# Damage Detection of Composite Materials with LAMB Wave Method

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*The aim of the experimental study described in this paper was Lamb wave method evaluation for damage/defects detection of epoxi/glass composites. Can be used piezoelectric transducers - actuator/sensor - glued on the surface of investigated composite, using transmission mode. The chosen control parameter was the sensor signal attenuation because of defects that exists in examinated samples. The proposed monitoring system was efficiently in the detection of damage/defects such as holes, allowing for damage/defect size estimation.*

*Keywords: composites damages detection, Lamb wave*

The composite materials are gaining acceptance and demand in several commercial markets including sporting goods, construction and transportation. However, for many of these applications such as aircraft, without a reliable damage/defects detection approach, the total cost of ownership may become a limiting factor for the structure's use.

There are several inherent difficulties in detecting damage/defects in composite materials as opposed to traditional engineering materials such as metals or plastics. One factor of differences between these categories of engineering materials is their nature, inhomogeneity and anisotropy; most metals and plastics are formed by one type of uniform isotropic material with very well known properties. The laminated composite materials on the other hand can have a widely varying set of material properties based on the chosen fibers, matrix and manufacturing process.

The importance of damage detection for composite structures is often accentuated over that of metallic or plastic structures because of their load bearing requirements. Therefore, the development of reliable damage detection methods is critical to maintain the integrity of composite structures.

The vibration-based damage detection techniques, especially modal analysis, are used currently for composite materials investigation. The structures can be excited by the ambient energy, an external shaker, or embedded actuators, and the dynamic response is then recorded. The embedded strain gauges or accelerometers can be used to calculate the resonant frequencies. The changes in the normal modes can be correlated with the loss of stiffness in a structure, and usually analytical models or response history tables are used to predict the corresponding location of damage. These methods are implemented easily within existing infrastructure of a composite structure at a low cost, however the data they produce can be complicated to read and analyze.

There are several active variants of vibration methods that use embedded or surface mounted actuators to excite a structure ultrasonically in order to produce various types of elastic waves that propagate over large distances, and complementary embedded sensors to detect reflected and transmitted waves. Some of these include Rayleigh waves in thick structures, shear waves and Lamb waves for thin structures. The Lamb waves have been found to be particularly effective in detecting the presence and location of damage in composite materials, with all the same advantages of the previously mentioned vibration techniques of small and lightweight sensors, as well as the disadvantage of complicated results.

The Lamb wave techniques have been implemented in a variety of fashions in the literature, including the use of separate actuators and sensors to monitor transmitted waves and/or reflected waves, and multipurpose transducers which have both actuation and sensing capabilities.

The Lamb waves represent the main support for many current applications of structures control. The best structures with high dimensions that allow embedding of a montoring system are thin plates – the ideal medium for Lamb wave propagation. Moreover, these waves present the avantage to investigate all thickness of propagation medium, without high attenuation like volumic waves. Finally, vibrational modes diversity create the posibility to realize a control system based on Lamb waves propagation, a system capable to give information about many types of damages.

The first application of Lamb waves to composite materials, conducted by Saravanos demonstrated both analytically and experimentally, the possibility of detecting delamination in composite beams using Lamb waves[SAR 94]. Similar conclusions were drawn by Percival and Birt, who began focusing their work on the two fundamental Lamb wave modes [PER 97]. Detection of other forms of damage in composite materials was also investigated by Seale, who examined fatigue and thermal damage [SEA 98], and Tang who observed the sensitivity of Lamb wave propagation to fiber fracture [TAN 89].

## Experimental part

*The investigated material*

The investigated laminate composite was glass E/epoxy, material used in aerospace, automobile industry, tanks for chemical industry. Matrix was epoxy resin DINOX010X with the properties presented in table 1 and reinforcement was bi-directional cloth E glass fiber (chemical composition: $SiO_2$-55.2%; $Al_2O_3$-14.8%; $B_2O_3$-7.3%; MgO-3.3%; CaO-18.7%; $Na_2O$-0.3%; $K_2O$-0.2; $Fe_2O_3$-0.3%; $F_2$-0.3%). The main characteristics of glass fibers are specified in table 2.

