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Hardware proposal for SHM in airborne vehicles

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Abstract

Nowadays, not only must the structures be in good health when they are manufactured and installed, but also their integrity must be monitored during their life cycle. Nondestructive Test (NDT) techniques are applied in the beginning of the cycle, and Structural Health Monitoring (SHM) techniques afterwards. There is a wide literature on how to monitor integrity in large civil structures, where the size of equipment and accessibility for testing are not serious problems. There are studies that deal about the integrity of airborne vehicles, some focused on the inspection technology or the algorithms used. However, the integrity inspection of an aircraft also requires the development of reliable low volume lightweight electronic equipment with high technical capability. The authors are developing electronic prototypes to satisfy such requirements. The goal of this research is to build an on-board electronic system that monitors the integrity of the airborne structures throughout its lifetime. The prototype uses ultrasound technology with piezoelectric transducers (PZT) and can emit and acquire waveforms on multiple channels simultaneously (pulse-echo or pitch-catch schedules). It can use many test techniques: simple test, beamforming transmission, fast round-robin (associated with beamforming reception), multiple delayed signal, etc. The prototype can generate steerable beams as required. It can also operate in passive mode, i.e. listening to acoustic emissions. The prototype weights 600 g, includes USB 2.0 connectivity, and compresses the data before uploading them to a computer.

Keywords: Structural Health Monitoring (SHM), Structural Health Monitoring Ultrasound System (SHMUS), Acoustic emission (AE), Ultrasound Guided Wave Test (UGWT)

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1. Introduction

To know the state of a structure over its lifespan is a research topic that is attracting more interest from the academia and industry. This fact is evidenced by the growing number of scientific journals and congresses related to materials and structures devoted to this subject area that focuses on Structural Health Monitoring (SHM). Capineri and Bulleti (2021) introduce a complete review of the state of the art in SHM, from the characterization of the signals to the main monitoring techniques. Among these, those based on piezoelectric transducers (PZT) are gaining increasing importance. The low cost and mounting simplicity of this type of sensors allow envisaging its generalized deployment in aeronautics in the near future.

SHM Ultrasound Systems (SHMUS) use PZTs by means of two strategies: passive or Acoustic Emission (AE), and active or Ultrasound Guided Wave Test (UGWT). In AE, the electronic systems are continuously acquiring and processing the signals read by the PZTs trying to discover a change in the signal compatible with an impact in the structure or a fibre breakage in a composite. Conversely, UGWT generates driving signals that are coupled to the structure through the PZTs producing waves that travel the structure and interact with its elements, bouncing back to the very same PZTs where they can be read back and processed to determine the state of the structure. Azuara et al. (2019) introduce a thorough review of the algorithms available to process the signals obtained by UGWT.

Most of the experimental articles related to SHM utilize commercial instrumentation to run the tests: arbitrary signal generators and oscilloscopes. Mei e al. (2019) publish a detailed compilation of the instruments employed in Piezoelectric Wafer Active Sensors (PWAS) based applications. Other researchers use generic IO systems, Lei et al. (2019). These electronic systems and instruments are very limited in terms of the number of available sensors, the driving signal generation in UGWT, and the available monitoring techniques. However, there are also some dedicated equipment. Tang et al. (2016) developed a highly integrated CMOS transceiver capable of transmitting and acquiring a signal for UGWT. The company Physical Acoustics (2021) has developed a standalone two-channel AE system to monitor pressure vessels, pipelines, slow-speed bearings and other machinery. The company Acellent (2021) has introduced a set of devices to actively and passively monitor several types of structures. There are also several ultrasonic devices available to know the state of a given structure either during its production or for maintenance purposes, Dattoma et al. (2021). But they cannot be used in monitoring tasks because they need an operator or their dimensions or cost make them unfeasible to be permanently installed in a structure.

