SMART DETECTION SYSTEM BASED ON PIEZO-COMPOSITE TRANSDUCERS FOR SHM APPLICATIONS

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Abstract

Ultrasonic-based SHM (Structural Health Monitoring) applications commonly rely on the use of piezoelectric patches to emit and receive ultrasonic waves. The objective is to study the propagation of the waves through a structure to assess its structural integrity. Because of the elevated number of echoes and possible modes of propagation of the waves within the structure, those applications suffer from a burden of signal processing. This paper presents a smart detection system based on piezo-composite transducers together with specific electronics that was developed and successfully tested for reducing the complexity of the SHM detection schemes by selecting the mode and direction of the Lamb waves received. The piezo-composite is composed of a row of eight independent ceramic pillars separated with polymer, so it is a 1-D array of independent piezo-patches. Used with adequate electronics and signal processing, it was shown that it allowed selecting direction and mode of the Lamb waves. The selective techniques are based on the knowledge that the modes of the Lamb waves propagate at different speeds. As the piezo-composite emits or receives eight signals from eight positions on the structure, it is possible to distinguish waves propagating at different velocities.

Keywords SHM, NDT, piezo-patches, piezo-composite, piezoelectric transducer array, ultrasonic methods.

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 piezoelectric transducers attached to the structure. 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 wave, also known as plate waves, cf. Fig. 21. 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 symmetric mode, the A_0 mode is the anti-symmetric 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.

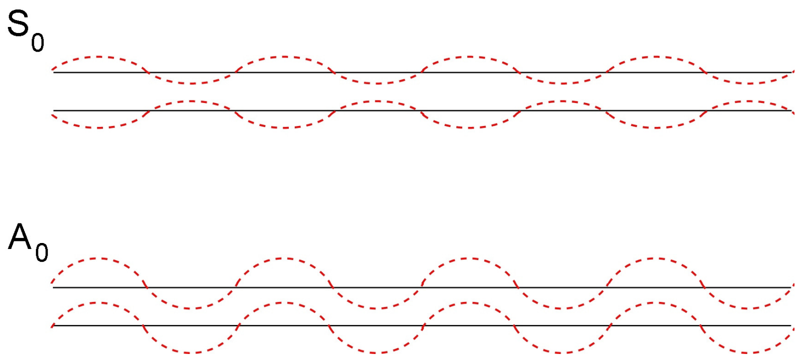

Fig. 1. Lamb waves in a thin plate: symmetrical S_0 and antisymmetrical A_0.

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 Fig. 2.

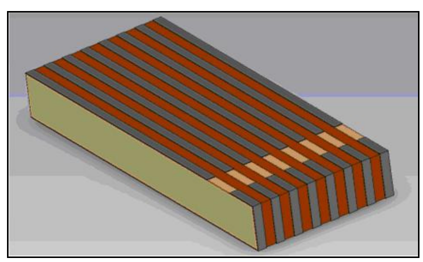

Fig. 2. Schematic view of a piezo-composite patch featuring 8 elements.

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 up 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 Fig. 3.

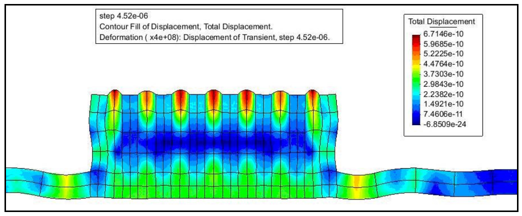

Fig. 3. FEM model of the piezo-composite patch.

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 Fig. 3.

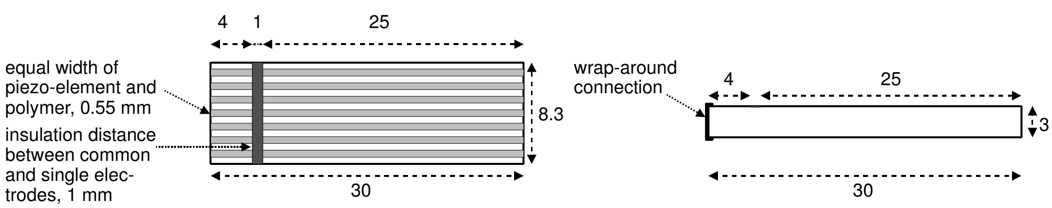

Fig. 4. Schematic representation of the the piezo-array patch, top view (left) and side view (right). All dimension are in millimeters. The common electrode on the bottom side is connected to the top side with a wrap-around connection.

