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Energy Harvesting Wireless Sensors for Helicopter Damage Tracking

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ABSTRACT

The knowledge of operational loads on a helicopter rotating components is important for condition based maintenance (CBM) and health usage monitoring systems (HUMS). In the past, the need to deploy slip rings has limited the monitoring of rotating components. Wireless technology eliminates slip rings, but the problem of battery maintenance remains a major obstacle. This paper reports on next generation wireless sensors which eliminate battery maintenance by using piezoelectric materials to convert strain energy to stored electrical energy. Stored energy is used to measure, record, and transmit strain and load information. A prototype energy harvesting wireless pitch link sensing system has been developed. Under low usage level helicopter operating conditions, the energy consumed was less than the energy harvested, enabling strain & load sensors to operate perpetually without battery maintenance. Breaking down the barriers to monitoring helicopter rotating components, this technology has the potential to greatly improve future HUMS capabilities.

INTRODUCTION

Advanced sensing technology continues to evolve at a rapid pace, and the requirements for advanced condition based maintenance (CBM) related projects can and will be addressed with present and future developments[1]. Sensors, signal conditioners, processors, and digital wireless radio frequency (RF) links continue to become smaller, consume less power, and include higher levels of integration. The combination of these elements can provide sensing, acquisition, storage, and reporting functions in very small packages. Wireless networks coupled with intelligent sensors and distributed computing enable a new paradigm of machine monitoring[2].

Wireless sensors have the advantage of eliminating wiring installation expense and weight as well as connector reliability problems. However, wireless sensors still require power in order to operate. If power outages occur, critical data may be lost. In some cases, sensors may be hardwired to a vehicle's power system. Doing so, however, defeats the advantages of wireless sensors and may be unacceptable for many applications. Most prior wireless structural monitoring systems have relied on continuous power supplied by batteries. For example, in 1972, Weiss developed a battery powered inductive strain measurement system, which measured and counted strain levels for aircraft fatigue[3]. The disadvantage of traditional batteries, however, is that they become depleted and must be periodically replaced or recharged. This constitutes an additional maintenance task that must be performed.

Given the limitations of battery power, there is a need for systems which can operate effectively using alternative power sources. We have described systems which are capable of energy harvesting from vibrating machinery and rotating structures[4,5]. Other researchers have been active in this area as well, and have described various strategies for harvesting, or scavenging, energy from the environment[6,7]. These sensing systems can operate truly autonomously because they do not require traditional battery maintenance.

MicroStrain, Inc. has utilized both single crystal PZT and PZT fibers to create working energy harvesting prototypes, with funding from the US Navy for shipboard CBM applications. One system uses a tuned flexural element for vibration energy harvesting, while the other system harvests strain energy directly from a vibrating (cyclically straining) composite beam[8]. In both cases, we demonstrated that sufficient energy could be harvested to power our wireless strain sensor transceiver[9].

Recently, the US Navy has asked MicroStrain, Inc. to adapt its energy harvesting sensor systems for damage tracking aboard helicopters, particularly to address their need to monitor cyclic strains, and dynamic and static loads, on rotating components, with the goal to eliminate slip rings and battery maintenance.

In order to perfect a sensing solution which exploits energy harvesting, the entire system must be considered. The power consumed by all of the system's components (sensor, conditioner, processor, data storage, and data transmission) must be compatible with the energy harvesting strategy and the available power levels. Obviously, minimizing the power required to collect and transmit data correspondingly reduces the demand on the power source. Therefore, minimizing power consumption is as important a goal as maximizing power generation.

OBJECTIVE

The structure identified by Navy personnel as a target for our first demonstration of a energy harvesting strain sensing prototype was the helicopter's control rods, or "pitch links", which control the pitch of the rotor blades as they rotate through the air. Figure 1 is a drawing of this rotating assembly. The strain sensor must operate using only the energy from typical operating pitch link strains and must be capable of sampling a strain gauge at minimum rates of 40 Hz.

