WISD - Wireless Intelligent Sensing Devices

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***Abstract*-WISD is a collaborative technology programme funded by the DTI/TSB. The programme comprises a series of demonstrators to de-risk wireless instrumentation for long term condition monitoring in harsh environments. Novel algorithms for reduction of data transmission requirement and identification of wear features have been demonstrated. Hardware platforms to carry these have also been developed and tested. New power harvesting devices have been developed to explore local power generation from vibration. Aircraft-ready wireless communication hardware and power saving protocols have been proven with a demonstration on a Lynx aircraft.**

I. INTRODUCTION

The overall objective of the programme is to develop “Wireless Intelligent Sensing Devices” (WISDs) for structural health monitoring of helicopter rotor blades and associated components. WISDs will enable major maintenance cost savings for helicopter operators by reducing the need for invasive inspection processes and unplanned maintenance. Strain and vibration sensing modules are mounted on key components (such as on the helicopter rotor assembly) to monitor their condition and predict their remaining safe lifetime.

The sensing modules are self-contained, powered by energy harvesting and contain local signal processing to run sophisticated life prediction algorithms – this is the “intelligent” part. The modules transmit information over a wireless link only when the structural health changes and requires attention or maintenance. This provides an alternative to the current approach of streaming raw data back to a central monitoring unit – WISDs are much more efficient in terms of RF bandwidth and power consumption.

Wireless sensing offers most advantage where running cables to sensors is difficult or impossible. This is particularly the case with rotating components of which there are many in aerospace applications. The main focus for WISD demonstrators has been to transmit data from rotating components on a helicopter to the fixed airframe. Primarily this is for long term sensing and prognosis of component wear. There are also many other potential applications for this technology, such as automotive tyre condition monitoring or for detecting leaks and damage along gas or oil supply pipelines. The protocols used in the WISD programme particularly provide for operation in cases where the communication path is only available intermittently.

A. Programme Outline

The WISD programme provided a progressive approach to the development of WISDs through demonstrators of increasing complexity, with design re-use at each stage of the phased programme.

It developed a robust integrated WISD solution focusing on:

- Micropower sensing and interfacing
- Micropower processor architecture and efficient data processing algorithms
- Data feature extraction and life evaluation algorithms
- Telemetry system (transmission and receiver) and protocols
- Vibrational energy harvesting and power management

As part of the programme the technology was demonstrated in a harsh environment (helicopter rotor hub) with real world problems.

II. DEMONSTRATORS

A. Bending Moment Rig Demonstrator

The first demonstrator in the programme was a laboratory based development of core designs and knowledge for the electronic interface and signal processing boards. The elements developed at this stage were the micropower strain gauge interface and wireless transmission of the signal from the test rig to a base station.

A foil strain gauge was selected for the measurement of static and dynamic strains. Most of the power consumption using these devices is due to the strain gauge bridge excitation current. Since the signal from the bridge is proportional to the excitation any

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significant reduction of the bridge excitation current would incur problems of drift, noise and bandwidth in the amplifier stages. The method used here overcomes these problems by using a high level of excitation current and reducing the average value by pulsing it at a low duty cycle. Presenting a chopped waveform to the amplifier would demand a greater bandwidth so a sample and hold technique was used to allow pulsing of the bridge supply whilst presenting the amplifier with a steady signal. In Fig 1 MOSFETs Q1, Q3 connect the bridge to the sampling capacitors C1, C2 whilst Q4 completes the negative return circuit of the bridge. The remainder of the circuit is a high gain signal conditioning amplifier. Fig. 2 shows the power consumption of the circuit for varying sampling pulse widths at a fixed cycle frequency of 5kHz. Clearly there are significant power savings (>90%) through the use of this technique.

The bending moment demonstrator was also used for initial investigation of transmission of the measured data using a wireless link and thus paved the way for the later harsh environment demonstrators.

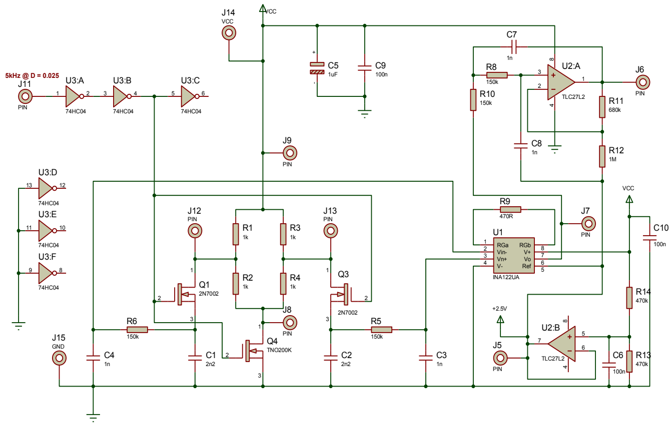

Fig. 1. Sampling circuit for the strain gauge interface.

