Tracking Pitch Link Dynamic Loads with Energy Harvesting Wireless Sensors

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ABSTRACT

Direct load monitoring of helicopter rotating structural components could provide enhanced condition based maintenance & improved flight regime recognition for future health & usage monitoring systems (HUMS). Our objective was to design, develop, bench & flight test a system capable of harvesting the energy of operation to power a wireless pitch link loads monitor. Piezoelectric materials converted the cyclic strains of pitch link operation into power for the microelectronics, which included strain gauge signal conditioning, analog-to-digital converter, microprocessor, non-volatile memory, precision time-keeper, and 802.15.4 transceiver. Loads were measured with a full bridge of bonded strain gauges, which amplified tensile & compressive loads and cancelled bending moments and thermal influences. The processor's embedded software included energy aware operating modes, which enabled the wireless system to self-adjust its energy consumption according to the amount of energy available. The system was successfully flight tested on a Bell model 412 helicopter in February 2007.

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INTRODUCTION

This paper describes the design, development, bench, and flight testing of a power harvesting wireless pitch link for in flight measurement of pitch link loads. We have previously described systems which are capable of energy harvesting from vibrating machinery and rotating structures (1,2). Recently, we described a methods for fitting a helicopter pitch link component with wireless strain gauges, and eliminating battery maintenance by harvesting strain energy (3). This work used a four point bending fixture to simulate cyclic pitch link strains, however, an actual "flight test ready" pitch link assembly was not built and tested.

MicroStrain, Inc. was asked by Bell Helicopter to support flight tests of the Bell M412 shown in figure 1. The original energy harvesting wireless pitch link load sensor design was based on typical cyclic strains of +/- 200 microstrain – much higher than those expected for the Bell M412 pitch link. Furthermore, the surface area available for mounting to the Bell M412 pitch link was greatly reduced as compared original pitch link design.

OBJECTIVES

1. To allow reliable operation of an energy harvesting load sensing system on the Bell 412 pitch link, which operates at typical strain levels of +/- 35 microstrain @ 5Hz.

2. To enable timed structural monitoring using a precision micropower timekeeper.

3. To bench test an energy harvesting wireless load sensing Bell 412 pitch link in a dynamic load frame which replicates helicopter straight & level flight

4. To conduct proof of concept flight testing in a standard Bell M412

METHODS

A block diagram for the energy harvesting wireless sensing node is provided in Figure 2. Note that the node used on the Bell M412 pitch link only used one Wheatstone bridge sensor channel. A fully integrated printed circuit board (PCB) module was designed and built. The board measured ~ 4" long by 0.5" wide by 0.1" thick and weighed 8.2 grams. The board included the following elements:

a) energy harvesting power conversion & storage electronics
b) programmable precision multi-axial strain gauge signal conditioner with integral self
calibration
c) low power system microprocessor
d) IEEE802.15.4 direct sequence spread spectrum radio transceiver
e) Flash memory for local data logging
f) Nanopower time keeper to activate scheduled data logging modes

Working in concert with Bell Helicopter, MicroStrain designed an electronics package that could be clamped to the M412 pitch link and which would allow removal without the need to remove the pitch link from the aircraft. The system was designed to support access to the electronics in the event that software and/or hardware modifications were required during the testing qualification process. A drawing of the instrumented Bell M412 pitch link is provided below in Figure 3.

Figure 4 shows the final proof-of-concept version of the Bell M412 pitch link with the test electronics package, strain gages, and piezoelectric elements installed and ready for testing. The electronics package was shifted to the bottom of the pitch link to achieve better clearance with the aircraft cowling.

The piezoelectric elements were uni-directionally aligned, PZT fibers (Smart Materials, Inc.) embedded in a resin matrix and epoxy bonded to the surface of the 412 pitch link by Bell Instrumentation Engineers, who also fabricated the final assembly for testing.

