A Wireless Accelerometer for in situ Gearbox Condition Monitoring of Rotating Components

George Jung[1], Riyazal Hussein[1] and David Blunt[1]

[1]*Aerospace Division, Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia*

Abstract

A prototype wireless three-axis accelerometer system has been developed for attachment onto the planet gear carrier inside a rotorcraft main transmission assembly. The prototype system will allow continuous in situ vibration monitoring during gearbox testing. It is anticipated that direct placement of the prototype system onto the gear carrier will enhance the sensitivity of the acceleration data, improving the detectability of emerging structural defects of the planet gears and their bearings during operation. The prototype system is capable of delivering a sustained data transmission rate in excess of 12.8 kilobytes/s, while consuming less than 50mW. A proprietary transmission protocol was developed to maximise data throughput. Installation of a receiver antenna within the gearbox housing facilitates very low power operation and improved immunity from external interference. For operational endurance the prototype system is powered by an inductive energy harvester. Potential uses of this system on operational rotorcraft are discussed.

Keywords: Wireless accelerometer, In-situ gearbox measurement, Battery-less operation, Autonomous sensor, HUMS, Planetary gearbox, Real-time condition monitoring, Energy harvester.

Introduction

Epicyclic (planetary) gearboxes are used in a variety of demanding applications, such as rotorcraft or wind turbines, where high power density, mechanical strength and low weight are important. Mechanical failure of a rotorcraft main gear box (MGB) is often catastrophic. To mitigate this risk, effective health and usage monitoring (HUMS) as well as real-time monitoring solutions are required [1]. Detecting faults in epicyclic gear trains using externally mounted vibration sensors is complicated by the complex modulation introduced by the time varying path lengths between the moving gears and stationary sensors [2][3][4]. To overcome these severe signal processing issues, a number of researchers have attempted to use in-situ sensors mounted onto the rotating planet gear carrier, as close as possible to the planet gear bearing of interest [5][6]. This approach minimises the number of acoustic interfaces and path lengths and has showed some promising results, although a number of difficulties were encountered in transferring the analogue signal to the stationary part of the gearbox. The use of slip rings severely reduced the signal to noise ratio while passive radio frequency receivers suffered from interference by the test system [7][8].

A promising method to overcome poor signal to noise ratios is to condition the signal close to the sensor, then transmit the data digitally over a wireless link. In particular, micro-electromechanical system (MEMS) accelerometers have previously been found suitable due to their small size and low power requirements [9]. This approach requires a small source of electrical power on the rotating planet gear carrier. A suitable electro-magnetic energy harvesting method has been presented in a previous paper [10] and shown to generate sufficient power for this purpose, avoiding the use and frequent replacement of batteries. Initially it was anticipated to power a semi commercial-off-the-shelf (COTS) wireless accelerometer system and use it in a helicopter gearbox test at the DSTG helicopter transmission test facility (HTTF), however, a number of difficulties were encountered in using the device and it was decided to attempt to construct a wireless sensor in-house. The design approach, construction and testing of this sensor is described in this paper.

Methodology

The traditional approach to electronic development (circuit design, printed circuit board fabrication, assembly, testing, etc.) is time consuming and typically requires a number of engineers to co-ordinate the design and manufacturing process. This is complicated by the fact that most newer integrated circuits are only available as millimeter sized surface mount devices that need specialist skills and equipment for soldering. The goal in this project was to have a prototype available for in-situ testing in the shortest time frame possible. The development process was adjusted accordingly by making extensive use of available COTS development kits and break-out boards. The signal processing requirements dictated the choice of the various sub-systems. The four basic modules comprising a typical wireless accelerometer are shown in Fig.1 and consist of: (1) Power source, as discussed in a previous paper [10], (2) Accelerometer, (3) Radio transmitter and (4) Microcontroller.

Accelerometer: Digital MEMS accelerometers are the preferred option for acceleration measurement, as they require very little power and contain 2 or 3 orthogonal sensing elements in a sub-cm sized package. They do not require external signal conditioning circuitry which consumes power and adds volume and complexity. The trade-off is generally higher noise, lower measurement bandwidth and lower environmental specifications. The minimum analogue bandwidth for the gearbox measurements was 1900Hz (the highest significant gear meshing harmonic), maximum operational temperature range 95 deg.C. and maximum acceleration approximately 50g. These requirements eliminated most commercially available chip scale MEMS accelerometers. ADXL372 from Analog Devices met all requirements, is available on a 20x20mm break-out board and features 3 orthogonal axes, a data buffer and interrupt capabilities to simplify microcontroller interfacing. The maximum data rate of 6400Hz and 12 bit resolution provided an adequate margin to cover the analogue bandwidth and dynamic range of interest.

