# Towards Wireless Sensor Usage and Health Monitoring of Helicopter Rotor Components

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**Abstract**

Wireless sensors offer the promise of a paradigm shift from traditional schedule-driven maintenance to condition-based maintenance of aircraft subsystems. In particular this technology will benefit applications where running cables to sensors is difficult or impossible. This is specially the case in rotary-wing aircraft. This work reports research carried out under the umbrella of the Wireless Intelligent Sensor Devices programme, supported by the UK Technology Strategy Board, to advance the development of the hardware and software required to continuously in-flight monitor the wear rate within the pitch link end bearings and fitting of the Lynx Helicopter. This shall greatly enhance the operational readiness and cost effectiveness of the helicopter. Results of this research are reported in three areas: 1) development of low power sensing interface and signal conditioning, 2) pitch link test carried out to aid the development of feature extraction and wear detection algorithms and 3) intelligent feature extraction algorithms, wear detection and results.

**Keywords:** Wireless intelligent sensor, rotor-head health monitoring, low-power signal conditioning, feature extraction, critical wear detection.

# Introduction

One of the long-term objectives of the aviation industry has been the continuous monitoring of the health of aircraft subsystems in order to identify early problems before they affect the airworthiness of the aircraft. The current way of addressing the health monitoring problem is by calendar-based or usage based scheduled inspection and maintenance of damage-sensitive parts and, if required, replacement of such parts [1]. These practices are time-consuming and labour-intensive, which make them expensive.

Wireless sensor offer the promise of a paradigm shift from traditional schedule-driven maintenance to condition-based maintenance of aircraft subsystems. In particular this technology will benefit applications where running cables to sensors is difficult or impossible. This is the case with rotating components of which there are many examples in the aerospace industry and, specially, in rotary-wing aircraft.

Wireless intelligent sensors could potentially be permanently placed in critical rotating components to monitor their state of health without human intervention. Algorithms running on-board the wireless sensor processor could perform feature extraction and pattern recognition algorithms to determine the level of wear of a component and estimate its remaining useful life, transmitting results only when maintenance or inspection is required. This offers the potential to lower operating costs and enhance flight reliability. However, placing sensors in rotating components is a challenging task. Major barriers are unavailability of robust sensors, low power consumption signal conditioning and processing, reliable and efficient feature extraction and damage detection algorithms, robust and reliable wireless data

transmission in harsh environments [2]. If it is considered that component condition-based maintenance could reduce the overall maintenance costs of aerospace systems by at least 25–50% [3], then there is a need of focusing fundamental research activities related to health monitoring of aerospace and other systems using wireless intelligent sensors.

In response to the aforementioned need, The University of Bristol is collaborating in a research project, supported by the UK Technology Strategy Board, to advance the technology needed for the development of wireless intelligent sensing devices (WISD). In general terms, a WISD includes four subsystems: 1) a computing subsystem consisting of a microprocessor or microcontroller, 2) a communication subsystem consisting of a short range radio for wireless communication, 3) a sensing subsystem that links the device to the physical world and consists of a group of sensors and corresponding signal conditioning interface, and 4) a power supply subsystem, which commonly houses a set of batteries but power harvesting devices are also currently being investigated [4]. Fig. 1 shows a modular structure of a wireless intelligent sensor together with the research scope within the WISD project.
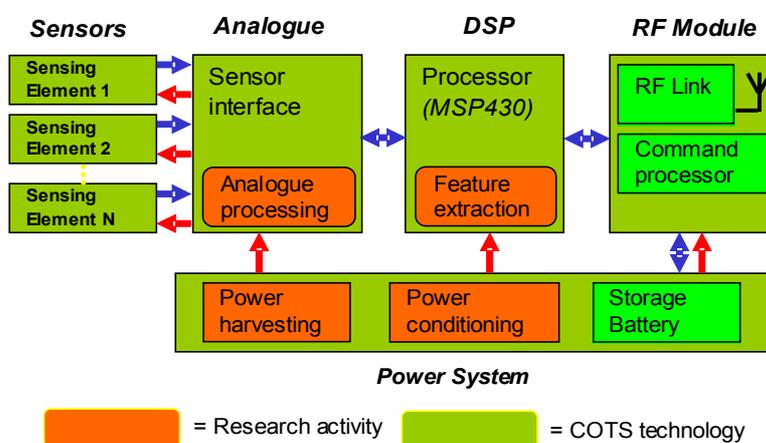


