AUTONOMOUS WIRELESS ACOUSTIC SENSORS FOR AERONAUTICAL SHM APPLICATIONS

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Abstract. Ultrasound technologies are of great interest for aeronautical structure inspection. Mainly deployed through Phased Array (PA) ultrasonic transducer, ultrasound inspection is thought as a local examination of the structure to determine geometry, damage or composition of invisible flaws like cracks, delamination and corrosion. This approach in aeronautical structure cannot be easily automated since it requires access to area of interest with various complex geometries, along a spatial inspection sampling in agreement with the structure composition and vulnerability requiring a high degree of human interaction.

Structure Health Monitoring, namely SHM, overcomes these limitations by enabling rapid, automated, remote, and real-time monitoring of the structure to reduce operational costs and increase lifetime of structures. This inspection strategy gains its strength from the use of a large amount of individual embedded sensors with basic cognitive skills (sensing, signal processing, communicating and storing relevant data in non-volatile memories) organized in dense network, a Neural Network.

We present in this paper the developments of a custom autonomous wireless acoustic sensor node, including a flat flexural acoustic sensor capable of working in transmit and receive, a custom vibrational piezoelectric energy harvesting device (PEH) charging a 0.8 Farad buffer supercapacitance through an off-the-shelf IC, an ARM based microprocessor driving digitalization, signal processing, memory storage and two ways RF communication. The main objective was to create a versatile hardware tool that can be embedded within the structure to monitor and capable of hosting different acoustic inspection strategies.

1. Introduction

Aircraft industries continuously face new challenges. Under a fierce competition, they indeed need to innovate to propose safer, lighter and cost-effective aircrafts with extended operational lifetimes. To take up such challenges, aircraft industries more and more include parts built in composite materials but this definitely sharpens aircraft designs and dramatically changes the control and the maintenance approaches which are key processes to ensure the safety of the structure and its end-users. Using more and more composite based parts in aircraft should lead to global maintenance costs soaring and can now be considered as a bottleneck to implement novel composite materials.

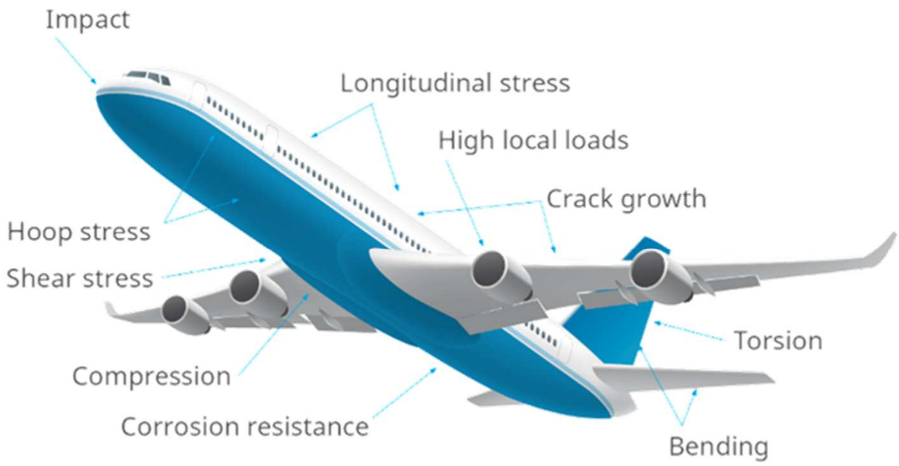

Figure 1 : Illustration of main failure causes in airplane structures.

But, despite these inherent costs, the trends are clear and composite materials are becoming the reference for the construction of new aircraft generations. The advantages of these materials are high strength, lighter weight, resilience and corrosion resistance. However, the structures become more fragile and often mixed with metallic parts posing particular challenges with important needs of constant survey. Main vulnerabilities can induce flaws hidden to maintenance technicians and threaten the integrity of the structure at different timeframes (see Figures 1). This inherently leads the designers to oversize the structure resulting in increasing the overall weight and the consumption.

