DEVELOPMENT OF A HELICOPTER ON-ROTOR HUM SYSTEM POWERED BY VIBRATION ENERGY HARVESTING

Daniel M Wells,
AgustaWestland,
Lysander Road, Yeovil,
Somerset, BA20 2YB,
UK

Tiziano Frattini,
AgustaWestland,
Via Giovanni Agusta 520,
21017 Cascina Costa (VA),
Italy

David L Churchill, Stephen DiStasi
LORD-MicroStrain Sensing Systems,
Suite 102, 459 Hurricane Lane,
Williston, Vermont 05495,
USA

ABSTRACT

Helicopter transmission health and usage monitoring is mature and operating on many helicopters worldwide. Attention is now being given to improving the monitoring of rotor systems, in order to 1) further enhance safety by the early detection of incipient failures, and 2) reduce the maintenance burden by minimising or ultimately replacing high-frequency on-aircraft rotor component inspections. To realise these aims, rotor monitoring needs to go beyond the traditional track and balance management based on airframe vibration measurement and one approach is more localised sensing on rotor components. AgustaWestland is currently evaluating self-powered wireless sensing technology in a two-phase research effort under its Rotorcraft Technology Validation Programme. Firstly, AgustaWestland has conducted trials on an AW139 helicopter of a single wireless sensor node developed by LORD-MicroStrain Sensing Systems, which was located on the main rotor rotating swashplate – this has proven the key technology enablers of vibration energy harvesting and low-power/low-range radio-frequency data transmission from the rotor to the airframe. The second phase will be the development of a multi-node main rotor monitoring system with sensors mounted on selected rotor controls components, with embedded data processing in the nodes to characterise backlash in non-rotating bearings, and to reduce the volume of data transmission. The programme to take the technology forward to service implementations will focus on continuing development of wear feature detection and condition indicators, design studies for integration of the sensor nodes within the rotor system, and validation/verification.

1. GLOSSARY

ADC	Analogue-to-Digital Converter
AW	AgustaWestland
CAA	(UK) Civil Aviation Authority
CI	Condition Indicator
EASA	European Aviation Safety Agency
GPS	Global Positioning Systems
HM	Health Monitoring
HUM/S	Health & Usage Monitoring / System
IEEE	Institute of Electrical and Electronic Engineers
kts	Knots
L-MS	LORD-MicroStrain Sensing Systems
mW	milli-Watt
PC	Personal Computer
PCL	Pitch Control Link
RAM	Random Access Memory
R&D	Research & Development
RF	Radio Frequency
RSSI	Radio Signal Strength Indicator
RTD	Resistance Thermometer Detector
RTVP	Rotorcraft Technology Validation Programme
SCV	Super-Capacitor Voltage
STA	Synchronous Time Average
VDC	Volts-Direct Current
VEH	Vibration Energy Harvester
WSDA	Wireless Sensor Data Aggregator
WSN	Wireless Sensor Node

2. INTRODUCTION

The primary focus in helicopter Health and Usage Monitoring (HUM) has been on transmission systems, to the point where transmission vibration monitoring is operating on many helicopter types in service today to enhance safety and assist maintainers.

To date, rotor HUM, or more specifically condition monitoring of the rotor, has largely been limited to post-maintenance and periodic assessment/control of track and balance, through measurements on the airframe of rotor 1/rev vibration and blade position. Over time, relationships between higher harmonics of 1/rev and the condition of some rotor components have been derived through service experience. Maintenance manuals typically contain component checklists for when airframe vibration exceeds empirically-based limits.

Of course rotor systems are also subject to routine on- and off-aircraft condition checking by visual inspection and wear measurement. The on-aircraft regime is usually at relatively high periodicity compared to other aircraft systems and often with disproportionate impact on aircraft availability.

Attention is now being given to improving rotor system HUM, both for enhanced safety and reduced maintenance burden. In 2008, the Civil Aviation

Authority (CAA) in the UK reported a review of Rotor HUM[1] and concluded, *inter alia,* that:

- Although the rate of [helicopter] accidents is declining, a few recent high profile cases have demonstrated that there is still significant safety benefit in main and tail rotor fault detection.
- For many rotor faults, improved detection is unlikely to come from existing fixed-frame vibration measurements, and rotating-frame technologies should be investigated.

In 2010, the UK Air Accidents Investigation Branch report[2] of a main rotor blade spindle failure included Safety Recommendation 2010-027 that "EASA, with the assistance of the CAA, should conduct a review of options for extending the scope of HUMS detection into the rotating systems of helicopters". EASA subsequently awarded a research contract to Cranfield University in the UK to review technology for improving the monitoring of both internal gearbox components and rotors.

In the same timeframe, AgustaWestland (AW) identified the possible benefits of focussed rotor condition monitoring in providing early warning of degrading condition at the component level, and initial cost/benefit studies indicated operating cost and availability benefits by reducing or ultimately replacing some of the relatively high-frequency and disruptive on-aircraft maintenance regimes for rotors. AW also identified that the sensing technology base had developed to the point where self-powered on-rotor HUMS was worth evaluating.

This paper describes an AgustaWestland research and development programme for the application of self-powered wireless sensor node (WSN) technology for on-rotor HUM, for which LORD-MicroStrain Sensing Systems (L-MS) is providing the experimental system. The paper first outlines AW's programme and approach to on-rotor HUM, then describes the development of the WSN technology and a risk reduction flight trial of the core technology elements. Next, the plan for a follow-on flight demonstration of a multi-node experimental system is outlined, and the paper concludes with thoughts on the anticipated programme for taking the technology forward to in-service application.

3. AW ON-ROTOR HUM PROGRAMME AND APPROACH

3.1 On-Rotor HUM R&D Programme Outline

On-Rotor HUM is being pursued by AW in its Rotorcraft Technology Validation Programme (RTVP), a four-year research and demonstration programme for rotor technologies supported by the UK Government's Technology Strategy Board, which commenced in 2010.

The overall aim of the On-Rotor HUM programme is to demonstrate generic technology that can be taken forward to product-specific application. The programme is structured as follows:

- Requirements capture
- Technology review and selection
- Rotating controls wear feature development
- Lab based system evaluation
- Phase 1: risk reduction trial of single wireless sensor node.
- Phase 2: development/trial of representative multi-node system.
- Routemap for application-specific development.

AW selected the Department of Aerospace Engineering at the University of Bristol, UK as their academic partner, and they led the technology review, lab-based demonstrator and bearing wear detection testing and analysis activities.

AW selected L-MS as the technology provider for the experimental flight trials, due to their sector-leading expertise and experience in helicopter wireless sensing and energy harvesting.

3.2 On-Rotor HUM Approach

AW's approach for On-Rotor HUM was driven by the requirements capture and technology review activities.

