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Structural Health Monitoring Ultrasound System

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Abstract

SHM systems have been under development for decades. Many technologies have been considered during these years (ultrasounds, optic fiber, Eddy current, electromagnetic, *imaging, impedance measurements,...) and many solutions for fault detection algorithms,* types of sensors, techniques for conducting the tests, etc. have also been introduced.

Even though the SHM technology is almost mature, just a few SHM experimental systems are frequently used. SHM systems usually focus on structures with no limitation on volume or weight. The SHM systems are still under test in applications for aircraft and wind generators, where the weight and volume is critical.

One of the most applied technologies in SHM is the monitoring through surface ultrasonic waves or Lamb waves. The main advantages of this technique are the low power consumption of the sensors and the capability to cover large areas using few sensors. The ultrasound technique for SHM consists of a system composed of several modules: signal generators that provide waves at specific amplitude and frequency with enough power to drive a series of sensors; several parallel acquisition systems for the signals received at the transducers; a digital control system to synchronize the modules, perform calculations on the signals and determine the state of the structure; a communications system with a central node, which is critical when multiple structures are monitored; and, obviously, the piezoelectric transducers.

All these modules must be embedded in a low volume system and show large capacities: high reliability, signal integrity, accuracy, speed of response, etc. Even more, the feeding of the system through the ambient energy leftovers (auto harvesting) is also set as target. This paper introduces the Structural Health Monitoring Ultrasound System, a system that gets SHM technology closer to the applications.

1 INTRODUCTION

The Structural Health Monitoring (SHM) brings together the techniques developed to monitor many structures as gas pipelines, bridges, wind turbine blades or the aeronautical structures. It is a key issue for the research and development department in many companies. In fact, the 11% of the total costs in aeronautic companies are due to the maintenance costs, whose meaningful portion corresponds to structure maintenance [1].

The structure maintenance is still carried out through the process defined by the Federal Aviation Administration [2], i.e., through visual inspection without almost any specialized instrumentation. This technique involves the removal of the panels of the structures in order to gain access to the most unreachable spots of the structures. However, it does not offer the great advantages of SHM, i.e., the reduction of both the inspection duration and the operative cost, or the increase in the measurement precision. So, new SHM techniques are necessary to cut the structure maintenance costs as well as to become aware of structure failures when they still are small and minor. This way, the security when flying is increased [3].

Several techniques have been described as promising solutions. For instance, the radiographic inspection, Microwave Antennas (MWA), Comparative Vacuum Monitoring (CVM), Fiber Bragg Gratins (FBG), magnetic particles, acoustic-emission, acoustic-ultrasonic, electromechanical impedance or Eddy Current Foil Sensors (ECFS). Moreover, Staszewski et al. [4] introduced some non-destructive testing (NDT) techniques to ensure the structural integrity. In particular, the ultrasonic method for SHM is based on Lamb waves, which were first described by Horace Lamb, the English mathematician. Lamb waves are ultrasonic elastic waves that travel along the surface of thick solid plates.

The SHM techniques introduce the steps that must be followed to generate and acquire Lamb waves by using piezoelectric transducers. First, the piezoelectric transducers are excited with a signal generator and, hence, the ultrasonic waves are generated. Then, the waves travel all the way through the structure under test, bounce off the obstacles they find (as flaws or borders), and then come back to the monitoring system. Next, the transducers catch the returning echoes or signals. The signals have the information about the structure, more specifically about its dimensions and the obstacles found when travelling all through it. Finally, an appropriate processing stage gives the position and significance of the flaw by comparing the signals caught before and after any damage happened.

When comparing this technique to other SHM techniques, some advantages can be seen. For instance, thanks to the longer range of Lamb waves, a big structure can be monitored with these waves using just several piezoelectric transducers placed in one of its ends, not as other techniques that involve the installation of sensors all along the structure. The monitoring of structures with Lamb waves eases the detection of damages long after they happened, so it does not require a continuous quest for changes over a preconfigured threshold. To sum up, the monitoring of structures with Lamb waves need less equipment and, as a result, less weight and power consumption. These last two features are key points when designing new systems for onboard structural monitoring in an aircraft.

