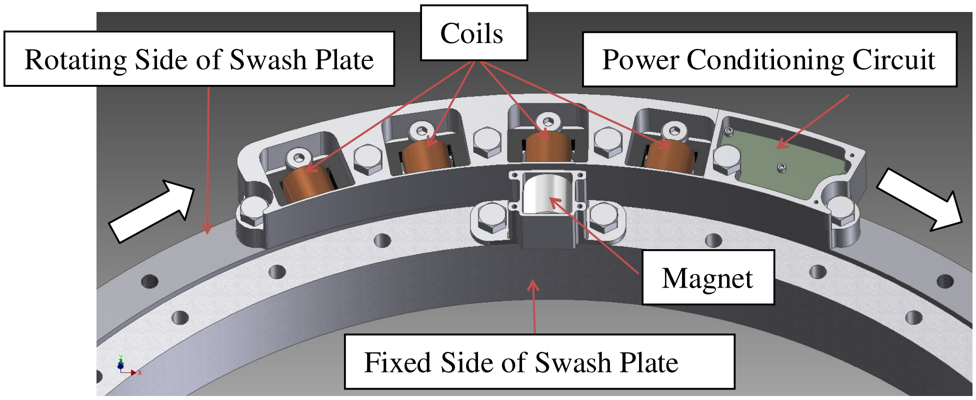

Figure 20: Spin Harvester Configuration

As with the other harvesters presented here, Schottky Barrier type diodes were used to rectify the raw AC harvester output (Figure 21). Their low forward conduction voltage drop results in higher efficiency. The resulting rectified raw DC power was conditioned by a highly efficient buck-boost switch mode power converter that can accommodate a wide range of DC input voltages. The output is conditioned DC power at 3.6V, suitable for use by sensor nodes.

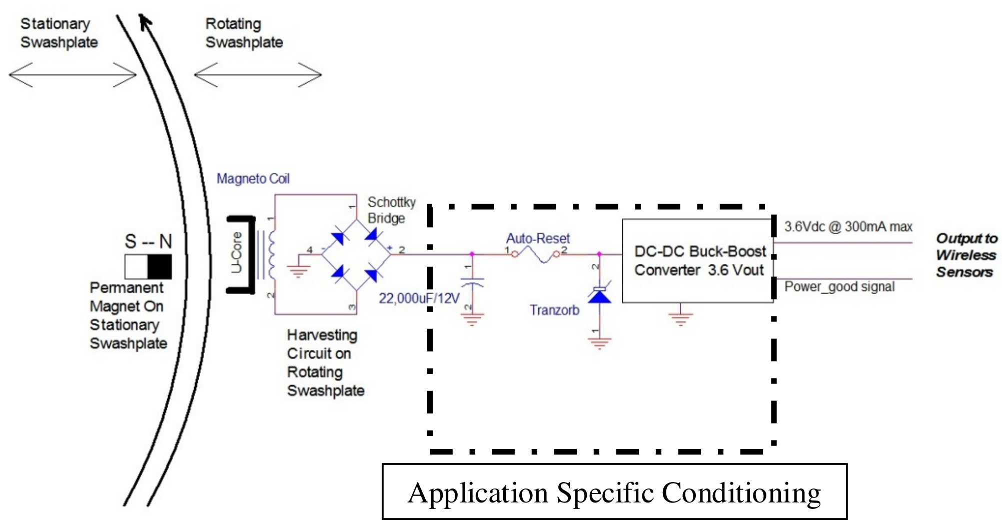

Figure 21: Power conditioning circuit used for the Spin Harvester.

A prototype spin energy harvester was fabricated and mounted to a test stand in our laboratory. This allowed for adjustable coil-magnet configurations and variable inner/outer swashplate relative velocity. The energy generated was used to power eight SG-Link nodes continuously monitoring full bridge strain gages at 128 Hz and broadcasting to a nearby WSDA.

