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Optimized piezoelectric sensor for a specific application: Detection of Lamb waves

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This work is devoted to the development and the optimization of a new piezoelectric sensor using Lamb waves destined to aerospace structures health monitoring. In such systems, Lamb waves are usually excited and received by thin single piezoelectric transducers. One of the most critical tasks in health monitoring is to identify all the generated Lamb waves in order to ease the damage estimation. A possible solution is to measure the Lamb wave signal at different locations along the propagation direction. So, the development of a distributed sensing technology using metallic multi-electrode deposited on a piezoelectric substrate was a key element, which built the bridge between the sensors signals and the structural integrity interpretation.

Firstly, the various manufacture stages of this new sensor by the tape casting technique were reported. Secondly, piezoelectric properties of this sensor were measured by the electrical resonance technique. The sensitivity of this new sensor to the multi-wave generation and the damage detection were then further demonstrated in the case of an aluminum plate.

Keywords: PZT; Tape casting; Multi-electrode sensor; Lamb waves; Damage detection

1. Introduction

Various technologies and sensing techniques for damage detection in metallic and composite materials were developed for recent years, in particular, new techniques using integrated detection systems to perform continuous and in service monitoring for aircraft maintenance [1–5]. These technologies use either optical fibers or transducers composed of classical piezoelectric materials (PZT or PVDF) to produce Lamb waves into the structures to be inspected [6].

The damage detection is traditionally carried out by analyzing the modifications in the received Lamb wave signals. However, due to the multi-mode and dispersive nature of the Lamb waves, the interpretation of the received signal is not always obvious [7].

Indeed, the major problems in using such techniques for realistic structures are to be able first to generate and receive specific Lamb modes and second to find solutions in order to ease the signal analysis.

To answer to the first point, Monkhouse et al. [4] designed PVDF devices to generate selected Lamb waves in plates of different thickness and materials. In the same way, Zhu and Rose [8] utilized time-delay periodic linear array (TDPLA) composed of PZT elements mounted on a thin polymer substrate to provide a better mode control. This technique gave promising results for unidirectional monitoring of isotropic plates. More recently, Giurgiutiu [9] proposed to enhance the monitoring strategy by using piezoelectric wafer active sensors (PWAS) phased arrays in order to cover a large surface area through beam steering. This concept was called “embedded ultrasonic structural radar” (EUSR). The EUSR methodology was successfully tested for the detection of broadside and offside crack in a large plate.

Concerning the second point, the solution investigated was to improve the damage identifications by using advanced

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signal processing at the reception. For example, Paget et al. [10] developed an automatic signal processing technique based on wavelet analysis to detect damage in composites. In a recent study [11], the authors demonstrated the interest of using a linear array instead of a single element in reception. Indeed, by measuring the Lamb wave signal at different positions along the Lamb-waves propagation, it allows to identify all the generated Lamb modes by applying on the recorded signal a spatial and temporal Fourier transform (2D-FT) [12]. Although, this technology already gives concluding results, designing better transducers array is the critical issue for improving the quality of the Lamb mode analysis. Indeed, the use of linear array is limited since the presence of these surface-bonded elements may constitute a local heterogeneity and could result in perturbations in the waveforms measured by the receiving array [13].

In this paper, the objective was to develop a new monolithic sensor constituted of 32 metallic electrodes (multi-electrode) deposited on only one PZT substrate in order to replace the linear array in reception. The most adapted process to manufacture this type of sensor is based on a tape casting technique [14–17]. It allows the realization of thin (between 40 and 1000 μm) and large sheets, which are not easy to obtain by the traditional ceramic techniques. Section 2 gives a description of the various manufacture stages of this sensor. Then, Section 3 is devoted to the characterization of the PZT material. The signal-to-noise ratio depends naturally on the PZT characteristics. In Section 4, an experimental analysis using this device as receiver in an aluminum plate is performed and compared to the results obtained with the linear array. The sensor sensitivity as function of a hole size is presented.

2. Device elaboration and microstructural characteristics

Tape casting technique is one of the most prominent techniques for thin flat ceramic sheets. It is used to produce electronic substrates, multilayer capacitors and ultrasonic devices.