On the other hand, there is a wide range of instrumentation for SHM [5]. But since it is necessary to take the structure off the aircraft to perform the structural inspections, most of these SHM systems cannot be automated nor used in real time configurations.

So, in order to satisfy these requirements, the authors set up a research line that came to the development of the Structural Health Monitoring Ultrasound System (SHMUS). They took advantage of prior research efforts [6-8] and made it possible to monitor the health of structures as aircrafts, bridges, buildings, pipelines, ships, and many more in real time. The SHMUS unit can perform ultrasound tests on composite material and control up to 18 channels of signal generation/acquisition with multiple testing techniques and good performance.

The paper is structured as follows. Section 2 introduces the Structural Health Monitoring

Ultrasound System (SHMUS) architecture. Section 3 shows some test result. Finally, the conclusions section resumes the main contribution of this communication.

2 SHMUS

The Structural Health Monitoring Ultrasound System (SHMUS) is an architecture that performs ultrasound tests on metallic or composite material. The unit controls thoroughly up to 18 channels of signal generation or acquisition with multiple testing techniques.

SHMUS is composed of a base board (Rear-End) that includes three slots to connect up to three generation and acquisition cards (Front-End). The Rear-End board includes a USB-FIFO interface to connect the system to a computer, as shown in Figure 1. The first type of Front-End card developed is the GA6C card (Generation-Acquisition for 6 Channels). The actual prototype is shown in Figure 2, where the whole system includes three GA6C boards. The size of SHMUS is just 124 x 100 x 45 mm.

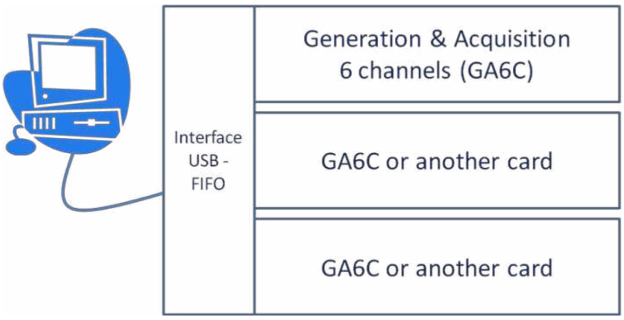

Figure 1. Scheme of the SHMUS system.

Each one of the three GA6C generation and acquisition cards includes an FPGA, a FIFO memory set and up to six connectors to manage six input-output channels, where piezoelectric devices are connected. The scheme of the board is shown in Figure 3.

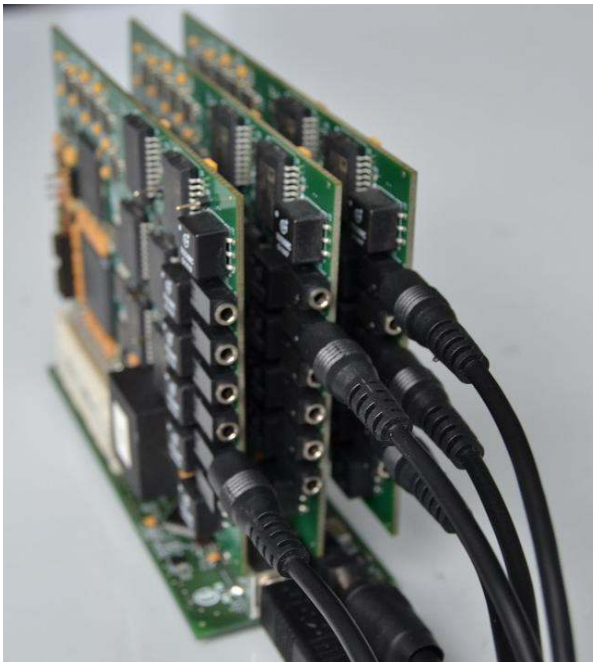

Figure 2. Actual SHMUS prototype that includes the connection of three GA6C boards.