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 Ferroperm Piezoceramics which has experience in piezo-patches (Lou-Møller *et al.*, 2007). The manufacturing process was developed in close cooperation between Cedrat Technologies and Ferroperm Piezoceramics. The resulting samples of piezo-composite are shown on Fig. 5.

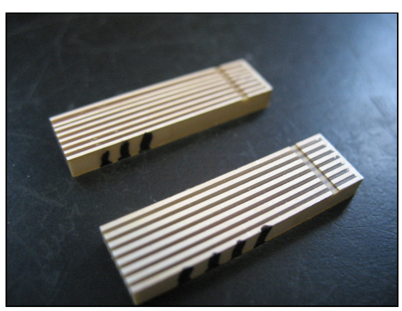

Fig. 5. Piezo-composite samples used for the tests.

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 60 pF. The characteristics of the piezo-composite patches are compared, and it is found that there is a good repeatability between their frequency responses (Fig. 6).

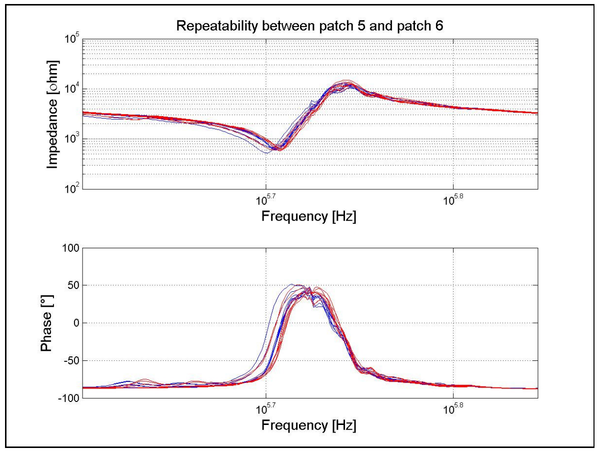

Fig. 6. Frequency response of the eight elements for the piezo-composite samples n°5 (blue curves) and n°6 (red curves).

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 (Fig. 7).

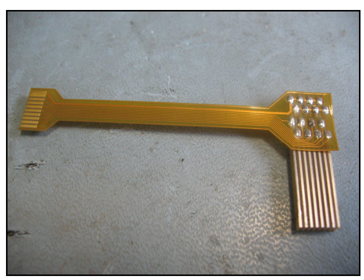

Fig. 7. Integration of the flex PCB on a piezo-composite sample.

A manual wiring of the electrodes is time consuming and offers poor reliability. The samples of the piezo-composite were integrated on aluminum 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. Fig. 8 is a picture of the piezo-composite patches after mounting on the aluminum test plate.

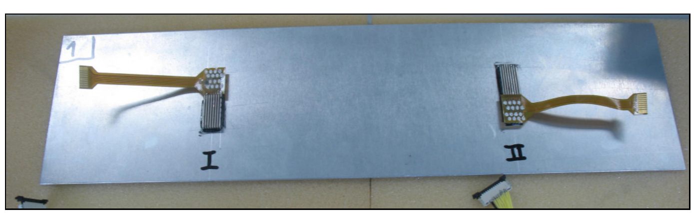

Fig. 8. Picture of an aluminum test plate with integrated piezo-composite patches.

After integration on the aluminum test plates, the piezo-composite patches are characterized again (Fig. 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 aluminum plate.

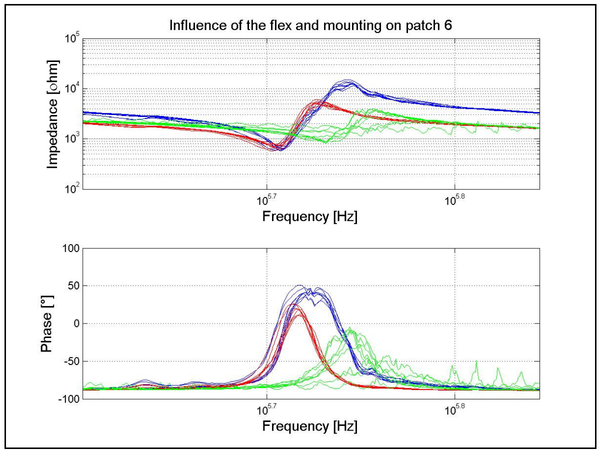

Fig. 9. Impedance of the patch n°5 before and after integration. Blue curves before integration, red curves after placing the flex PCB, green curves after integration completed.