<u>The requirements capture activity</u> was conducted by AW and involved reviewing international civil accident/incident statistics and internal workshops. The conclusions of this activity were that:

- Most rotor failures occur in main rotors rather than tail rotors and in the rotor hub and controls rather than blades.
- Most benefit from on-rotor HUM will come from condition monitoring of mechanical components subject to wear, in particular bearings, eg swashplate duplex bearing, Pitch Control Rod bearings, rotating scissors bearings, damper spherical bearings.
- Acceleration and strain will be the primary parameters for condition monitoring, but temperature and stiffness also need to be considered.
- Initially, the main rotor should be addressed since this will show most benefit and is easier to do, compared to the tail rotor.
- Usage monitoring by component level sensing is not required, mainly because other ongoing AW programmes on the logging of the as-flown operational aircraft usage spectrum are expected

to provide improvements in component life tracking.

- On-rotor monitoring needs to be self-powered rather than powered by the aircraft via an electrical slip-ring or batteries.

As usage monitoring is not being pursued, from this point the subject system is referred to as On-Rotor Health Monitoring (HM).

The technology review was conducted through literature and product searches, and determined that:

- Vibration or strain energy harvesting is the most promising means of local power provision for helicopters, but application-specific implementations will be required.
- However, the power available is not likely to exceed a few 10s of milli-Watts (mW) for a practicable size/mass of harvester mounted on a rotor, this therefore drives for a system with very low power requirements.
- The IEEE 802.15.4 radio type is arguably the most applicable for wireless data transmission, since its base form is predicated on low-power/low-range operations and it is in widespread use. Nevertheless, the radio data transmission is likely to be the most power-hungry process in the WSN.
- There are several existing low power microcontrollers available that are suitable.
- Novel forms of low-power sensing technology need to be evaluated, particularly for strain.

AW's derived approach for an On-Rotor HM system is therefore as follows:

- It will consist of multiple independent wireless sensor nodes (WSNs) operating in a star network via an IEEE 802.15.4-based radio protocol with a data collector in the airframe (ultimately the central HUMS). A self-configuring mesh network is not deemed necessary and in any case would add complexity and increased power requirements.
- The WSN will be powered by an internal vibration energy harvester (VEH), acquire data from 3-4 sensors at most, conduct initial data processing for Condition Indicator (CI) generation and routinely transmit only the CIs so as to reduce the volume/power of data transmission.
- Data acquisition will follow the windowed 'snapshot' approach of typical transmission vibration monitoring, since power constraints preclude continuous real-time acquisition (note that this also effectively precludes usage monitoring which generally requires continuous data acquisition).
- CI threshold checking will be performed by the central HUMS and will command the WSN to transmit raw acquired data when thresholds are exceeded, and on an occasional scheduled basis for sensor checking and data-basing.

3.3 RTVP On-Rotor HM Evaluation Approach

The RTVP On-Rotor HM activity aims to evaluate/demonstrate the key 'generic' technology elements, as a risk reduction step before the decision to pursue a fully-realised type-specific on-rotor HM implementation.

To ease the design and implementation of the evaluation system, it was decided that:

- The system would be independent from any other aircraft systems, including the central HUMS.
- The WSNs would be mounted on the rotating swashplate, since this provides the most free space and ease of attachment via existing bolts.
- Sensors would be external to the WSNs to allow flexibility in locating them on target rotor components; the need to wire the sensors to the WSNs is seen as an acceptable compromise.
- The system would be autonomous requiring no intervention from aircrew.

AW is following a two stage approach to the evaluation.

Phase 1 is the key risk reduction step aimed at proving the vibration energy harvesting and rotating-to-fixed frame RF data communications, using a single WSN and sensors mounted on the rotating swashplate. Two accelerometers and a Resistance Thermometer Detector (RTD) temperature sensor were chosen as representative types, however their purpose and locations were selected only so as to allow the WSN's functionality to be demonstrated.

Phase 2 will build a multi-node system to demonstrate all the essential elements of an On-Rotor HM system, with candidate rotor components monitored using relevant sensors mounted on the components, and data processing/reduction added to the WSNs.

Flight trials in both Phase 1 and 2 are being conducted on one of AW's AW139 prototype aircraft designated to the RTVP. This has a typical helicopter main rotor and rotor controls configuration, so it provides a 'generic' test-bed and therefore the On-Rotor HM technology being investigated should eventually be applicable to other helicopter types.

4. EXPERIMENTAL WIRELESS SENSOR NETWORK

4.1 Requirements

AW contracted L-MS to provide flight-worthy experimental-standard wireless sensor network technology as the heart of the evaluation On-Rotor HM system. AW specified a set of operational, functional, and design requirements, including:

- Energy harvesting performance
- Low-power wireless data transfer with means to prevent/minimise loss of data
- Multi-node synchronization
- Network scalability
- Configurable operational settings.
- Minimal weight and volume
- Durability/reliability at the outset given the eventual need for long-term ‘fit-and-forget’ service use

AW also specified experimental safety-of-flight requirements, selected from DO160F and MIL-STD-810F.

L-MS developed a new vibration energy harvesting device for the programme, as their existing technology base was not available. However, L-MS tailored and re-packaged their existing wireless data network and communications technology for the other elements of the wireless On-Rotor HM system.

The remainder of this section describes the wireless system. The installation onto the AW139 main rotor is described in sections 5 and 6.

4.2 Wireless Sensor Network

The system concept is a ‘star’ network of WSNs communicating independently with a data collector. Data collected by the nodes are transmitted wirelessly to the data collector located in the airframe, which stores the data for download after the flight. For the technology evaluation, the network is completely independent of other aircraft systems, to ease embodiment and safety-of-flight approval. Ultimately, for any final embodiment, a decision would be needed as to whether the additional functionality would be integrated into existing central HUMS for the weight and data management advantages, or left as standalone to reduce the complexity/cost of implementation.

4.3 Wireless Sensor Node

The WSN architecture is shown in **Figure 1**. The WSN interfaces with two piezoelectric charge-mode accelerometers and one RTD temperature sensor. The accelerometer inputs pass through separate charge-amplifiers and low pass anti-aliasing filters, before being read by a high-speed 16-bit ADC. The RTD input goes through an amplification stage before being sampled by a 12-bit ADC. An IEEE 802.15.4 compliant, 2.4 GHz radio provides the node bi-directional wireless communication with the data collector. Data is sampled and transmitted as described in section 4.6.

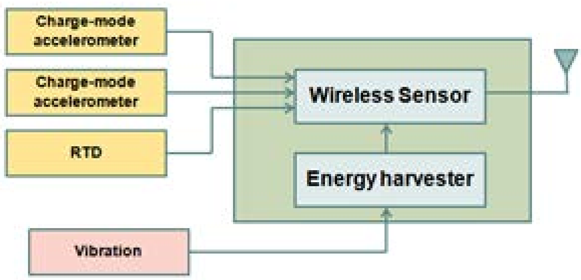

Figure 1. Energy-harvesting wireless sensor node for vibration and temperature monitoring block diagram.

The electronics are powered by a super-capacitor charged by a resonant magneto-inductive vibration energy harvester (VEH) tuned to the blade passing frequency of the target helicopter. The super-capacitor was chosen as the energy storage device rather than a re-chargeable battery, since although it does not retain charge when not powered, this is outweighed by its higher power density, longer life and ability to sustain more charge/discharge cycles, quicker charge time, better capability to meet rapid changes in demanded current, operates across a wider temperature range and no flight safety issues.