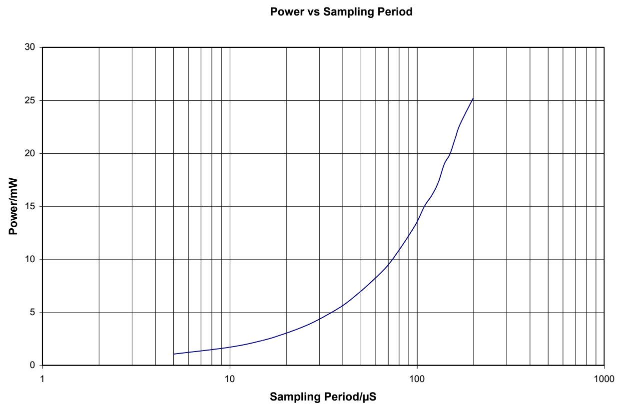

Fig. 2. Strain gauge power consumption as a function of sampling time with a 5kHz cycle rate.

B. *Pitch Link Rig Demonstrator*

In order to develop wear and damage monitoring algorithms it is necessary to have ongoing measured data using different sensors. Recording such data on an airborne platform is not feasible both due to the cost of the flight time and the fact that a normal flight profile does not provide an accurate datum for comparison. A rig based system shown in Fig. 3 was developed to apply representative and reproducible cycles of loading to a helicopter pitch link. This work is ongoing, but at the time of writing data corresponding to 22 loops of pitch-link testing on the rig have been analysed, correspond to 54 hrs 20 mins 28.4 sec of flight.
The loading applied by the rig is varied so the pitch-link is tested as if under four flight conditions: level flight, ground run-up, low speed including hover and once per flight (ground/air/ground).

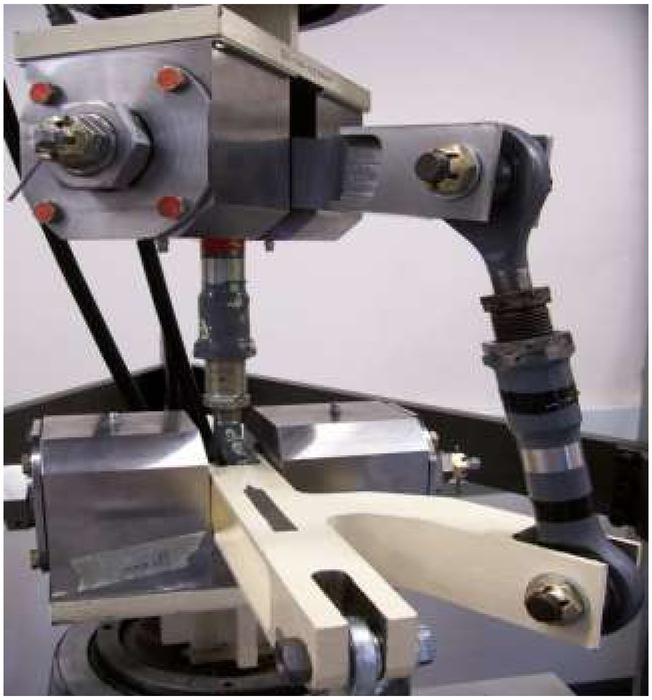

Fig. 3. A pair of pitch links undergoing laboratory wear testing to gather data for developing feature extraction algorithms. The link has a ball joint at each end which the WISD project aimed to monitor.

Fig. 4 shows examples of the load, strain and acceleration signals logged from the level flight test (22 loops). The corresponding comparison analysis curves obtained from the feature extraction analysis using a soft histogram feature extraction algorithm are shown in Fig. 5, the values have been normalised to unity. The same figure shows the value of the fault flag (used to indicate level of wear or damage), calculated using the statistics and trend of the angle between the reference feature vector and subsequent feature vectors. These statistics are used to define a dynamic fuzzy set, through which the fault flag is calculated. From Fig. 5 it can be seen that the flag is only activated during the warming up or cooling down processes during the test.

