Piezo-composite patches applied to the detection of defects using Lamb wave focusing

T. Porchez, N. Bencheikh & F. Claeyssen
Cedrat Technologies SA, Meylan, France

ABSTRACT: Ultrasonic-based SHM (Structural Health Monitoring) applications usually rely on the use of piezo-electric patches to emit and receive ultrasonic surface acoustic waves. The principle is to study the propagation of the waves through a structure to assess its health. Because of the elevated number of echoes and possible modes of propagation of the acoustic waves within the structure, those applications suffer from a burden of signal processing. This paper presents a composite piezo-electric patch and its electronics that were designed and successfully tested for reducing the complexity of the SHM detection schemes. The system allows for selecting the S_0 mode and for emitting and receiving it with a high directivity. As shown experimentally, a defect on the propagation path significantly modifies the signal and can be more easily detected.

1 INTRODUCTION

1.1 *Problematic*

SHM requires the fusion of different engineering disciplines such as signal processing, electronics, acoustics, or mechanics. One of the most common detection techniques is to emit and receive ultrasonic waves with piezo-electric transducers attached to the structure (Boller et al. 2009). A simple setup to assess the propagation of the wave is to have two piezo-patches, one acting as emitter and the other acting as a receiver. The properties of the wave transmitted from the emitter to the receiver will be very likely to change in the case of a defect between the two patches. These SHM detection schemes suffer from a burden of signal processing due to different modes of propagation and the large number of interfering echoes (Debarnot et al. 2006). Mode and direction selectivity of the waves is a way to reduce the complexity of the signal processing, by selecting one mode of propagation, and by looking only into the transmitted waves and not their echoes.

A type of ultrasonic waves particularly suited for SHM is Lamb waves, also known as plate waves. For acoustic waves at frequencies around several hundred kHz, it can be considered that only the S_0 mode and A_0 mode are present (Ostachowicz 2008). The S_0 mode is known as the symmetrical mode, the A_0 mode is the anti-symmetrical mode. An interesting property is that the S_0 mode is faster than the A_0 mode, i.e. the S_0 mode is always the first to arrive to the receiver. The S_0 mode is more affected by the defects than the A_0 mode, thus there is a strong interest in this mode for SHM detection schemes.

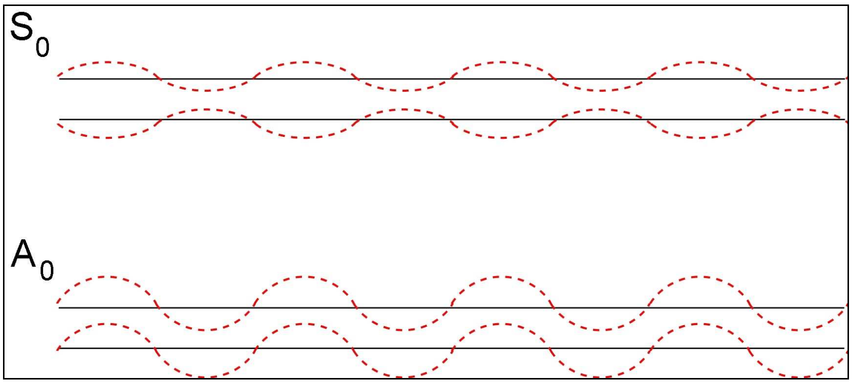

Figure 1. Lamb waves in a thin plate: symmetrical mode S_0 and anti-symmetrical mode A_0.

1.2 *Concept*

The piezo-composite structure is a way to obtain mode and direction selectivity as it features several independent patches separated with a fixed pitch (Ostachowicz 2008; Xuecang et al. 1999), as shown on Figure 2.

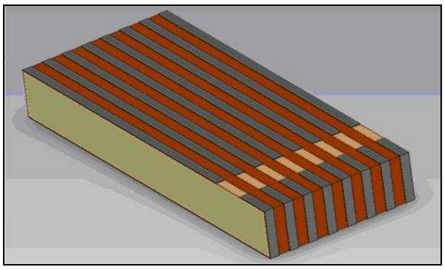

Figure 2. Schematic view of a piezo-composite patch featuring 8 elements.

