Wireless and autonomous sensor for Integrated Engine Health Management

Yoann Hebrard[1], Guillaume Bastard[2], and Tony Lhommeau[3]

[4] SKF Aerospace, 22 rue Brillat Savarin, 26958 Valence, *FRANCE*
yoann.hebrard@skf.com

[2,3]*Safran Aicraft Engines, Rond point René Ravaud, 77550 Moissy Cramayel, FRANCE*
guillaume.bastard@safrangroup.com
tony.lhommeau@safrangroup.com

ABSTRACT

Providing the best availability of aircrafts is a main cause for concern in aeronautics industry. Integrated Engine Health Management (IEHM) is the up to date solution that is used by Aircraft Engine Manufacturers in order to maintain a fleet of engines operative. IEHM detect signs of failure before they happen is the key tool for improving the level of aircraft operability. There is a strong focus on the sensor part and particularly on a wireless autonomous load sensor. Measuring load can have a high value to estimate the remaining useful life of equipment's like suspension rods or gears after a hard landing. Indeed, after such an event, aircraft companies need to know if suspension rods/gears are safe or could have been damaged. This paper presents the current CORALIE sensor development (autonomous wireless load recorder) that will enable maintenance operators to determine the load level seen by an engine link after a hard landing by simply setting a portable device near the mounting system. Interesting features are Energy Harvesting and RFID communication modules that have been developed for this sensor. Such autonomous SHM systems typically include embedded sensors, and elements for data acquisition, wireless communication, and energy harvesting. Among all of these components, this paper focuses on RFID technologies. Actually, low power sensors and wireless communication components are used in newer SHM systems, and a number of researchers have recently investigated such techniques to extract wirelessly communicate data stored in these stand-alone systems. The first part of the paper is dedicated to benchmark the different wireless communication protocols against RFID available for the project application (engine pods). The second part gives a presentation of the RFID communication system (Antenna, reader and RFID front end circuit) developed for transmitting local data stored in the memory of the system for analysis in a SHM maintenance strategy. The last part presents real test of RFID wireless communication and provide a maturity assessment on the technology.

1. RFID SENSOR CONCEPT AND CONSTRAINTS FOR SHM APPLICATION

Engine Mount System (EMS) is the structure which links the engine to the Aircraft.

The engine mounts system is attached to the turbine rear frame and intermediate case. The sensors shall be introduced on Engine mounts system to record a complex load spectrum.

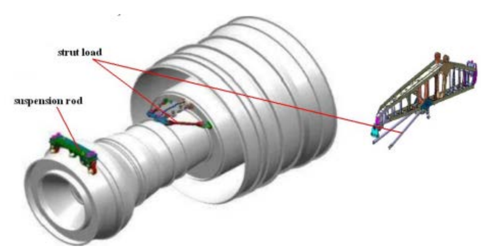


Figure 1. Engine Mounts System overview

The fatigue meter sensors installed on engine mounts system shall record loads to give an indication on the engine mount system fatigue life. The Engine mounts system is a PSE structure CS25 certified. The sensor shall be able to record all the life of the Aircraft.

The system main function is to record a complex fatigue load spectrum which could be represented as follow:

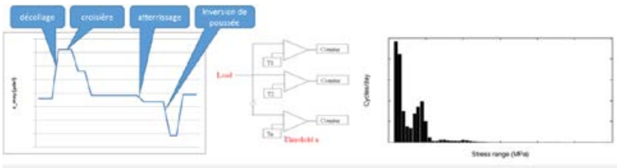


Figure 1. Equivalent electrical schematic

For each load, higher than a given load threshold, the sensor shall detect it if load is much higher than a defined threshold, the sensor shall increase the counting only once. For one load, few thresholds can be over passed. In this case, each concerned sensor shall detect it and increase the counting once. For each detection, the sensors shall stock the information until the next data analysis. The storage capability shall be above 1000 loads detection for each flight. Consequently, the storage capability of the sensor shall be determined in accordance with the flight count between each data analysis. For the ground test, the minimum deformation shall be around 100 µdef. The load range to be measured shall vary from 100 to 800 µdef. Between 2 sensors the gap shall be around 100 µdef. The project intended to conduct ground tests and flight tests on a real engine. The measurement of the real load spectrum histogram seen by the parts can be used to identify the remaining life, and assess also potential overloading damage in assocation with SN curves of the part.