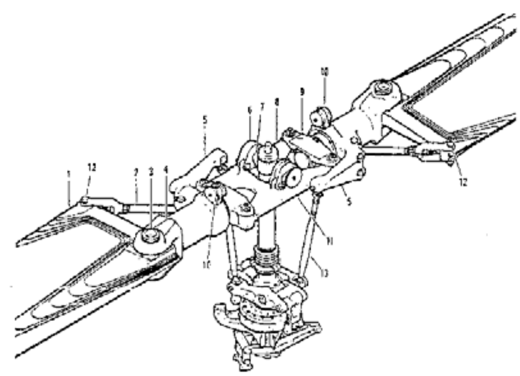

Figure 1. AH-1W main rotor hub assembly with pitch links

METHODS

We focused on energy harvesting using simulated pitch link strain-time history, using 4.3 Hz sinusoidal waveforms at strain levels between +/-100 and +/-500 microstrain. This approach was based on previously acquired usage data provided by Titan Systems and was verified by our Navy technical contacts and program managers.

The pitch link application was modeled analytically, using load information provided by NAVAIR engineers. The live loads from field data were stated to be 1600 pounds (in static compression) and +/-7800 pounds (under cyclic dynamic conditions). However, our existing vibration table, is capable of only 100 pounds of dynamic load capacity. Therefore, a scale model of the system was required in order to perform a test using our existing vibration table.

A four point bending loading fixture was designed in order to create a uniform strain field in the area where our piezoelectric energy harvesting material (PZT) would be bonded. The width of the plate matched that of the circumference of the control rod in order to provide an equivalent surface area to bond the PZT. The thickness of the plate was chosen to allow our test apparatus to develop at least +/- 600 microstrain under dynamic conditions and at the rated capacity of 100 pounds.

Figure 2 is a photograph of the test fixture which we have designed and built to generate four point bending dynamic strain tests of the PZT. This test fixture is currently in service. The piezoelectric elements consisting of unidirectionally aligned, 250-micron diameter PZT fibers embedded in a resin matrix and subsequently bonded to the surface of control rod test specimen, as shown in Figure 4.

To record applied strains, a foil strain gauge was bonded on top of the piezoelectric element at its center and shunt calibrated. The specimen was loaded in a four point bending fixture using an electrodynamic shaker to create a uniform strain field of various amplitude strain levels at 4.3 Hz, a frequency corresponding to pitch link external loading.

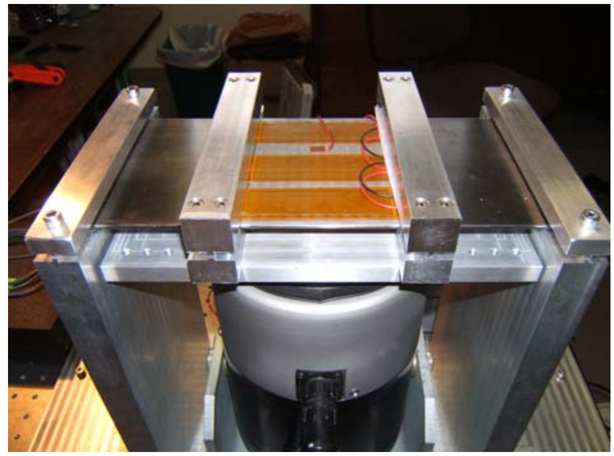

Figure 2. Four point bending fixture which delivers uniform vibratory strains to a pitch link simulation plate. The PZT elements are bonded to the plate to harvest strain energy. The strain gauge at the center of the plate is used as a feedback element to control the electrodynamic actuator.

During cyclic loading, the PZT element converted the applied strain energy into electrical output. This output was connected to an energy harvesting and storage circuit consisting of a rectifier and storage capacitor. MicroStrain has described the microelectronics required to accomplish this in detail in two recently published, pending US patent applications[10],[11].

In order to allow for sensor operation under low levels of harvested energy, a new operating mode was developed for our wireless strain gauge node (this node is termed "SG-LINK"). This mode not only minimized the power consumption, but it supported a moderately fast digital sample rate. Our goal was to be able to sample and transmit data collected from the strain sensors at a 40 Hz rate (which represents approximately ten times the pitch link strain signal frequency content), while requiring less then 1.0 mW of power. To achieve this goal, three major enhancements (a-c) were made:

a) The bandwidth of the sensor signal conditioning chain was increased. This allowed for faster settling of the sensor signal conditioner, and minimized the time required for the sensor to be powered, thereby lowering the overall power requirement of the sensor.

b) A burst mode sampling feature which buffers data for one second prior to sending the data was developed. There is significant overhead in sending a RF data packet using the standard IEEE802.15.4 packet protocol. It is advantageous to send one large data packet as opposed to sending many smaller packets. By reducing the number of data packets sent per second, power was greatly reduced. In this sampling mode, the sensor data was digitized at a 40 Hz rate and buffered for one second before data transmission to the receiver.

c) The power up sequencing of the amplifiers in the analog signal chain was optimized. In order for the analog electronics signal chain to settle quickly, it is important to keep the amplifiers out of saturation during their warm-up period. Firmware was optimized to ensure that the power up sequence minimized the time that the amplifiers were in saturation.