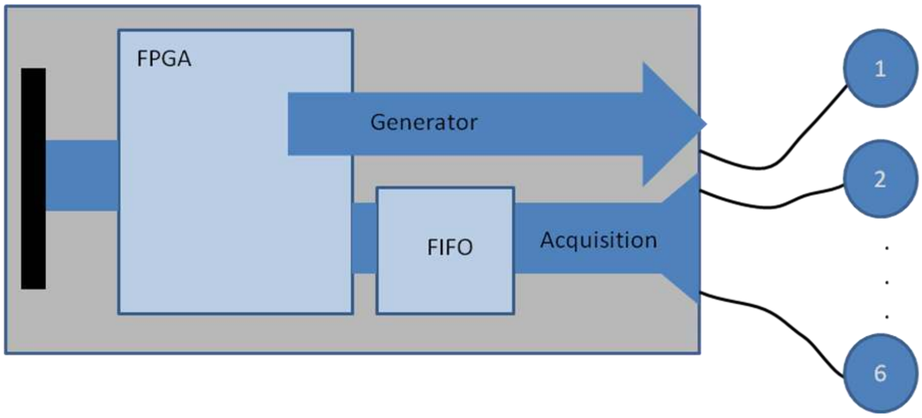

Figure 3. Block diagram of the GA6C board.

The generation part of the G6AC board gives enough power per channel so that the piezoelectric device generates an acoustic wave with the appropriate power level to monitor the structure health of a composite piece under test. The excitation signal ranges from 10 kHz to 6 MHz to handle many different piezoelectric transducers. The waveform can be defined with an algorithmic generator (sine, triangular or square waveforms) or it can be pattern defined. Hamming and Hanning window functions are available for the generation of signals. The excitation signal is generated with an amplitude resolution of 12 bits, given by the digital-to-analog converter (DAC) of the system, and the maximum voltage amplitude that can be obtained in the output of the board is more than 50 V_{pp}. Some delay can be set among the transducers in multiples of 16.6 ns for the beamforming test. Moreover, the excitation signal can last over multiples of 0.5 cycles. The block diagram of the generation part of the G6AC board is shown in the Figure 4.