*Fig. 1: Scope of research of the WISD project.*

The goal of this paper is to present the latest findings of the research carried out under the umbrella of the WISD programme. In particular, one of the target applications for the WISD technology is the continuous in-flight monitoring of the wear rate within the pitch link end bearings and fitting of the Lynx Helicopter. The goal is to design a system that, only when the wear rate reaches a predetermined level, will this information be transmitted to the flight crew or maintenance personnel. This shall greatly enhance the operational readiness and cost effectiveness of the helicopter. Therefore, for the case of the pitch link health monitoring, in the next sections of this paper results of this research are reported in three areas:

1) development of low power sensing interface and signal conditioning
2) pitch link test carried out to aid the development of feature extraction and wear detection methods
3) intelligent feature extraction algorithms, wear detection and results

**Importance of Pitch Link Health Monitoring**

The rotor blades of a helicopter (see Fig. 2a) possess three degrees of freedom: flap, pitch and lead-lag motion. Of these, the pitch degree of freedom can have the most profound influence on rotor loading, and as a consequence, aircraft stability and control. The pitch control linkage (see Fig. 2b), commonly referred to as pitch link, on a conventional helicopter swash-plate control system transfers the pilot control inputs to the rotor blade in order to effect both collective and cyclic changes in blade pitch. It is therefore vitally important that the blade

pitch motion is a faithful transfer of pilot control inputs and that backlash in the control system is kept to an absolute minimum.



*Fig. 2: a) Rotor blades of the Lynx Helicopter; b) Location of the Pitch Link*

In the context of pitch link health and usage monitoring, the manifestation of backlash in the control circuit can lead to severe vibration at best and blade flutter in the limit, with obvious flight safety implications. It is for this reason that stringent wear limits are put on the pitch link end bearings and the in-service control of these limits is a time consuming procedure. It requires removal of the pitch link to enable a physical measurement of bearing wear. It is known that the rate of wear is very dependant upon both the environmental conditions and the aircraft mission profiles. It is also known that after the onset of any initial wear, the wear process can accelerate rapidly. Thus, fixed period inspection times are difficult to optimise and must therefore be overly conservative to ensure critical wear levels are detected in good time.

## Low Power Interface and Signal Conditioning

In order to monitor the state of pitch links two types of "wear detection" sensors are proposed. The first one is a dynamic strain sensor consisting of a piezoelectric element which generates a voltage proportional to change in strain. This has the advantage of not requiring an excitation current supply to produce an output, as in the case of resistive types. As the piezoelectric element only produces an output with change in strain it cannot give an indication of static strain but has a low frequency cut-off determined by the self capacitance of the element and the input impedance of the interface. A buffer amplifier is used with input impedance set to a cut-off frequency below the lowest frequency of interest. In this application, if the cut-off frequency is set to below the pitch-link oscillation frequency of 5.5Hz the output will, for an unworn pitch-link, show a smoothly varying voltage corresponding to the change between tensile and compressive loads in the pitch link, as imposed by cyclic loading. But as the pitch-ling bearings wear, this waveform will have superimposed on it high frequency oscillations due to shock waves as the slack is taken up in the bearings with each force reversal. The second sensor is an accelerometer attached to the body of the pitch-link. This detects sudden changes in acceleration resulting from backlash in the load path as imposed by cyclic loading. For these tests a Kistler sensor was used together with its companion mains operated signal conditioning unit. If this type of sensor was eventually adopted, micropower signal conditioning would need to be developed.

As the feature extraction algorithms use a combination of higher and lower frequencies in the measured signal (see next section), two analogue filters are designed. Note that a first feature extraction process was designed using a single wavelet transform decomposition to obtain

these two frequency bands [5]. Thus, by substituting that operation by analogue filters, this reduces the processing burden put on the WISD microprocessor.