Survey of conventional aircraft structures relies on predictive maintenance operations which consist of immobilizing the aircraft during a certain amount of time, to replace some of the parts according to a predicted maintenance plan and monitor the rest of the structure by visual inspections and NDT techniques using ultrasound, Xray, etc. The baseline of this maintenance approach consists in overestimating aging effects (thermal, stress and strain efforts) for security reasons and in assuming that inspection procedures are efficient enough to detect flaws even at inaccessible locations or inside the structure itself. Composite based aircraft structure democratization could render this predictive maintenance approach out of date or at least very costly. Composite materials are indeed much more difficult to survey and can present invisible flaws with various time evolving behaviours (cracks, delamination) forcing aircraft manufacturers to widely invest in the definition of efficient and cost effective predictive maintenance tools capable to detect, localize and monitor flaws, namely to add aircraft Structure Health Monitoring (SHM) systems/technology.

2. Motivations

Acoustic sensing is also a very promising SHM inspection technology and has been supported by several collaborative research projects on aeronautical SHM using wireless sensor networks like ADVICE, TRIADE and FLITE-WISE [1-2] projects.

Our approach, similarly to these projects relies in the hardware development of a highly versatile of autonomous acoustic sensor node capable to host various ultrasonic inspection algorithms and be part of an intelligent wireless network of various topology/architecture. We also deliberately chosen a product-oriented approach taking into consideration at this early stage the technology and quality management complexities of aircraft maintenance and foreseeing the coming progress of low-consumption hardware components.

3. Hardware definition

3.1 Integrated power units

As a first requirement, the sensor nodes needs to be self-sufficient in terms of energy allowing an automated or an on-demand inspection process at the highest duty cycle (typically every 2 to 3 hours). According to literature a surrounding vibration noise is propagated within the in-flight structure in a frequency spectrum ranging from 10 to 60Hz mainly, with an average acceleration level ranging between 1 to 10m.s^{-2}.

For this typical mechanical solicitations, we have demonstrated [3] that it is possible to reach a power density around 6mW/cm^3/g^2, meaning for a reasonable volume of 25x40x2mm3, an available output power around 120µW at 1m.s^{-2} obtained on an optimized resistive load. however, 120µW is pretty low since the maximum achievable yield through the rectifier and the electronics (LT3588 from linear technology) is about 50-60% according to leaks and electrical impedance mismatch but one have to take into account the facts that the device may operate at a very low duty cycle (100ms every three hours) and that we are free to stack two or more energy harvesting devices. In Figure *2*, we present a schematic of our test electronic.

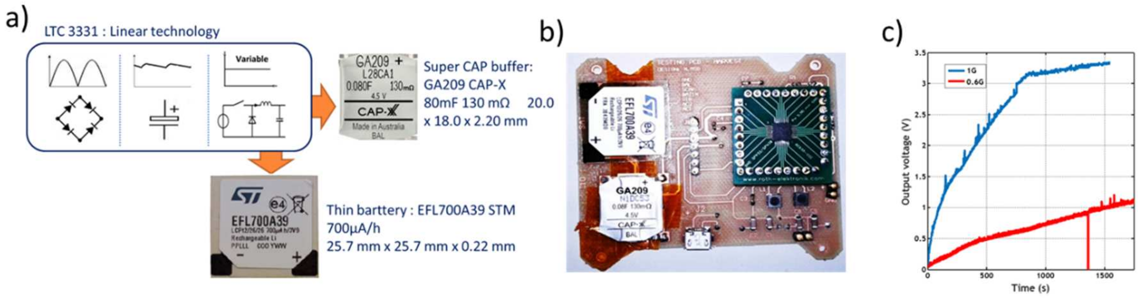

Figure 2 : Representation of power module architecture (a), test PCB (b) and charging profile at 1G on PEH maximal frequency.