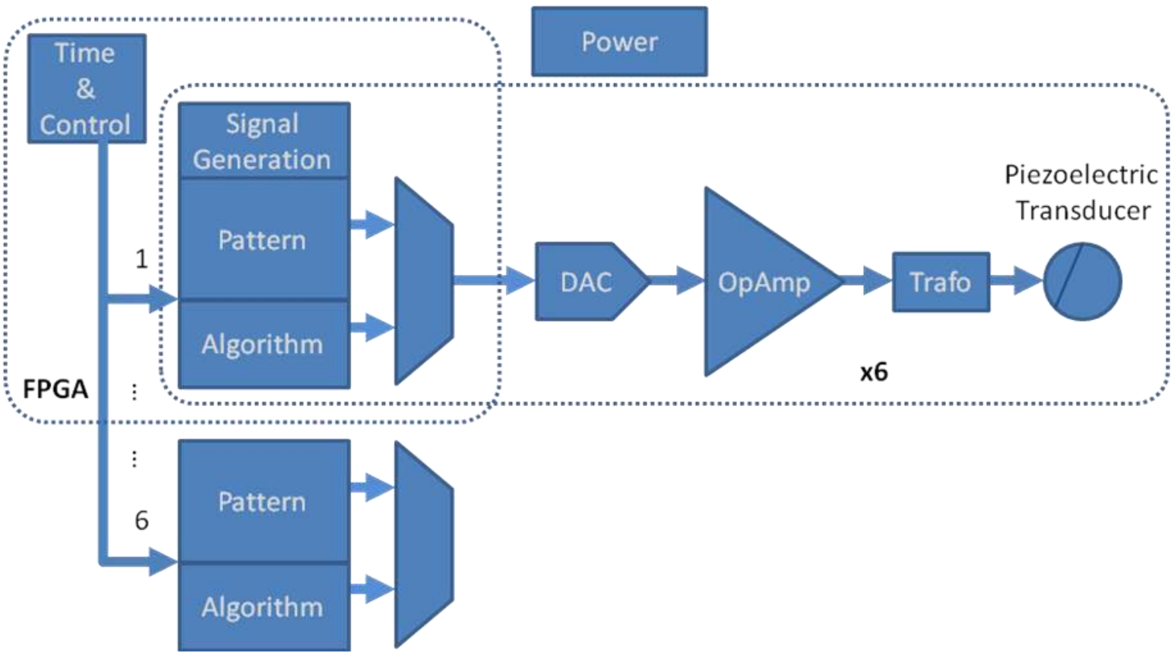

Figure 4. Block diagram of the generation part of the G6AC board.

On the other hand, the acquisition part of the G6AC board includes six channels for simultaneous acquisition. The wave travelling along the piece under test is acquired through a piezoelectric transducer (PZT). Then, it is adapted with a transformer (TR) and several transient-voltage-suppression diodes (TVS), and after that it is digitalized with the analog-to-digital converter (ADC). The digital signal is acquired at adjustable sampling rate of 1 to 60 megasamples per second (MSPS). The FIFO memory included in the board uses 128 kbytes per channel. Hence, the time necessary to acquire the information from the transducers ranges from 2.18 ms (when sampling at 60 MSPS) to 131 ms (when sampling at 1 MSPS). The signals measured with the transducers are converted into digital signal with a resolution of 12 bits given by the ADC of the system. The block diagram of the acquisition part of the G6AC board is shown in the Figure 5.

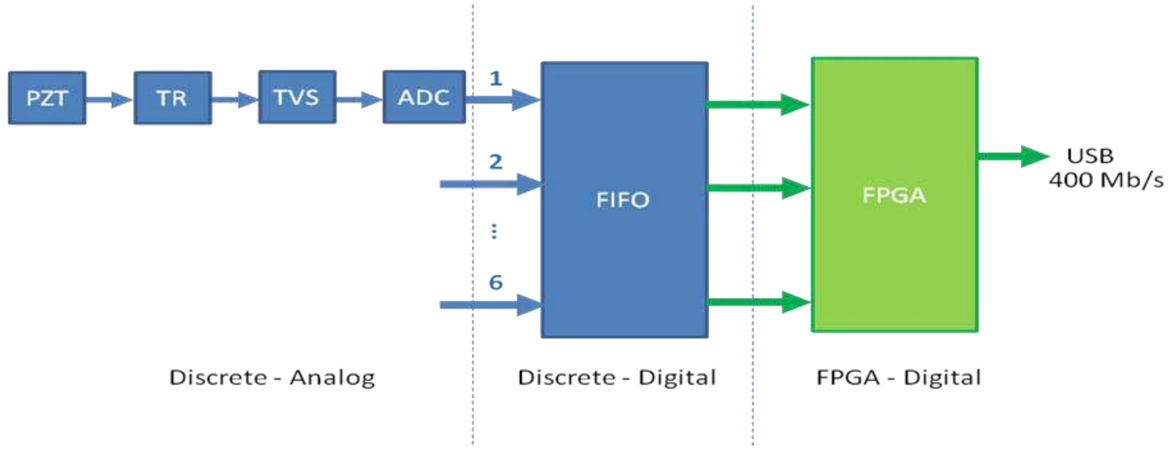

Figure 5. Block diagram of the acquisition part of the G6AC board.

So, the SHMUS system can manage simultaneously up to 18 channels for signal generation when three GA6C boards are connected. The channels are used to both excite the piezoelectric transducers and to acquire the data of the surface waves travelling along the piece of composite under test. The piezoelectric transducers are connected to SHMUS through a stereo audio jack (2.5 mm). Furthermore, SHMUS is connected to 12 V power supply and the power consumption of the system is below 5W.

SHMUS runs ultrasound tests that include both types of waves, longitudinal and surface waves. There is no restriction in the resonance mode of the piezoelectric transducer that can be connected to SHMUS. For instance, the transducer can work on d_{31} or d_{33} resonance modes and, hence, longitudinal and surface waves, respectively, will travel along the piece under test.