The selective reception technique is based on the knowledge that the modes propagate at different speeds. The piezo-composite receives several signals from different positions on the structure. By simple processing of those signals, it is possible to distinguish waves propagating at different velocities. This is done by summing the different signals received with a delay corresponding to the time of propagation of the selected wave from one element to the next. This technique filters out the undesired waves by virtually creating destructive interferences, and amplifies the interesting wave by virtually creating constructive interferences.

1.3 *Modelling*

A FEM model of the piezo-composite was built and simulated with the ATILA software (Cedrat 2005). The piezo-composite targeted features eight channels, and has a mechanical resonance frequency at 500 kHz. This FEM model is shown on Figure 3.

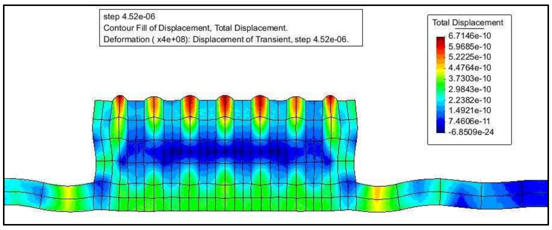

Figure 3. FEM model of the piezo-composite patch.

With this FEM model, transient simulations of the selective reception technique were performed. It was shown that this technique was theoretically able to amplify the waves for the mode and direction selected.

2 DESIGN AND MANUFACTURING OF THE PIEZO-ARRAY PATCH

2.1 *General features of the piezo-composite patches*

With encouraging results obtained in simulation, the objective was to obtain a proof of concept with practical tests. A piezo-composite patch was designed and manufactured based on the model and the dimensions are given in Figure 4.

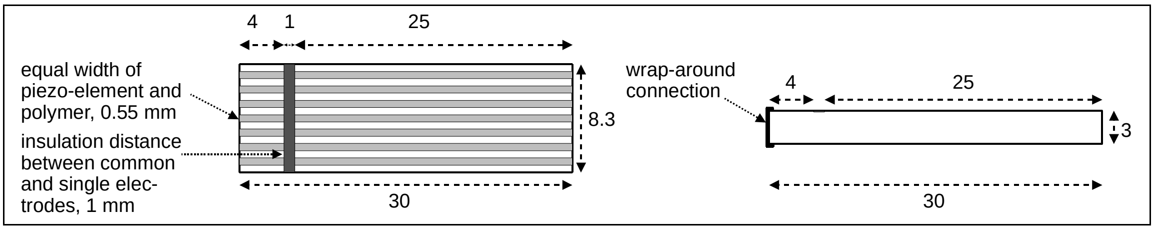

Figure 4. Schematic representation of the the piezo-array patch, top view (left) and side view (right). All dimensions are in millimeters. The common electrode on the bottom side is connected to the top side with a wrap-around connection.

The spacing between the piezo-elements was chosen to be equal to the element width and gaps have been filled with a stiff polymer. In order to be able to make electrical contact to the common bottom electrode, a wrap- around connection has been made to the top. The major part of the manufacturing of the piezo-composite patch was done by Meggitt A/S which has experience in piezo-patches (Lou-Møller et al. 2007). The manufacturing process was developed in close cooperation between Cedrat Technologies and Meggitt A/S. The resulting samples of piezo-composite are shown on Figure 5.

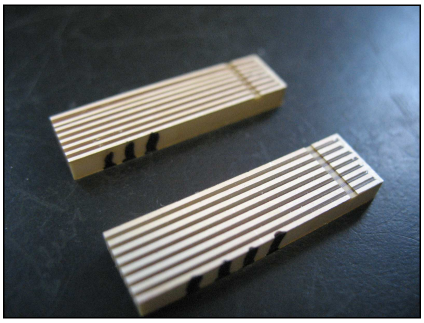

Figure 5. Piezo-composite samples used for the tests.