Simulation showed that second-order filters are adequate and a design using Sallen and Key circuits was prepared. A low-pass filter with poles at 100 Hz and a band-pass filter from 100Hz to 1kHz was suggested at first, but it has been found from FFT of measured signals that optimum frequencies are 30 Hz for the low-pass and 30 to 100Hz for the band-pass filters. Fig. 3 shows the analogue filter design. The signal from the piezoelectric element feeds U1a which can be configured as a unity-gain buffer by omitting R2 or can have gain defined by the ratio of R1 and R2. R3 determines the input impedance and thus defines the low frequency cut-off, which for an element capacitance of 13.4nF as used in these tests is 5.4Hz. The total current draw for the filter is 154µA at 3.3V, giving a power consumption of 0.5mW. As the outputs drive analogue-to-digital converters in the MSP430, op-amps suitable for this service are required, precluding the use of the very lowest power devices. As power for the WISD system is proposed to be obtained by harvesting energy from ambient vibrations, there is a drive to keep power consumption of signal interfaces and processing at the lowest possible level.
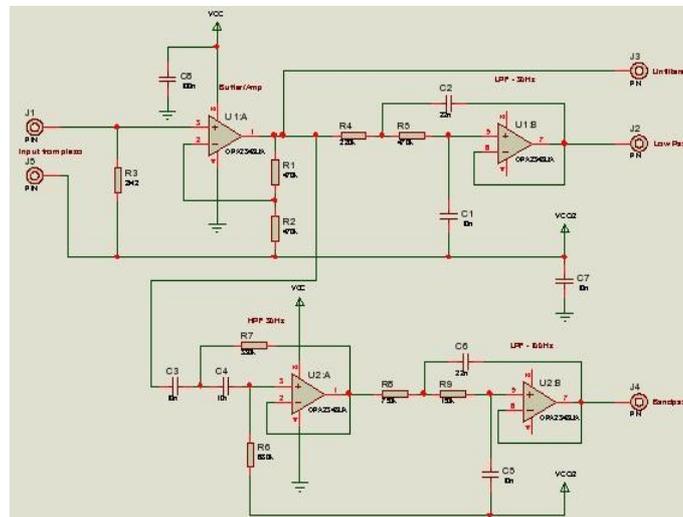


*Fig3. Low-pass and band-pass analogue filters.*

**Pitch link testing**

The ideal component maintenance will be that performed just before the component is close to failure. Obviously, in practice, this could only be achieved if there is any possibility to detect the component deterioration before its failure. However, in order to develop wear and damage monitoring algorithms for the pitch link bearings it is necessary to have ongoing measured data using the proposed sensors. Recording such data on a helicopter 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. Therefore, a solution to this problem was the designing and manufacturing of the test rig based system shown in Fig. 4. The test rig made possible to apply representative and reproducible cycles of loading to a helicopter pitch link. The test rig was designed by AugustaWestland, manufactured by a specialist engineering company and assembled by technical staff at the University of Bristol.
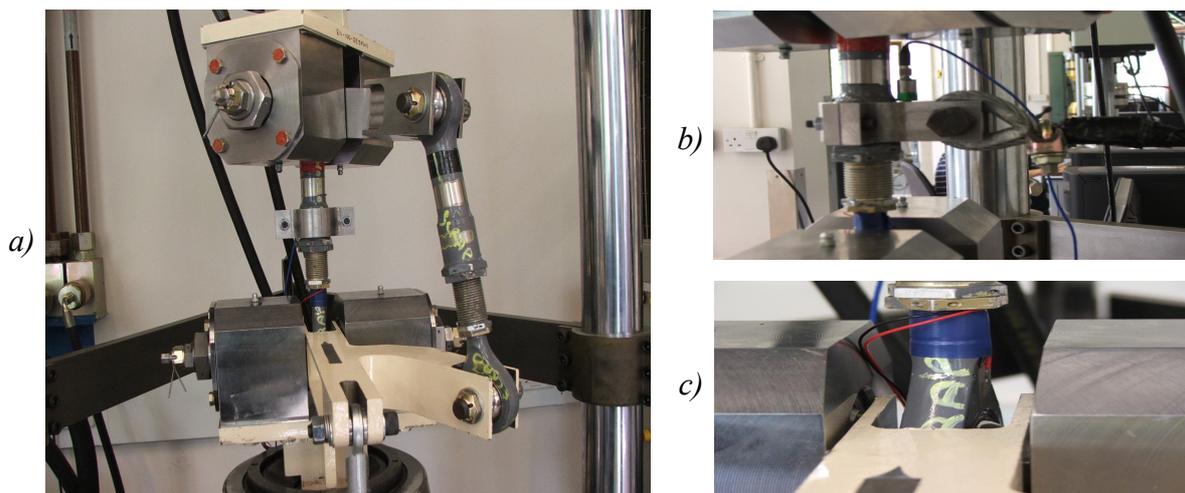
*Fig. 4. a) Purposed-built pitch link test rig; b) accelerometer location; c) piezo-ceramic patch location.*

The design of the rig has had to consider how best to represent the loads, motions, etc., that the pitch link and end bearing components experience during a wide range of aircraft operating parameters including those cases where wear upon the bearing is most prevalent and also where the effects of a worn bearing are felt most. An accelerometer was fitted to the pitch link to detect acceleration in the axis along the pitch-link, as shown in Fig. 3b. A piezo-ceramic patch was attached to a flat area near to the spherical ball bearing, shown in Fig. 3c. Signals were recorded from these sensors during testing.