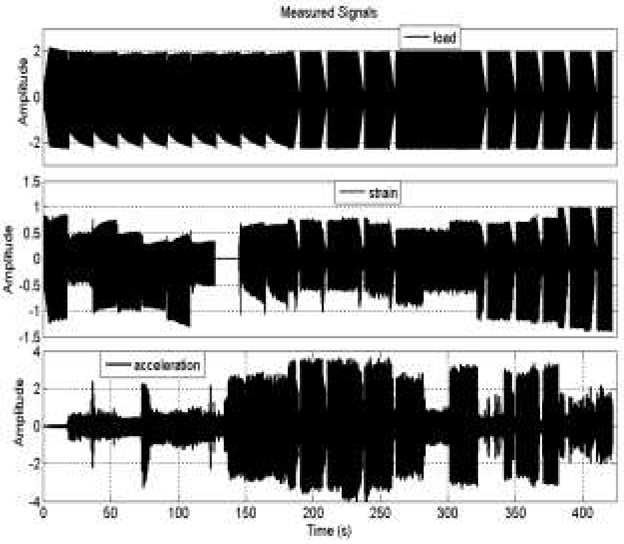

Fig. 4. Measured load, strain and acceleration as a function of time on the pitch link rig. The changes in measured values are representative of different phases of helicopter flight.

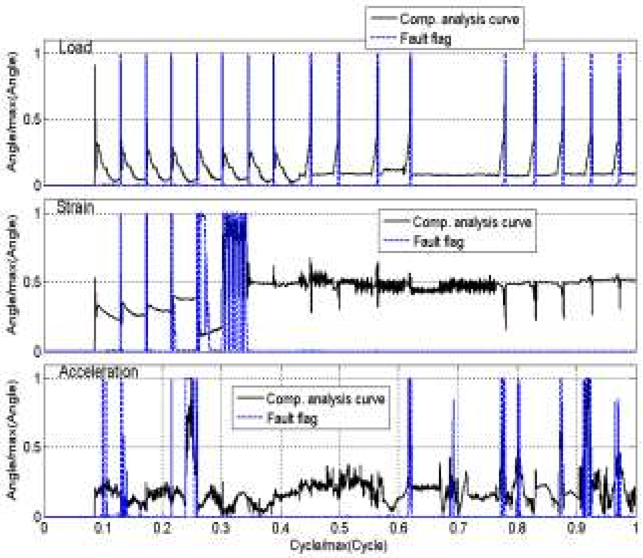

Fig. 5 Comparative analysis output from the pitch link data. The dashed blue lines represent health condition output requiring transmission.

From the comparison analysis curves and the fault flag values, it is deduced that no appreciable wear of the pitch-link has yet occurred. In this analysis the reference feature vector was obtained by averaging the extracted feature vectors corresponding to cycles 130 to 200.

Similar results were obtained using more complex feature extraction algorithms using analogue filtering and the wavelet packet transform.

C. Feature Extraction Algorithm Demonstrators

Within the WISD programme a number of algorithms have been explored for extraction of damage and wear features. The data from the Pitch Link rig is a means to validate and test feature and wear detection algorithms. A number of algorithms have been explored and shown to be effective for reduction in the transmission requirement on different data types. The rain-flow algorithm is based on the analogy of raindrops falling on a pagoda roof and running down the edges. It is a fatigue cycle counting method. This algorithm has been implemented as a representative hardware demonstrator to show the effectiveness of the algorithm directly as a power saving.

The rain-flow algorithm has been implemented in a MSP430 development board including the wireless transceiver CC2420. To test the algorithm, signals from a purposed built hand-held strain strip with a strain gauge attached to it were fed to one of the ADC12 ports of the MSP430F1611 MCU. The digital data was then processed in real time by a rain-flow algorithm developed as part of the WISD programme and the number of cycles within the data was counted and the cumulative damage index was calculated. The resultant information was communicated via the wireless link to a receiving module connected through an RS232 cable to a PC. The data received by the PC was displayed in real time in a specifically developed graphical user interface (GUI). The experimental set up is shown in Fig. 6. In order to measure the energy consumption of the development board, two wireless transmission scenarios were considered. Firstly, raw strain measured data was transmitted at a rate of 200Hz; while in the second case only the cumulative damage index, obtained from the rain-flow algorithm, was transmitted at a rate of 10Hz (note that the raw signal still was sampled at a rate of 200Hz by the wireless sensor device and processed every sample time). The average current consumption was measured in both cases with values of 51.8 mA and 10 mA for the raw and processed data transmissions, respectively. This means that transmitting raw data consumes about five times more energy than transmitting processed data.