On the different samples, the resonance frequency is measured around 530 kHz, which is not far from the simulation which predicted 500 kHz. The capacitance of the single elements of the piezo-composite is approximately 60pF. The characteristics of the piezo-composite patches are compared, and it is found that there is a good repeatability between their frequency responses, see Figure 6.

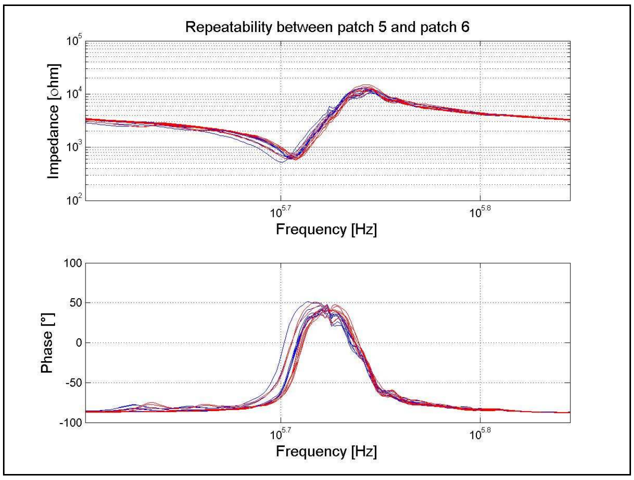

Figure 6. Frequency response of the eight elements for the piezo-composite samples n°5 (blue curves) and n°6 (red curves).

2.2 *Integration*

It is required to achieve high robustness and reliability of the Structural Health Monitoring system as this system should last the life time of the structure. This means that the integration of the piezo-composite on the structure is a critical step. In addition, the integration should be eased for the applications in the industry. The samples are bonded on the structure, and the wire connections are made to the electrodes. A good bonding is important to obtain a good coupling between the patch and the structure, as well as a high robustness. A flex-PCB that can be soldered directly on the electrodes was designed in order to achieve high reliability and to ease the integration, as shown on Figure 7.

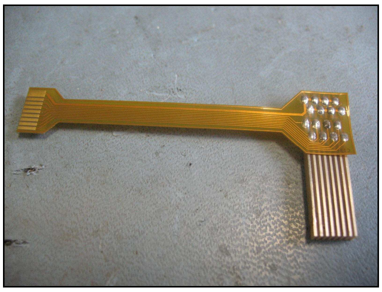

Figure 7. Integration of the flex PCB on a piezo-composite sample.

A manual wiring of the electrodes is time consuming and offers poor reliability. The samples of the piezo-composite were integrated on aluminium test plates, where their functionality could be assessed. Two piezo-composite patches are placed on a plate, so that the transmission of the waves from one patch to the other can be studied. Figure 8 is a picture of the piezo-composite patches after mounting on the aluminium test plate.

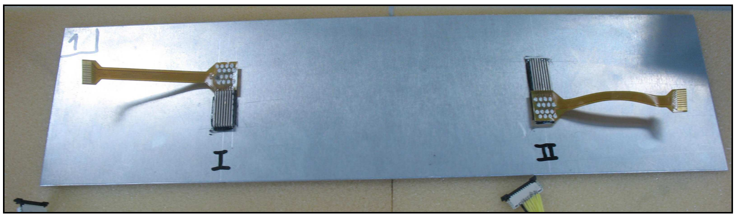

Figure 8. Picture of an aluminium test plate with integrated piezo-composite patches.

After integration on the aluminium test plates, the piezo-composite patches are characterized again on Figure 9. It is found that the resonance frequency has increased to 560 kHz. This increase is attributed to the parasitic stiffness of the bonding, plate, and flex PCB. Another consequence of the integration is that the quality factor of the resonance frequency has dropped, which means that there is a good coupling between the patches and the aluminium plate.