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**Table 1**
DINOX010S RESIN PROPERTIES

| Property | Measuring unit | Value |
|---|---|---|
| Density | $g/cm^3$ | 1.2-1.3 |
| Impact strength | J/m | 0.1-1.00 |
| Tensile strength | MPa | 55-130 |
| Flexural strength | MPa | 125 |
| Modulus of elasticity (Young) | MPa | 2800-4200 |
| Poisson's ratio | | 0.2-0.33 |
| Thermal conductivity coefficient | W/mK | 0.17-0.21 |
| Liniar thermal expansion coefficient | m/m°C | $(5-8)10^{-5}$ |
| Specific heat capacity | J/KgK | $(1.25-1.8)10^3$ |

**Table 2**
CHEMICAL COMPOSITION AND MAIN PROPERTIES OF E GLASS FIBRES

| Characteristics | Measurement unit | Value |
|---|---|---|
| Density | $g/cm^3$ | 2.5 |
| Mohs hardness | - | 6.5 |
| Tensile strength | GPa | 2.40 |
| Thermal expansion coefficient | $10^{-6}$/°C | 4.8 |
| Modulus of elasticity | GPa | 72 |
| Poisson's ratio | - | 0.22 |
| Diameter | Mm | 0.15 |
| Elongation | [%] | 3 |
| Specific heat capacity | kJ/KgK | 0.81 |

By ambient temperature - press technology $[0/90]_4$ laminate composites DINOX010S/E glass were realized from which tensile specimens were cut. These specimens were clamped on one end, PZT 4 piezoelectric disks (transducers) were affixed with epoxy resin so that they were firmly attached during testing.

Holes were drilled into the center of each specimen– ranging in diameter from 2 to 16 mm, with 2mm steps - using a silicon-carbide core drill to minimize damage during the drilling process.

Lamb wave method was implemented using piezoceramic actuators for waves generation and piezoceramic sensors for transmitted waves monitoring by investigated structures. Both the actuation and the data acquisition were performed using a laptop running Labview™ as a virtual controller.

Experimental setup used to monitor epoxi/glass composites is presented in figure 1.

To obtain Lamb waves the actuator transducer was excited with Hann windowed 5 sinusoidal pulses; a Hanning window (approximated by a half-sine wave multiplied over the pulse width) helps to narrow the bandwidth further to focus the maximum amount of energy into the desired actuating frequency. Actuating pulse with driving voltage of 10V peak-to-peak and frequency 11.9 kHz was obtained with virtual signal generator created with the