3.2 Acoustic Sensors

Sensing surrounding mechanical noise within a polymer matrix as an acoustic coupling may be accomplished by membrane transducers. Such transducers [4] exhibit multiple advantages: the first, they handle both the acoustic emitting and sensing functions. Second, they enable a high integration level thanks to a very low profile, typically below 0.5mm of overall thickness and be coated with an acoustic friendly layer, a rubber silicone typically.

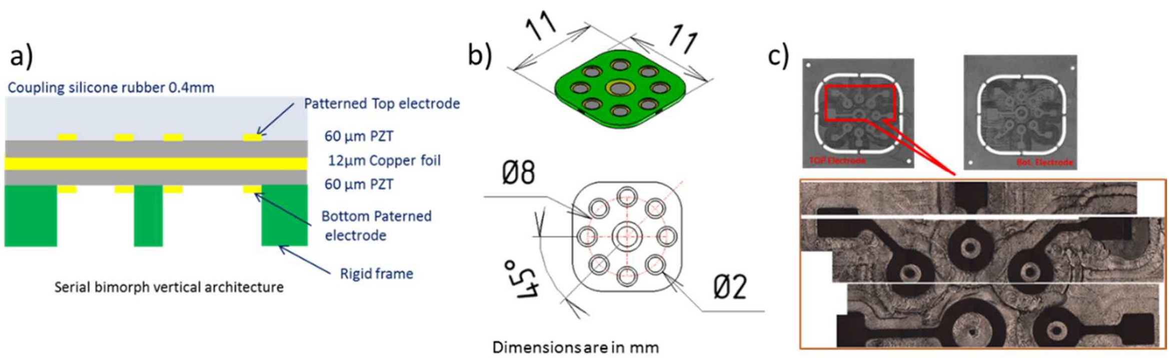

Figure 3: Representation of a multiple channel acoustic sensor. The center membrane (3.5mm diameter) is a transmitting flexural transducer, the outer/surrounding transducers (2mm diameter) are the receivers arranged along a 6mm diameter circle ©.

To this end, we have designed (see Figure *3*) and manufacture piezoelectric bimorphe structures to enable efficient d31 based flexural transductions.

3.3 Computing and communicating subsystems

One of the main enabler to build such a hardware sensor nodes is related to the advent of off-the-shelf low consumption ARM based components. We have selected the EFM32™ Leopard Gecko 32-bit Microcontroller from Silicon Labs (USA) and have integrate it on a dedicated PCB with required miniaturized RF communicating hardware.

3.4 3D Integration

As presented above, our strategy is mainly centred on off-the-shelf components and most of the innovations are related to the integration development to allow the mounting of such a sensor on or within the structure to be monitored. This hardware offers a versatile platform to investigate the benefits of an acoustic sensor node in a SHM network. This is the scope of the Smart-Memphis research project funded by the European commission through the H2020 program.

4. Conclusion

The different functions of a smart autonomous acoustic wireless sensor node have been designed with a modular integration approach. Based on our in-house piezoelectric-based energy harvesting device, we have successfully charged a thin film battery (EFL700A39 from STM - 700µA/h 3.9V) through a LTC3331 (Linear technology) power management component. Under an harmonic mechanical solicitation centred at 25Hz with a maximal acceleration along one direction of $1 m.s^{-2}$.

5. Acknowledgment

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References

[1] http://cordis.europa.eu/project/rcn/108855_en.html

[2] D Dumas,and Al., « Damage detection in composite structures using autonomous wireless systems: simulation & validation », Published under licence by IOP Publishing Ltd • Journal of Physics: Conference Series, Volume 305, Number 1.

[3] G. Ferin & al, « *Powering autonomous wireless sensors with miniaturized piezoelectric based energy harvesting devices for NDT applications* », IEEE ultrasonics and frequency control symposium, 2015.

[4] Savoia, A.S.; Mauti, B.; Caliano, G.; Lamberti, N., "A low frequency broadband flexural mode ultrasonic transducer for immersion applications," in Ultrasonics Symposium (IUS), 2014 IEEE International , vol., no., pp.2591-2594, 3-6 Sept. 2014,doi: 10.1109/ULTSYM.2014.0647