The purpose of the tests carried out is to aid in the development of wear detection methods conductive to the purpose in-flight condition monitoring. Here in-flight condition monitoring means the ability of continuously monitor the wear rate at which the pitch link end fittings is deteriorating and only when a predetermined level has reached a certain predetermined level, transmit an alarm signal to the flight crew or maintenance personnel.

The test matrix was generated by AgustaWestland and consisted of a series of axially applied oscillatory loads that resembled a typical ($\approx$ 2.5 hours) flight case. The loads are exaggerated by 20% to accelerate the wear rate of the pitch link spherical end bearings which are the components under test. In addition to the axial and lateral loadings on the pitch link end bearings, the orientation of the bearings are rotated during each load cycle as would be experienced in flight due to the application of cyclic pitch.

Ten "flight" cases were performed back to back so that a full block of flight case takes approximately 25 hours to complete. The test procedure is automated, in that the four different loading spectra within each flight case are performed sequentially and repeatedly (10 times) without manual intervention.

Each test block consists of four flight states (see Fig. 5):

1. Ground conditions (rotor acceleration)
2. Level flight and banked turns
3. Low speed and transitions (climb)
4. Once per flight (ground/air/ground)
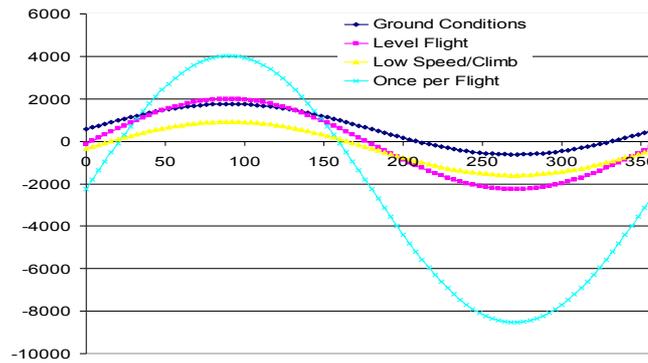
*Fig. 5: Load testing matrix.*

## Intelligent feature extraction algorithms

The research in the area of feature extraction for health and usage monitoring of the pitch link bearings in particular and rotor-head components in general aims to find better anomaly detection methods that discriminate between data characteristics from an acceptable wear condition and trends which are associated with developing critical wear. The goal is to enhance the feature extraction capabilities with the aim, in the long term, of replacing the current physical measurement of bearing wear and damage detection process by a wireless-based automatic health monitoring mechanism. To do this, a combination of techniques from wavelet transform theory and soft computing technology are being explored.

Current helicopter rotors spin at near constant revolutions per minute (RPM) throughout a flight mission [6]. Consequently, it is assumed that for a given regime of operation (ground conditions, level flight, low speed, or once per flight) the signals coming from the sensors installed on monitored components of the main rotor hub will be periodic signals, where the basic frequency is the rotor frequency. Having this in mind, the general idea explored to analyse the mechanism of degradation in rotor-head components is as follows, if a feature vector can be extracted which represents the characteristics of a cycle or a series of cycles of the measured signal, from the component being monitored, then this feature vector can be used to perform comparisons with a cycle or a series of cycles of the signal obtained over different periods of time (but in the same regime of operation). This in turns will make possible to assess how the signal is evolving until critical wear in the monitored component is reached and this can be used for pattern recognition and component critical wear detection before the point of catastrophic failure. In other words, the main postulate is that the change of the dynamic behaviour of the component being monitored can be expressed in terms of changes in the feature vectors extracted from every cycle (or series of cycles) of the measured signals when compared over time.

The effective content of information in a cycle of a periodic signal is captured in its extracted feature vector. Thus, if two cycles of the signal are apparently different, then their traits can be extracted in very different feature vectors. But if the two cycles of the signal are approximately the same, then their feature vectors should be very similar.