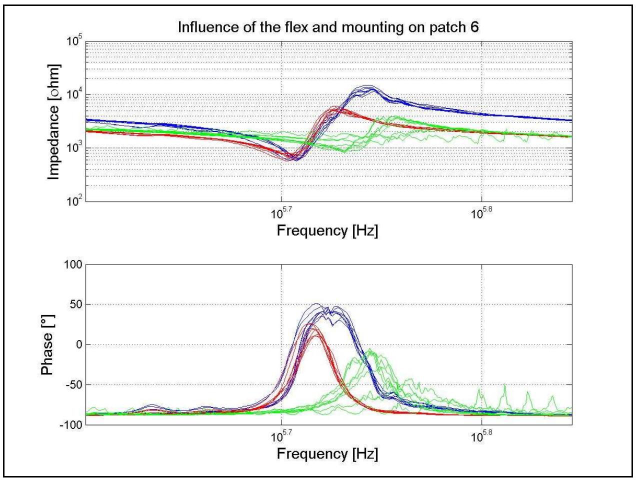

Figure 9. Impedance of the patch n°5 before and after integration. Blue curves before integration, red curves after placing the flex PCB, green curves after integration completed.

3 ELECTRONICS

For the purpose of driving and sensing the signals on piezo-patches, a specific electronic board was designed by Cedrat. This board, named LWDS45-2 (Cedrat 2009), is shown on Figure 10.

Figure 10. Picture of a rack with two LWDS45-2 modules, i.e. multi-channel drive and sense electronic for piezo-patches.

The LWDS45-2 electronics are designed to be versatile in order to fulfill the specific needs of the SHM domain. A LWDS45-2 features four independent channels. Each channel of the LWDS45-2 features a power amplifier that can drive piezo-electric patches up to 10nF at 30Vpp, with a bandwidth up to 2 MHz depending on the load. There is a low-noise conditioning unit with selectable gain to monitor the signals received on the patches. The LWDS45-2 offers the unique functionality, called PULSECHO, of being able to switch a patch from excitation to reception mode (and reciprocally) in less than 1µs. This allows to send a signal with a patch, and to monitor the echo of the signal on the exact same patch. This functionality is controlled through a logic input. The structure of a channel of the LWDS45-2 is presented on Figure 11.

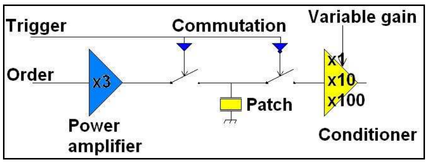

Figure 11. Structure of a channel of the LWDS45-2.

The LWDS45-2 offers modularity, several LWDS45-2 can be plugged in a rack to obtain more channels if desired. There is also the possibility of integrated solutions, as the LWDS45-2 features a daughter board that can be used as embedded board, as shown on Figure 12.

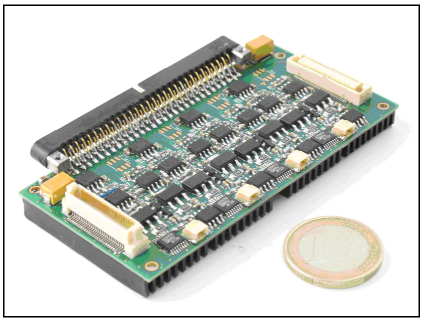

Figure 12. 4-channels PULSECHO amplifier. Daughter board or embedded board.

With this multi-channel architecture, the LWDS45-2 is ideally suited for applications using piezo-composite arrays.

4 PRACTICAL RESULTS

After the integration of the patches on the test plates, tests are run on the plates to verify that the mode and direction selectivity of the Lamb waves can be applied in practice.

4.1 *Test setup*

The LWDS45-2 electronics are used for the emission and reception of the waves on the piezo-elements. One piezo-composite is used for the emission of the acoustic wave. It has its elements driven independently, and it is excited with sine bursts at 600 kHz windowed by a Hanning function. Those signals are generated with LWDS45-1 electronics (Debarnot et al. 2006), and fed to the LWDS45-2 for driving the piezo-composite elements. The delay between the signals emitted can be adjusted by steps of 33ns, as shown on the Figure 13. With the proper delay, mode selection at emission can be achieved.

