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An improved wireless vibration sensor for real time in situ rotorcraft gearbox condition monitoring

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Abstract

Epicyclic gear boxes are used in many high performance applications such as rotorcraft and wind turbines. Failure of these components is often catastrophic, with serious consequences. Condition monitoring by means of vibration data analysis is a difficult task due to the many and time-varying transmission paths between gears and sensors that are typically mounted externally onto the housing. Previous laboratory investigations have shown that vibration measurements acquired physically close to the moving gears have improved signal fidelity and are much easier to process and interpret. Sensors are being developed that will be located on, or in close proximity to, the gears being monitored. To date, experimental in situ vibration data is scarce and often contaminated by noise through use of slip rings for signal extraction. In this paper, an improved design of an in situ wireless rotorcraft gearbox vibration sensor is described. Step improvements in data throughput, signal-to-noise ratios, signal bandwidth and packet loss were achieved by changing from a permanent magnet energy harvester design to an active inductive power transfer scheme that provides in excess of 250 mW to the sensor circuits. Previously, lack of power severely limited the component choices and operating modes in the earlier design. Removing the permanent magnets also solved the potential problem of any wear debris being trapped on the magnets, which would have compromised the efficacy of the wear debris detection system. The sensor and power delivery system are designed to allow retrofit inside the gearbox and to have a long, maintenance-free life span. The completed sensor assembly is scheduled for a full performance test in a rotorcraft main gearbox in the Helicopter Transmission Test Facility (HTTF) at DST Group Melbourne.

Keywords: epicyclic, gearbox, helicopter, wireless, vibration.

Introduction

Epicyclic gearboxes are a safety critical item on rotorcraft and their failure on wind turbines leads to extensive down times [1]. Typically, health and usage monitoring systems (HUMS) make use of vibration sensors attached to the gearbox housing or main shaft bearing. However, the unique working principle of epicyclic gear trains, where a number of planetary gears rotate between a central sun gear and a fixed ring gear, produce multiple time and amplitude variable transmission paths that can mask fault signatures. This has led researchers to develop highly complex signal processing chains in attempts to extract specific damage information from the vibration data [2, 3]. It has been noted and experimentally shown that vibration measurements in close proximity to the planet gears and their bearings could provide superior signal-to-noise ratios and simultaneously simplify the signal processing algorithms required [4, 5, 6]. However, any near-gear or on-gear sensor will rotate with respect to the housing and therefore require a battery or mechanical slip ring assembly. These solutions are not satisfactory for long-term HUMS as batteries need frequent replacement and slip rings have a limited life span and are often unreliable/noisy. DSTG has therefore embarked on a research programme to assess the feasibility of an alternative rugged and real-time wireless gearbox monitoring solution that could be installed at manufacture or retrofitted into existing gearboxes during major maintenance.

In a previous paper [7], the design and testing of a prototype in situ wireless gearbox accelerometer for epicyclic gear trains was described. The performance of this sensor was severely limited by the lack of available power from the energy harvester that necessitated the selection of a low-power accelerometer with insufficient signal-to-noise ratio and bandwidth. It was decided to switch the power transfer scheme from a passive system using permanent magnets to a fully active electromagnetic wireless power transfer (WPT) system. WPT systems are well established for consumer electronics, with high efficiencies and developed standards [8]. However, these are not designed for low-noise operation and it was decided to utilise a more basic, linear setup with passive compensation networks to achieve the desired power transfer and low electromagnetic interference (EMI).

Having sufficient power available allowed the selection of a better analogue accelerometer and a higher-performance analogue-to-digital converter. Additionally, the output power of the wireless transmitter could be increased to its maximum, reducing the packet loss rate of the wireless link to less than 0.001%. The packet-oriented transmission mode also allows other low-bandwidth sensing capability to be added, for example, high-resolution temperature measurements.

Care was taken in the design of the system to allow retrofitting to a specific gearbox without requiring physical modifications. In practical applications, the system would be customised to fit into a specific type of transmission. In the system described below, approximately 20mm of clearance is required between the gearbox housing and planet gear carrier for installation.

System description

The sensor assembly was implemented on a single printed circuit board of approximately 100 × 40 × 10 mm and consists of four distinct functional blocks: power, control, analogue and radiofrequency (RF). The sensor was shaped to fit into the space available in between the planet gears on the planet gear carrier. Encapsulation and mounting on the planet gear carrier was similar to the previous prototype [7]. A proper industrial design could shrink the sensor footprint to a fraction of the size of the present prototype.

The fundamental meshing frequency of the planetary gears is approximately 568 Hz, therefore it was desirable to increase the system bandwidth to above 2 kHz. The selected accelerometer has a linear (− 3 dB) response up to 11 kHz, a sensitivity of 20 mV/g and a range of ±100 g, which is more than sufficient for the task. It was mounted on the printed circuit board with its sensitive axis in the radial direction with respect to the sun gear.