Three different level of hierarchy feature extraction algorithm (FEA) were proposed and applied with similar results. The first level is referred to as soft histogram feature extraction algorithm (SH-FEA) [7]; the second level is referred to as analogue filters plus fuzzy associative memory feature extraction algorithm (AFFAM-FEA), and the third one is referred to as wavelet packet transform plus fuzzy associative memory bank feature extraction algorithm (WPT-FAMB-FEA). A schematic representation of each of these FEAs is shown in Fig. 5. They also are simply referred to as, level 1, level 2 and level 3 FEA, respectively. These

FEAs were developed as part of the WISD project. For the matter of space, the background and extended description of each one of the FEAs is given in [8]. Therefore, only the results obtained with the level 2 FEA, for which the sensors and signals conditioning have been reported above, are presented in this section.
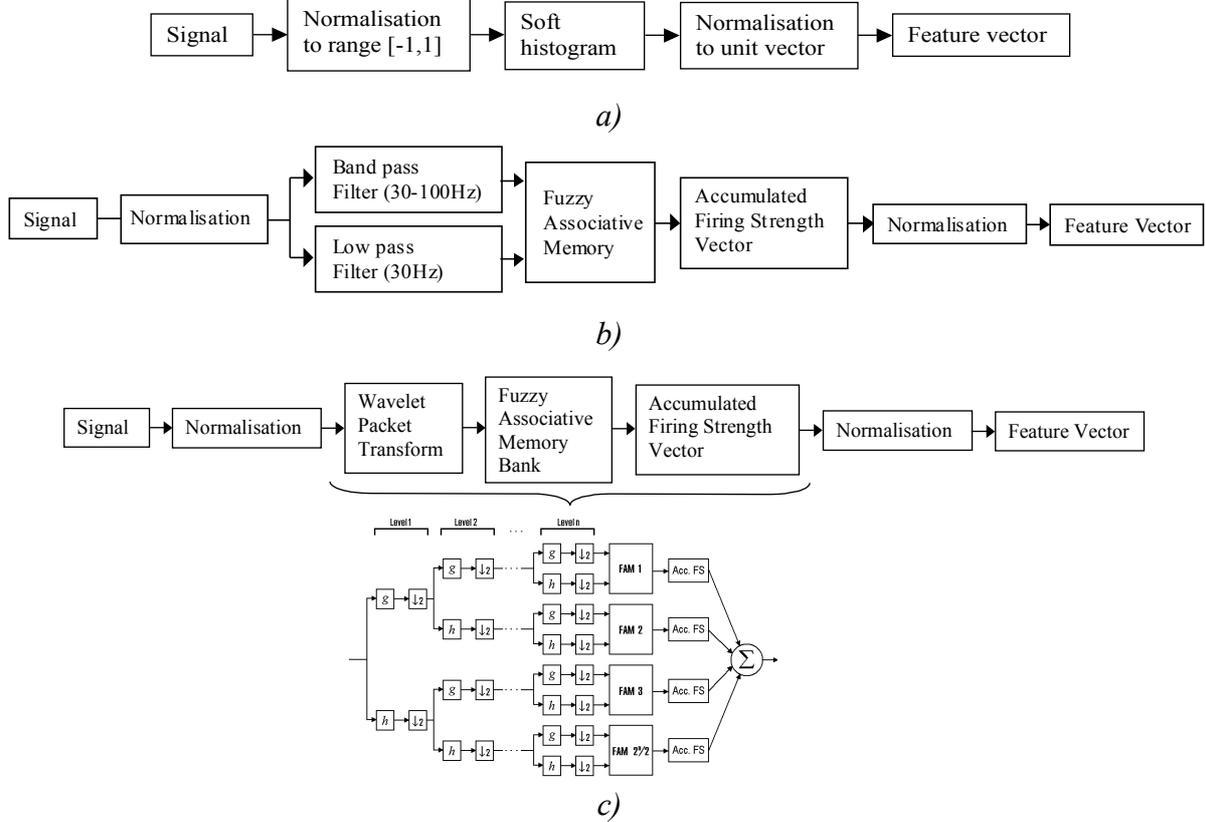


*Fig.5: Different level of hierarchy feature extraction algorithms. a) SH-FEA; b) AFFAM-FEA; c) WPT-FAMB-FEA.*