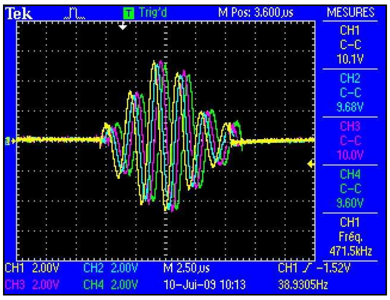

Figure 13. Four excitation signals to obtain selective emission.

The second piezo-composite is used in reception. The consecutive elements of the piezo-composite are paired two by two so that only four channels are sufficient to sample the signals received. An oscilloscope with four channels is used to sample the signals received. The test setup is presented on Figure 14.

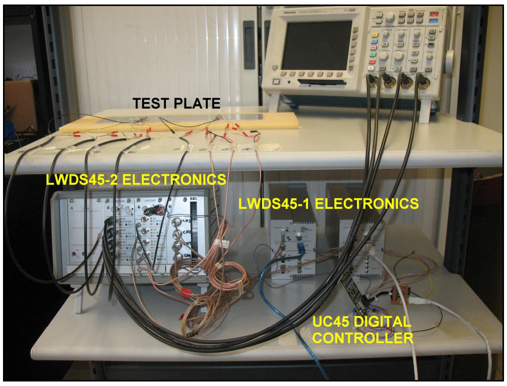

Figure 14. Photo of the test setup.

After the sampling of the received signals with the scope, they are extracted to be processed offline. The distance between elements is fixed by the design of the piezo-composite. The speed of propagation of the A_0 and S_0 modes can be computed knowing the material and thickness of the plate. Thus, the delay to apply for the mode and direction selection on emission and reception can be easily computed as $T_{delay} = Pitch / Speed$.

4.2 *Performance of the wave focusing techniques*

Tests are performed on the aluminium test plates to verify that the wave focusing methods (or selective techniques) can amplify the selected mode. Particularly, the tests are focused on the S0 mode, which presents an strong interest. The Figure 15 shows the comparison of the signal received when no mode selection is applied (blue curve), and when the S_0 mode is selected at emission and reception (green curve).

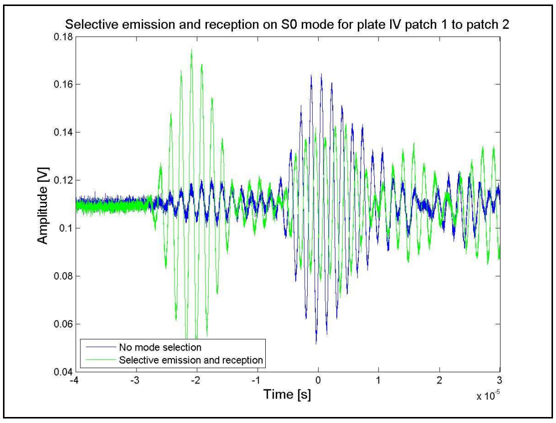

Figure 15. Performance of the mode and direction selection techniques with S0 mode.

As it can be seen on the previous figure, applying the mode selection techniques allows to amplify significantly the S_0 mode, and to attenuate the A_0 mode. This means that the mode and direction selection techniques are functioning in practice for choosing the S_0 mode, so that it can be easily detected.

4.3 *Application to defect detection*

The objective of the mode selection technique is to amplify the S_0 mode so that the influence of a defect can be more easily detected. In the tests presented here, the detection system is parameterized to focus on the S_0 mode. At first, reference measurements are taken without defect. Then, a hole of increasing size simulating original crack is drilled between the two patches. Finally, the hole is extended on both sides to simulate the crack’s growth. Measurements are taken with this pseudo-defect, and compared with the measurements without defect on the Figure 16, to verify if the system is capable of detecting the defect.