WPT technology has progressed substantially, driven by demand for wirelessly charging portable devices. Still, the number of design variables makes predicting WPT efficiency difficult [9]. The power subsystem had to provide a minimum of 250 mW of power to the sensor node with a 4 mm air gap without causing excessive noise or RF interference. This was achieved by driving the transmitter coil with a sinusoidal waveform and utilising a linear amplifier. However, the power factor at the receiver end was very poor due to the presence of nonlinear circuit elements. Consequently, LCC compensation networks [10] were added on both transmit and receive sides to provide more efficient power transfer and to reduce waveform distortion.

The geometry of the power driving coil was determined by available space within the gearbox housing and the estimated minimum gap required. It was decided to wind two banana shaped coils (Fig. 1a), these were easier to mount and simplified the task of wiring while also providing only two gaps in the electromagnetic field where no power could be transferred to the sensor. Ferrite sheet was added to the base and centre of the coil to increase the coupling coefficient and reduce the volume of the stray field. The linear coil driver was fed by a 93 kHz sine wave from a signal generator.

The power harvester consisted of a ferrite-backed coil with a 20 mm outer diameter and an LCC compensation network (Fig. 1b). The rectifier was followed by energy storage capacitors and low-noise regulators that supplied the analogue and digital circuits. The storage capacitors were designed to provide sufficient energy storage for 35 ms of operation, which was approximately twice the transit time of the energy harvesting coil across the no-power gap between the WPT coils.

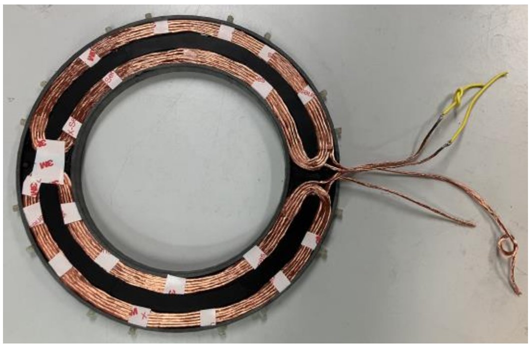

Fig. 1a: WPT coils in carrier

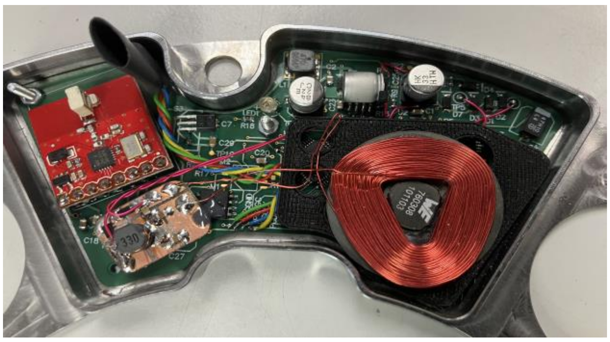

Fig. 1b: Sensor assembly prior to potting

The analogue subsystem consisted of a low-noise analogue micro-electromechanical system (MEMS) accelerometer with a 21 kHz resonance frequency coupled to a fourth-order active analogue low-pass (Nyquist) filter and a 24-bit analogue-to-digital converter (ADC) with adjustable bandwidth. The ADC has a large oversampling ratio of 512:1 and provides a digital anti-alias filter with 100dB rejection at the Nyquist frequency.

To provide a means of planet carrier synchronisation, a Hall sensor was incorporated to provide a once-per-revolution pulse whenever the sensor passed a small permanent magnet mounted in the gap between the WPT coils on the outer rim of the coil bracket. The location information was encoded as a relative time stamp and embedded in a data packet.

An MSP430 series microcontroller is used to control all aspects of data acquisition, buffering and RF transfer. A state-machine based hardware-interrupt driven algorithm provided maximum use of processor resources and code efficiency. Non-volatile memory was added on the board to provide a capability of buffering data at twice the maximum streaming rate of the wireless interface, effectively doubling the data acquisition bandwidth.

Radio transmission, including packet assembly, error detection and decoding was handled by dedicated transceiver chips operating at 2.4 GHz. The protocol used a simple 32-byte data packet including header bytes. The receiver antenna consisted of a loop of thin coax (RG-178) with its shield stripped off. It was mounted with polytetrafluoroethylene (PTFE) standoffs adjacent to, and around the entire circumference of, the WPT coils (Fig. 2). The distance between transmit and receive antennas was less than 20 mm. The end of the antenna cable was connected to the receiver module and matched to approximately 50 Ω impedance to minimise reflections. The receiver extracted the packets and streamed the binary data to a computer via RS232 protocol.