Data corresponding to 50 loops of testing of a pitch-link from new were made available. In total, the test correspond to 123 hrs 30 mins 10 secs of flight. Each loop represents 2 hrs 28 mins 12.2 secs of flight. Note that only sets of 20 secs of data for each one of the flight conditions among each testing loop were logged, at a sampling frequency of 5KHz, for analysis and feature extraction purposes (completing approximately 5500 cycles of rotor rotations). Hence, for the pitch link and assuming that measured signals correspond to tests performed under a given regime of operation, a feature vector was extracted for every cycle of the load excitation, and the measured strain and acceleration signals. Having available the extracted feature vectors, a reference feature vector was calculated by averaging the feature vectors corresponding to cycles 1 to 500 (to give statistical significance). The reference feature vectors for each signal represent the signature of the pitch link bearing when they are in a healthy or unworn state. It is expected that the degradation of the pitch link bearings can be expressed in terms of the variations of the extracted feature vectors over time when compared with the reference feature vector. The plot of the number of cycles versus the angle between the reference feature vector and the remaining feature vectors is referred to as comparison analysis curve. Recall that the angle between two vectors $x$ and $y$ is defined as:

$$\theta(x,y) = \cos^{-1}\left(\frac{(y^T x)}{\|x\| \ \|y\|}\right)$$

(1).
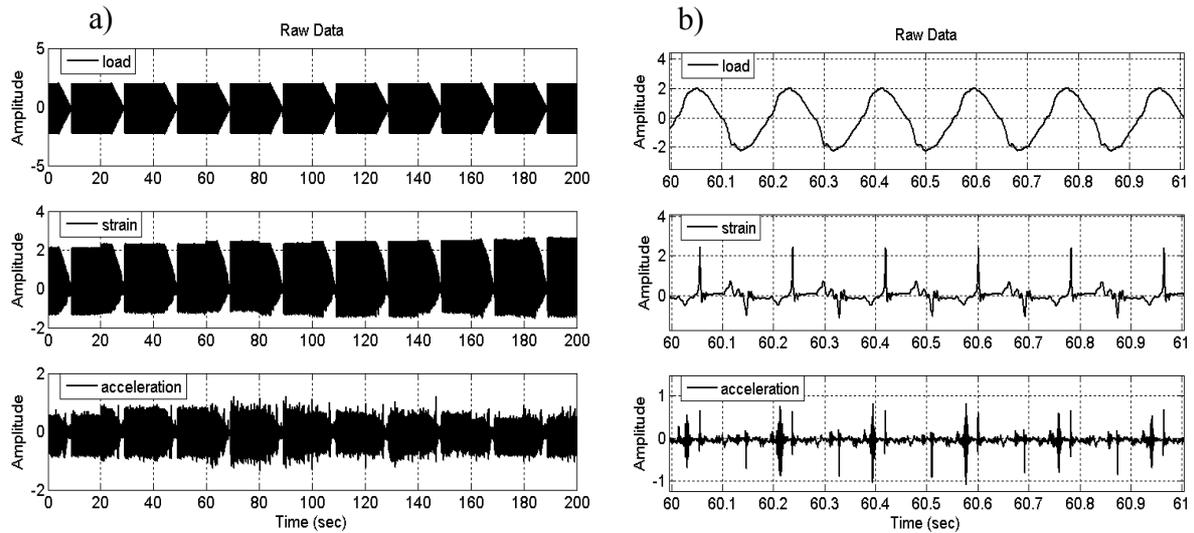
*Fig. 6: a) raw data; b) close up (the load amplitude is given in KN, strain and acceleration amplitudes are given in Volts).*
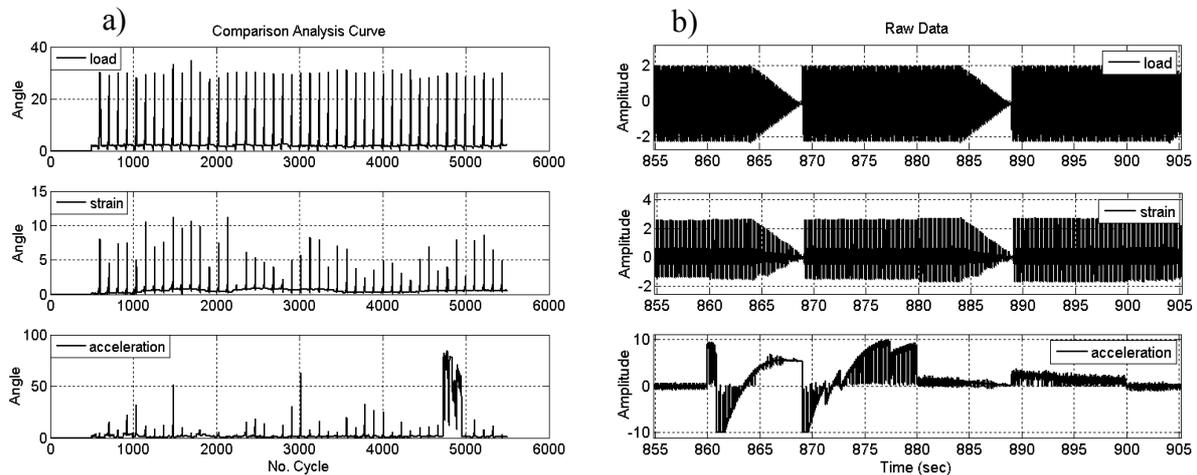