The wireless sensor electronics, VEH, and super-capacitor are mounted within a single ruggedized enclosure, shown in **Figure 2**. This also features two sealed microdot connectors for the accelerometer inputs and a Glenair connector for the platinum RTD input, as well as a separate Glenair connector for connection of backup 9V DC power and data download. The antenna is embedded into a moulding located on the top of the enclosure.

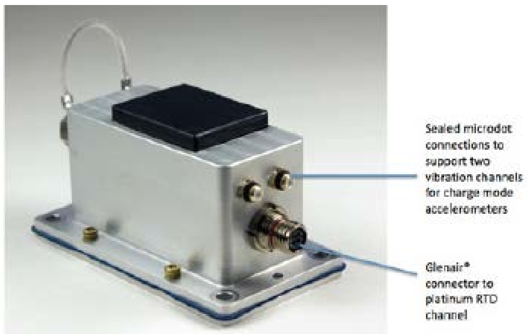

Figure 2. Energy-harvesting wireless sensor node for vibration and temperature monitoring.

4.4 Vibration Energy Harvester (VEH)

Vibration centred on the blade passing frequency (rotor 1/rev multiplied by the number of blades) is evident on the helicopter main rotor and had been quantified previously by AW. This vibration provides an opportunity to power low to medium duty cycle WSNs mounted on the rotor.

L-MS designed a VEH utilising a resonant spring-mass architecture with a magneto-inductive energy generating element (**Figure 4**).

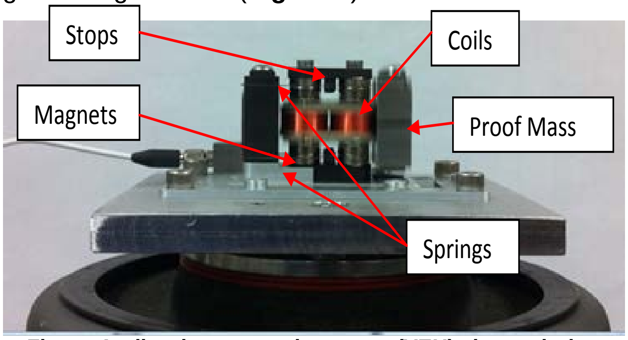

Figure 4: vibration energy harvester (VEH) shown during preliminary testing on shaker.

The VEH is tuned to the main rotor blade passing frequency (5R) of the AW139 helicopter. The dynamic mass moves in parallel with the rotor axis and includes the coils, while the magnets are fixed to avoid damping due to nearby ferrous materials and to lessen damping due to eddy currents. Current is conducted from the coils through the springs to the stationary PC board; the voltage is rectified, stepped up or down with a DC-DC buck boost converter and then used to charge a super-capacitor. Charging is controlled to stop when the super-capacitor achieves 3.6VDC to protect the WSN electronics, and to restart when the voltage drops to 3.5VDC (to provide some hysteresis).

Vibration data for the steady-level speed range of the AW139 helicopter provided by AW were used to design and size the VEH, and for preliminary testing of the harvester on a vibration shaker table. The VEH exhibited an output power ranging from 2.0mW for 80kts steady level forward speed, to 8.5mW for the 150kts, a bandwidth of ±1 Hz (**Figure 5**) and resonance shift of only 2% across the specified operational temperature range **(Figure 6**).

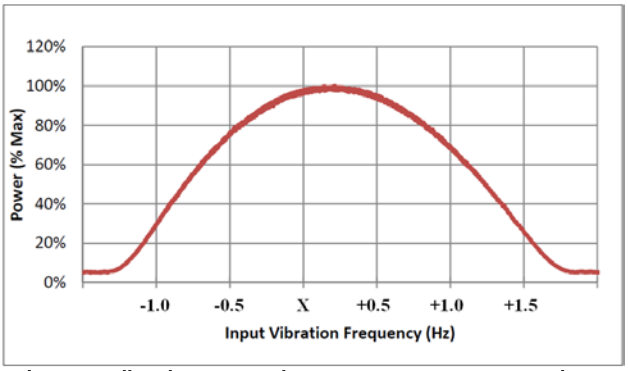

Figure 5: vibration energy harvester output power vs. input vibration frequency.

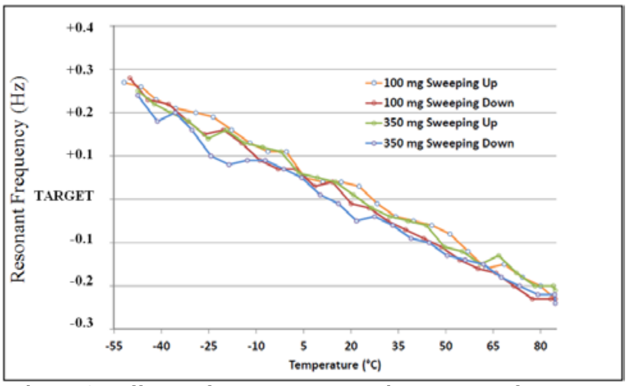

Figure 6: Effects of temperature on the resonant frequency of the structural vibration energy harvester.

4.5 Wireless Sensor Data Aggregator

A ‘wireless sensor data aggregator’ (WSDA) from L-MS’ existing product range is used as the data collector for this application (**Figure 3**).

Figure 3. MicroStrain Wireless Sensor Data Aggregator

The WSDA collects all data transmitted by the WSNs and stores it locally, for post-flight download to a PC via an Ethernet port (the WSDA may also be configured to push the data directly to the cloud or central HUMS). The WSDA provides a periodic "beacon" broadcast in order to synchronize WSNs in the network to its own time source, which is synchronized to GPS. The beacon also works as the indicator to the WSNs that it is time to begin monitoring. When the WSDA is unpowered, or the beacon disabled, the WSNs will know to remain in a low power 'sleep' state. In addition to being a time source, the GPS also provides location and altitude data time synchronized to the sensor data.

4.6 Operational Mode and Settings

The WSN operates autonomously to a sequence of pre-configured operations which starts when the super-capacitor voltage (SCV) is above a node 'wake-up' threshold of 3.2VDC, continues while the SCV is above an activation threshold of 2.7VDC, and 'sleeps' when the SCV drops below this value. The difference between the two thresholds provides hysteresis, to allow time for the WSN to conduct some activity when the power input to the super-capacitor is marginal.

The operation of the WSN is a balance between the amount of data required, and the power available from the vibration energy harvester. In order to ascertain valuable information from vibration on rotor components, the accelerometers must be sampled at a high rate (several kHz). However, sampling at high rate continuously would require much greater continuous power than is available from a practically sized VEH, therefore sampling can only be conducted for short periods of time.

The operational sequence therefore consists of two basic processes: a) continuous low-rate sampling of the temperature sensor and the SCV; b) periodic 'bursts' of high rate sampling of the accelerometers followed by RF transmission of both the high-rate data and the low rate data gathered between the previous and current burst. The 'burst' approach gives periodic snapshots of the vibration environment, which is similar to the approach followed for transmission vibration monitoring. Note that while a set period between bursts is expedient for experimental trials, in a fully realised system the bursts would be demanded according to 'windowed' aircraft operational conditions, such as engine torque or air speed.