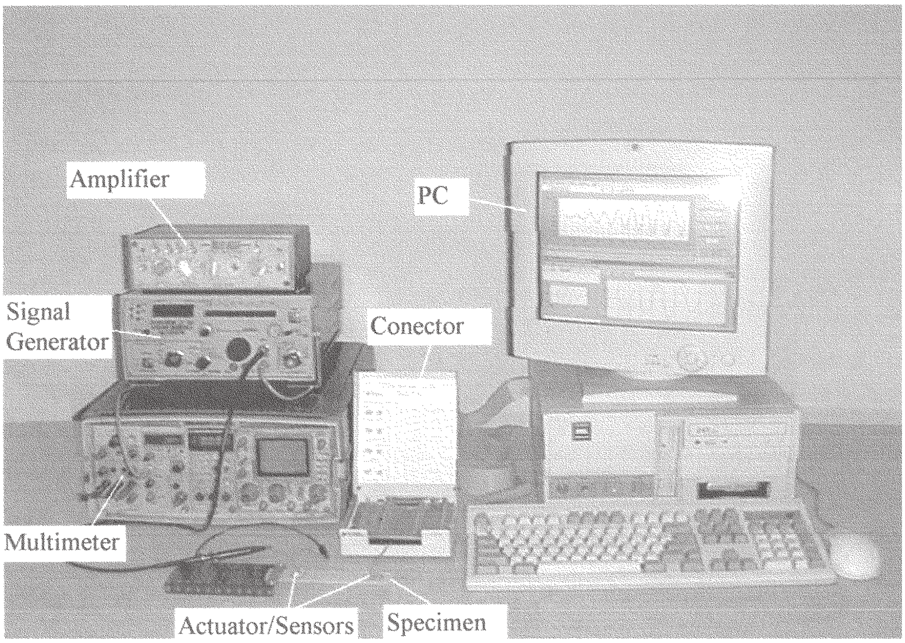


Fig. 1. Experimental setup used to monitor epoxi/glass composites

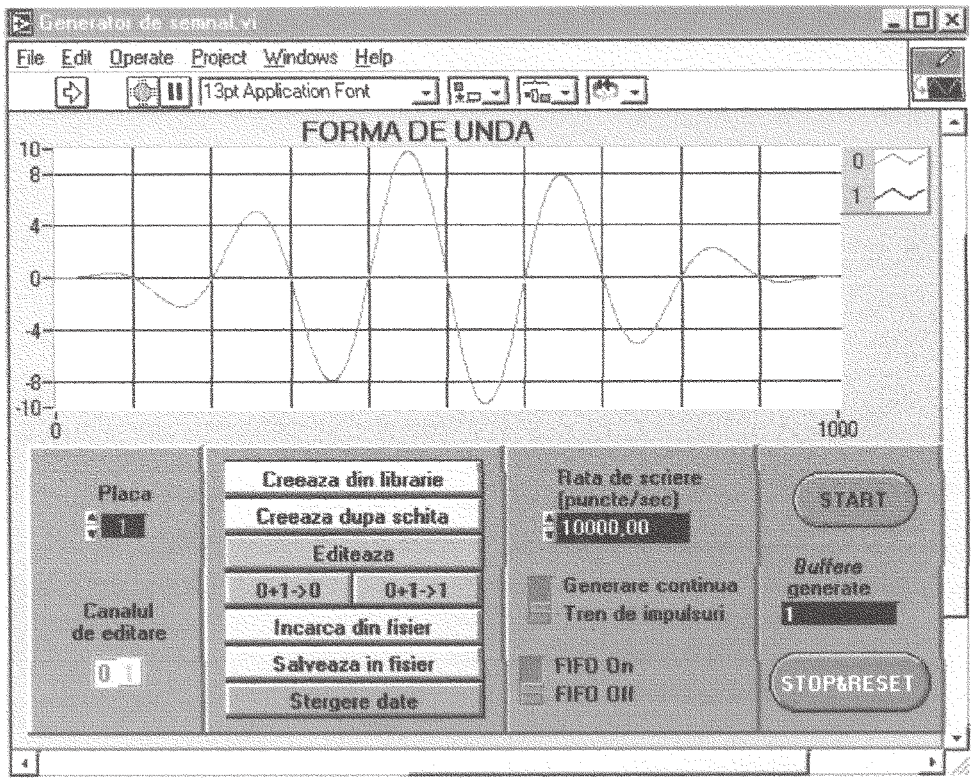


Fig. 2. The frontal panel of signal generator

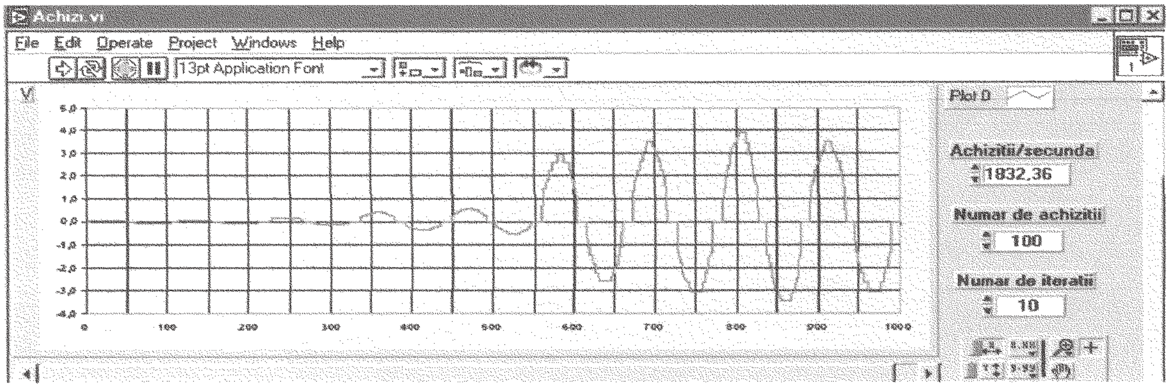


Fig. 3. The frontal panel of acquisition apparatus

LabVIEW software. Testing frequency was chosen to stimulate an Ao mode Lamb wave. Furthermore, its value represents one of the real frequencies of the actuator transducer.

In order to monitor composite damages the sensor voltage caused by strains induced by the impinging Lamb waves was measured. The sensor signal was then amplified, being acquired with virtual apparatus, created with LabVIEW software.

Signal generator allows creation and saving waves to one or two data aquire channel. The frontal panel of signal genrator is presented in figure 2.

This apparatus acquires the piezoceramic sensor signal (voltage, in volts) produced by Lamb waves transsmision. The frontal panel of acquisition apparatus is presented in figure 3.

In figures 4 - 9 are presented the signals of piezoelectric sensor for undamaged specimen for and specimens with through thickness -holes, diameter 4mm, 8mm.