A device that implements AE and UGWT techniques usually must have some well-known features. AE technique demands a very high number of PZTs, in the range from 10 to 50. UGWT related research usually includes one single PZT, as the commercial instrumentation can only use one signal generator without changing the connections, which make them impossible to be used with more complex techniques such as round-robin with multiple PZT or beamforming transmission, Olson et al. (2007). In UGWT, it would be desirable to be able to excite from 5 to 20 PZTs driven by signals out of phase by a few nanoseconds. The amplitude of this exciting signals is conditioned by the maximum peak to peak voltage that the signal generator can handle, usually in the range of 10 to 20 Vpp. Metallic structures can give good results with this kind of excitation, but composites materials need higher voltages that can reach even 100 Vpp. Moreover, a monitoring device must operate without human intervention, transmit the information to a control central autonomously, and be small and lightweight in order to be usable in aeronautics.

The Electronic Design Group of the University of The Basque Country (UPV/EHU) has tightly collaborated with Aernnova over the last years to develop a SHMUS that implements both AE and UGWT techniques. It is the successor of PAMELA III (Phased Array Monitoring for Enhanced Life Assessment), introduced in Aranguren et al. (2013), based on a Virtex 5 FPGA (Field Programmable Gate Array) with a PowerPC processor running Linux as Operating System. The ever-growing demand for new processors and up to date operating systems motivates the development of a new version. This paper aims at introducing the last developed SHMUS prototype and it shows its suitability in SHM applications.

2. Features of the developed prototype

The current prototype, named PAMELA IV, is a modular system consisting of an USB interface and from one to eight input/output electronic cards. Many electronic systems become deprecated due to the planned obsolescence of the operating systems or their embedded firmware. To avoid this issue, the prototype is designed on a FPGA containing only logic circuits, with the support of no firmware or embedded processor. The operational control of the system is located in an external computer. The input/output cards feature an FPGA belonging to the Xilinx Artix 7 family. Specifically, it is a XC7A50T containing more than 50,000 logic cells.

Figure 1 shows a prototype fitted with three cards, which allows the generation and acquisition of six channels each. Therefore, the depicted prototype has the capability to generate and acquire 18 channels simultaneously. Each channel can drive a PZT to emit an excitation signal and, at the same time, acquire the excitation signal and the reflected signals after travelling throughout the monitored structure. This prototype, inside its aluminum box, weights 600 gr and its dimensions are 125 x 125 x 50 mm.

Figure 2 shows the main window of the control software. It can be seen that it allows the selection of the generating and acquiring sensors, which can be different (pitch-catch test) or the same (pitch-echo test). Excitation signal is synthetized inside the FPGA based on the parameters selected by the user: frequency in the range from 30 kHz to 1 MHz, amplitude as a percentage of the maximum 48 Vpp, number of periods of the signal, and its shape, which can be sinusoidal or convolved with Hanning, Hamming or Blackman window. It can also generate arbitrary waveforms such as sine sweep or a combination of signals with different frequencies. This flexibility enables the implementation of complex excitation strategies like beamforming transmission or time reversal, Fink (1992). A 12-bit resolution and a sampling frequency in the range from 10 MHz to 60 MHz complete the description of the features of the acquisition unit.

Output exciting signals are isolated from each other and, therefore, driving channels can be arranged in series so that the exciting voltage achieves values higher than 100 Vpp. The acquired waveforms can be fully retrieved by the control software. They can also be processed, while they are acquired, looking for minimum and maximum voltages that conform a set of characteristic points. This is named the *compressed acquisition mode* as the time spent in the transmission of data is dramatically reduced, Castillero et al. (2020).

The system can run the following types of tests:

- Simple. The test consists of the excitation of just one transducer and the sampling of the received echoes by the sensors mounted on the structure (pitch-catch type of test). As a result, if *N* sensors are installed in the monitored structure, *N* waveforms per test will be obtained.