Radio: The choice of radio frequency (RF) transmitter was determined by the practically achievable data throughput rates, power consumption and estimated microcontroller work load. RF transmitter or transceiver chips covering the license-free industrial, medical and scientific (ISM) bands of 433, 915 and 2400 MHz are plentiful, however, the required real data rate of ~130kbits/s could only be met by a few 915 and most 2400 MHz transmitters. Desirable features that reduce the programming and microcontroller overhead (built-in data buffer, automated packet assembly and detection) as well as frequency agility reduced this even further. Finally, two radios were selected for evaluation, the nRF24L05+ (2.4GHz) from Nordic Semiconductor was selected due to its wide support base and after passing a 100 deg.C operating temperature test. Most RF transmitter chips are qualified for operation at 85 deg.C or less, including the one selected. Complete modules based on Nordic's reference design are readily available at low cost from various manufacturers.

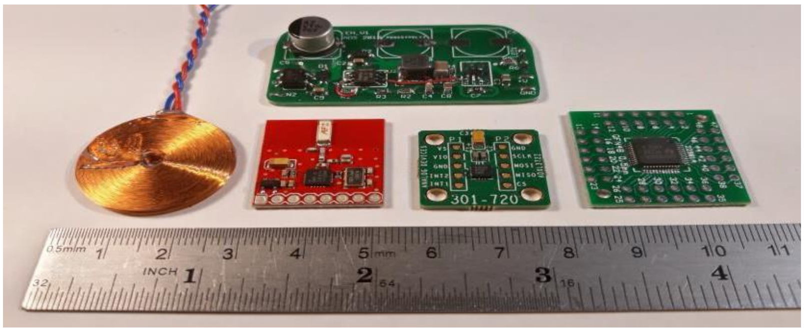

Fig.1: Accelerometer system modules. Energy harvester (top), coil (left), transmitter (red), accelerometer (centre) and microcontroller (right).

Microcontroller: Microcontroller selection was done with regard to readily available programming toolchains and required operating temperature range. The Texas Instruments MSP430FR series of 16-bit microcontrollers were found to be suitable for this project, as this series utilises F-RAM instead of flash memory for program storage. This is faster, uses less power and has a specified maximum operating temperature of 105 deg.C. All firmware development was done in C, and this translated into compact and efficient code. The operating frequency was 16MHz, well below the maximum of 24MHz.

Firmware: The radio consumes approximately twice the power of all the remaining sub-systems on the sensor in both transmit and receive modes. To keep power consumption low and data throughput high, it was decided early on to avoid two-way communication entirely. This significantly reduced overall power requirements as well as microcontroller firmware complexity. Break-out boards or evaluation modules were purchased and loosely wired together to facilitate firmware development (Fig.1). A low power start-up delay of 60 seconds was programmed to add hysteresis to the power consumption level. This prevented possible inadvertent power cycling situations during spin-up of the gearbox and ensured reliable start-up of the system. A state machine was coded to co-ordinate data transfer between accelerometer and transmitter. The system had to start reliably and transmit acceleration data while power was available. As the data link bandwidth was just sufficient to transmit a single accelerometer channel, it was decided to sequentially switch X, Y and Z channels at approximately 1 minute intervals. Data were transmitted in packets of 32 bytes (the size of the radio buffer), including a sequence byte and channel designator/optional status indicator byte. A battery powered test transmitter and receiver was constructed first to develop the data link. It became evident that some packet loss occurred in electrically noisy environments. A packet loss detection algorithm and LED indicator were added to the receiver. In addition, the receiver needed to accept an external pulse signal from the main shaft tacho for synchronisation. At each rising tacho pulse edge, a full sync data packet is added to the data stream to facilitate synchronous signal averaging algorithms to be applied at the data processing stage. Communications between PC and receiver is via 230Kbps virtual asynchronous serial link over USB.