To test and record operational pitch link loads, a conventional full strain gauge bridge was bonded to the pitch link using high resistance (4500 ohm) bonded foil strain gauges. The complete pitch link assembly was placed in a hydraulic loading apparatus for bench testing and cycled at 5 Hz, the frequency which corresponds to the 412's pitch link external loading. Dynamic test loads of +/- 220 pounds and +/- 300 pounds were applied. A photograph of the loading fixture is provided in Figure 5.

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 (1,2).

Efforts to reduce the power consumed by the sensing, recording and data transmission electronics were prompted by the Bell M412 pitch link flight test application, which, ideally, would operate perpetually even under conditions of low strain amplitude (+/- 35 micro strain). Through optimization of the embedded firmware and careful power management strategies, we achieved a roughly 50% savings in operating power as compared to our previous systems. The average power consumption was measured at 34 microamperes at 3 VDC excitation (102 microwatts), using a 4500 ohm resistance strain gauge bridge as the sensing element, and sampling the strain gauge bridge at 32 samples per second.

This leads to a preliminary "figure of merit" power consumption specification of ~3.2 microwatt/sample/sec, where sample/sec is the programmable strain gauge bridge sampling rate. Note that this power consumption specification includes logging of data only, with the real time clock used for precise time stamping of the sampled data. Embedded software was written to allow the PCB to modify its sampling rate to adapt to the amount of available energy (Mode 2, "Energy Aware Option", below). Modes 1,2,3 have the option to be battery backed. In battery backed mode, the device drops to a low power sleep mode when there is no power provided by the PZT. All four software modes (see list below) are programmable for a sample rates from 8 Hz to 1024 Hz.

*Mode 1 - Real Time Transmission***:**

This is the highest power option. Data are both transmitted & logged to non-volatile (flash) memory. Device logs data at a specified rate, and once 100 samples are acquired, the system transmits these data. Power consumption at 32 samples/sec was measured at ~250 microwatts.

Mode 2 - Real Time Transmission with Energy Aware Option:

Device logs data at specified rate, once 100 samples are acquired, the system checks to see if enough energy has been stored to permit transmission of these data over the RF link. If enough power is available, data are transmitted, if not, data are logged to memory and are not transmitted. Power consumption at 32 samples/sec was ~250 microwatts provided enough power is available. Otherwise the consumption varied with available energy.

Mode 3 - Real Time Data Logging:

Lowest power option. All data were logged to memory for download at the end of the flight test. Power consumption at 32 samples/sec was ~100 microwatts.

Mode 4 - Data Transmission When Storage Capacitor Reaches Threshold:

This mode simply charges the input capacitor to a certain level, and once this level is reached, a nanopower comparator turns the circuit on, and then a pre-determined amount of data were transmitted. This differed from Mode 2 in that no data were logged in the background and the system did not consume any power until sufficient energy had been stored. Average power consumption varied with available energy, but the timekeeper always drew 9 microwatts.

BENCH TEST RESULTS

Output (strain harvested) power for the fully instrumented Bell 412 pitch link was measured as a function of axial load. The results are plotted in Figure 6. The Bell 412 pitch link system was demonstrated to log load data continually at data acquisition rates up to 128 samples/sec, running entirely from strain energy harvested from the pitch link, at loads of +/- 300 pounds (5 Hz). A representative data set from these tests is provided below in Fig 7.

FLIGHT TEST RESULTS

The energy harvesting wireless pitch link was installed on a Bell Model 412 experimental rotorcraft and successfully flight tested at the Bell XworX facilities in Fort Worth Texas during February of 2007 (see figure 8 for installation details). The test included ground and in-flight EMI evaluations, Rotor Track and Balance verification, and data collection during a scripted flight. Data were collected wirelessly on board the aircraft with no indication of data loss. Data were simultaneously collected external to the aircraft during ground operations at various locations around the aircraft and at distances up to 50 feet. No data could be received at a distance of 100 feet from the aircraft.

FUTURE WORK

MicroStrain has developed algorithms to estimate accumulated damage to optimize machine maintenance scheduling and to predict and prevent failures. These techniques can be applied to a wide variety of aircraft components, airframe structures, and aircraft engines for advanced condition based maintenance.