Preliminary signals examination has found reduction of waves amplitude received by the sensor after interaction with the damages. For small values of holes diameter this appeareance is easy to perceive if the examination is limited to observation of transsmited signals. The power

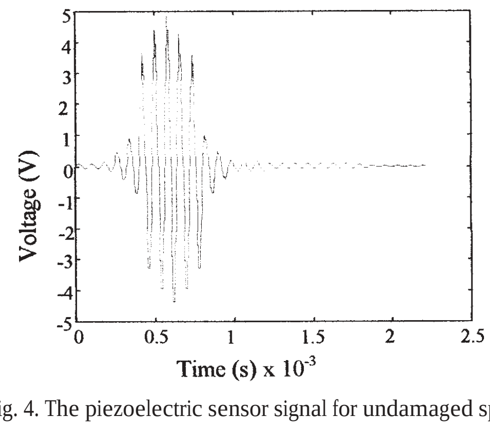


Fig. 4. The piezoelectric sensor signal for undamaged specimen

spectral density of sensor signal was used to recognize the damage „signature”. The maximum value of this parameter was obtained for undamaged specimens.

For specimens with damages type through thickness - holes an attenuation of signal amplitude of the received pulse by piezoelectric sensor after interaction of Lamb waves with damage into composite material was produced. Also, the attenuation increases with the increase

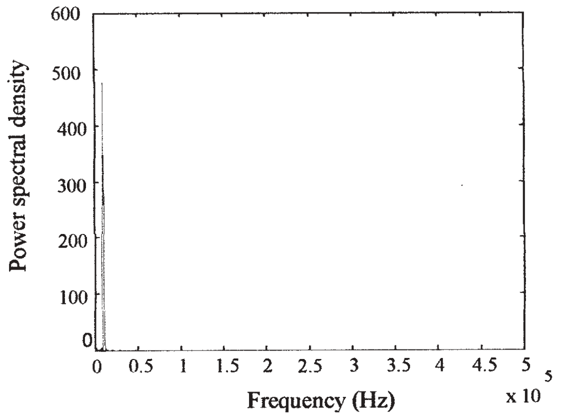


Fig. 5 Power spectral density of sensor signal for undamaged specimen

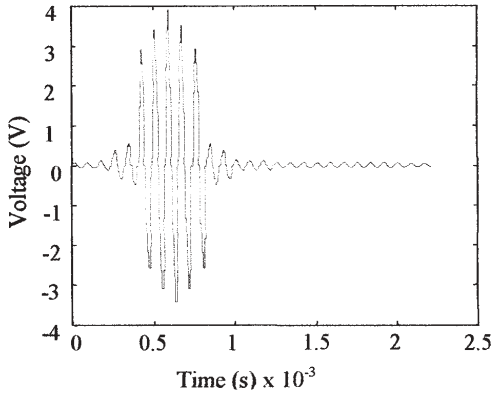


Fig. 6 The piezoelectric sensor signal for specimen with through thickness -hole, diameter 4mm