Mechanical support: The electronic sub-assemblies had to be mounted onto the planet gear carrier, with the accelerometer placed as close as practicable to the notched gear. The presence of hot oil lubricant as well as strong centrifugal forces and vibrations necessitated that the entire system be potted into a solid block. This would provide adequate protection for the circuit sub-assemblies while eliminating the necessity for exposed and fragile electrical wiring. By incorporating the energy harvesting circuit within the same module, a completely autonomous sensor could be assembled. A thin walled mild steel housing (Fig. 2) was machined from a single billet, incorporating mounting holes to fit the planet gear bearing carrier bolts. To balance the planet gear carrier, a second, inert unit had to be mounted on the opposite side of the carrier (Fig.3). Future work is directed at operating a second unit at a different frequency.

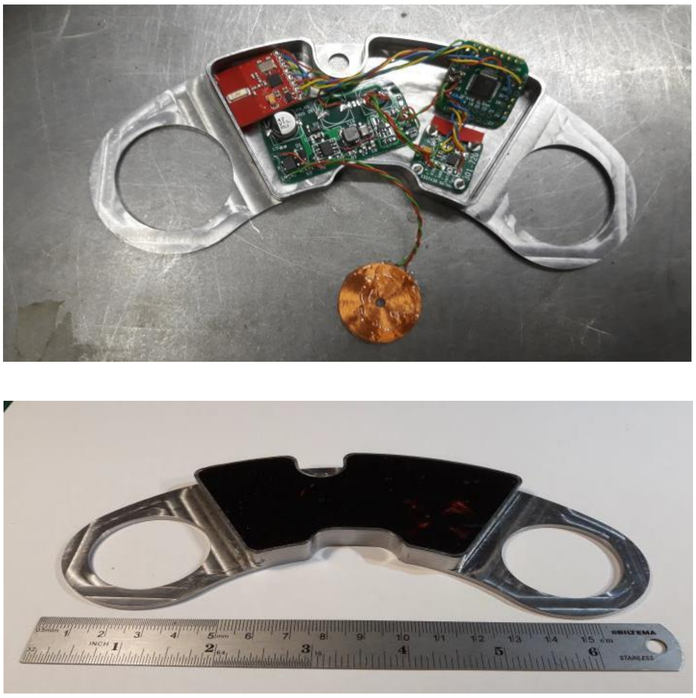

Fig. 2: Module placement before (top) and after potting (bottom). The coil was located above the accelerometer and supported by a small 3D printed table. Note accelerometer bolted to steel housing.

Receiver antenna: The gearbox casing acts as a Faraday cage, severely attenuating RF signals and presenting a major challenge for error-free, low power data transmission. However, it is possible to operate RF antennas in the near field region, less than a wavelength from the transmitter antenna [11]. A feedthrough adapter on the bell housing oil filler plug served as the entry point for a thin coaxial cable, whose braided shield conductor was removed over a length of 650mm. This section acted as the receiver antenna and was attached to nylon stand-offs mounted on the magnet carrier plate around its entire circumference, in close proximity to the transmitter antenna location (approximately 10mm).

Prior to potting, the modules were wired together (the energy harvester was supplied with external power directly instead of using the inductive pickup) and the assembly placed in a closed-loop digitally controlled oven at 100 deg.C for 30 minutes while transmitting. To ensure the modules remained in the correct place during the potting process, small support structures were 3-D printed and inserted below and above some boards. The entire carrier was then filled with high temperature epoxy potting compound. After complete curing, the oven test was repeated for 25 minutes with the energy harvester powered by placing a small electromagnet operating at 300Hz above the coil.