As noted this is a proof of concept demonstrator. Future plans include development of system requirements, design, and test of a system that would be compatible with typical flight test requirements or possible production aircraft loads monitoring.

CONCLUSIONS

An energy harvesting wireless pitch link strain sensor for the Bell 412 has been developed, bench tested, and successfully flight tested. Under extremely low usage levels, 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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1. M.J. Hamel et al., Energy Harvesting for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2004/0078662A1, filed March 2003*

2. S.W. Arms et al., Shaft Mounted Energy Harvesting System for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2005/0017602A1, filed Jan 2004*

3. Arms et al., Energy Harvesting Wireless Sensors for Helicopter Damage Tracking, 62nd Annual AHS Forum, Phoenix, AZ, May 11th, 2006

FIGURES (1-8)

Figure 1. Bell Helicopter Model 412

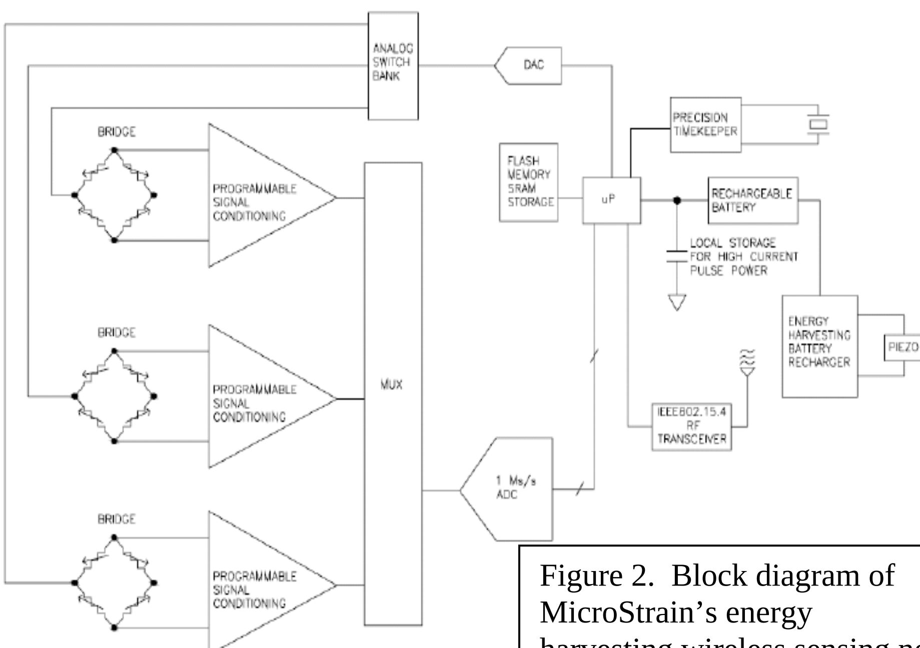

Figure 2. Block diagram of MicroStrain's energy harvesting wireless sensing node

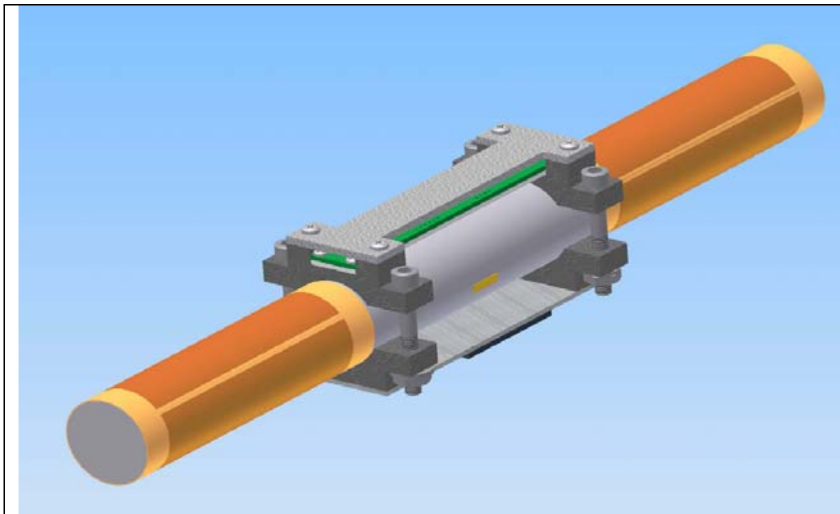

Figure 3. Original design of energy harvesting wireless sensing system on Bell 412 pitch link