3 TEST OF SHMUS

This section summarizes some of tests that show the correct performance of the SHMUS unit. First, the amplitude of the output signal in the piezoelectric load of the system was measured. Next, the appropriate output waveform shaping was checked. Afterwards, the capability of SHMUS to tune the output signal frequency in each one of the output channels independently and simultaneously was verified. In addition, it was proven that the delay among the output signals can be adjusted according to the needs of the actual application. Finally, the acquisition of data with SHMUS was verified.

Usually, the electronic impedance features of the piezoelectric load make the amplitude of the output signal decrease when connecting the load to the system output. SHMUS was designed to give enough output power to piezoelectric loads, even for actual applications on composite materials. Figure 6 shows the output signal of SHMUS when applied to a piezoelectric load coupled to a piece of composite material. As shown in this example test, the signal lasted three periods and the voltage level measured is about 40 V_{pp}. Furthermore, the small amplitude wave after the output signal generated in SHMUS is due to the mechanical vibrations in the transducer that come from the voltage applied to it.

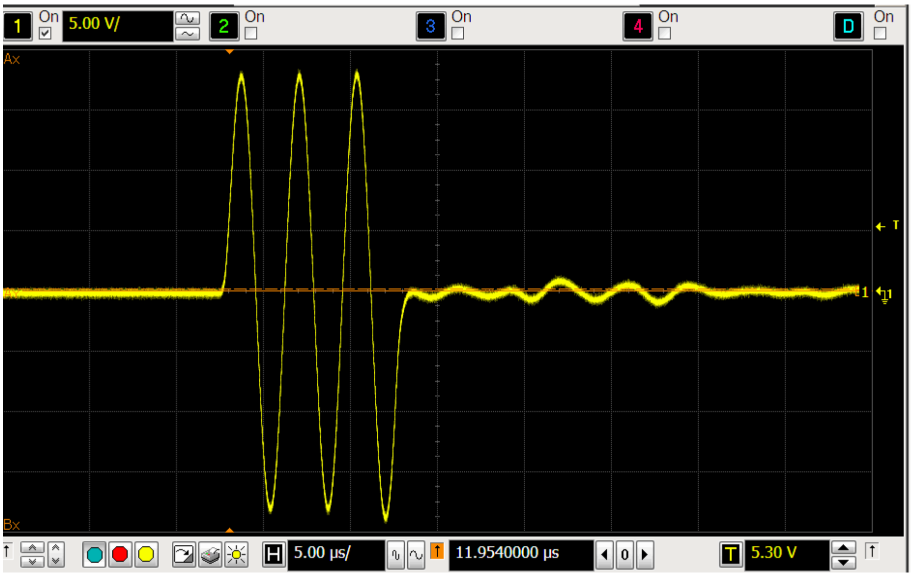

Figure 6. Example of output signal in SHMUS when applied to a piezoelectric load.

SHMUS can generate several waveforms of many frequencies simultaneously. Then, it was verified that SHMUS could tune independently the frequency of the signals generated in each one of the output channels. Figure 7 shows the voltage measurement of four of the output channels in SHMUS. It can be seen that none of the signals measured have the same period and, therefore, frequency.

Figure 7. Voltage measurement of four of the output channels in SHMUS. All the signals have different period and frequency.

SHMUS can generate waveforms with different delays at once. This feature is useful in the beamforming test. Figure 8 shows the measurement of four of the output channels in SHMUS. It can be seen that all the signals have the same frequency and amplitude. However, none of the signals measured start at the same instant and, therefore, they have different delay.