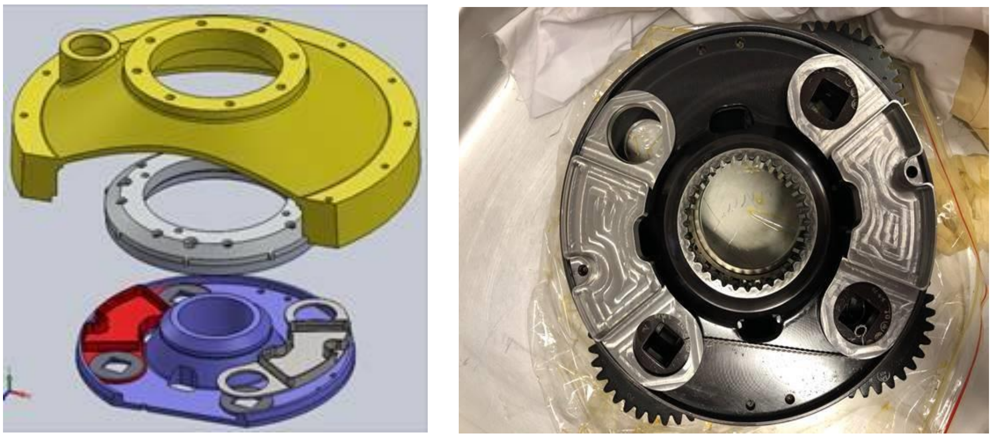

Fig.3: Left – Transmission top gear cover (yellow, top), magnet holder ring (centre) and planet gear carrier with sensor locations (bottom). Right: Actual placement of sensor enclosure on planet gear carrier.

Conclusions and future work

Rapid development of a prototype wireless, battery-less accelerometer system, necessitated by shrinking project timelines, budgets and personnel availability, was demonstrated for non-critical applications. By packaging all sub-systems including energy harvesting into a single, compact package, a robust in situ, low cost, zero maintenance sensing solution was obtained. The prototype system will enable the development of epicyclic gearbox vibration analysis algorithms in a gearbox test rig. It is envisaged that future gearbox designs could potentially incorporate in-gearbox, self-powered sensors as a standard component of rotorcraft HUMS.

At the time of writing, final testing and assembly of the sensor into the test gearbox was under way. Further development is aimed at design and manufacture of the entire sensor system into a package less than half the current volume, qualifying entire system to environmental specifications and enabling co-location of multiple independent sensors for redundancy and enhanced data quality.

Acknowledgements

The authors would like to express thanks to Peter Stanhope for providing neat solutions to numerous mechanical problems and Scott Moss for providing the specialised magnets and coils for the energy harvester.

References

1. Elasha, F., Greaves, M., Mba, D., “Planetary bearing defect detection in a commercial helicopter main gearbox with vibration and acoustic emission”, *Structural Health Monitoring*, Vol. 17(5), pp. 1192–1212, 2018.

2. Sharma, V. and Parey, A., “An Approach to Acquire Vibration Signals for Gear Fault Detection”, *Recent Advances in Sustainable Technologies, Lecture Notes in Mechanical Engineering*, 2021, pp. 153-163.

3. Ha, M.J. et al., “Autocorrelation based time synchronous averaging for condition monitoring of planetary gearboxes in wind turbines”, *Mechanical Systems and Signal Processing*, Vol. 70-71, 2016, pp 161-175.

4. Lei, Y. et al., ”Condition monitoring and fault diagnosis of planetary gearboxes: A review”, *Measurement*, Vol. 48, 2014, pp. 292–305.

5. Suryavanashi, A. et al, “Condition Monitoring of Helicopter Gearboxes by Embedded Sensing”, *58th Annual Forum of the American Helicopter Society*, Montreal, Canada, June 11-13, 2002.

6. de Smidt, M. R.,”Internal Vibration Monitoring of a Planetary Gearbox”, M. Eng. Thesis, University of Pretoria, 2009.

7. Smith, W., Deshpande, L., Randall, R. and Li, H., “Gear Diagnostics in a Planetary Gearbox: A Study Using Internal and External Vibration Signals”, *International Journal of Condition Monitoring*, October 2013.

8. Fan, Z., and Li, H.,”A hybrid approach for fault diagnosis of planetary bearings using an internal vibration sensor”, *Measurement*, Vol. 64, 2015, pp. 71–80.

9. Lewicki, D.G., Lambert, N.A. and Wagoner, R.S. "Evaluation of MEMS-Based Wireless Accelerometer Sensors in Detecting Gear Tooth Faults in Helicopter Transmissions", NASA white paper, NASA/TM—2015-218722, 2015.

10. Hussein, R., Moss, S.D., Jung, G. and Kissick, H.J., “A Prototype Energy Harvester for Powering a Wireless Acceleration Transducer inside a Rotorcraft Gearbox”, *18th Aust. International Aerospace Congress*, 2019.

11. Wang, S., Song, Y. “A Near-Field 2.4GHz Ring Antenna for High Data Rate & High Security Data Transmission in Short Range for Rotational Joint”, TE Connectivity (TE) White Paper: *Designing a Near-Field Antenna for Rotatable Devices*, October 2017.