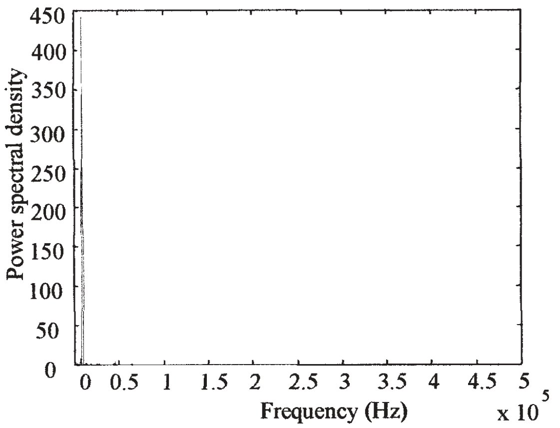


Fig. 7 Power spectral density of sensor signal for specimen with through thickness -hole, diameter 4mm

of the damage dimensions.

**Conclusions**

This paper proposed a new method for evaluation of composite materials integrity based on Lamb waves.

There are generally four goals for damage detection, each of which is gained with increasing difficulty and complexity. The first is the determination of the presence of damage in a specimen. The second is an estimation of the extent of the damage. The third goal is to be able to differentiate between different types of damage. The fourth goal is to be able to calculate where the damage is located. It appears that the Lamb wave methods carry enough information to meet potentially all of these goals with a

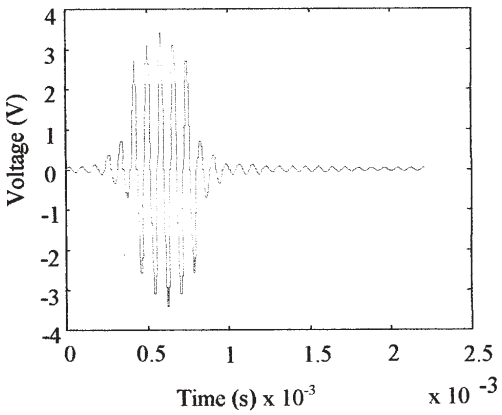


Fig. 8 The piezoelectric sensor signal for specimen with through thickness -hole, diameter 8mm

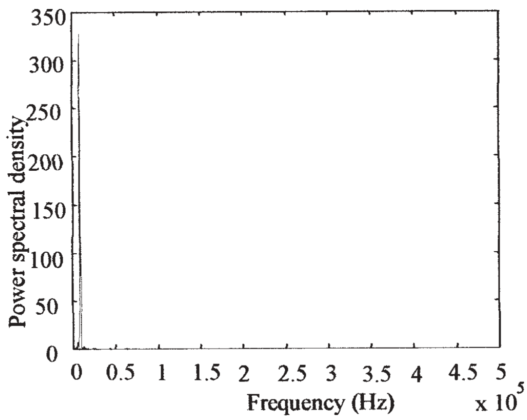


Fig. 9 Power spectral density of sensor signal for specimen with through thickness-hole, diameter 8mm

strategically placed array of sensors and suitable processing codes.

The aim of this paper was to indicate presence of damage type holes for epoxi/glass composites and the size of the damages. Apparatus realized with LabVIEW software and actuators/sensors glued on specimens was used. For undamaged specimens was obtained maxim value of sensor voltage – 5V, for specimens with holes of 4mm diameter, sensor voltage was 4V, for specimens with holes of 8 mm diameter, the sensor voltage was 3.5V. Power spectral density permits quickly evaluation of composite integrity for all holes, including those with small diameters.

The experimental results sustain the concept that Lamb wave method can give valuable information for the inspection of composite materials by correlation between sensor voltage and damage state of glass/epoxi composites.

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