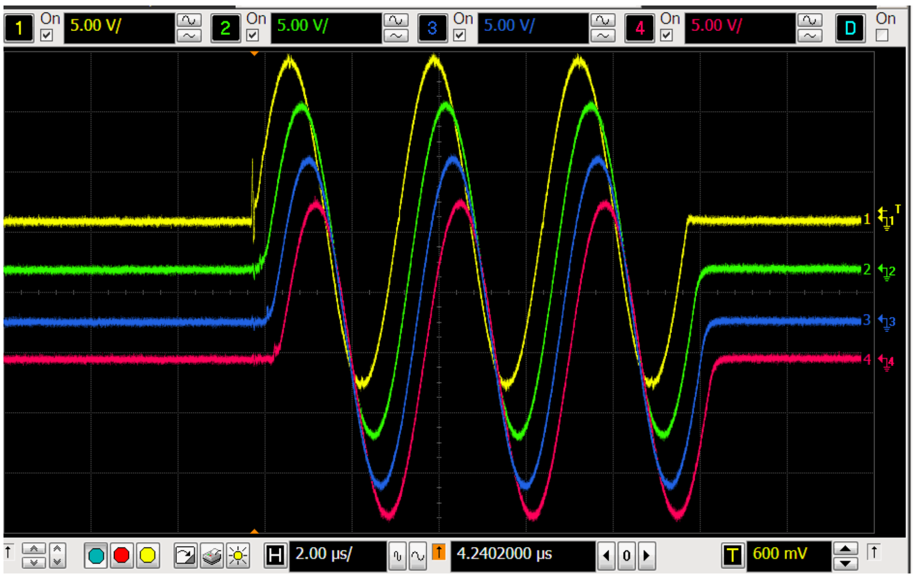

Figure 8. Voltage measurement of four of the output channels in SHMUS. All the signals have different delay.

Figure 9 shows the software for the acquisition control in SHMUS. The Waveform Graph window in the right side of the figure shows an example of the acquisition of signal.

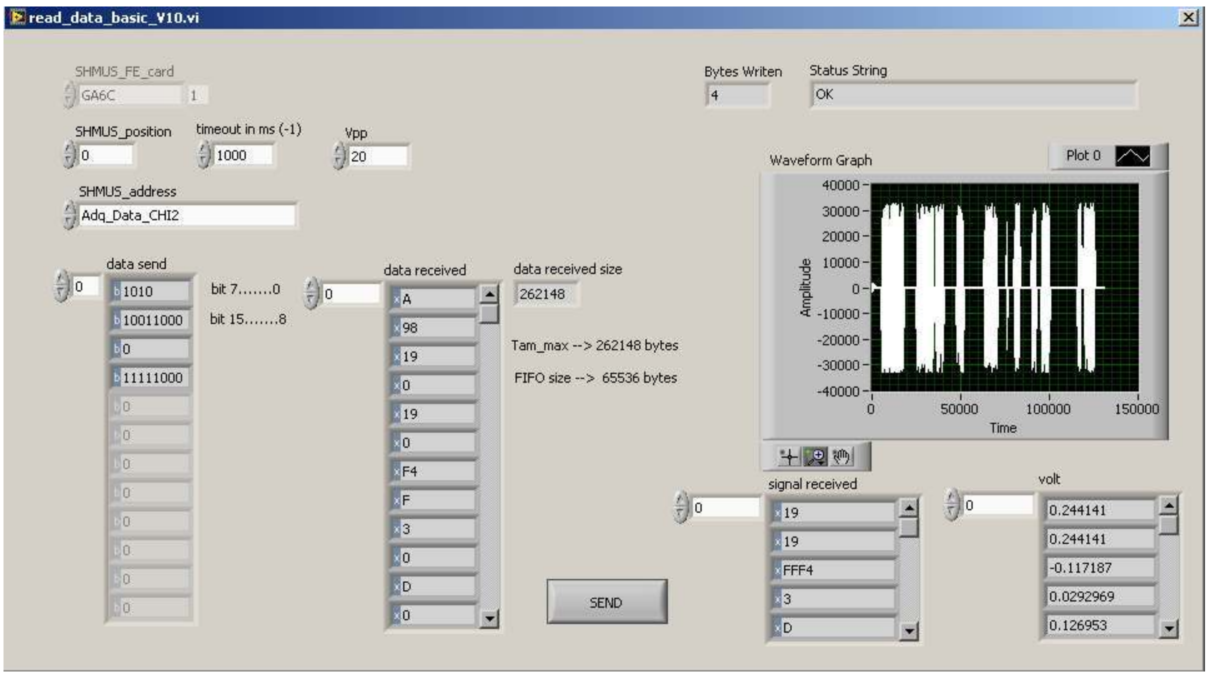

Figure 9. Software for the acquisition control in SHMUS.