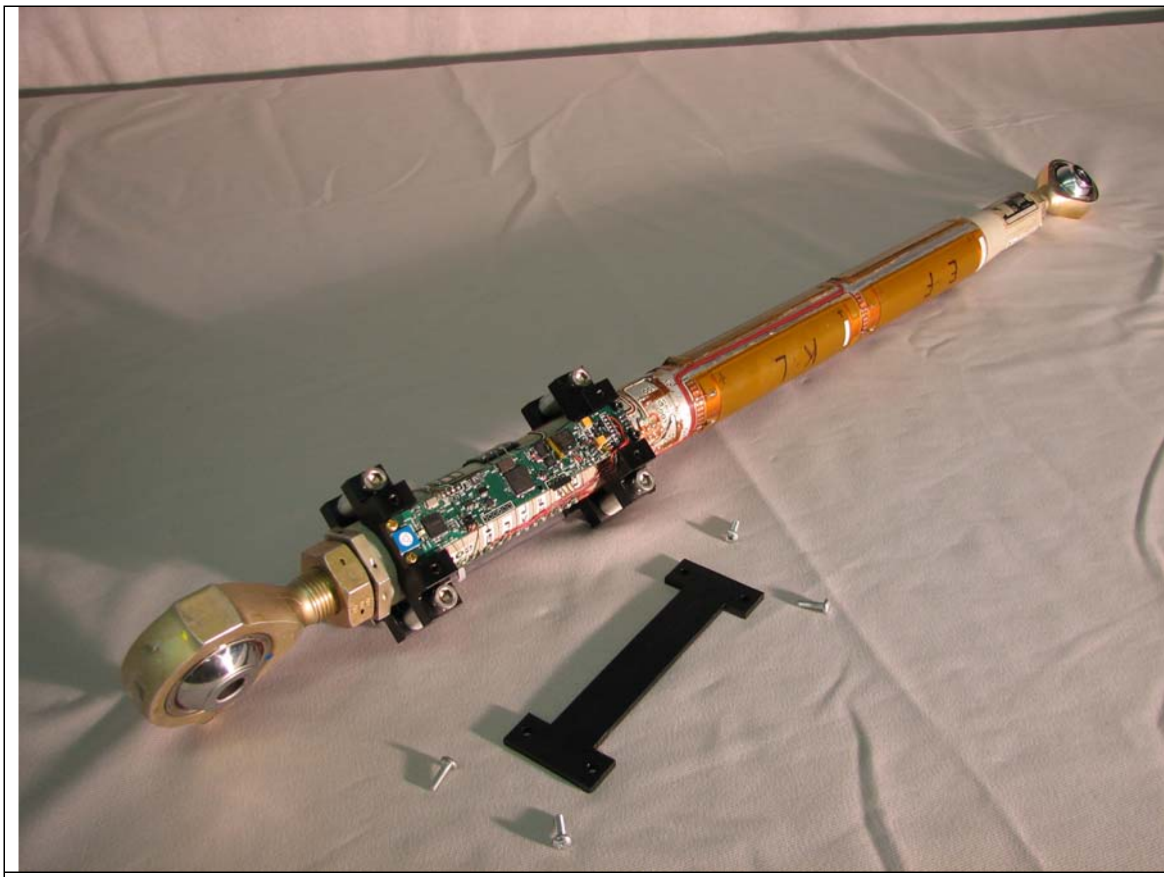

Figure 4. Bell M12 Pitch Link with energy harvesting wireless sensing system installed (The wireless microelectronics and strain gauges are located within the clamped assembly at the lower end of the pitch link.)