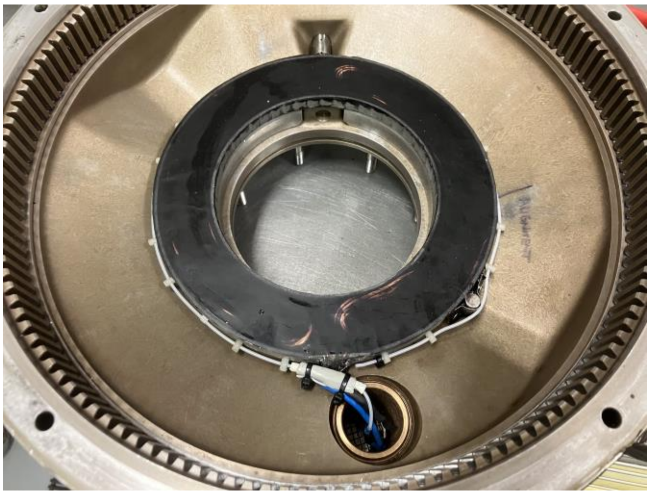

Fig. 2: WPT coil and RF receiver antenna mounted on gearbox housing

The transmitter coil was potted into a 3D-printed nylon formwork designed to bolt directly onto the inside of the upper gearbox housing using slightly longer versions of existing bolts. The antenna and WPT cables were routed to the outside of the gearbox housing through cable glands mounted on a short extension tube on top of the oil filler/breather. No physical modification to the gearbox itself was required. As in [7], the sensor and balance weight were bolted to the planet carrier utilising the existing bearing bolts (Fig.3).

Dynamic tests included spin testing on a lathe and vibration measurements on a shaker (Fig. 4). The RF system showed excellent immunity to the WPT system's operation, although a small vibration signal was suspected to be induced via magnetostriction in the ferrite shield on the sensor harvester coil.

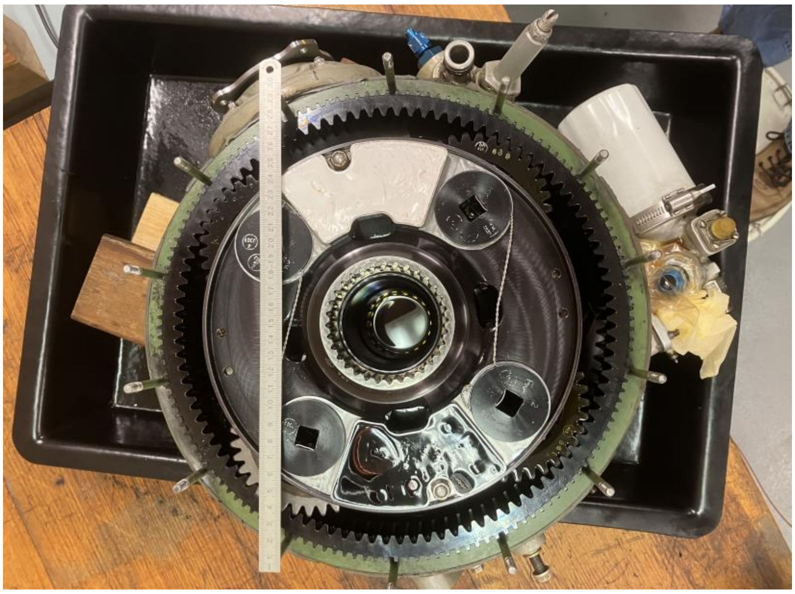

Fig. 3: Sensor and balance weight mounted on planet gear carrier.

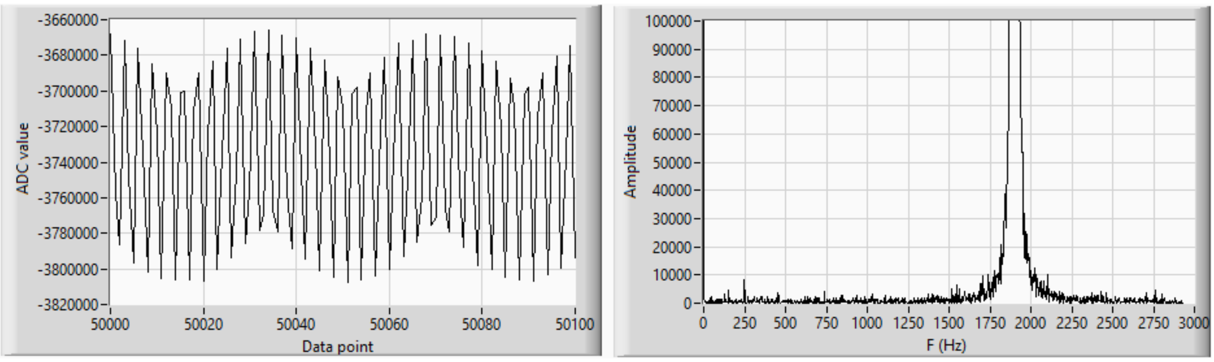

Fig. 4: Shaker test at 1.9kHz and 1G acceleration, time domain waveform(left) and frequency spectrum (2048 samples) on right.

Conclusions

A working prototype of a gearbox accelerometer using WPT and wireless communication has been developed and demonstrates the feasibility of integrating HUMS sensors on rotating components to provide a low cost, minimally intrusive system. Whilst many limitations of the previous prototype have been addressed, a number of improvements are still possible. The packet transmission scheme provides a maximum streaming rate of 6 kHz at 24 bits; this could be increased to 9 kHz at 16 bits. Furthermore, the size of the circuit could be reduced substantially, allowing multiple accelerometers to be placed on the planet carrier.

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