Key operational parameters are configurable, as shown in **Table 1** below, however L-MS has defined default settings based on expected power input from the VEH and WSN power consumptions. Firstly, the period between bursts is 10minutes. Secondly, the high rate sampling of the accelerometers is set to 4 kilo-samples/second for 2 seconds. Finally, the continuous low-rate Temperature and SCV sampling is set to 1 sample every 10 seconds; temperature will vary slowly, and the SCV provides a measure of how the WSN as a whole is performing from a power balance point of view.

Parameter	Min	Max	Default
Accelerometer burst sampling rate	1 kHz	60 kHz (2 accels)	4kHz
Temperature sampling period	1 sec	24 hrs	10 sec
Burst sampling length	100 samples	100,000 samples	8,000 samples
Burst interval	10 sec	24 hrs	10 min

Table 1. Configurable settings for wireless sensor node

After each burst sampling event, data is transmitted in fixed-sized packets to the Wireless Data Aggregator (WSDA) at a slow rate of 1-2 packets per second for several minutes. Data transmission is the most 'power-hungry' of the WSN's processes, so the transmission rate needs to be low so as to spread the energy consumption, allowing the energy-harvester to provide greater power than is being expended over time.

4.7 Synchronization and Scalability

The WSDA broadcasts the wireless beacon packet is broadcast every second. This beacon is used by the WSNs to time-stamp sensor sampling and accurately schedule transmissions. By re-synching periodically, separate WSNs are able to synchronize sampling events to within +/- 30 us of each other (although only a single WSN was implemented for Phase 1). With time as a unifying factor, data from separate nodes may be directly compared.

The beaconing protocol also allows for accurate transmission scheduling (Time Division Multiple Access - TDMA), greatly increasing the number of nodes which can communicate over the same radio band without interfering with one another. Using the mode of operation described above, a node requires only 1.56% of the available radio bandwidth. The network may be scaled to include other wireless nodes configured with differing operational settings.

4.8 Lossless Data Transmission

The wireless network protocol was designed to maximise communication success rate, even in the harsh environment of a rotorcraft, where multipath, moving parts, and other anomalies can cause significant challenges. This is accomplished through the use of buffering, acknowledgements, and re-transmissions without compromising the energy-constrained nature of the devices.

All data collected by the node are time-stamped and immediately pushed into a high speed RAM buffer, with their corresponding time stamps. Data is pulled from this buffer and transmitted in packets by the WSN on a first-in first-out basis. The WSDA than sends an acknowledgement message to the WSN immediately on receipt of each packet. The WSN waits for the acknowledgement but if this is not received, re-transmits the packet up to 5 times, then if it still hasn't been received, stores the 'lost' packet in its non-volatile memory for possible later retrieval

4.9 Power Profiling

For the default burst configuration, average WSN power consumption is 1.5mW. The VEH performance outlined in 4.4 above suggested that the power output of the VEH should be more than sufficient for uninterrupted operation in flight.

Power consumption varies significantly around the average. **Figure 7** shows a typical profile of the Super-Capacitor voltage (SCV) for a fixed VEH power output, recorded during L-MS qualification testing. This indicates the power balance of the WSN as a whole due to the input power from the VEH and the consumed power of the WSN operation. The balance is generally negative during the burst data acquisition and transmission periods when instantaneous consumption is much higher than the average, then positive during the periods in between when only the low-power low-rate sampling is conducted (note also the upper 'sawtooth' profile due to the super-capacitor voltage limiting/hysteresis).

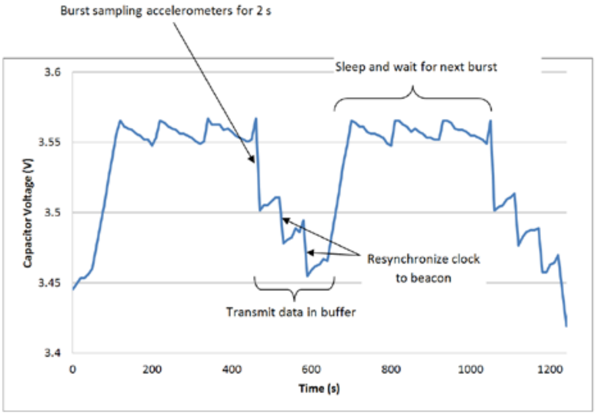

Figure 7: SCV profile for fixed VEH power output

4.10 Qualification Testing

The WSN was qualified by analysis and testing to AW's functional and experimental safety-of-flight requirements, including:

- VEH fatigue testing: to give confidence in the durability of the critical spring element of VEH, the VEH dynamic assembly (without coils) was subjected to full motion range fatigue testing for over 6000 equivalent flight hours at its 5R operating frequency. Steady sideways load was applied to the dynamic mass to represent the centripetal force the WSN/VEH is subjected to on the main rotor. No failures occurred during this testing.
- Vibration to DO-160F Section 8.
- Acceleration to MIl-STD-810F
- Shocks and Crash to MIL-STD-810F Section 7.
- Structural strength – static and fatigue analysis of the WSNs structural interface and enclosure.
- Temperature to MIL-STD-810F Sections 501.4, 502.4, 503.4.
- Humidity to MIL-STD-810F Section 507.4
- EMI/EMC – susceptibility and radiated emissions to DO-160F Sections 20 and 21 respectively.
- Magnetic Interference – compass safe distance to DO-160F Section 15.

5. PHASE 1 RISK REDUCTION FLIGHT TRIAL

AW designed and produced an installation for the WSN on the AW139 rotating swashplate in parallel with L-MS' development of the WSN. AW also installed the WSDA data aggregator on an existing instrumentation rack in the helicopter cabin. Both installations were designed and qualified for experimental flight.

The WSN was then tested on the RTVP AW139 prototype helicopter during March to June 2014.

5.1 WSN and WSDA Installations

The WSN was installed on the rotating swashplate by means of an aluminium bracket attached to the swashplate body through existing bolts, as shown in **Figure 8**.

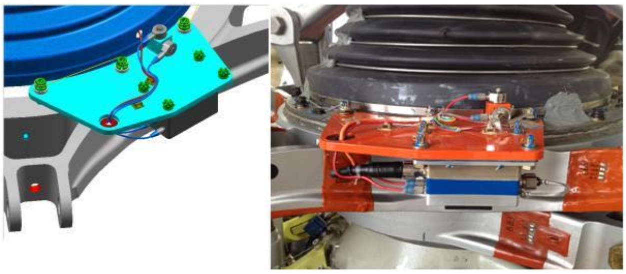

Figure 8: WSN Installation on AW139 Rotating Swashplate

The bracket was designed so as to pass the vertical 5R vibration at the swashplate unmodified to the WSN. Normal modes analysis was performed on the bracket plus WSN assembly. This showed the lowest natural frequency to be 363Hz, well above the 5R frequency.

The sensors selected for the Phase 1 trial were two piezo-electric accelerometers oriented to measure vibration parallel and radial to the rotor axis, and an RTD1000-type temperature sensor. While the primary drivers for the sensors for the Phase 1 installation were to exercise the WSN functionality and ease of installation, the accelerometers and their locations also serve to provide a 'snap-shot' of the 5R vibration excitation of the WSN's VEH. They are also candidate locations for vibration monitoring of the swashplate duplex bearing and data from the trial will allow an early assessment of this. Note that it was not possible to install an independent accelerometer for continuous vibration measurement since the trials helicopter does not currently possess an instrumentation slip-ring for the main rotor.