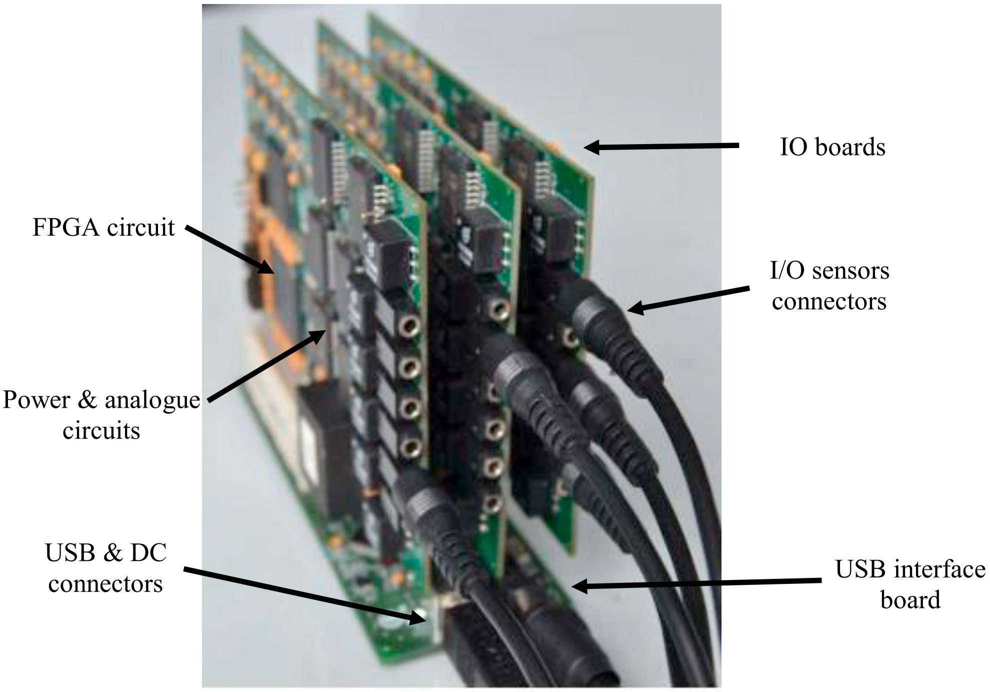
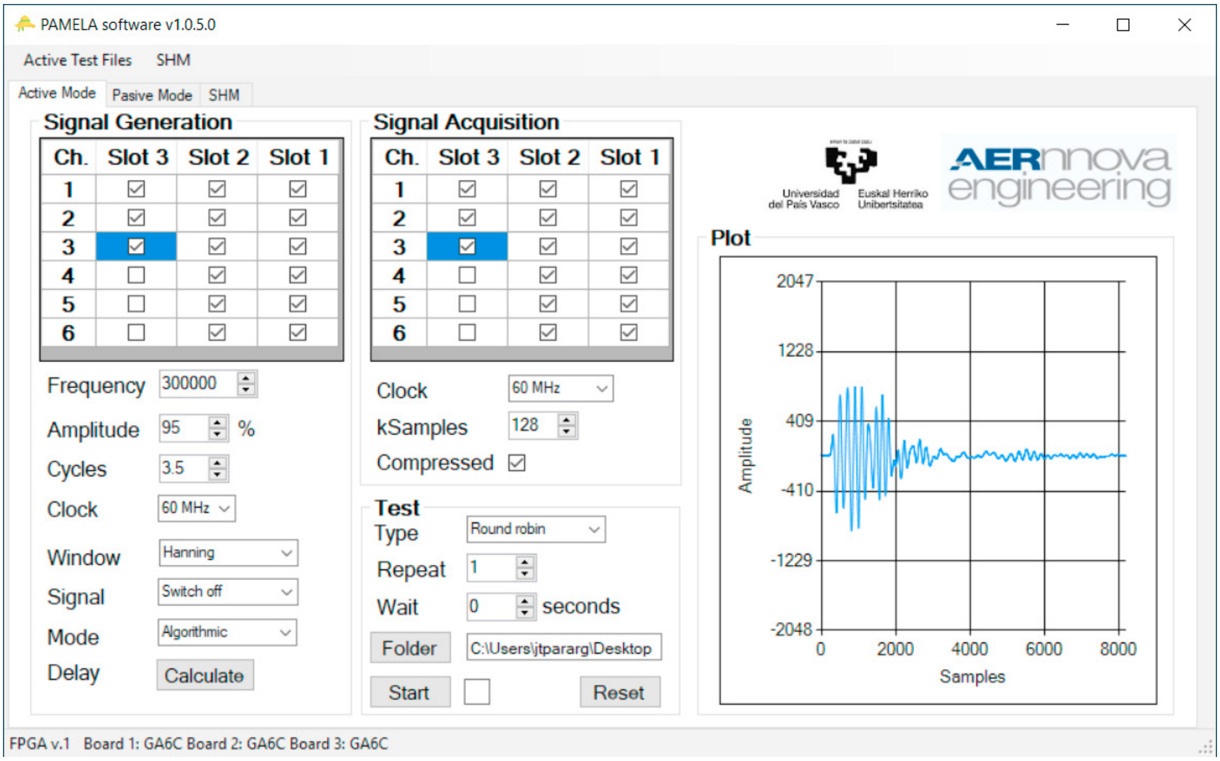