Figure 10 shows a detailed graph of the signal acquired in the example above. The quantification levels of the ADC can be seen in the vertical axis, where the level 2000 corresponds to 0.7 V. The sampling rate was 60 MSPS, so the units in the horizontal axis are equivalent to 16.6 ns. The test signal consisted of a three cycle signal of 280 KHz. The signal includes some typical overshoots in the step response of band-limited systems. The TVS diodes clamped the excitation signal to adapt it to the ADC. The test was performed on piezoelectric transducers and, hence, the dumping wave of the transducer can be seen after the excitation signal ends (see also Figure 6). Finally, the clamping level is correctly set up and the dumping signal is acquired as sinusoidal wave and not square.

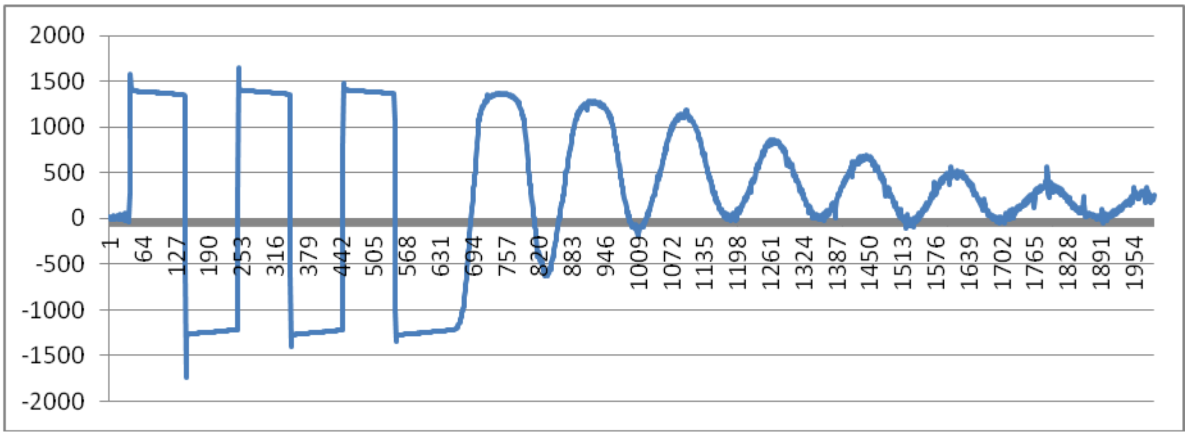

Figure 10. Detailed graph of the signal acquired in the example in Figure 9.

4 CONCLUSIONS

The Structural Health Monitoring Ultrasound System (SHMUS) is an architecture that performs ultrasound tests on pieces of metallic or composite materials. The tests can be simple, Round-Robin, beamforming, time reversal or some other. The control and data processing capability of SHMUS is placed in the software running in the computer connected to it. This fact makes it possible to reduce the size and complexity of the SHM electronic system.

SHUMS can generate electronic signals that can be adjusted in the waveform, amplitude, frequency, and delay for each one of the 18 channels available. On the other hand, SHMUS can acquire data concurrently from 18 channels at a sampling rate of up to 60 MHz.

The maximum amplitude of the excitation signal is about 50 V_{pp}, but it can be enlarged to approximately 200 V_{pp}. In addition, the amount of channels for generation and acquisition of data can be increased to 48 easily upon request.

Finally, the future work of this research is focused on the development of new electronic boards, as for instance, the one that includes one channel for the generation of signals and eight channels for the acquisition of the data from transducers. Moreover, a passive impact detection board is also under development. The FPGA included in SHMUS is also in the spotlight and it will be enhanced by adding new functions and hardware algorithms, as for example high-pass and low-pass filters, maximum and minimum peak-detectors, frequency scanner to find the precise resonant frequency of the piezoelectric transducer,…

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