Tape casting slurry is prepared by powder dispersing in an organic solvent in presence of several organic species such as dispersants, binders and plasticizers. The solvent used in this work is an azeotropic mixture of MEK–ethanol (i.e. methylethylketone–ethanol). The dispersing agent was the phosphate ester (Beycostat C213 CECA, France). The polyvinylbutyral resin (PVB, Butvar B98 Monsanto) and the dibutylphthalate (DBP, Aldrich Chemical) were used as binder and plasticizer, respectively. They provide a good cohesion to the green sheet and flexibility necessary to its manipulation. The composition used in this study is shown in Table 1.

The tape casting slurry is prepared in two steps (Fig. 1). Firstly, the PZT powder was deagglomerated and dispersed in solvent with the dispersant by ball milling. A uniform dispersion of powder in the ceramic slurry is needed to assure its stability and the production of a quality product. With micron and submicron-size powder, the dispersing agent must be added to prevent the particle agglomeration caused by the strong electrostatic forces associated with these high surface area-to-mass ratio materials [14]. Secondly, the binder and plasticizer were

Table 1
Slurry composition

Ingredient	Function	wt. %
PZT ^a	Ceramic powder	73.6
MEK–ethanol	Solvent	20
Phosphate ester	Dispersant	0.4
DBP	Plasticizer	3
PVB	Binder	3

^a The PZT stoichiometry is: $\text{PbZr}_{0.58}\text{Ti}_{0.42}\text{O}_3$ (confirmed by the X-ray diffraction measurement, ICDD card number 73-2022).

added and the slurry was mixed for 4 h to achieve a good homogeneity. These milling operations were carried out with a planetary ball milling.

The slip was, then, poured into the casting bench tank and cast, at ambient temperature, onto a polymeric film displacing thanks to an electric engine.

The relative movement of the polymeric film with regard to the tank and the blade height adjustment allow to achieve a green ceramic sheet with a uniform thickness. After the solvent evaporation, the tape was cut and shaped according to the required dimensions. A heat treatment was performed at 400 °C for 1 h and at 1100 °C for 6 h for de-binding and sintering, respectively.

This thermal treatment was specifically devoted for the used powder. It was conducted with a protective powder bed, which is optimized on chemical point of view to assure an atmosphere enriched in PbO vapor. This atmosphere drastically limits any loss of lead oxide from the sample during sintering. The densification level was estimated by means of bulk density measurements and microstructure observations by SEM. Relative density was estimated to be more than 98% of the theoretical one. Figs. 2 and 3 present a cross-section rupture facies and some details of the microstructure. On this cross-section, it can be seen that the microstructure is dense and regular. No evidence of packing fault is observed confirming that tape casting and sintering steps have been well conducted.

On the right and bottom of this rupture face, it can be pointed out some indices of a subcritical growth of flaw. This behavior could be related to some grain boundaries corrosion due probably to the lead oxide excess present in the grain boundary.

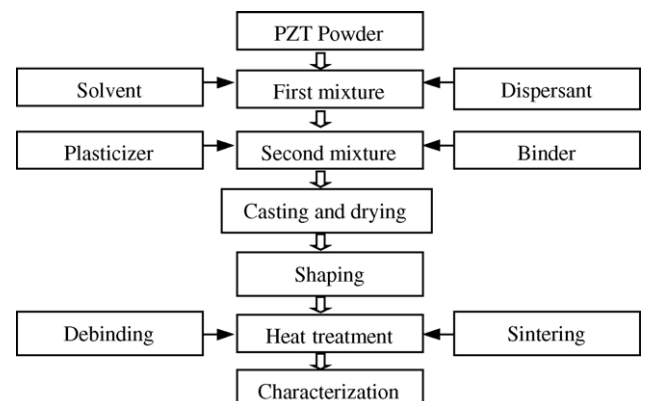


Fig. 1. Flowchart of the procedure used for the samples' preparation.