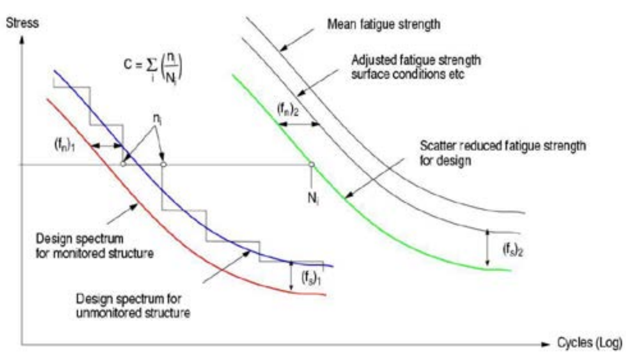


Figure 2. Durability analysis

For a ground test and a flight test, the sensors shall be located on the thrust link and designed to cope with traction loads of the links, given that these links shall not withstand any compression nor any torsion.

The sensor shall be interrogated wirelessly to provide information to people in charge of checking the EMS state, allowing fatigue and damage management.

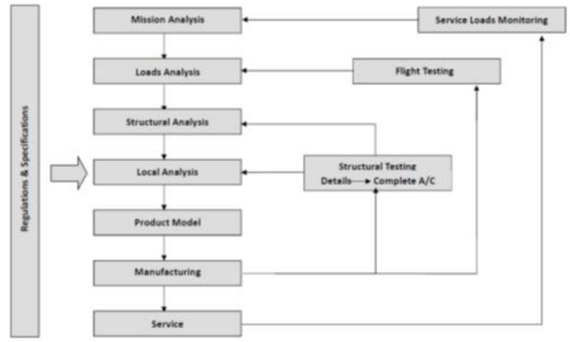


Figure 3.Fatigue and damage management

1.1. Current technological challenges

The aim of the project is to develop a technology helping to reduce maintenance actions. So, the way to use the strain sensor and particularly to interrogate it is really important: reading the strain value of the sensor shall not add maintenance constraints. For that, a wireless system has been chosen. Furthermore, the system does not require any external power supply. So, the developed system is not only a sensitive part but a complete autonomous and wireless device.

The device shall measure a load on the Engine Thrust Link, use his own data and power management system with his own harvester.

The device consists of the following sub-systems:

- **A strain gauge bridge**. This is a mature technology that is well suited to measure strain on the strut.

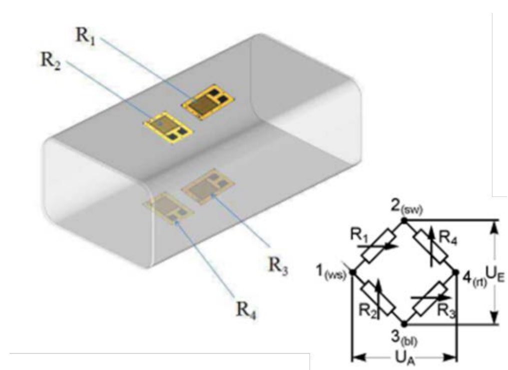


Figure 4. Strain gauge bridge

- **An Energy harvesting system** to supply the additional strain gauge and the non-volatile memory. Energy is harvested from vibrations and thermal differences of the engine.

- **Data and power management system.** Sensors data are stored into a NVM that will be interrogated using a wireless RFID transmission. Energy harvesters provide energy but it must be stored and managed to supply strain gauge and memory. All these parts are managed by an integrated electronic device. However, not all sources hold sufficient potential to provide enough power to a sensor system. The most critical parameter for comparing these technologies in the scope of aircraft applicability is their power-to-weight ratio (per flight cycle). Another important criterion is the reliability of these devices. Energy sources that seem most likely to meet the sector constraints are thermal and vibrational energies (Le et al., 2015).

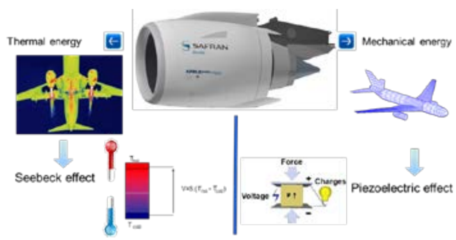


Figure 5. Energy sources in engine enviroment

- **An interrogating system.** It is a RFID interrogator and is not embedded into the road but approached by an operator.