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 Fig. 10.

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

The LWDS45-2 electronics are designed to be versatile in order to fulfil 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 10 nF at 30 Vpp, 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 1 µs. 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 Fig. 11.

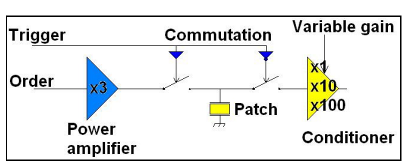

Fig. 11. Structure of a channel of the LWDS45-2.

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 Fig. 12.

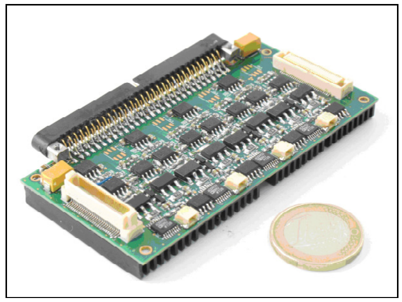

Fig. 12. 4-channels PULSECHO amplifier. Daughter board or embedded board.

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

4. Practical Tests

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 all its elements connected together so that it reduces to the case of a bulk patch. The excitation signal is a sine burst at 600 kHz windowed by a Hanning function. This signal is generated with LWDS45-1 electronics (Debarnot *et al.*, 2006), and fed to the LWDS45-2 for driving the piezo-composite. 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 Fig. 13.

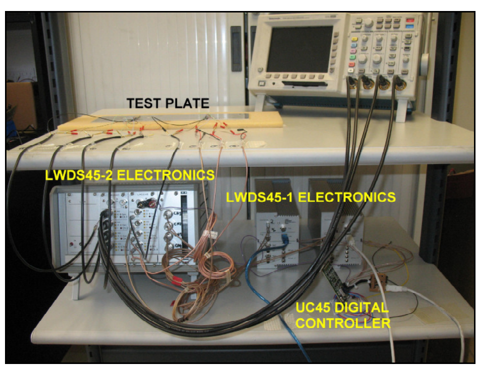

Fig. 13. Photo of the test setup.

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 selection can be easily computed as $T_{delay} = Pitch / Speed$.

4.2. *Test results*

The test is run for selecting the S_0 mode. The signals received are used to reconstruct the interesting signal with the selective reception technique. The signal reconstructed with proper delay is compared with the signal reconstructed without delay, which is equivalent to the case of a bulk patch. The result of this comparison is shown on Fig. 10.

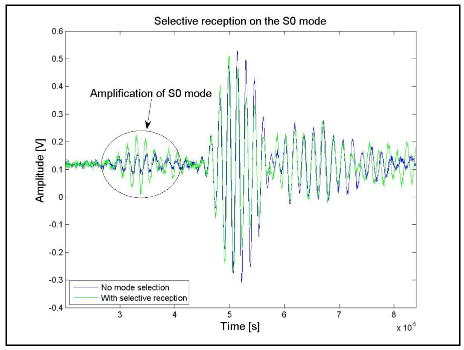

Fig. 14. Performance of the selective reception technique with the S_0 mode.

As can be seen on the previous figure, the selective reception technique improves significantly the quality of the signal due to the S_0 mode. The S_0 mode is amplified when the selective reception technique is applied. The same test can be run for the selection of the A_0 mode, and the results are similar. The application of the selective reception technique to the A_0 mode allows amplifying it, as it can be seen on the Fig. 15.