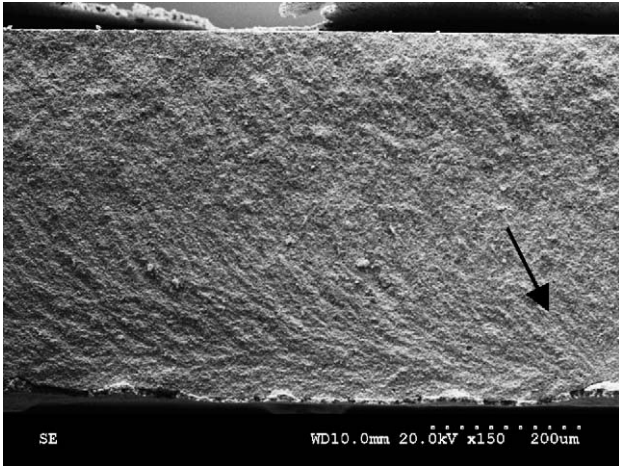


Fig. 2. SEM observation of a fracture of as prepared PZT device after sintering.

Fig. 3 shows some details of this fracture. The fracture mode is almost purely intergranular. This SEM observation confirms the high densification level of the ceramic.

Such low level of porosity (<2%) cannot be easily observed on a cross-section. It can be postulated that at this level of densification rate, this closed porosity is spherical and located at triple point. Grain population seems homogeneously distributed. Their size is around 1 μm .

After sintering, silver electrodes were, then, deposited on the two sample faces by screen-printing technique. The silver paste was dried at 150 $^{\circ}\text{C}$ for 15 min and fired at 600 $^{\circ}\text{C}$ for 2 min.

The original sensor developed in this paper is constituted of a PZT substrate with a succession of electroded and unelectroded surfaces. The dimensions of this substrate are 70 mm \times 15 mm with an average thickness of 1 mm \pm 30 μm . The width of each electrode is equal to 1 mm with an inter-electrode distance of 1 mm (Fig. 4).

With the same procedure, other PZT plates were also manufactured and used for the generation of Lamb waves (see Section 4).

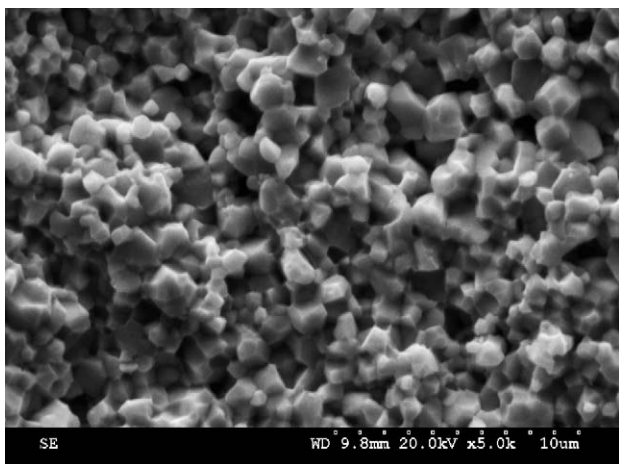


Fig. 3. SEM observation of the microstructure of as prepared PZT device.

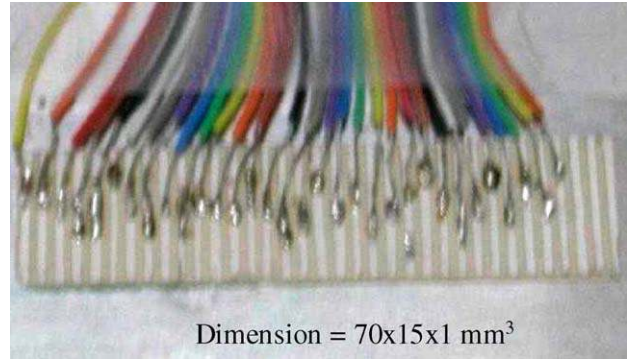


Fig. 4. Multi-electrode used as receiver.

3. Poling, dielectric and piezoelectric measurements

The PZT, initially ferroelectric, becomes macroscopically piezoelectric by the application of a high electric field (polarization) across the ceramic. The poling process involves realignment of the dipoles in the direction of the field. The poling apparatus consists of an oil bath and an external power supply; the voltage was applied stepwise until the maximum field was reached (between 32 and 35 kV/cm). The polarization graph versus applied field, measured on one electrode of developed sensor, is presented in Fig. 5. After removal of the electric field there is a remanent polarization $P_r = 17 \mu\text{C}/\text{cm}^2$ in the ceramic, which is responsible for its piezoelectric properties. The coercive field $E_c = 11.7 \text{ kV}/\text{cm}$ is the necessary external electric field for the reorientation of the ferroelectric dipoles.