The temperature sensor was also installed on the top of the bracket close to the accelerometers. This provides local air temperature for comparison with outside air temperature (OAT) measured by the avionics. Ultimately temperature sensors might be used to monitor lead-lag damper and swashplate bearing condition.

The WSDA standalone data aggregator was installed on an instrumentation rack inside the cabin and supplied with helicopter 28VDC electrical power.

5.2 WSN Operational Set-Up

As described in 4.6 above, the WSN operational parameters are configurable, and for the Phase1 trial the WSN was set to the default 1 per 10sec low-rate sampling, 10min burst period with high-rate sampling at 4ksamples/sec for 2sec.

5.3 Ground Test Activity

A ground test activity was performed before flight, to determine the best location for the WSDA's antenna, test the RF communication, configure the node, test the execution of the tasks by the node and verify the data storage in the base station. This was done by powering the WSN by a 9VDC battery connected to the node via the maintenance connector and the WSDA from the helicopter 28VDC system driven by an external 28VDC ground power supply rig.

The installation of the base station antenna was determined through RSSI (radio signal strength indicator) measurements performed at different locations in the cabin. For each antenna position, the RSSI was evaluated by rotating the main rotor in steps of 60 degrees, starting with the WSN aligned with the helicopter nose, and performing a range test at each angle using L-MS' Node Commander™ software.

The best location for the antenna was determined to be the co-pilot upper transparency. This doesn't have unimpeded line-of-sight to the WSN, but is better than any other location in the cabin, where the structure of the roof and the presence of the main gear box cause significant signal attenuation. With the selected antenna installation (a three-metre long low loss RF cable was used to connect the antenna to the base station), the measured RSSI ranged between a maximum of -57 dBm and a minimum of -63 dBm dependent on the position of the WSN around the rotor azimuth. L-MS had advised that a minimum of -72dBm would guarantee no packet loss, however, while some data packet re-transmissions were required, these were always successful and no data packets were lost.

The correct execution of the configured tasks was confirmed by allowing the node to sample and transmit data for many burst cycles and by checking the time interval and the transmission statistics in real time with the Node Commander™. The data time stamps and content were verified by analysing the data downloaded from the base station via Ethernet connection. The presence of the beacon generated by the WSDA to synchronise the WSN was tested by using another base station as a beacon detection system and data sniffer.

5.4 Flight Test Activity

The performance of the WSN was assessed in an extended flight test campaign that covers the whole usage spectrum of the helicopter. Rather than limiting the test to some dedicated manoeuvres, the WSN has been allowed to operate on the helicopter for more than two months during other planned trials: this 'ride along' approach has ensured that the WSN has been tested in a comprehensive set of flight conditions and helicopter configurations (weight, centre of gravity, kits) and provides a representative simulation of the helicopter operation on the field.

Two WSNs have been flight tested, the first suffered a premature failure of the VEH coil, the second has been fitted for the majority of the tests. Together they have to date flown for a total of 19 flight hours over 22 flights.

In the absence of independent continuous measurement of the vibration on the swashplate, relevant helicopter flight parameter data (true airspeed, barometric altitude, engine torques and rotor speed) were collected from the central HUMS, in order to provide a qualitative correlation of 5R vibration with WSN performance. Both the WSN data and helicopter data have GPS based time stamps, therefore they can be aligned and overlaid.

Results are presented below to show how the WSN has achieved its key capabilities of vibration energy harvesting and RF data communications. Firstly, plots of SCV and flight parameters are given, as the SCV profiles give a good view of both the operation of the VEH and the overall operation of the WSN. Statistics on the RF data transmission are also presented.

The WSN accelerometer and temperature data were in all cases as expected and proved that the WSN conducted the high-rate sampling as specified. However, as the data themselves are of little interest in relation to the operational performance of the WSN, they are not presented or discussed further.

5.5 Flight Test Results – Power Harvesting

The WSN operated in most flights, indicating that the VEH performed mostly as expected. The WSN conducted burst operations most consistently in those flights with longer periods of high speed/torque, where 5R vibration at the swashplate is undoubtedly higher. In 14 of the 22 flights the WSN performed between 1 and 9 bursts, in 12 of these the WSN continued bursts to the 10min schedule for the duration of the flight after initial wake up.

Three of the 8 flights where the WSN did not wake up were for engine failure tests, characterised by prolonged sequences of take-offs/landings and manoeuvres close to the ground, where vibration is expected to be low, and higher variation than usual in rotor speed is evident. These flights are not representative of any normal missions, and such manoeuvres occur very rarely and for much shorter duration. The other 5 flights where the WSN did not wake up were at mid-speed/low torque, for which 5R vibration can again be expected to have been low. Two of these flights were repeated and the WSN was able to wake up and perform some acquisitions and transmissions. All these flights indicate that the VEH performance is marginal in low vibration conditions.

The mean time from take-off for the WSN to conduct its first burst was 19minutes, but with a variation from 2 to 36minutes for the range of flights conducted.

In all flights the SCV profile and the timing of bursts are qualitatively well-correlated with the flight condition profiles – this is shown by the following examples.

An example of continuous WSN operations is shown in **Figure 9**, for the first flight of the test campaign - this was performed at a TAS ranging from 90 to 150 Kts and mostly at a fixed altitude of around 1500m. The SCV (dark-blue points at the top of the plot) and the selected flight parameters (black – TAS in knots, red – barometric altitude in kilometres, sky blue - Engine1Torque in %) are plotted against GPS time; the triangles show the start of the WSN's high-rate data sampling/transmission bursts.

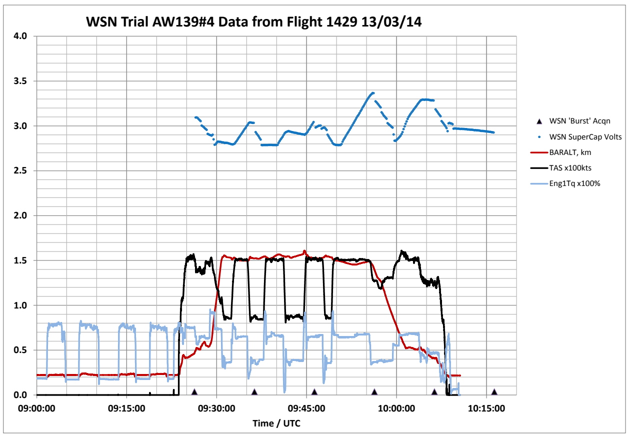

Figure 9: WSN SCV vs TAS, ALT and Eng Tq, 13/03/14

Figure 9 shows that the WSN woke up during a climb at approximately 145kts, about 2 minutes after the final take-off at 09:23:03. Subsequently, the WSN was active for the rest of the flight without interruptions, since all the bursts are separated by exactly 10mins. The SCV profile can be seen to climb and fall broadly as expected with vibration, as inferred from the flight parameters. The drops during bursts all last for about 3 minutes, which is the expected duration of a completed data transmission operation.