Results – Spin Harvester

The spin energy harvester's power output was proportional to the square of the relative velocity of the magnet to the coils. 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 22 shows continuous power output as a function of gap at these two relative velocities, with a matched load impedance on the four coils.

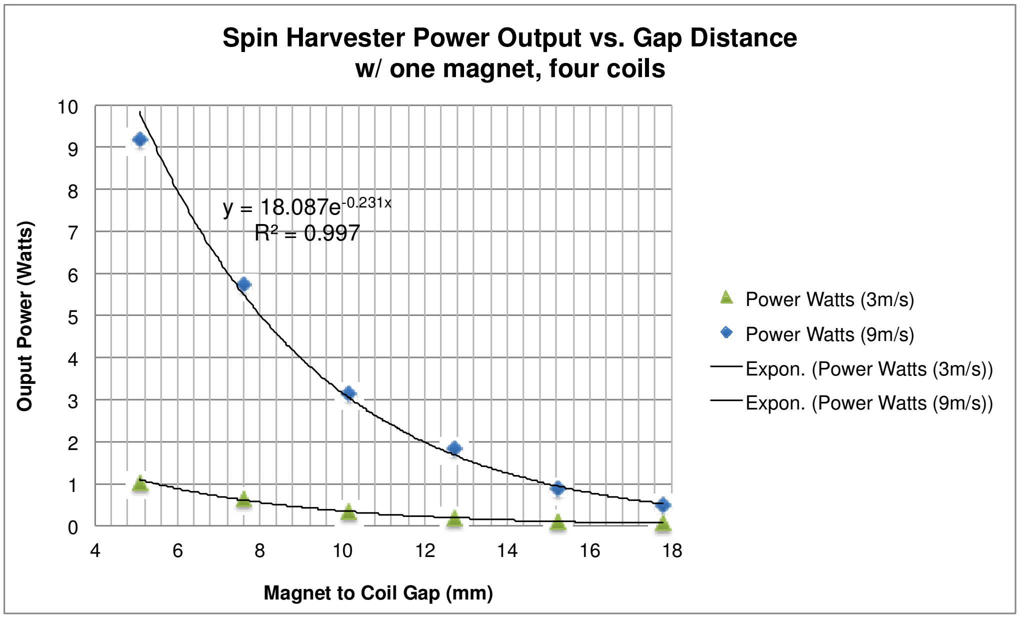

Figure 22: Spin energy harvester's output power versus magnet/coil gap for two relative velocities: 3m/s and 9m/s. An exponential curve was fit to the 9m/s velocity data, representative of the H-60 swashplate application.

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 aluminium mounting hardware) may be calculated at 21 Watts/kg. This result compares favourably with the more complex PMA design of Andrews and Augustin [2], 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 for 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 from the rotating frame to a WSDA in the fixed frame continuously, with a measured bit error rate of less than 1%.

Conclusions

This work reports on four energy harvesters that were successfully paired with MicroStrain wireless sensor nodes to reliably collect and transmit critical structural data to a MicroStrain wireless sensor data aggregator (WSDA) base station where the data was logged and synchronized. The four harvesters operated in different physical locations in an aircraft, generated energy based on significantly different input parameters and serviced three different platforms, demonstrating the flexibility of these solutions.

This effort demonstrates the success of these systems in laboratory environments using test conditions which are as realistic as was feasible. The next logical step to further advance the readiness level of these systems is to apply them in the operational environment. Several of these systems have flight tests scheduled and MicroStrain is working to include all of them in operational environment tests in the near future. With properly designed and tuned harvesters, these systems can be used to monitor fixed and rotary wing aircraft, bridges, buildings, heavy equipment, wind turbines, and other critical structures. These new wireless sensing networks can be deeply embedded into structures and structural components for improved condition based maintenance (CBM) and advanced structural health and usage management systems (SHUMS) without the need to consider the difficulties of extended wiring runs and battery replacement.

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