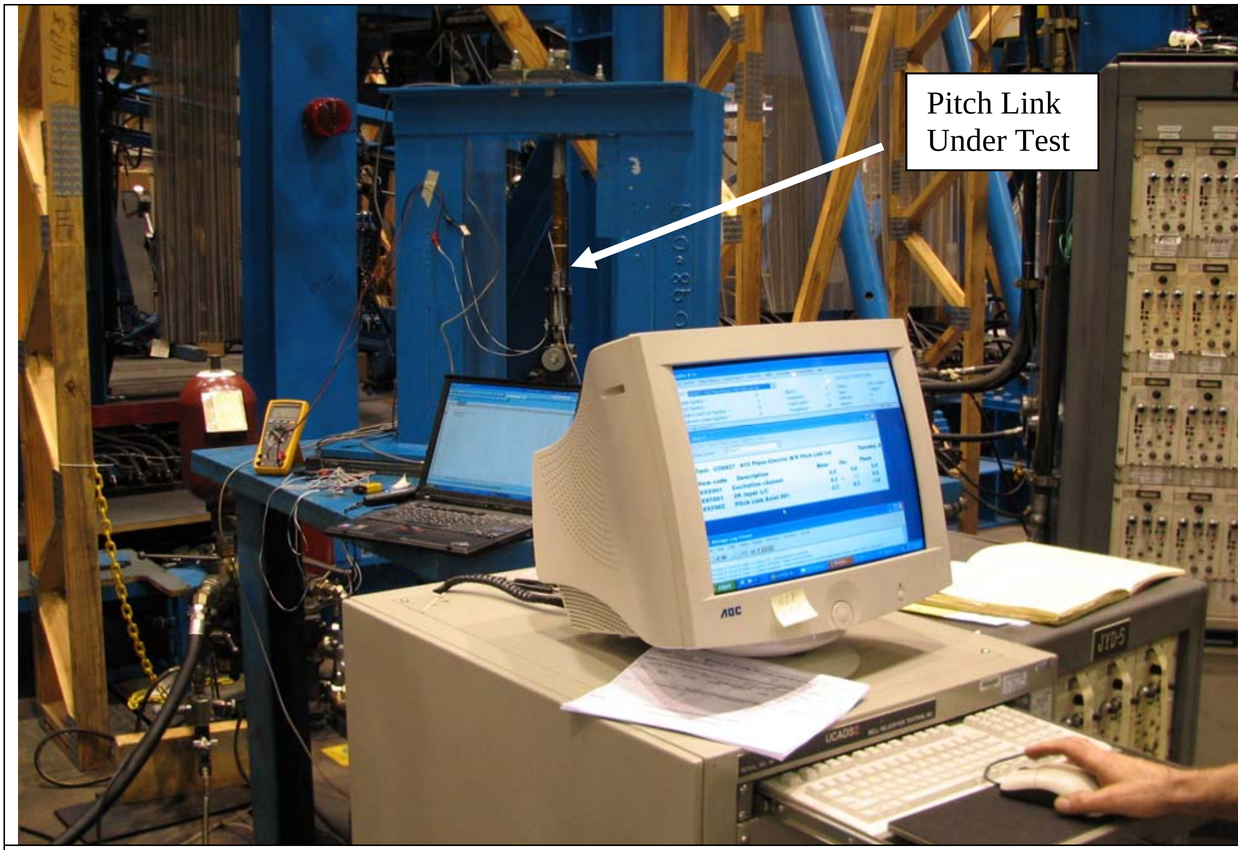

Figure 5. Hydraulic test fixture used to deliver dynamic loads for bench testing

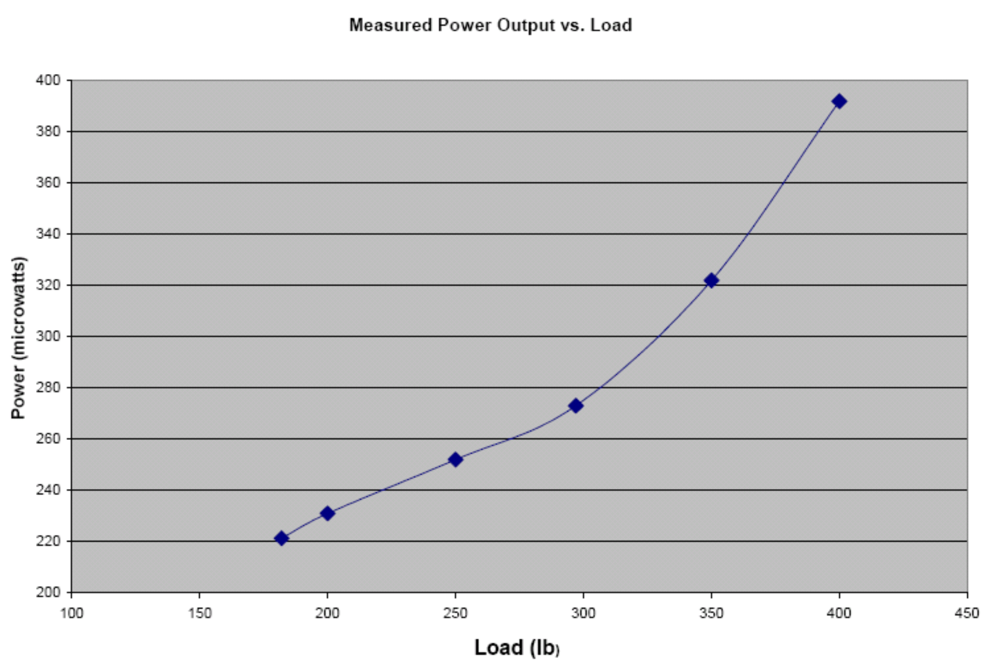

Figure 6. Power generation by strain energy harvesting on Bell M412 pitch link vs. axial pitch link load levels at 5 cycles/sec.