Figure 10 shows SCV profile detail around the 4th burst from the same flight, with the inter-burst re-charging and key burst activities identified. The re-charge phase is quite linear, meaning that the vibration level was stable; this can also be inferred from the stability of the flight conditions in this time period (Figure 9). For this charge recovery period the VEH power output is estimated to have been 3.4mW, which correlates very well with expected power for the 5R vibration at the swashplate acquired by the WSN at the previous burst and the same flight condition. In comparison with the SCV profile from L-MS' lab testing presented in Figure 7, the characteristics are the same, while the levels and slopes are different, reflecting the different VEH power input in the two cases.

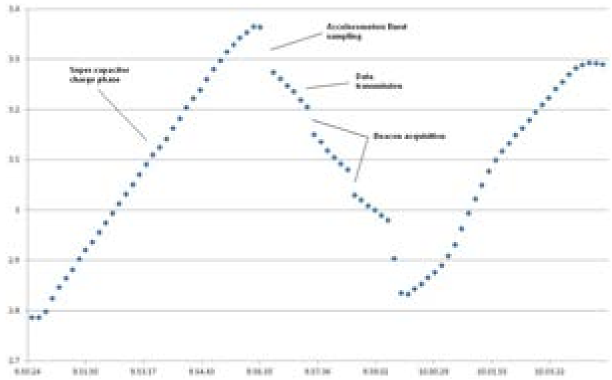
Figure 10: Super-Cap Voltage detail during a burst

Figure 11 shows the WSN's SCV profile during a flight in which the helicopter spent most of the time at high speed/high torque. The WSN woke up at about 17 minutes (after take-off and an initial climb at high speed then level flights at increasing speed from 40 kts to Vh), then stayed active for the whole flight.

The SCV saturated at the maximum limit for most of this flight, indicating high VEH power output and by inference, high 5R swashplate vibration. The burst sampling and data transmission occurred every 10 minutes and lasted 3 minutes each. The two bursts at 8:33 and 8:53 are characterised by small drops in SCV during beacon acquisitions then increasing SCV during data transmissions, indicating that the node was still harvesting more power than consumed during data transmission. Conversely, the data transmission at 08:43 caused a deeper drop in the SCV, indicating lower VEH output; a corresponding decrease of the true airspeed and engine torque can be seen.

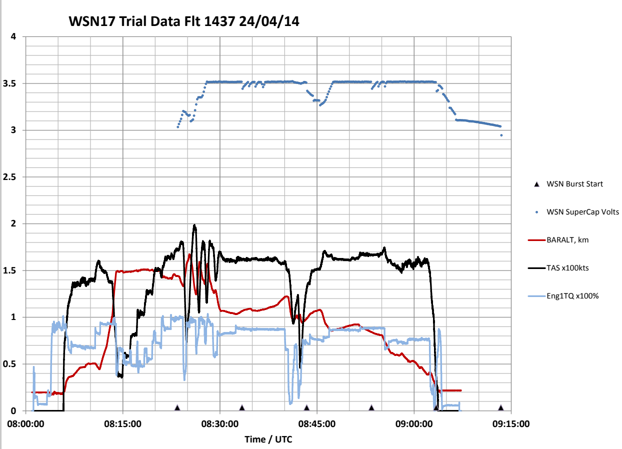

Figure 11: WSN SCV vs TAS, ALT and Eng Tq, 24/04/14

Figure 12 shows an intermittent behaviour of the WSN. There was just sufficient vibration during the initial period of low TAS/medium-to-high torque for the WSN to perform on early burst, but the WSN was in 'sleep' mode for the following 10mins at 80-130kts when vibration would have been much lower. The node re-awoke at the end of the stepped speed range, was able to conduct two bursts through the subsequent period of high speed flight, then went to sleep again briefly during the period of flight at about 120kts. The final re-awakening occurred soon after a short period of flight at low speed/high torque, which indicates that the super-capacitor was not completely discharged in the sleep period and the SCV was close to the 3.2V activation threshold.

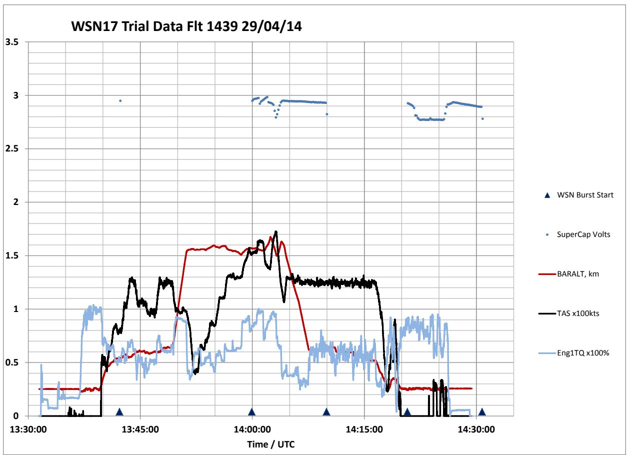

Figure 12: WSN SCV vs TAS, ALT and Eng Tq, 29/04/14

Although there is variability in the time to first burst for the range of different types of flights flown, **Figure 13** shows the consistency of VEH performance for similar flight profiles. Here, the time to first burst was between 18 and 19mins from take-off, for three flights characterised by initial positioning flight to altitude at high speed/torque followed by speed range steps; note that there were intervening flights with quite different profiles.

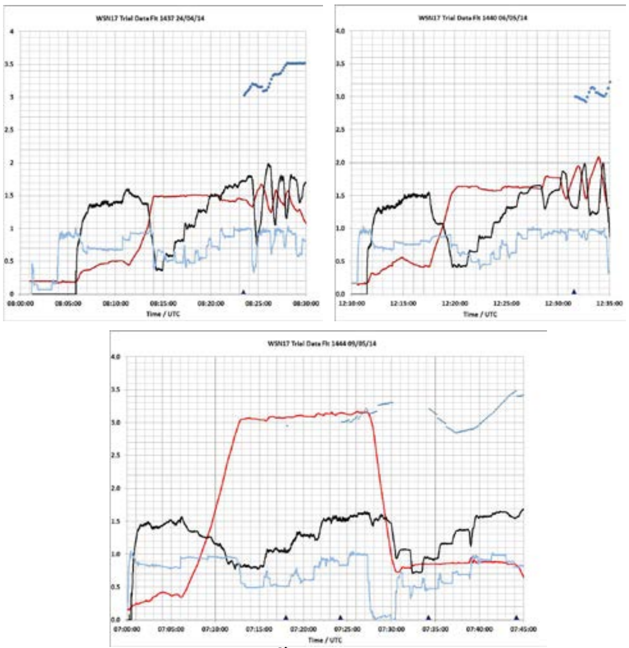

Figure 13: Time to 1st Burst for 3 Similar Flights

5.6 Flight Test Results – RF Data Transmissions

The 802.15.4 based wireless communication has proved to be very reliable.