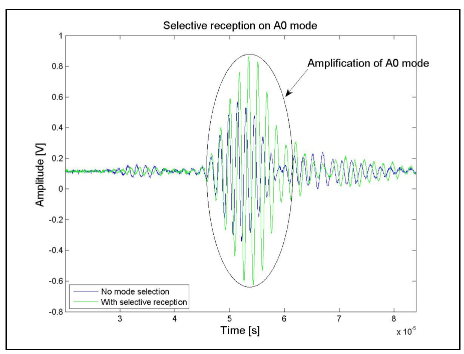

Fig. 15. Performance of the selective reception technique with the A_0 mode.

5. Piezo-Composite patch as a smart transducer

It has been shown that the piezo-composite patch can be used as a smart sensor to select the acoustic waves at reception. Work has also been carried out to use the patch as a smart actuator, to select the mode and direction of propagation at emission. A technique similar to that of the selective reception can be applied at emission to choose the mode and direction of propagation. The principle is to generate the same signal on the different elements of the piezo-composite, but with a particular delay. This delay corresponds to the time of propagation of the wave at desired speed from one element to the next, i.e. the same delay as for selective reception. In that case, the technique will create real destructive interferences in the medium of propagation (here the aluminium plate) for the undesired waves, and real constructive interferences for the interesting wave.

A LWDS45-2 is used for the emission, with four independent channels at emission, each driving a pair of elements. The delay is set with a UC45 digital controller that triggers the channels of the LWDS45-1 to generate the appropriate signals. Fig. 16 shows an example of the signals generated on the piezo-composite to achieve selective emission.

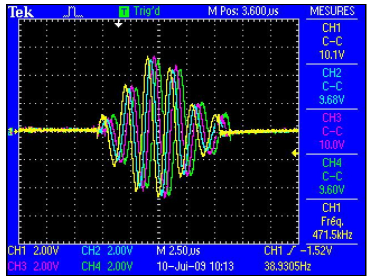

Fig. 16. Four excitation signals to obtain selective emission.

Tests are run with the emitting patch using the selective emission technique to select the S_0 mode, in the direction of the receiving patch. The receiving patch uses the selective reception technique for the S_0 mode coming from the emitting patch. By combining the two techniques simultaneously, the mode and direction selection is significantly improved, as shown on Fig. 17.

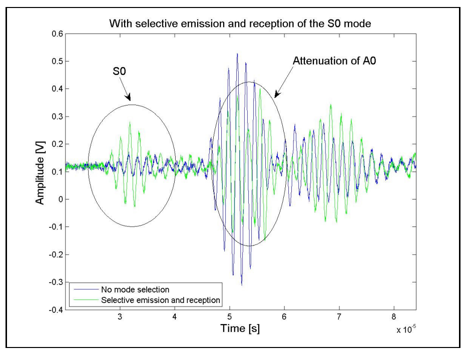

Fig. 17. Performance of the mode and direction selection techniques with S_0 mode.

The use of the two selective techniques significantly amplified the S_0 mode so that it can easily be detected, and the A0 mode was attenuated. Its properties can be studied to detect the presence of a defect on the surface of transmission, i.e. between the patches. It is also possible to use the combination of the two techniques for selecting the A_0 mode, as it can be seen on the Fig. 18.

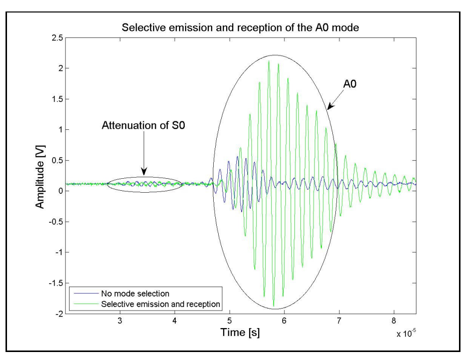

Fig. 18. Performance of the mode and direction selection techniques with A_0 mode.

6. Conclusion

A piezo-composite patch featuring eight independent elements was simulated, designed, and finally tested in practice. A smart detection system featuring piezo-composite patches together with the specific electronics developed was built. Using this smart detection system, the concept of selection of the mode and direction of propagation of acoustic waves was applied. It was shown that the selective techniques allow to amplify significantly the chosen mode in the direction considered. This helps reducing the complexity of the ultrasonic-based SHM detection schemes.

7. Acknowledgements

The research leading to these results has been carried out in the frame of the AISHA II project, which has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n°212912.

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