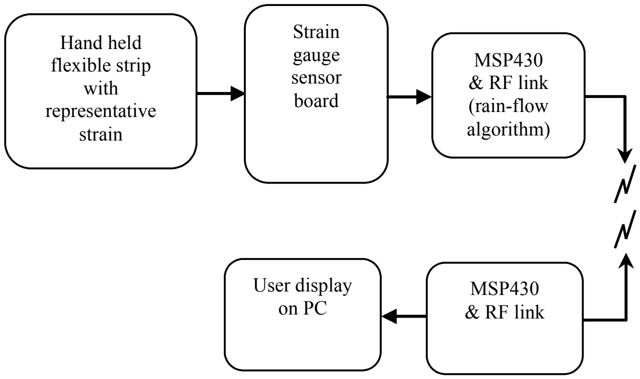

Fig. 6. Experiment setting to test the rain-flow algorithm.

Further optimisation of the algorithm implementation made it possible to reach 800 Hz sampling rate with wireless processed data transmission at a rate of 8 Hz. Note that in this case the raw data was processed in blocks of 100 data samples and not sample by sample as in the previous case. The same two scenarios for wireless data transmission were tested. If raw data is transmitted at a rate of 3 data samples each transmission, then the average current consumption was 34.3mA. When only the cumulative damage index was transmitted, then the average current consumption was 6mA; meaning a greater than 80% reduction in power consumption.

D. *Power Harvesting Demonstrator*

The helicopter environment provides considerable scope for energy harvesting from vibrations. Fig 7 illustrates the spectrum of vibration measured at several locations on the body of a helicopter in forward flight. The magnitude of the vibration has been removed for commercial reasons, however typically 1-2g of acceleration can be found if the harvesting device is located favourably. The development of the power harvester as part of the WISD project represents the most ‘blue sky’ activity within the project, and therefore the goal was to successfully demonstrate an energy harvester, excited by an accurate vibration spectrum, powering the WISD remote sensing module as a bench test. The location of the device in the target application makes it impossible to access the energy harvester to adjust or set-up during operation; however, the space available fro the harvester does not place particularly onerous constraints upon the design and the approximate power consumption of the sensing module (100-150mW) can be met by a harvester built using conventional meso-scale techniques.

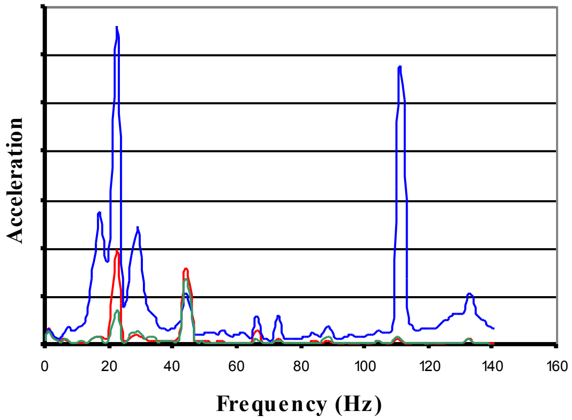

Fig. 7 Measured vibration spectrum at several helicopter body locations during forward flight. The amplitude data is omitted for commercial reason, however vibration peaks of >1g can be found in some locations.

Several novel techniques resulting from the energy harvesting research for WISD have been published [1,2,3] including the application of non-linear dynamics to energy harvesting and active power conditioning.

At the power level required for this application the most appropriate method of extracting power from vibrations is to use a mass/spring resonant generator with electro-magnetic coupling between the mechanical and electrical domains.

Typical linear systems have a narrow transmissibility and this causes difficulties when trying to harvest energy from vibrations in environments where the frequency of vibration changes or where the vibration energy is spread out over a wide bandwidth. It is also a problem for the manufacture of energy harvesting devices since it is necessary to have extremely high tolerance manufacture or provide physical adjustment to the resonant components in service. For the WISD project an energy harvester was developed featuring a high magnetic coupling by incorporating high permeability materials into the stator and armature of the device. As a consequence of this magnetic circuit design the armature experienced reluctance forces that summed with the compliance of the spring to give and overall non-linear compliance characteristic and a wider frequency response compared to linear devices. This harvester is shown in Fig. 8 and full details are to be found in [1] and [3].