Figure 1. PAMELA modular system fitted with three input/output cards capable to drive and acquire 18 signals.



Signal Generation

Ch.	Slot 3	Slot 2	Slot 1
1	☑	☑	☑
2	☑	☑	☑
3	☑	☑	☑
4	☐	☑	☑
5	☐	☑	☑
6	☐	☑	☑

Frequency 300000
Amplitude 95 %
Cycles 3.5
Clock 60 MHz
Window Hanning
Signal Switch off
Mode Algorithmic
Delay

Signal Acquisition

Ch.	Slot 3	Slot 2	Slot 1
1	☑	☑	☑
2	☑	☑	☑
3	☑	☑	☑
4	☐	☑	☑
5	☐	☑	☑
6	☐	☑	☑

Clock 60 MHz
kSamples 128
Compressed ☑

Test
Type Round robin
Repeat 1
Wait 0 seconds
C:\Users\jtpararg\Desktop
☐

FPGA v.1 Board 1: GA6C Board 2: GA6C Board 3: GA6C

Figure 2. PAMELA IV control software main window.

- Round-robin. It consists of running one simple test for each of the *N* installed sensors. Hence, *NxN* waveforms per test will be obtained. This test can be used for beamforming reception techniques.
- Beamforming transmission. In this type of test, the amplitude and delay of the exciting voltage of each transducers are tuned to boost the creation of constructive interferences in a given direction. Specifically, in the designed prototype, directions from 0° a 180° in steps of 5° are swept obtaining 37 tests and *37xN* waveforms per test.
- Multiple delayed signal. In this type of test, the delay of each exciting signal can be arbitrarily configured in order to be able to concentrate the transducers' energy on a given area of the structure (see Figure 3).
- Time reversal. Consists of running any of the test mentioned above and, then, utilize the acquired waveforms again to drive the PZT in a new test.

3. Prototype validation

To check the viability of the prototype, tests on isotropic (aluminum) and anisotropic (composite) specimens were carried out. Figure 4 shows the setup for a UGWT configured to measure the dispersion of guided waves on composite material.

The prototype is providing satisfactory results when testing it with different algorithms to detect all kind of damage, and specimens, including real-world aircraft parts. Namely, this device has been validated using the beamforming technique on metals, Cantero-Chinchilla et al. (2020), on composite materials, Aranguren et al. (2020), and with fatigue stress tests on aluminium, Cantero-Chinchilla et al. (2021).