The piezoelectric properties of the sensor are estimated by the characterization of samples with simple geometry (discs and plates). These piezoelectric parameters are measured by the electrical resonant method, at room temperature, by using the resonance and anti-resonance frequencies, which correspond to the minimum and the maximum of the electric impedance, respectively [18–20]. The electrical measurements were carried out using Hewlett Packard model HP 4194A impedance analyzer

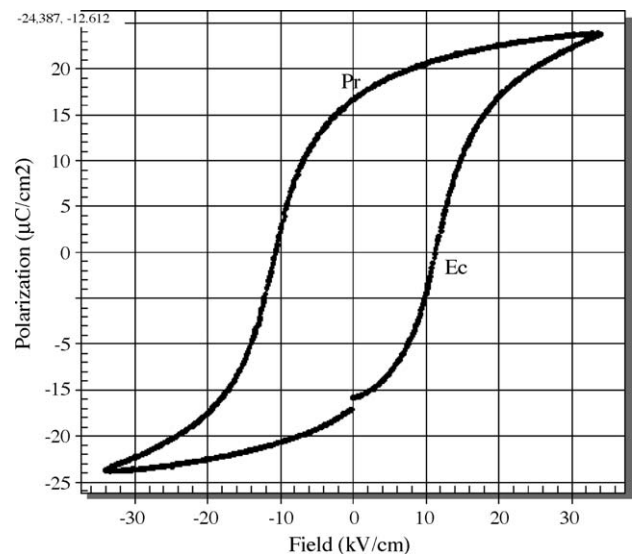


Fig. 5. Polarization vs. applied field.

Table 2
Main characteristics of used material

Dielectric properties		Electromechanical properties						
K_{33}	$\tan(\delta)$	k_p	k_t	k_{31}	d_{33} (pC/N)	d_{31} (pC/N)	g_{33} (mV m/N)	g_{31} (mV m/N)
3000	0.025	0.57	0.49	-0.34	450	-230	16	-8

controlled by a computer. This computer allows the acquisition of the electrical impedance magnitude $|Z|$ and phase angle Θ of the samples at different modes (radial mode for discs and lateral mode for plates).

The main characteristics of the material used for the specific sensor fabrication are reported in Table 2. The presented values are an average of measurements taken on six samples. The obtained piezoelectric values (coupling factors k , charge coefficients d and voltage coefficients g) demonstrate that this ceramic is useful as starting material for good sensitivity in transmitting and receiving transducers [20]. The relative dielectric constant K_{33} and the dielectric dissipation factor $\tan(\delta)$ were measured at 1 kHz. The charge constant d_{33} was measured by a d_{33} -piezometer system (Take Control PM 37) at 112 Hz.

4. Application

4.1. Lamb waves and 2D-FT

In order to identify the generated Lamb waves, the developed sensor was used at the reception. In harmonic regime at the frequency f_0 , each generated Lamb mode in the positive x direction and of wave number k_i can be expressed using the following relationship,

$$\phi_i(t, x) = e^{j(k_i x - 2\pi f_0 t)} \quad (1)$$

Nevertheless, the analyzed data measured by the sensor are usually characterized by numerical samples on the grid given by,

$$t = n \Delta t, \quad x = m \Delta d \quad (2)$$

where Δt and Δd are the temporal and spatial sampling, respectively and n and m are integers. This concept leads to numerical signals. Hence, substituting Eq. (2) into Eq. (1) yields,

$$\phi_i(n \Delta t, m \Delta d) = e^{j(k_i m \Delta d - 2\pi f_0 n \Delta t)} \quad (3)$$

Moreover, the wavenumber k_i and the frequency f_0 are replaced by the following expressions,

$$K_i = k_i \Delta d, \quad F_0 = f_0 \Delta t \quad (4)$$

where K_i and F_0 correspond to the normalized wave number and the normalized temporal frequency, respectively.