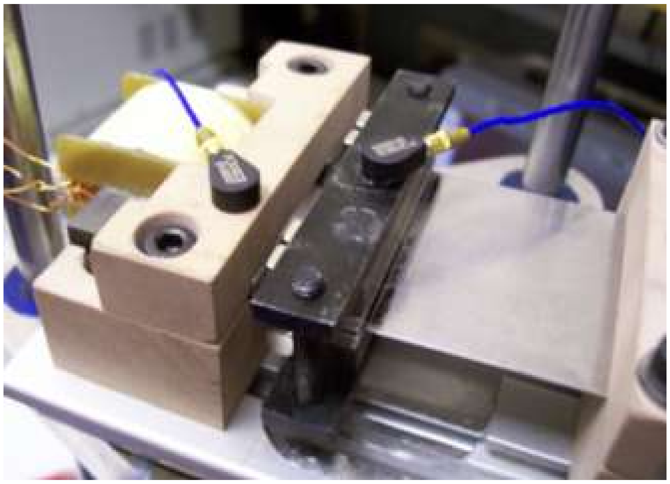

Fig. 8. Harvester prototype under test. The prototype is able to produce in excess of 200mW when excited by vibrations representative of the helicopter environment.

E. Rotating Frame Communication Demonstrators

Communication to and from the rotating elements of a helicopter platform was initially trialed on a whirl tower, a motor driven, ground mounted rotor assembly used for pre-flight testing of rotor head components Fig 9. The hardware has since been developed further and made flight-worthy. The main goal of these trials has been to explore the technical requirements and challenges in implementing a wireless link to and from rotating reference frames using the COTS Zigbee technology. The technology has been successfully implemented in this environment.

Fig. 9. Whirl tower installation with prototype WISD communication hardware installed.

Aircraft-ready communication hardware and power saving protocols utilizing sleep and waiting states has now been proven with a demonstration on a flying Lynx aircraft, Figs 10 to 14.

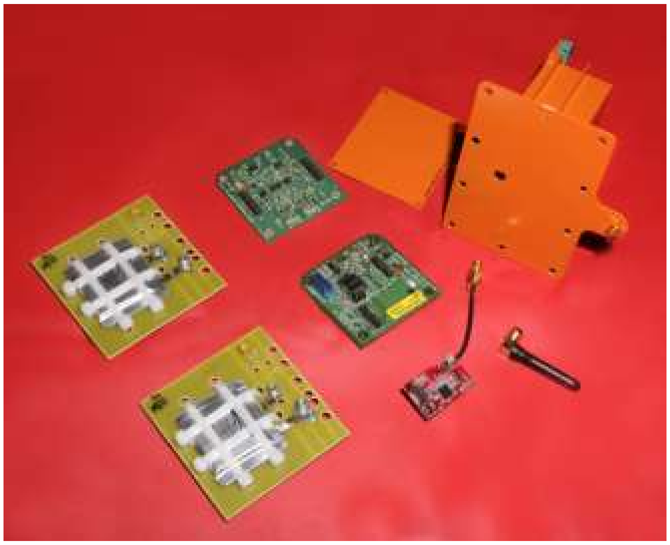

Fig. 10. WACD rotor mounted electronics prior to assembly. The battery cards mount directly into the rotor head encoder. The other components are fitted to the encoder using the orange housing.

Fig. 11. WACD rotor mounted electronics. The orange painted box carries the signal conditioning, processing and communications electronics. The antenna is mounted on the tab nearest the camera.

Fig. 12. Battery cards installed on the rotor head. The battery leads are shown unconnected prior to connection and final closure before flight.

Fig. 13. Lynx helicopter fitted with the WACD system for the flight trial.

This Wireless AirCraft Demonstrator (WACD) shows reliable transmission of information from the main rotor head rotating frame to the static airframe that can replace conventional slip ring technology. To instrument the rotor head presents a thorough test of the technology: with a unit located on the rotor head there is a periodically occluded transmission path with a significant number of multi-path reflections and also Doppler shifts of the transmitted and received signals. The environment of operation is also one of high vibration and high levels of EMC from radio and other equipment. The WISD project and the WACD aircraft demonstration are possibly the first time that low-power radio links have been demonstrated on a flying aircraft for transmitting sensor data.

Fig. 14. Static airframe low profile antenna (black disk) mounted on the cockpit roof.

III. Summary and Conclusion

The WISD programme has demonstrated the main elements of a novel approach to structural health monitoring in harsh environments. Through power saving technologies and algorithms it has been shown to be feasible to use energy harvesting to fulfil instrumentation power requirements. Implementation of the hardware in a harsh environment demonstrator has also been achieved.

Though still at the R and D stage, the programme has a strong commercial focus in the longer term. There are potential cost and weight reductions through the avoidance of cabling for instrumentation and also through product life enhancement and maintenance efficiency improvements by utilization of the additional data that is available with this type of technology.

The demonstrators of the WISD programme offer the elements of a new approach to condition monitoring of aerospace and other systems. Having shown the technology to be effective now opens up the discussion with end users and systems designers for its effective implementation. The approach demonstrated in this programme may be broadened out sideways with the development of additional specific sensors and applications.

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