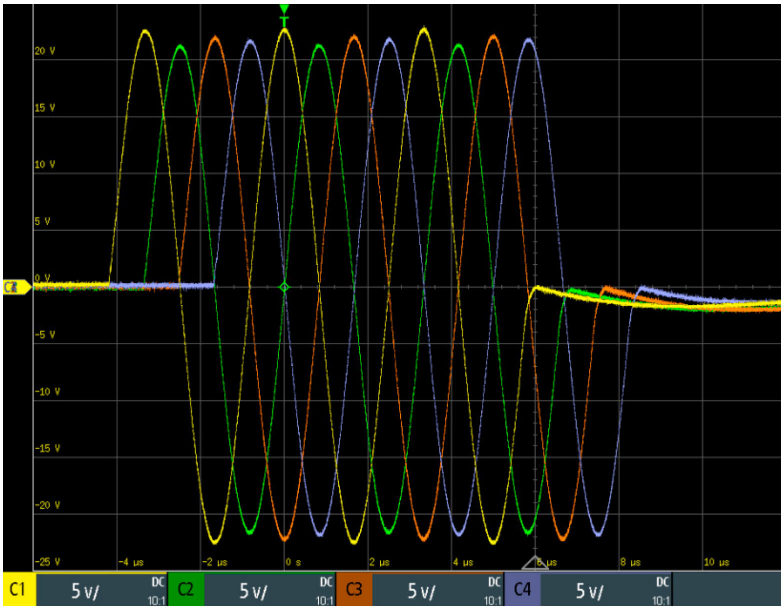


Figure 3. Signals synthetized by PAMELA IV prototype and delayed 833 ns. Oscilloscope acquisition in the leads of four PZTs.

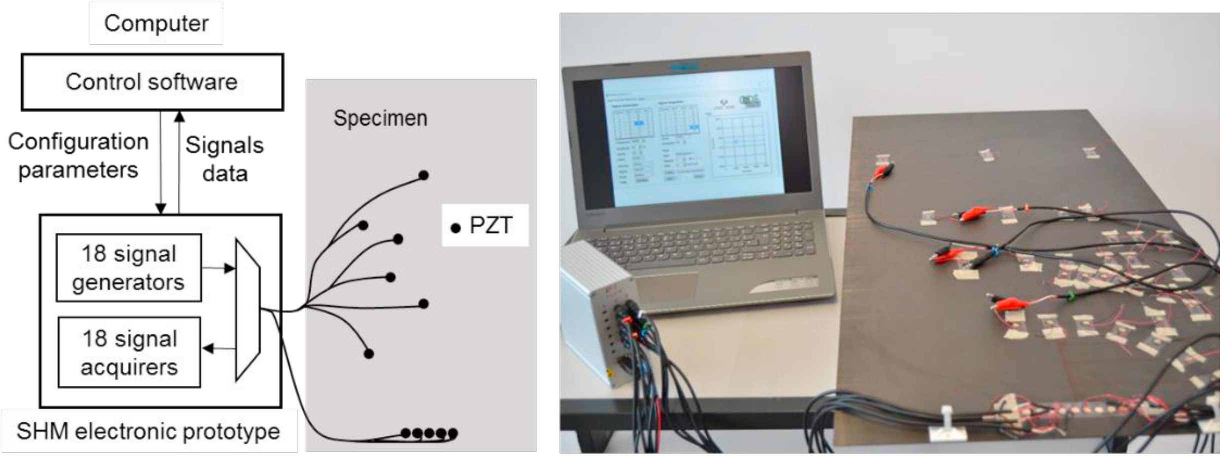


Figure 4. Schematic and photography of the setup of the tests.

4. Conclusions

A prototype intended for SHM testing has been introduced. It is based on ultrasonic techniques employing PZTs and it is capable of implementing both active, or AE, and passive, or UGWT, strategies to monitor structures. It can drive and acquire up to 18 channels simultaneously (48 channels in systems with 8 Input/Output boards). In standard configuration, UGWT driving signals can be of 48 Vpp, but it can reach more than 100 Vpp in extended configuration.