The main effects of the near metallic environment on the antenna performance are the near field losses and the so-called detuning effect. Losses in the near field reduce the radiation efficiency of the antenna. The detuning effect is due to the change of the antenna feed impedance visible to the microchip. The detuning of the antenna ruins the power matching between the antenna and the chip. These two effects affect the measured effective aperture of the antenna. The effective aperture also contains the directivity of the antenna. The realized gain, determined by the effective aperture of the antenna, in the direction of the reader is, together with a certain sensitivity of the microchip, what basically determines the read range of the tag.

By thinking how the world around us looks at the UHF frequencies, i.e. around 900 MHz, we see that it is magnetically quite neutral but very heterogeneous in terms of electric field. This means that the environmental disturbances of the antenna operation, reducing the realized gain, take place mainly via the electric near field of the antenna. Consequently, in a platform tolerant antenna, the magnetic near field of the antenna can be allowed to burst out of the outer dimensions of the tag antenna, whereas the electric field should be kept within the antenna structure. It also means that in all of the platform tolerant structures, the magnetic dipole is always of special significance as a radiator. By concentrating the near electric field inside the antenna itself and taking advantage of radiators based on magnetic dipole, both effects of the antenna near environment can be minimized, thus implementing a platform tolerant structure.

As HF RFID is based on utilizing magnetic coupling, the system is less sensitive to electrical disturbances and changing permittivities in the near environment of the tag. Metal platforms, however, are problematic also for HF. In fact, magnetically coupled near field tags are also available for UHF. These tags are typically simple one-round metal loops of 10 mm in diameter and they are used for item-level tagging. With those, some tens of centimeters of reading distance can be achieved. Metal platforms, however, are problematic also for these near field tags.

As the feed impedance of a platform tolerant antenna is very stable from a mounting platform to another, the antenna is allowed to be narrow-banded, whereas with other types of antennas the sensitivity to external disturbances is typically reduced by broad-banded impedance matching. This difference is illustrated in Fig.8. The goal impedance, which is the complex conjugate of the chip impedance, is marked with a red spot. As broad-banded tuning is based on a compromised match (Fig.8 left), using platform tolerant antennas, we can implement a better match and gain in the read range.

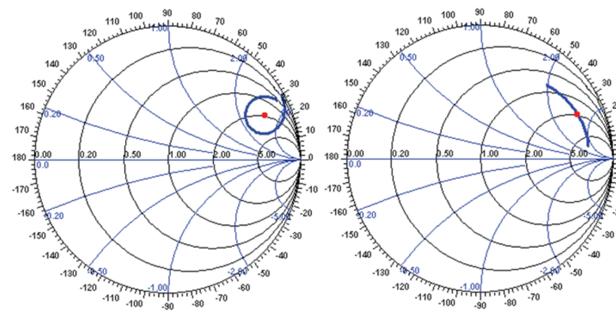


Figure 8. Broad-banded (left) and narrow-banded impedance (right) match between the antenna and the microchip.

2. DESIGN OF CORALIE CMOS-BASED RFID SENSOR

This PCB based component is a passive RFID tag with embedded MCU (Microcontroller Unit) to manage communication protocol and application. RFID solution is a passive radio system without emission. The architecture is presented in Figure 9.

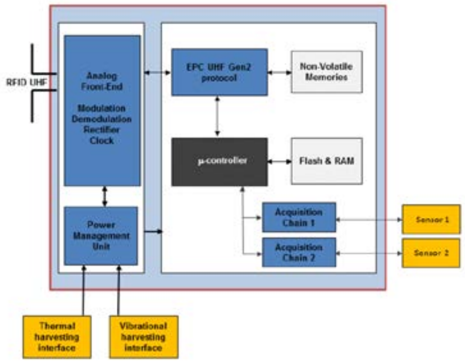


Figure 9. CORALIE RFID Architecture

From a PCB point of view, a modular approach is proposed based on a motherboard including the existing RFID tag design and harvesting boards specific to each energy source. The following table presents the antenna specification

Parameter	Min Value	Max Value	Units
Tag input impedance	50		Ω
Temperature	-50	150	°C
Volume	5x3x2		mm
Center frequency	866		MHz
Input Power	-20	10	dBm
Reading Range	2	20	m
Vibration	6		g

Table 1. Antenna specification.