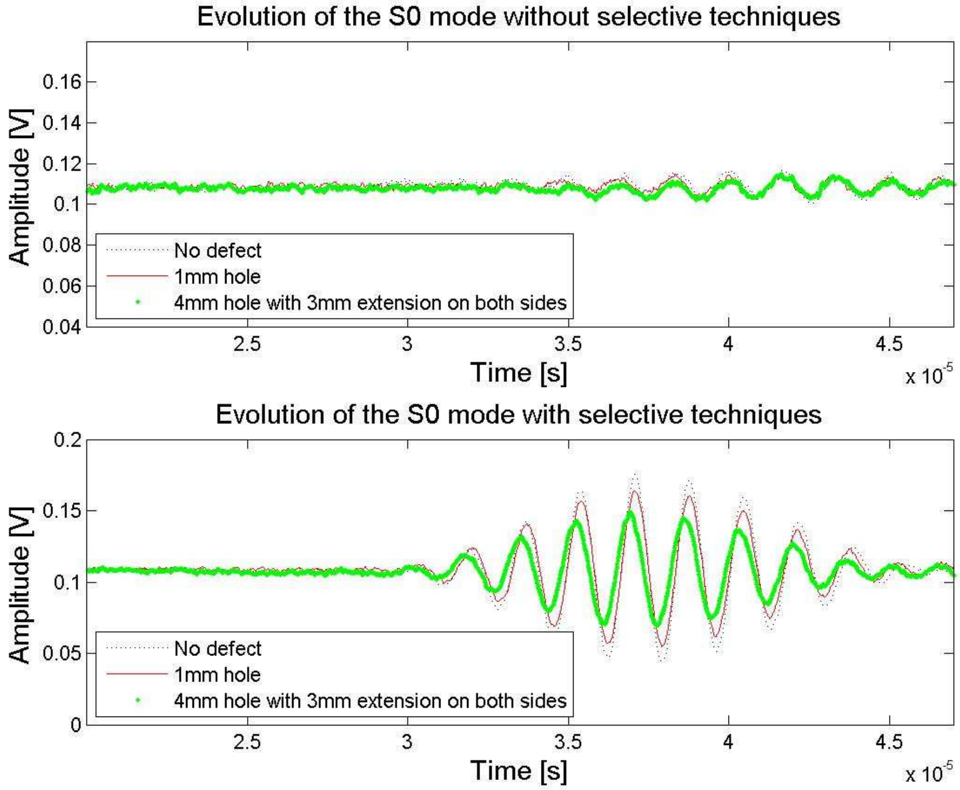

Figure 16. Transmitted S_0 mode without (top) and with (bottom) selective techniques in 3 case: No defect, 1mm hole, and 4mm hole.

The previous figure shows that when no selective technique is applied, the S_0 mode is drown in the noise and its evolution with the appearance of a defect is difficult to assess. With the selective techniques applied, the S_0 mode is taken out of the noise, and its evolution with the appearance of a defect can be quantified. In that case, it is looked in the amplitude of the transmitted S_0 wave, which is the most straight forward way to see if something is changed, even though it is very sensitive to many other parameters (temperature, strain, humidity, ageing…). From the Figure 16, it is noticed that the amplitude of the S_0 mode decreases with the appearance of the defect, and the influence of a 1mm hole can be detected.

5 CONCLUSION

It was shown that a smart detection system can be built using the piezo-composite patches together with the proper drive electronics. Using this smart detection system with the proper drive signals and signal processing allows obtaining mode and direction selection at emission and reception of the S_0 mode. This means that the S_0 mode received is significantly amplified when selected by the detection system, and it can be used for defect detection. Thanks to the wave focusing technique, the influence of a 1mm hole can be detected. When comparing with the detection when the wave focusing is not applied, it is difficult to assess the changes of the S_0 mode. Those results show that the wave focusing technique enhances considerably the sensitivity of the detection system to the presence of defects.

6 ACKNOWLEDGEMENTS

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