The prototype is light, small and can run several types of test according to different requirements: simple pulse-echo or pitch-catch tests, or test with multiple transducers such as round-robin, beamforming emission, multiple delay signal, and time reversal. It can also carry out a pre-processing stage of the acquired waveform searching for its characteristic points so that the time required to transmit the full original acquired signals is reduced.

The prototype has been validated both on metallic and composite structures, showing satisfactory performance on both materials.

In the near future, this research will continue performing new test campaigns and improving this prototype, i.e. reducing its size, weight, and adding new features, in order to improve its suitability for the aeronautical structure monitoring needs.

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References

Acellent (2021), https://www.acellent.com/products/hardware (Accessed: 20 July 2021)

Aranguren, G., Monje, P. M., Cokonaj, V., Barrera, E., Ruiz, M., 2013. Ultrasonic wave-based structural health monitoring embedded instrument. Review of Scientific Instruments, 84 (12), 125106.

Aranguren, G., Etxaniz, J., Cantero-Chinchilla, S., Gil-Garcia, J. M., & Malik, M. K., 2020. Ultrasonic guided wave testing on cross-ply composite laminate: An empirical study. Sensors, 20(18), 5291.

Azuara, G., Barrera, E., Ruiz, M., Bekas, D., 2019. Damage detection and characterization in composites using a geometric modification of the RAPID algorithm. IEEE Sensors Journal, 20(4), 2084-2093.

Cantero-Chinchilla, S., Aranguren, G., Malik, M. K., Etxaniz, J., Martin de la Escalera, F., 2020. An empirical study on transmission beamforming for ultrasonic guided-wave based structural health monitoring. Sensors, 20(5), 1445.

Cantero-Chinchilla, S., Aranguren, G., Royo, J. M., Chiachío, M., Etxaniz, J., & Calvo-Echenique, A., 2021. Structural health monitoring using ultrasonic guided-waves and the degree of health index. Sensors, 21(3), 993.

Capineri, L., Bulletti, A., 2021. Ultrasonic Guided-Waves Sensors and Integrated Structural Health Monitoring Systems for Impact Detection and Localization: A Review. Sensors, 21(9), 2929.

Castillero, J., Aranguren, G., Etxaniz, J., Gil-Garcia, J. M., 2020. Composite Leading Edge Monitoring with a Guided Wave System. European Workshop on Structural Health Monitoring (pp. 830-837).

Dattoma, V., Nobile, R., Palano, F., Panella, F. W., Pirinu, A., Saponaro, A., 2021. Ultrasonic and thermographic fatigue monitoring on a full-scale CFRP aeronautical component after repairing. IOP Conference Series: Materials Science and Engineering (Vol. 1038, No. 1, p. 012027).

Fink M., 1992. Time reversal of ultrasonic fields. Basic principles. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 39(5): 555–566.

Lei, Q., Shenfang, Y., Qiang, W., Yajie, S., Weiwei, Y., 2009. Design and experiment of PZT network-based structural health monitoring scanning system. Chinese Journal of Aeronautics, 22(5), 505-512.

Mei, H., Haider, M. F., Joseph, R., Migot, A., Giurgiutiu, V., 2019. Recent advances in piezoelectric wafer active sensors for structural health monitoring applications. Sensors, 19(2), 383.

Olson, S. E., DeSimio, M. P., & Derriso, M. M., 2007. Beam forming of Lamb waves for structural health monitoring. Journal of Vibration and Acoustics 129, 6 730-738

Physical Acoustics (2021), https://www.physicalacoustics.com/by-product/micro-shm-structural-health-monitoring-system/ (Accessed: 20 July 2021)

Tang, X., Zhao, H., Mandal, S., 2016. A highly-integrated CMOS transceiver for active structural health monitoring. IEEE National Aerospace and Electronics Conference (NAECON) and Ohio Innovation Summit (OIS) (pp. 133-138). IEEE.