2.1. Analog Front end

The Analog Front-End block is meant to demodulate signal from the UHF readers, modulate by backscattering the tag signal to the reader, rectify RF signal from the antenna to power the whole chip in autonomous mode. It also generates information signals to the MCU such as:

- RF_power which indicates that RF field is available. This signal is useful to inform the MCU that it needs to look at demodulation data. It is polled during monitoring phase to be able to get out from monitoring mode.

- Demod which contains data sent by the reader. Those data are EPC Gen 2 compliant embedding Inventory, Read and Write function.

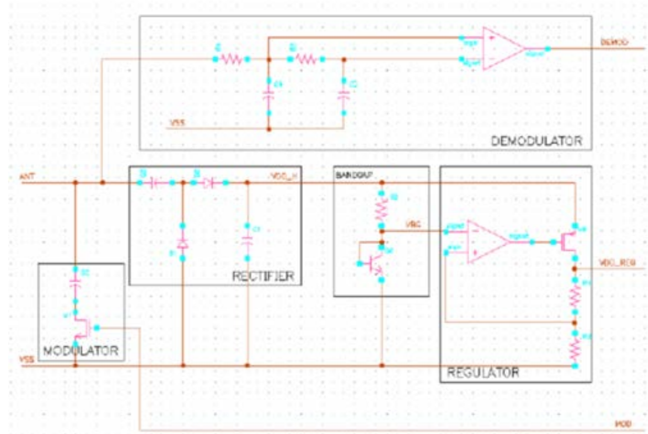


Fig. 10 - Block Diagram of the RF front end

The RF front-end is composed of four main blocks, rectifier to generate DC supply voltage from RF field, regulator to supply whole circuit with a regulated and low noise 1.8V supply voltage, demodulator to provide data bit stream to MCU and modulator to backscatter signal to the UHF reader.

RF front end will be used to transmit data stored into the NVM memory to the RFID reader. Reading range will strongly depend on the environment and antenna choice. For this project, a simple dipole antenna has been used.

RF communication has been validated by measurement up to 85°C. Validation means communication between reader and tag in both direction, downlink and uplink.

Sensitivity with correctly chosen matching network is 3dBm at ambient temperature without any battery (passive mode). This sensitivity can be increased up to -15dBm with energy harvesting available. It is important to note that in order to put the Tag out of data logging mode while TeG harvesting is active, sensitivity can be reduced significantly down to 15dBm.

2.2. Tag-to-reader communication

The communication principle which is used in passive UHF RFID systems is backscattering of the incident RF power. In order to modulate the reflected power, the Tag-to-Reader signal is changed caused by the impedance of the RF node's analog front-end implementation. The EPC UHF Class1 Gen2 standard for RFID backscattering communication permits two types of modulation: amplitude shift keying (ASK) and phase shift keying (PSK). Both modulate the complex impedances $Z_c = R_c + jX_c$ and $Z_a = R_a + jX_a$ between two different states.

If the imaginary part of the tag impedance is zero, an ideal ASK modulation can be realized by a switchable resistance Otherwise a more complex modulation circuit is required. The PSK modulation is more efficient than ASK, as the available power to the tag is kept almost constant during both modulation states. A PSK modulation can be achieved by a complex modulation circuit only, which is comparable to an ideal modulation. The Tag integrate a ASK modulation circuit and also an integrated modulator is used for the Tag-to-Reader communication. The transformational coupling between the coil of the transponder and the coil of the reader causes a change of the transponder impedance, which can be detected by the reader.

2.3. Reader-to-Tag communication

The bidirectional data transmission between the RFID transponder and the reader includes the ASK demodulator as an important circuit block. It recovers the information which is ASK modulated on the carrier by the interrogator and deliver the data to the digital logic. The more the reception of data is ensured at low power levels the higher is the reading range. In recognition of different modulation depths and different input power levels for UHF, two demodulation blocks are used.

2.4. Antenna design

Dipole antenna demonstrated weak communication capability for the project application environment. Anti-metal antenna design has been investigated to prose an alternative to dipole antenna.