It is assumed, here, that around the excitation frequency, the effect of dispersion is relatively unimportant. Although this assumption is not strictly true, it is a reasonable approximation when the input signals are windowed tonebursts with a precise center frequency and limited bandwidth and the Lamb waves are barely dispersive around the excitation frequency [21]. In this case, the numerical transient Lamb wave response at the m th

electrode of the device may be approximated as:

$$\begin{aligned} s(n, m) &\approx \sum_i A_i e^{j(K_i m)} \eta(n, r_i, b_i, F_0) \\ &\approx \sum_i A_i \phi_i(n, m) w[(n - (m - 1)r_i - b_i)] \end{aligned} \quad (5)$$

where i corresponds to the number of the Lamb modes, η should be similar to the transient excitation signal of the Lamb wave generator (i.e. the product of the function w by the harmonic term at the normalized frequency F_0) and A_i , is the maximum amplitude of η at $n = (m - 1)r_i + b_i$. The time $[(m - 1)r_i + b_i]\Delta t$ is the time of flight of each Lamb mode i between the emitter and the m th electrode of the sensor. These terms are given by,

$$b_i = \frac{d}{\Delta t v_{gi}}, \quad r_i = \frac{\Delta d}{\Delta t v_{gi}} \quad (6)$$

where d is the distance between the emitter and the first electrode of the sensor, Δd the inter-electrode distance and v_{gi} the group velocity of the Lamb mode i .

The interest of using a multi-electrode in reception instead of a single element is the ability to analyze the Lamb wave propagation not only as function of time, but also as function of space. Hence, by applying the following Fourier Transforms on the time and space dimensions (2D-FT),

$$S(K, F) = \sum_{m=0}^M \sum_{n=0}^N s(n, m) e^{-j(Km - 2\pi Fn)} \quad (7)$$

where $F = f\Delta t$ and $K = k\Delta d$ are the normalized frequency and the normalized wave-number, respectively, Eq. (7) can be rewritten as:

$$\begin{aligned} S(K, F) &= W(F - F_0) \sum_i A_i \frac{\sin\left(\left[\frac{K - K_i + 2\pi(F - F_0)r_i}{2}\right] M\right)}{\sin\left(\frac{K - K_i + 2\pi(F - F_0)r_i}{2}\right)} \\ &\quad \times e^{-j[(K - K_i)(M - 1)/2 - \pi(F - F_0)(2b_i(M - 1)r_i)]} \end{aligned} \quad (8)$$

where W is the Fourier transform of w on the time dimension.

By taking the modulus of the 2D-FT at the frequency $F = F_0$ and considering that W is a rectangular window of length N_W , the amplitude of the Lamb wave signal can be described as function of the wave number:

$$|S(K, F_0)| = N_W \left| \sum_i A_i \frac{\sin\left(\left[\frac{K - K_i}{2}\right] M\right)}{\sin\left(\frac{K - K_i}{2}\right)} e^{-j[(K - K_i)(M - 1)/2]} \right| \quad (9)$$

Moreover, it can be noticed that the different maxima of the Eq. (9) occur when $K = K_i$. Knowing the theoretical wave number

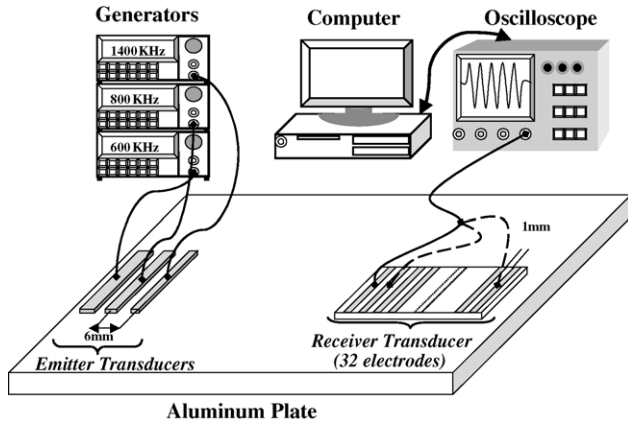


Fig. 6. Principle of experimental measurements.

of the Lamb waves, it is then easy to identify which modes are generated in the structure [11].