RESULTS

At a vibration frequency of 4.3 Hz, the system repeatedly charged the storage capacitor using strain amplitude between 50 µ in./in. and 175 µ in./in. The output power from the PZT elements is plotted as a function of strain in Figure 3. The power output ranged from ~1 to 5.5 milliwatts over operating strain levels of +/- 100 to +/- 500 microstrain. We note that straight level flight corresponds to pitch link strain levels of ~ +/- 150 microstrain.

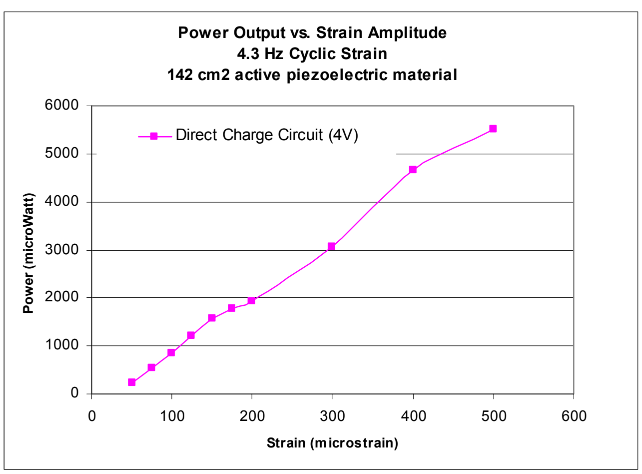

Figure 3. Output power harvested from three PZT elements bonded to simulated pitch link vs. strain amplitude

The new operating modes developed for the wireless strain sensing microelectronics resulted in significant improvements in power consumption. Our previous low power sampling mode drew 21 milliwatts, while the new design drew 0.98 milliwatts, which represents a greater than twenty-fold reduction in power consumption.

The wireless strain node was then tested with the PZT elements as the sole power source, and with the electrodynamic actuator generating pitch link cyclic strains. The enhanced SG-LINK (with new operating modes) was connected to a conventional 1000 ohm foil type strain gauge (Vishay Micro-Measurements), which was bonded to the pitch link test specimen. It was shown that the device was able to sustain sampling and transmitting of strain data at the desired 40 Hz rate for pitch link cyclic strain levels above +/- 100 microstrain. A representative snapshot of the received data collected during this test is shown in Figure 4.

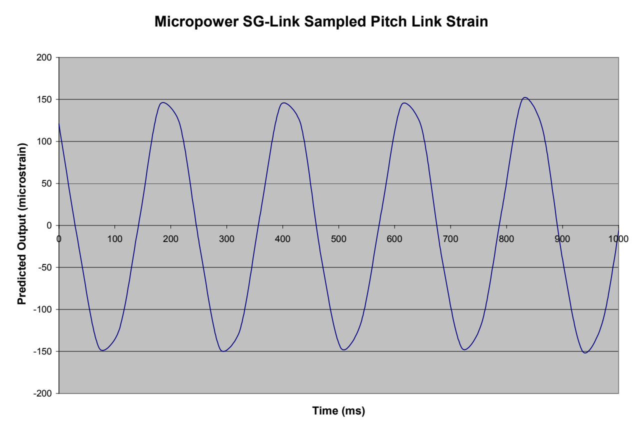

Figure 4. Strain data sampled from pitch link at 40 Hz rates and wirelessly communicated using burst mode transmission

DISCUSSION

MicroStrain has built and demonstrated wireless strain sensing nodes with embedded routines for peak valley compression and rain flow fatigue calculations. We plan to embed these routines within the microprocessor of the energy harvesting wireless strain sensing nodes. These algorithms further reduce power consumption by reducing the amount of wireless data communications, and enable the wireless nodes to track accumulated damage. The