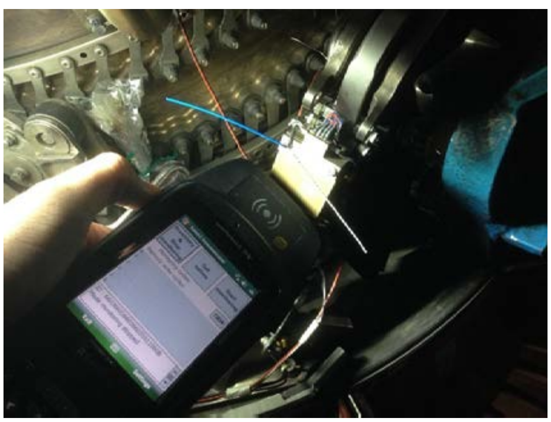


Figure 11. Reading distance with dipole antenna

The idea about Anti-metal antennas is to explore others designs that are different from the commonly used dipole structure. These antennas should able to radiate efficiently above a metal surface. The micro strip patch antennas and the printed inverted-f antennas (PIFA) are, actually the most promising designs (Zhang & Long, 2014). They are conceived to work with a ground plane giving the best results when placed over a metallic surface.

Two antennas were proposed in (Zhan, 2008), the first is an inverted-L shape antenna, which is a compact and low-profile design (Zhan & Weber, 2012). The other is a slotted planar antenna which has a very high gain. Also, (Zhang & Long, 2014) proposed a dual-layer electrically small antenna that is compact but uses stubs to be connected with the ground. (Elboushi, Haraz, Jamil, & Sebak, 2015) proposes a very small antenna that uses a proximity couple method to load two via-patches trough a PIFA antenna. (Petrariu & Popa, 2015) presented an antenna with two elliptical globes that actives a good radiation but is too large for this project. Antennas that combines a dipole design with a rectangular pattern at it borders where also considered. Those designs present good results but are impracticable because of the presence of stubs, large area or thicker substrate.

Figure 12. Printed antenna design. Right, the reference meander antenna. Left, the reference slot antenna

The antennas were measured using an equipment from Voyantic, the Tagformance® measurement kit. It is a simple but efficient test and performance bench for UHF RFID tags. It is composed of a reader antenna, a foam support that does not interfere with the electromagnetic radiation behavior and a signal generator and detector. Everything was driven by an external computer using the equipment software.

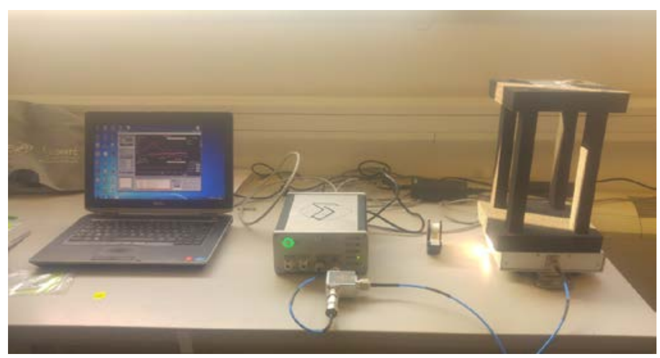


Figure 13. Tagformance®'s test bench for UHF RFID tag characterization

The equipment is able to change the emitted power and to find the lower power still able to active the tag. With this value, the software could calculate the theoretical maximum distance of reading for the tag. All the measurements were made inside an anechoic chamber to avoid any electromagnetic interference from the environment.

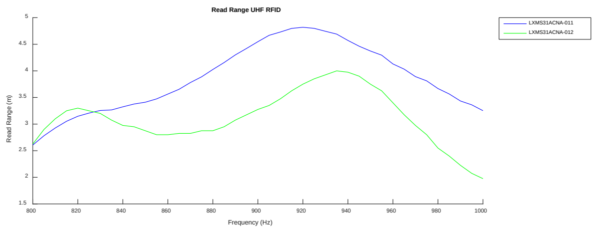


Figure 14. Read range measurements from Meander reference tags obtained with the test bench

The meander antenna is designed to be read from 5 meters while the slot antenna is designed to be read from 4 meters. The measurements in the lab demonstrated good level of performances. Decision was done to check performance on the application environment.