4.2. Characterization and instrumentation of the aluminum plate

During these experimental studies, the tests were performed on two aluminum plates of 500 mm length, 300 mm width and 3 mm thickness (Fig. 6). The emitter array consists of three piezoelectric elements with different widths. They have the same length and thickness, which are equal to 15 and 1 mm, respectively.

Their widths are 4, 2 and 1 mm, and their transverse resonance frequencies are equal to 350, 750 and 1500 kHz, respectively. These elements were stuck on the plate by keeping an inter-element distance of 6 mm. The excitation in phase of these elements by a 5 cycle sinusoidal tone burst at their resonance frequencies allowed to work on a wide frequency band and consequently to generate several Lamb modes.

At the reception, two configurations were proposed: one with the new developed sensor and the other with the multi-element

array used in a previous study [11]. The developed sensor was chosen to be able to receive all the resonance frequencies of the emitters. As shown in Fig. 6, 32 electrodes were deposited to allow the application of the 2D-FT with an inter-electrode distance of 1 mm. Concerning the multi-element array used for the second plate, each element was 15 mm × 1 mm × 1 mm in size and the inter-element distance was the same as for the multi-electrode sensor.

4.3. Comparison between the multi-electrode sensor and multi-element array

The Lamb wave signal emitted by the emitter array propagated along the plate and was received either on the different electrodes of the developed sensor or on the multi-element array depending on the plate which was tested.

After comparison of the received signals on both receivers, it can be seen (see Fig. 7) that the use of one piezoelectric substrate allows obtaining an equivalent electric response on each electrode contrarily to the multi-element array. Indeed, except the first element of the multi-element array, where the received signal is similar to that received at the first electrode of the developed sensor, a big decrease in amplitude occurs for the neighbouring elements. This problem may be due to possible conversions and reflections on each element.

4.4. Lamb wave identification

All the signals of the sensor were then recorded by a digital oscilloscope and transferred to a PC computer in which signal processing, i.e. 2D-FT, could be applied.

Fig. 8 shows the result of the 2D-FT of the received signal when all elements of the emitter array are excited in phase. The experimental points were determined by applying the 2D-FT based method presented in Section 4.1, i.e. by measuring the amplitude of the Lamb wave modes at different space positions, whereas the computed points (lines curves) were obtained

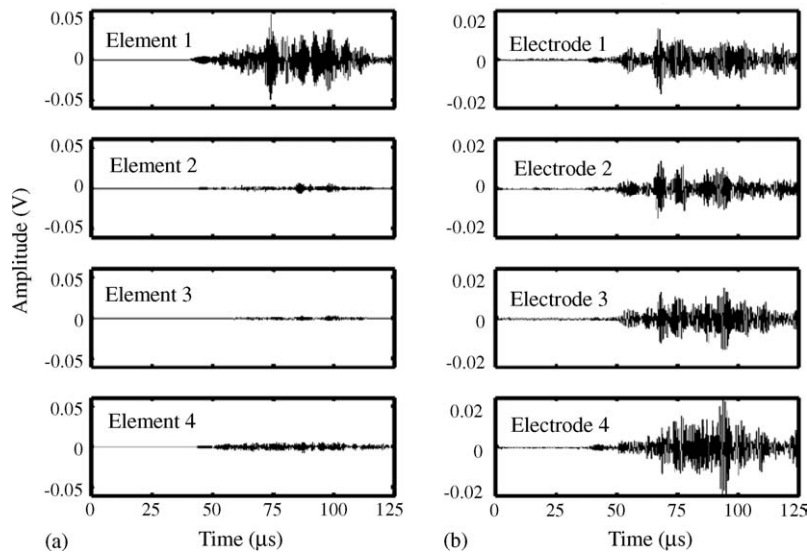


Fig. 7. Time domain signals recorded: (a) on the first four elements of the multi-element array and (b) on the first four electrodes of the multi-electrode sensor.