*Fig. 7: a) level 2 FEA results; b) close-up of the raw acceleration signal showing sensor failure.*

In order to detect critical wear the level 2 FEA was applied to all the signals measured under the four flight conditions (regimes of operation). Results are presented only for the flight conditions level flight. Examples of the raw signals measured for this case are shown in Fig. 6 (10 sets of 20 secs, corresponding to 10 test loops, are all appended together as a single time series). The comparison analysis curve obtained is presented in Fig. 7a. It is expected that the degradation of the pitch link will be manifested in three stages on the comparison analysis curve [7]. In the first stage, degradation occurs rapidly during the first cycles. In the second stage, degradation shows a relatively slow and steady growth rate. In the third stage, degradation grows rapidly, resembling an exponential function. Note that this coincide with the typical bathtub failure over life curve [9] observed in health monitoring of equipment. Thus, by analysing Fig. 7a, it is deduced that no significant wear of the pitch link has taken place, as not appreciable drifting is appreciated in the comparison analysis curves (from current maintenance procedures it is expected that a pitch link will start to wear-out at around 800 hours of flight). The transient picks observed in the analysis comparison curve correspond to the cooling down process at the ending of each testing loop, which is when the samples of 20 secs of data are logged. However, note that a change is detected from cycles 4730 to 4951 in the analysis comparison curve corresponding to the acceleration signal. A close-up of the original acceleration raw signal, indeed revealed that a change took place, as can be seen in Fig. 7b. From the curve, it is inferred that a sensor failure occurred, due that not change is

detected in the curve corresponding to the strain signal. Therefore, although deterioration and critical wear has not being reached the feature extraction algorithm is able to detect changes in the signals, which in this case is due to a sensor failure. At the time of writing this paper the pitch link was undergoing more testing in order to reach 800 hours of flight, but data was not yet made available for analysis.

**Implementation on Hardware**

The level 2 feature extraction algorithm was implemented in the chosen hardware for the WISD project (see figure 8) [10]. This includes the MSP430F1611 MCU low power consumption microcontroller from Texas Instruments and an Ember Zigbee protocol based RF transceiver, powered by batteries. Although the feature extraction algorithm was tested in the hardware using actual data from the pitch link test, currently the monitoring sensors for the pitch link are not installed in the helicopter, and therefore they were not tested in a real flight. However, the hardware and communications have been tested and validated on an actual flight. Current work is in progress to install the required sensors in the pitch link for in-flight pitch link health monitoring.



*Fig. 8: WISD hardware and installation on the helicopter.*

**Conclusions**

The concept of wireless sensing provides a different paradigm for helicopter structural integrity and system health monitoring, prognostics and management. It has the potential to change health and usage monitoring procedures in many areas. In particular, on the helicopter rotors and rotor head, the possible applications of wireless sensors include: monitoring of rotor hub bending; real time indication of "minimum pitch on ground"; monitoring of pitch link wear; warning of lag damper failure; prognosis and remaining life prediction of critical components; measurement of critical flight dynamic parameters; control and monitoring of rotor-embedded and active rotor systems.

Wireless sensors will enable major maintenance cost savings for helicopter operators by reducing the need for invasive inspection processes and unplanned maintenance. Intelligent feature extraction and critical wear detection algorithms together with low power signal conditioning and processing will be the core of these kinds of applications.

## Acknowledgments

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