Figure 14 shows that, taking all transmissions from all flights together, the RSSI averaged -60dBm, with a standard deviation of some 7dBm and a range from -44 to -84 dBm. For individual flights, the average RSSI and standard deviation ranged from -58 to -63dBm and 5 to 9dBm respectively, indicating a very consistent characteristic. This form of widely spread and skewed RSSI distribution is typical of RF communications where there is no direct line-of-site and the received signal is dominated by reflected RF.

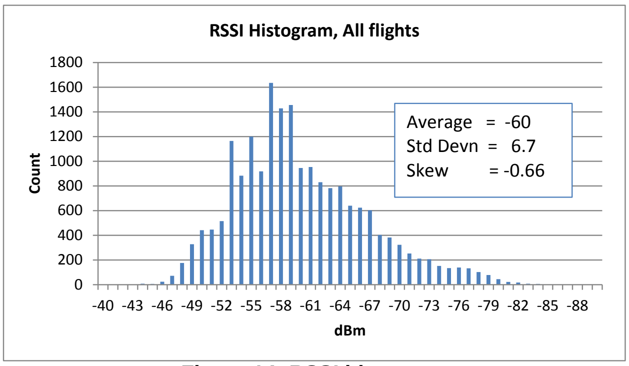

Figure 14: RSSI histogram

The RSSI range was mostly above the 'no loss' value of -72dBm with some below, however not a single packet was lost with rotors turning and the number of packet re-transmissions was consistently only about 7%.

The flight RSSI results were similar to the those measured during the ground test activity with static main rotor, suggesting that rotation of the main rotor and flight manoeuvres have minimal effect on the RF communication.

5.7 Phase1 Conclusions

Phase 1 has achieved its aim of proving the vibration energy harvester technology and rotating-to-fixed frame radio data transmissions.

Overall, the flight test campaign has demonstrated that the VEH generates energy according to the 5R vibration expected on the swashplate from flight parameter profiles, except at medium speeds, where 5R vibration is at its lowest and the VEH performance appears to be marginal.

The WSN default 'burst' configuration was found to be a good balance with respect to the VEH performance and the actual energy requirements of the 'sampling & transmission' cycle. This configuration provides consistent operation for flights with higher forward speeds and higher 5R vibration at the swashplate. It should be noted that the flight conditions in which the WSN conducted earlier and/or more bursts are those that dominate the AW139 aggregated in-service usage spectrum.

However, the VEH needs to be optimised to improve the likelihood of operation at lower swashplate 5R vibration levels and to shorten the time to first burst, since for any future production On-Rotor HM system, there must be a high probability of acquiring data every flight. The design of the Phase 1 VEH was set so that it operates most efficiently at a 'design-point' vibration excitation level. It operates less efficiently at either higher or lower vibration levels, one consequence being that there is effectively a low vibration threshold below which no energy is generated. It is expected that the VEH's performance at low vibration excitation levels can be improved by reconfiguring the VEH design for a lower 'design-point' vibration level, allowing it to generate additional power under those conditions. At high vibration conditions, it would operate less efficiently, but this would be acceptable, since the current design generates excess energy under those conditions (as illustrated by Figure 11).

The Phase 1 trial also confirmed that the RF data transmission is the WSN operation that consumes most energy, therefore a reduction in the amount of data transmitted by the implementation of local processing and the generation of Condition Indicators is foreseen – this should allow a reduction in burst periodicity and/or increased sampling rate/volumes.

The RF data transmission from the rotor to the airframe performed very well and requires little development.

In all other aspects, the operation of the WSN met AW's specified requirements.

This successful first risk reduction step has given AW the confidence to proceed to the Phase 2 system demonstration.

The Phase 1 test campaign has also indicated that a better understanding of the VEH performance, particular in the marginal mid-speed conditions, would be provided by continuous measurement of the swashplate 5R vibration, and this will be added for the Phase 2 trial.

6. RTVP PHASE 2

6.1 Rationale

Phase 1 has demonstrated the key enablers for wireless on-rotor HM. Phase 2 will build these into a more representative HM system comprising:

- Multiple WSNs with an optimised VEH.
- Monitoring of 1 Pitch Control Link (PCL), 1 rotating scissors and the swashplate duplex bearing as example components.
- Low-power accelerometer and strain sensors on each monitored component.
- Data processing/CI generation in the WSNs, aimed at local detection of abnormal condition and reducing overall WSN power consumption.

With respect to the VEH, Phase 2 will allow AW and L-MS to determine if sufficient improvements in performance can be achieved within the current self-powering concept, and to anticipate possible changes to the concept.

The system will be tested on the AW139 trials aircraft in early 2015 with worn and new examples of the above rotor components, to assess the performance of candidate CIs and provide sensor datasets for their ongoing development.

The aim is to demonstrate all the generic key elements of an On-Rotor HM system, rather than a fully-specified system for the AW139 aircraft type.

6.2 Multi-Node On-Rotor HM Installation

The design of the multi-node system installation is underway, based on the following concept (**Figure 15**):

- 3 WSNs, individually dedicated to the Pitch Control Link, Rotating Scissors and Swashplate duplex bearing.
- Vibration and strain sensors mounted externally on each of the three rotors control components.

- A variable reluctance speed sensor mounted on the rotating swashplate, to provide a common 1/rev input to the WSNs for data processing.

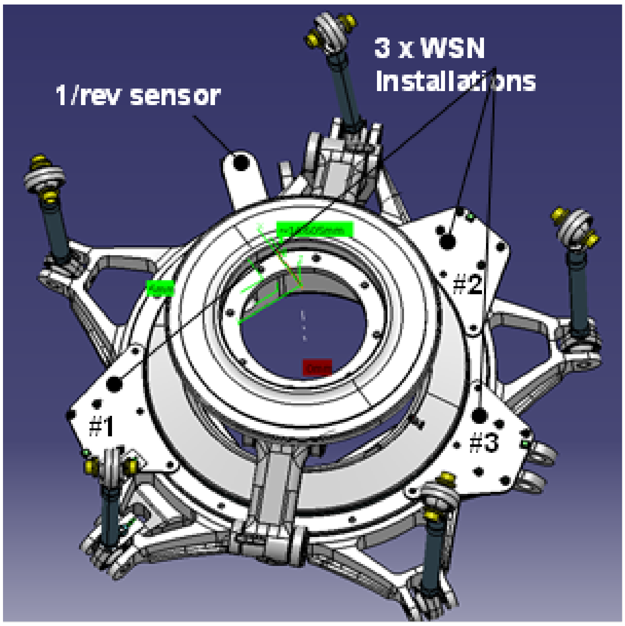

Figure 15: Phase2 Multi-Node On-Rotor HM Installation

For the strain sensors, traditional resistive strain gauges consume too much power, therefore state-of-art conformable piezo-capacitive types will be trialled, since these are intrinsically low-power devices.

As identified from the Phase 1 trial, an 'instrumentation' accelerometer will added to one WSN mounting plate, as part of a separate instrumentation package to be installed on the trials aircraft for other aspects of the RTVP. This will give a direct view of how the VEH performs against its 5R vibration excitation, to confirm the improvements to be made to the VEH for the Phase 2 WSN.