2.5. Vibration harvester

The operating principle of a piezoelectric generator is based on the direct piezoelectric effect, i.e. the internal generation of electrical charge resulting from an applied mechanical. Two families of piezoelectric micro-generator can be found. The first one, named direct coupling, is directly bonded to the host structure (Figure 15 a). The second, called indirect or seismic coupling, is connected to the host structure through a secondary element, e.g. a beam (Figure 15 b).

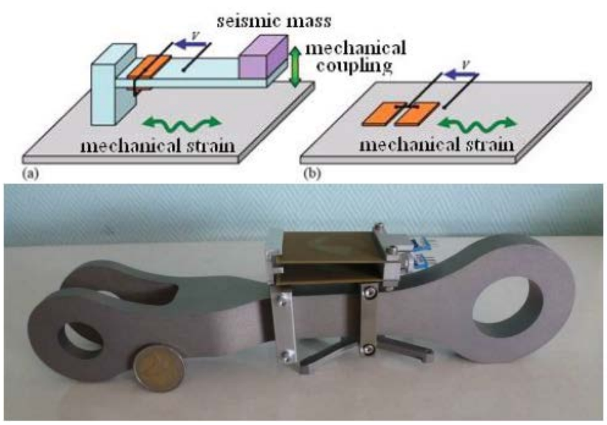


Figure 15. Kind of coupling: (a) seismic; (b) direct and real harvester

Piezoelectric composite fiber material (PZT type P2) was coupled to the engine trust in seismic mode. This flexible composite is composed of many PZT fibers and is highly damage tolerant and fatigue resistant.

The piezoelectric elements provide substantial power densities (250µW/cm3 at 120Hz and 2.5m/s²), which makes them particularly attractive for various energy harvesting applications. Seismic coupling had been selected for the vibration harvester, as it can provide up to ten times more energy than the classical method.

To keep a stable voltage value, the technique of Synchronized Switching Harvesting on Inductor is used: an electronic switch is synchronously commanded with the vibration and connects briefly the piezoelectric module to an inductance leading to voltage inversion and keeping voltage value stable.

The module performances have been established experimentally.

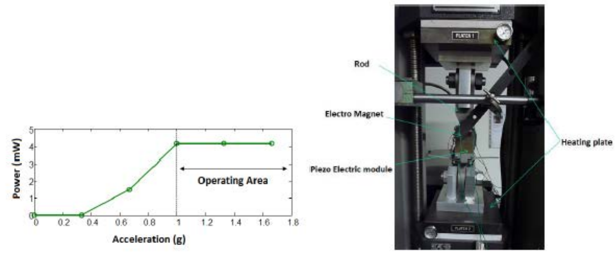


Figure 16. Vibration harvester characterization

The power needed (4mW) by the system is provided for an acceleration level of 1g.

2.6. Thermal harvester

Thermoelectricity is the conversion of heat into electricity (Seebeckeffect), or inversely, of electricity into heating or refrigeration (Peltier effect). The use of the Seebeck effect could make it possible to save heat that would otherwise be lost. A good thermoelectric generator (TEG) must have a high Seebeck coefficient to produce the required voltage, a high electrical conductivity to reduce thermal noise, and a low thermal conductivity to reduce thermal losses (see figure 17).

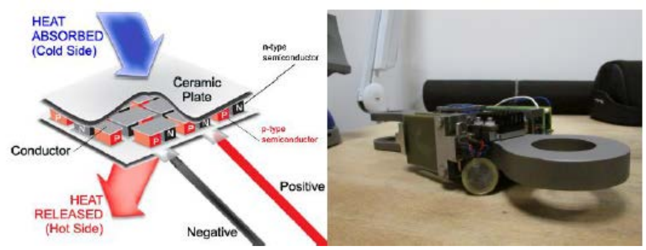


Figure 17. Illustration of Seebeck effect where S is the Seebeck coefficient

The engine link is connected to a hot part, so it can be used as the hot source temperature. The air around must be cooler than the strut load and will be used as the cold source temperature.

The module performances have been established experimentally. The mechanical connection of the rod is linked to heating plate, allowing a thermal gradient equivalent to the application, expecting ambient temperature.