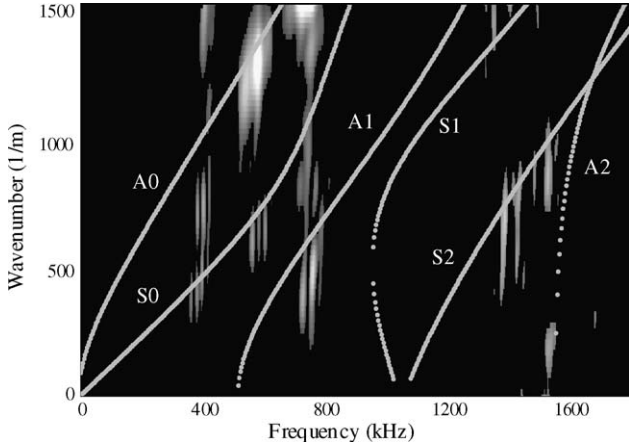


Fig. 8. 2D-FT of the generated Lamb waves by the three elements excited in phase.

by using the formalism of Viktorov [6]. The amplitude of each transmitted Lamb wave signal is here described in level of gray as function of the wave number k and the frequency f .

After comparison of the theoretical curves with the experimental results, five Lamb modes were identified. First, the A0 and S0 modes were excited in a frequency band varying between 300 and 700 kHz. The S0- and A1-modes were also identified but at higher frequencies, i.e. between 700 and 800 kHz. At last, the use of the emitter of 1 mm width allowed to generate two others modes, i.e. the S1- and the S2-modes around 1500 kHz. This result validates the choice of using a multi-element array to generate a Lamb wave signal with satisfactory amplitude on a wide frequency band.

Moreover, it is then shown that this new sensor can be used for the detection of Lamb waves in health monitoring application and likely more accurate and easier to use than classical multi-element receiver array [11].

4.5. Application to damage detection

In order to study the Lamb modes sensitivity to damage, a 1 mm hole was introduced in the plate center. Then, its diameter was increased from 1 mm until 13 mm. So, the 2D-FT of the received signal is obtained as function of the hole diameter.

To be sure to detect damage, a necessary condition but not always sufficient, is to select a Lamb-mode wavelength that is lower or equal to the size of the damage to be detected.

In this paper, only sensitivities of fundamental Lamb modes (i.e. A0 and S0) identified around the frequency 600 kHz (see Fig. 8) are shown. At this frequency, the wavelengths of the S0 and A0 modes are around 8 and 4 mm, respectively. Fig. 9 displays the variation of the normalized amplitude of the 2D-FT as function of the hole diameter for both A0 and S0 modes.

After analysis of the amplitude variations for these modes according to the hole size, it can be seen in Fig. 9 that each mode is sensitive to the damage. Indeed, the Lamb modes amplitudes decrease with increasing the size of the damage. Moreover, as

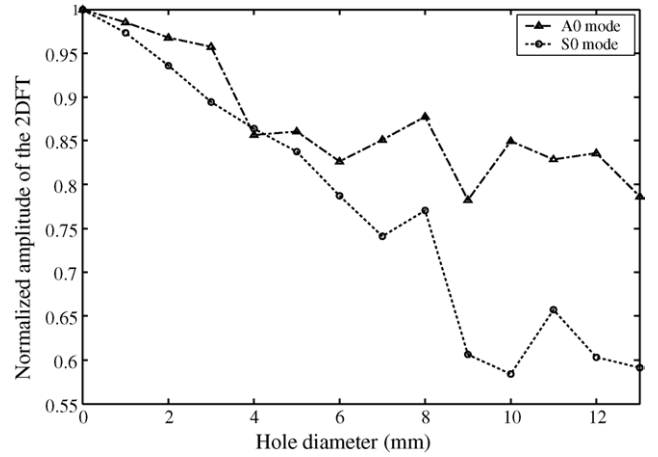


Fig. 9. Variation of the 2D-FT normalized amplitude of S0 and A0 modes as function of the hole diameter.

expected strong attenuation occur when the hole diameter is of the same order than the wavelength of the generated Lamb mode, i.e. around 4 mm for the A0 mode and around 8 mm for the S0 mode. Finally, the S0 mode seems to be more sensitive than the A0 mode, especially for hole size greater than 8 mm.