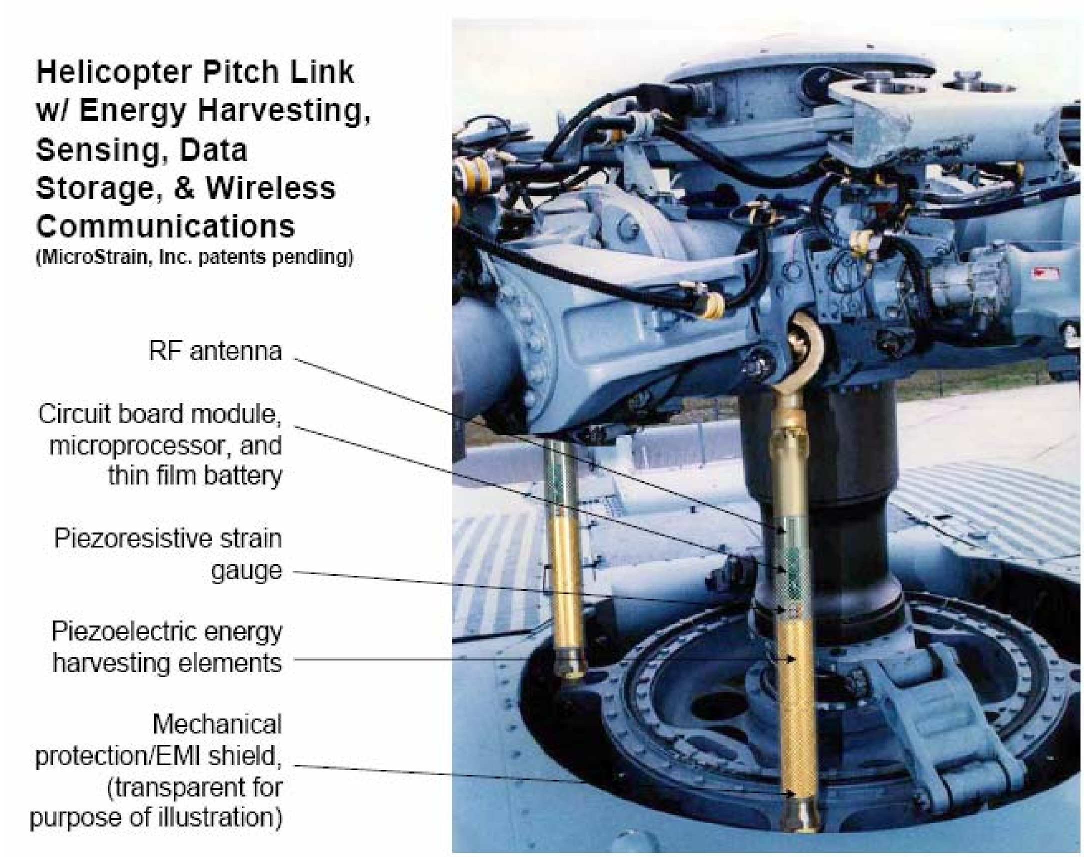

Figure 5. Graphic illustration showing wireless load sensing pitch links with energy harvesting, energy storage, data processing, and RF communications elements.

estimate of accumulated damage can be used to optimize machine maintenance scheduling and to predict and prevent failures.

In the case of the pitch link, strain readings may be easily converted to loads through a prior calibration step. Monitoring live service loads of pitch links is important for HUMS structural monitoring applications, because the pitch link is a key structural member - connecting the rotor blade pitch horn with the rotating swash plate. Previous authors have reported Bell helicopter AH-1W pitch link peak loads in a range of flight regimes[12]. Pull ups and gunnery turns resulted in mean pitch link loads roughly 8 times that for hovering, demonstrating the pitch link's inherently high sensitivity to the severity of flight maneuvers. Therefore, there is potential for improved characterization of helicopter flight regimes, and enhanced structural HUMS, by the development and deployment of instrumented pitch links. Below, in Figure 5, we provide a graphic illustration of our instrumented, wireless, energy harvesting pitch links and its main components. By integrating sensing, data acquisition, energy harvesting, energy storage, and wireless communications elements, we eliminate battery maintenance and provide a complete solution to rotating component load monitoring.

These techniques can be applied to a wide variety of aircraft components, airframe structures, and aircraft engines for advanced condition based maintenance.

CONCLUSION

A prototype energy harvesting wireless pitch link strain sensor has been developed and tested. Under typical (low usage level) helicopter operating conditions, the amount of energy consumed was less than the amount of energy harvested. This enables an on-board strain sensor to operate perpetually without battery maintenance.

ACKNOWLEDGEMENTS

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