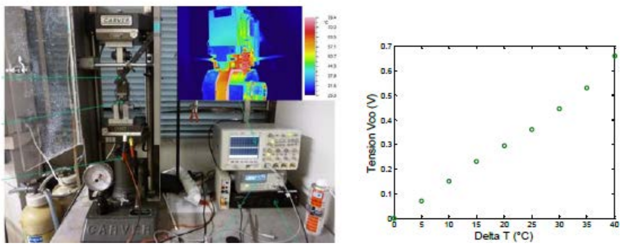


Figure 18. Thermal harvester characterization

With the circuit load, the module provides for a gradient of 10°C 500mW of power. Two modules are integrated to the system.

3. SYSTEM TESTS

Several prototypes of tag systems have been manufactured and will be tested for RFID communication in application environment.

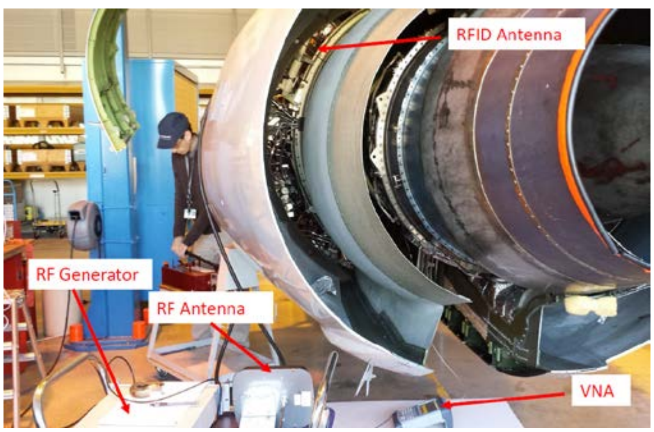


Figure 19. System tests in application environment for the first test

The tag is placed on the engine thrust link.. The evaluation is done with the reader and the tag always at the same spatial position (3 meters). Two configurations are tested:

- Configuration 1: The nacelle are opened, this can be considered as an O-level Maintenance situation – easiest situation for RFID tag interrogation – direct access to RFID tag can be provided.
- Configuration 2: The nacelle are closed, this can be considered as a Visual Inspection configuration – no direct access to RFID tag which is located in the IPPS (Integrated Power Plant System)

3.1. Measurement setup

The measurement setup is composed of:

- RF generator, with fixed 25dBm output power equipped with a RFID circular 8dBi antenna.
- Software to drive the generator, able to provide the system impedance in application environment and the power received on antenna.

The antenna design tested are the following:

- Whip dipole antenna
- Dipole antenna zebra design
- Anti-metal patch antenna for metallic environment (two different design)

Figure 20. Measurement setup

3.2. Results and comparison between antennas

The RF generator provided the following results

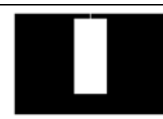
N°	Antenna design	Input impedance	Power received	
			Conf 1	Conf 2
1		21-j35 Ohm	-20 dBm	-50 dBm
2		21-j7 Ohm	-9 dBm	-50 dBm
3		21-j40 Ohm	-9 dBm	-45 dBm
4		21-j37 Ohm	-9 dBm	-40 dBm

Table 2. Antenna measured performance

The best communication reliability has been reached with the anti-metal design.

During the first test, with the first design, antenna showed no strong communication issues on configuration 1

During the second test, anti-metal patch design (design 2, 3, 4) provided better results.

Signal is lost when the nacelle is closed.

Once developed and characterized in a laboratory environment, the demonstrator was integrated to engine tests. Environmental packaging for the system was based on silicon sealant. Before engine test, full scale demonstrator was tested and submitted to qualification testing.

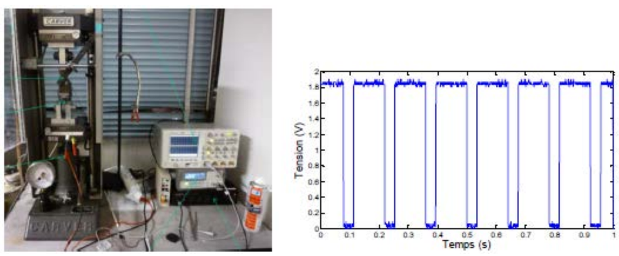


Figure 21. System laboratory validation

System was submitted to compressive loads. Thermal difference (80°C/120°C) was applied at each ends of the strut for thermal harvesting and a piezoelectric buzzer was used to apply excitation to the vibration harvester. The regulated voltage at output of the power module was check and the read write memory voltage output at the microcontroller level.