The hole being a three-dimensional damage, a better understanding of the mode sensitivity is, however, not possible without developing a numerical study.

Since all these measurements demonstrate the ability to detect damage, this new kind of sensor appears to be well suited for health monitoring applications.

5. Conclusion

In this work, a new sensor using metallic multi-electrodes deposited on a piezoelectric substrate has been especially designed and developed in order to detect Lamb waves generated by PZT transducers in aluminum plates. The process used for this device fabrication is the tape casting technique, which is adapted to manufacture large and thin piezoelectric sheets. The resonance method was used to characterize the PZT material. The obtained piezoelectric properties show that this material is adapted to the ultrasonic applications.

As for the multi-element array [11], the advantage of such a sensor is the ability to apply a 2D-FT on the received signals and thus to allow an easier Lamb mode identification. Moreover, this study demonstrates some significant improvements when using this new sensor compared to the multi-element array. First of all, the integration of this sensor becomes easier, since only one component has been realized and stuck on the structure to be monitored. Secondly, the use of only one piezoelectric substrate allows to get an equivalent electric response on each electrode, which eases the conditioning of the signal to be processed. Thirdly, the problem of possible conversions and reflections on each element that can be observed when using the multi-element array is now solved. Finally, the sensor sensitivity to Lamb wave variations in presence of damage has been demonstrated.

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Biographies

Mohamed Rguiti was born in 1973. He studied physics and materials and received a master's degree in physics in 1996 and a PhD degree in 2002 in the near-field acoustic technique. His major research interests include the development and characterization of PZT materials and their applications as sensors and actuators. He is currently Assistant Professor.

Sébastien Grondel was born in Tours, France, in 1972. He received the engineering degree from the Ensimév (presently Ensiamé) in 1996. He, then, received the DEA degree in solid and structures from the University of Valenciennes in 1997. He began to study for his PhD degree in 1997 at the Optical-Acoustical-Electronic Department of the IEMN Institute. After receiving his PhD in 2000 from the University of Valenciennes, he worked as a Research Associate until 2001, studying elastic guided waves in composite materials and focusing on health monitoring of aeronautic structures. Currently, he is an Assistant Professor in the same department and his research interests include the use of multi-elements in Ultrasonic inspection and their application to medical imaging and health monitoring.

Faysal El youbi was born in 1975. He studied electrical engineering and obtained a master's degree in NDT domain in 2000. Currently, he is a PhD student and its research field is about the use of signal processing techniques to evaluate the integrity of aeronautical structures.

Christian Courtois was born in Poitiers, France, in 1963. He studied chemistry and materials and received a master's degree in material sciences in 1988 and a PhD degree in 1992 in the material sciences and surface treatment at the University of Limoges. Since that date, his work is focussed on the synthesis of perovskite structure in powder form for electrical and piezoelectric applications (BaTiO₃, PZT). Currently, he also develops new shaping or finishing steps to realize improved piezoelectric devices.

Marc Lippert was born in Hergnies, France, in 1970. He received the DEA degree in Acoustic and Electronic from the University of Valenciennes in 1994. His study about the piezoelectric materials began in 1995 at the Opto-Acoustical-Electronic department of IEMN Institute to obtain his PhD degree. After receiving his PhD in 1999 from the same University, he worked as a Research Associate, studying the possible devices with piezoelectric materials. His works have consisted in their elaboration (thin and thick films, bulk materials), their characterization and their applications (piezoelectric transformers, sensors, ...).

Anne Leriche was born in 1959. She received his PhD in the inorganic chemistry discipline. After having worked in ceramic research institute and ceramic industry, she got a Professor position at the University of Valenciennes. Since September 1999, she is the Manager of the Laboratoire des Matériaux et Procédés LMP (UPRES 2443). Her research interests include elaboration and characterization of high tech ceramics particularly oxide powder synthesis by chemical routes (barium titanate, lead titanate-zirconate, zirconia toughened alumina ZTA, ...) and elaboration of micro and nano composites for thermomechanical applications (mullite and ZTA, alumina reinforced by SiC particles and fibers and metal particles, silicon nitride-SiC, ...). She is member of the University administration board and is member of several French academic associations in ceramic field.