6.3 Embedded Data Processing

As well as a revised sensor interface and optimised VEH, the functionality of the WSN will be enhanced for Phase 2 by adding data processing, to operate after data sampling and before data transmission. The aim is to explore how total power consumption can be so as to shorten the burst periodicity and/or increase sample rate/duration. Bench testing indicated that conducting analysis in the WSN to reduce the acquired raw data to Condition Indicators metrics, then routinely only transmitting the CIs, could reduce overall burst power consumption by up to 80% compared to routinely transmitting all raw data. Candidate data processing software routines with a range of complexity/size and power requirement will therefore be loaded to the WSNs microcontroller, to allow an assessment of the power relationships. Generation and transmission of the Synchronous Time Average (STA) on its own is expected to be of significant benefit.

6.4 Condition Indicator Development

As well as robust means for data collection, a condition monitoring system can only be fully realised with validated methods for detecting abnormal component condition.

AW's On-Rotor HM programme is therefore also evaluating feature extraction methods and Condition Indicators for detecting wear in mechanical elements of rotor components, particularly backlash. The aims are two-fold: a) to determine appropriate initial candidate methods for future development, b) to explore the boundaries of WSN capability for data processing against the internal power budget, for a range of process complexity.

Rig testing of a set of PCLs with a range of wear/backlash in their spherical bearings was conducted – sinusoidal and flight-representative axial loading was applied and data were acquired from accelerometers and strain sensors mounted on both the PCL and test machine. This showed that both quantifies can reveal backlash in the spherical bearings but an accelerometer mounted on the PCL probably gives the clearest picture (**Figure 16)**.

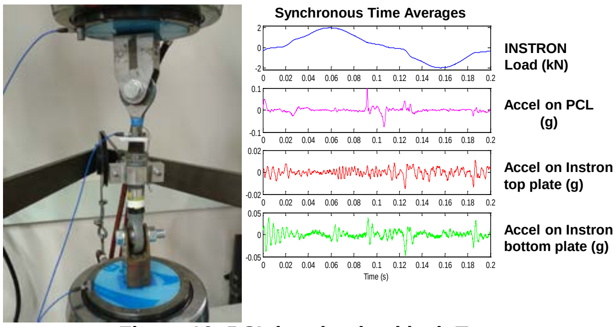

Figure 16: PCL bearing backlash Tests

Furthermore, simple CIs such as Peak-Peak, Root Mean Square and Kurtosis derived from the STA appear to be good initial candidates for wear/backlash detection, and will be included with the STA as test data processing methods to be loaded to the Phase 2 WSN.

Strain data from rotating scissors with worn journal bearings, and a replacement new scissors (gathered during a helicopter flight load survey programme conducted by AW some years ago) were also analysed and compared.

Figure 17 shows examples of STAs of strain against time for worn (upper plot pair) and unworn (lower plot pair) scissors at 50kts level flight (left plot pair) and Vne (right plot pair), where each plot has profiles for two values of all-up-mass (AUM) at the same centre-of-gravity (CG). The body of data from a range of airspeed, altitudes and AUMs/CGs exhibits more complicated data structure than for the PCL, and it appears that the simpler metrics that are promising for detecting wear of the PCL bearings are not sufficient to discriminate between worn and unworn rotating scissors. A much wider base of data processing approaches is therefore being investigated currently, and because the relationship between harmonics appears to be worth exploring, it is planned to include an FFT algorithm in the Phase 2 WSN data processing suite. Also, the primary motivation for adding the accelerometer to the rotating scissors for the Phase 2 trial is to determine if vibration is a better data source for discriminating between worn and unworn rotating scissors.

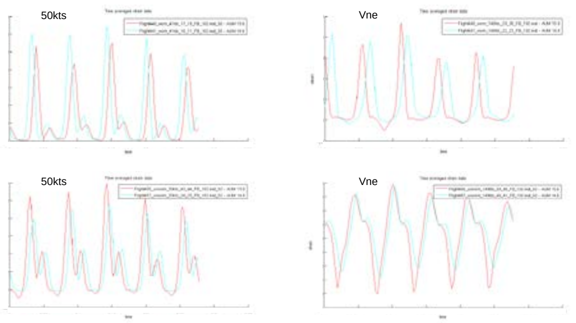

Figure 17: Rotating Scissors Loads Data Analysis

Although the RTVP activity will provide a useful starting point for likely methods, and an understanding of the constraints in WSN capability, significant further work will clearly be required to develop and validate appropriate feature extraction methods. This will also need to consider other types of components, in particular, the increasing prevalence of elastomeric bearings in rotor systems demands methods for in-situ sensor-based monitoring of stiffness.

7. WAY-AHEAD POST R&D

The RTVP R&D activity is the first step in an ongoing AgustaWestland programme to realise On-Rotor HM, by providing the enabling technology to acquire data from rotor systems. The subsequent steps to evolve this into a fully-realised system include:

- Further cost/benefit studies to confirm the business case for On-Rotor HM.
- Continuing evaluation of the Phase 2 system on the full AW139 prototype fleet, to provide longer-term evaluation and ongoing development of the WSN, development and test of CIs, and main rotor component condition trend data.
- Review of rotor component monitoring requirements, and relevant technologies (eg for monitoring for elastomeric bearings, higher rate/low power radios such as Ultra-Wide Band).
- Ongoing development/testing/validation of methods for detecting abnormal component condition and related CIs – this will arguably be the most challenging of the activities.
- Discussion and agreement with Airworthiness Authorities regarding the certification approach and process to transition from ‘no hazard – no credit’ safety enhancement, to b) maintenance credit.
- Design studies for integration of WSNs and sensors and rotor components, and scaling of technology for tail rotors if required.
- Product-specific system design, qualification and controlled introduction to service, either as retrofit or new-type.

It is anticipated that this on-going programme will take 3 to 5 years to fielding of the first On-Rotor HM system, the drivers for this timescale being the development and validation wear detection methods and CIs and integration of the WSNs into the rotor.

8. CONCLUSIONS

Improved helicopter rotor health and usage monitoring potentially offers safety and operating availability and cost benefits. AgustaWestland is investigating the technologies to achieve these benefits in its R&D Rotorcraft Technology Validation Programme (RTVP) and is currently focussing on condition monitoring of mechanical main rotor components using self-powered Wireless Sensor Nodes (WSNs) mounted on the main rotor swashplate.

A successful Phase 1 risk reduction trial of a single WSN has just been completed on an AW139 helicopter, and has proven the key enablers of vibration energy harvesting for WSN power-provision and data transmission by radio to a data collector in the helicopter cabin. In parallel, lab-based work has assessed WSN power consumption trade-offs between data processing in the WSN and data transmission. In addition, candidate wear detection metrics for non-rotating bearings have been identified, from the analysis of data from pitch control link rig tests and from a flight load survey for rotating scissors.

A Phase 2 activity will trial a multi-node system monitoring three selected rotor controls components and with data processing added to the WSNs. This aims to demonstrate all the key generic elements of an On-Rotor Health Monitoring system.

A programme of ongoing development will be required to bring On-Rotor HM to fruition. The critical activities will be cost/benefit studies to confirm the usefulness of On-Rotor HM, and the development and validation of the methods/metrics for indicating abnormal component condition.

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