System was autonomous for a thermal gradient of 10°C for the thermal harvester, and a vibration level of 1g at 100Hz.

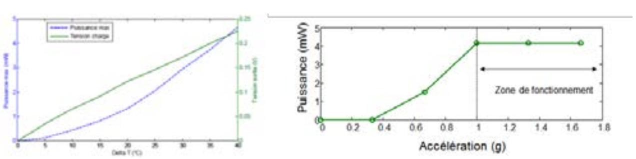


Figure 22. Thermal and vibration harvesters output

The system was submitted to ground testing inside a real engine. During the tests, system failed to be autonomous. Measurement done externally showed that the vibration and energy sources were lower than forecasted for the sizing of the system.

4. CONCLUSION

We have seen through the different parts of this article, from theoretical RFID sensor concept and constraints, to the active development of various sensors which will have to adapt to the real environment of the engine that developing a functional RFID tag is not as simple as expected. The metallic environment of the Integrated Power Plant System prevents the good performance of the RFID tag. Despite the development of specific anti-metal design, the first design does not allow to read correctly the RFID tag when the nacelle are closed. But not negligible progress has been made with the latest designs. Those tests demonstrated the robustness and good performances of the anti-metal design. The attenuation level is good for reliable communication, but presents not enough margin to consider the RFID link stable enough as stable power source to feed the sensor system.

A future prototype version with one of the antenna design associated with a SoC RFID chip will be manufactured for load measurement and tested again in the application. This future technical advancement will allow to test the concept of smart engine parts in the frame of Integrated Engine Health Management.

ACKNOWLEDGEMENT

Work in the project was been done in the EPICE-CORALIE program, a funded project from French CORAC.

Experimental work was supported by LGEF-INSA Lyon, université de Lyon.

References

Elboushi, A., Haraz, O., Jamil, K., & Sebak, A.-R. (2015). Analysis and design of a metal-backed RFID tag antenna. In *Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2015 IEEE International Symposium on* (pp. 1572–1573). IEEE.

Le, M. Q., Capsal, J.-F., Lallart, M., Hebrard, Y., Van Der Ham, A., Reffe, N., … Cottinet, P.-J. (2015). Review on energy harvesting for structural health monitoring in aeronautical applications. *Progress in Aerospace Sciences*, *79*, 147–157.

Petrariu, A.-I., & Popa, V. (2015). Low profile flexible metal mountable UHF RFID tag antenna. In *Signals, Circuits and Systems (ISSCS), 2015 International Symposium on* (pp. 1–4). IEEE.

Zhan, S. (2008). Analysis and design of metal-surface mounted radio frequency identification (RFID) transponders.

Zhan, S., & Weber, R. J. (2012, May 1). Low profile metal-surface mounted RFID tag antenna. Google Patents.

Zhang, J., & Long, Y. (2014). A novel metal-mountable electrically small antenna for RFID tag applications with practical guidelines for the antenna design. *IEEE Transactions on Antennas and Propagation*, *62*(11), 5820–5829.

BIOGRAPHIES

Yoann HEBRARD holds a PhD degree in mechanical engineering from Université Lyon I and a Master Degrees in Mechanical Engineering from Ecole Centrale. He is Program Manager of SKF-Aerospace. He is involved in development of technologies dedicated for mechatronic and machinery condition monitoring applied to self-diagnostic bearing application. His current activities are in Energy harvesting solutions, low intrusive sensing solutions and Prognostics and health monitoring management of bearings in transmission.

Guillaume BASTARD is referent for PHM integration in Safran Aircraft Engine. His mission is to help in the development and industrialization of Analytics and Engine Health Management. He received the degree of Engineer from the Conservatoire National des Arts et Métiers (CNAM) in 2013 and received a MSc degrees in complex system engineering from University of Lorraine.

Tony LHOMMEAU is in charge of the technological research for Predictive Maintenance in Safran Aircraft Engines. He has a PhD in Mechanical Engineering on “Failures modes and reliability of IGBT modules in aeronautical constraints” from the Institut national polytechnique de Toulouse