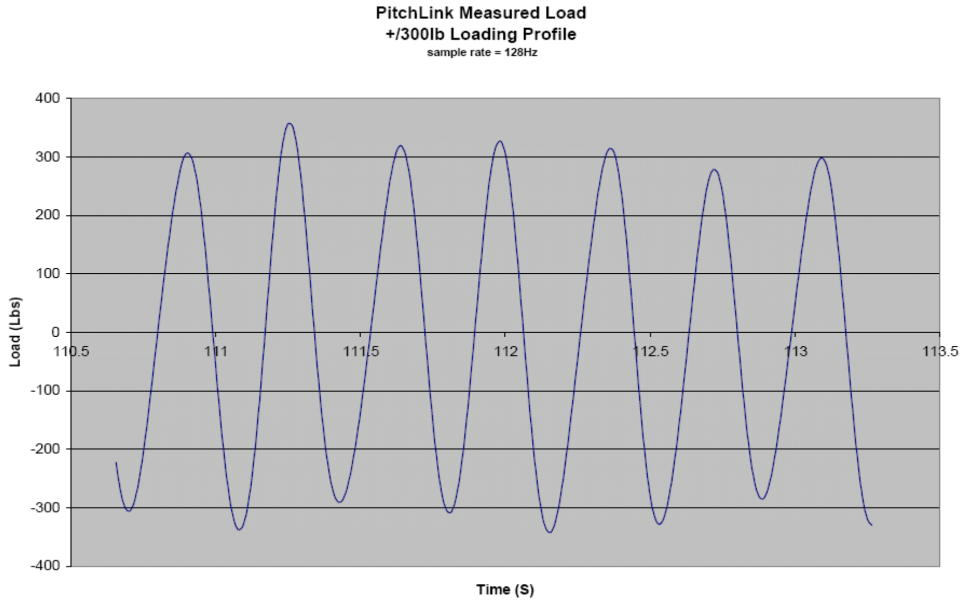

Figure 7. Load data recording from energy harvesting wireless electronics, in data logging mode (Mode 3) for Bell M412 pitch link under sinusoidal axial loading of +/- 300 lbs at 5 cycles/sec.

Figure 8. Energy harvesting wireless pitch link installed on Bell M412