Journal of Optoelectronics and Advanced Materials Vol. 4, No. 4, December 2002, p. 949 - 957

NONDESTRUCTIVE TESTING TECHNIQUES AND PIEZOELECTRIC ULTRASONICS TRANSDUCERS FOR WOOD AND BUILT IN WOODEN STRUCTURES

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A survey of the main NDT methods used to evaluate the quality and properties of wood and wooden structures is given. Among the most important ones there are visual inspection, sonic and ultrasonic stress wave. Some other methods include: deflection, electrical, isotope and X-ray methods. The ultrasonic methods seem to be the most suitable ones in many cases especially for quality control purposes, but these methods depend on the quality of the piezoelectric transducers. Consequently, the construction and characteristics of a new type of piezoelectric transducer are reported. The new transducer is a composite type transducer, consisting of a sandwich type piezoactive element and a steel cylinder glued together. The sandwich piezoactive element was made of five thinner discs of 20 mm diameter and 2 mm thickness. The whole construction has the resonant frequency at 60 kHz, proper to wood investigation. The transducer can be successfully used for NDT of wood, either in the trough transmission or pulse-echo arrangements. The transducers were tested for sound velocity measurements in different wood samples.

(Received August 15, 2002; accepted October 31, 2002)

Keywords: Piezoceramic, Transducer, Ultrasonic, PZT, NDT

1. Introduction

Nondestructive Testing (NDT), sometimes called Nondestructive Evaluation (NDE) is known as the science able to identify some physical and mechanical properties or defects in a piece of material or structure, without altering their end use capabilities. When researches of wood and wood composites are evolved some questions arises, such as, what is the goal of the research, what resources are available for the investigation, the current state of the investigation techniques and so on.

Though some testing were earlier tried on plywood [1] and on live trees [2] one can say that NDT of wood composite specifically is still at the beginning and more knowledges are necessary before being able to predict the successful outcomes in advance. For example, there is only partial correlation between the strength and modulus of elasticity of wood products [3] and there is no theoretical relationship between strength and stiffness. The resources in the wood field may take different approaches such as the tree itself, the solid wood, the wood laminates, or the wood composites. In each case the investigation may take different aspects. Thus in the case of trees (a standing tree) we would be interested in properties like growth rate, strength, defect distribution or density variation, since any tree is a very complicated structure due to its shape, specie, age, climate or silvicultural practice. In the case of wood laminate, which are layered structures of wood and glue, the research typically faces problems such as interface by the glue line with NDT measurements, effects of directional grain orientation, variation of the material quality, how the glue line controls the properties of interest (such as rolling shear bending, compression and tensile strength). In the case of wood composites, in which wood is used in particle or fiber from, bound together by an adhesive, there are factors that influence the NDT such as size, shape, spatial distribution of binder and additives, layering and density variation through the panel thickness. Therefore, care must be taken to select those NDT variables that closely respond to the controlling variable of interest and to minimize the influence of the other components which is not always an easy task to accomplish.

2. NDT main methods

The NDT techniques used in the forest products industry can be applied to control and evaluate the quality and properties of wood and wood structures and may be classified in the following categories.

a. ***Detection of defects:*** it is known that wood contains knots, slope of grain, resin packets or can be deteriorated by fungal or insects. If these defects are accurately detected the field of production process increases as well as the value of the finished product.

b. ***Sorting and grading of structural products.*** The strength and stiffness characteristics of any wood product must be assessed individually, in order to sort the material to grade classes. Though this may be accomplished by visual inspection, the use of NDT techniques has the advantage of reliability and repeatability. On the other hand properties such as density, stiffness, moisture content can be simultaneously assessed by using ultrasonic grading of veneers.

c. ***In situ evaluation of wooden members***. Traditionally, the integrity of the structures is inspected visually by experienced people. But such inspection cannot always detect decayed parts of the structure thus causing undoubtedly replacement of a substantial amount of some intact wooden structural elements. In turn NDT techniques minimize misjudgment and critical parts of the structure can be examined more closely. Anyhow, there are some difficulties encountered with application of NDE on *in-situ* members. These factors include: inaccessibility of the segment where the deterioration is critical, variable moisture distribution, degradation at different rates, difficulties in attaching NDE sensor.

Among the most frequently NDT methods used to evaluate the wood products we can mention the following.

2.1. Visual inspection.

The simpler and the oldest one is still relying in practice, but it is very subjective. By this method one can say if the wood member is broken up or shows mechanical damage. A little more advanced inspection may use listening to a hollow sound often knocking with a hammer or scraping a degraded surface to determine the depth of degradation.

2.2. Sonic stress wave

This technique is based on the fact that the speed of sound and attenuation depend on the strength and stiffness of wood. According to the theory, the dynamic modulus of elasticity can be calculated from the equation:

$$E_{din} = \rho \cdot v^2 \qquad (1)$$

where ρ is the density of wood that can be easily estimated and v is the velocity of the stress wave. In practice the compression wave is generated in the wood sample either by tapping it with a hammer or by a forced vibration produced by a sonic instrument. Two piezoelectric transducers (accelerometer type) are mounted at a distance d near the two ends of the wood specimen and they determine the flying time t of the stress wave. In this way the velocity v is given by the well-known relation $v = d / t$ and so the dynamic module E_{din} can be easily determined.

For *in-situ* application of this technique the decay detection is determined by means of two piezoelectric transducers; one transmitter placed at one of the grid point and one receiver placed on opposite side of the member, the measurement being carried out in the transverse direction. This method was successfully applied in a number of cases in the last decades [4-7].

2.3. Ultrasonic stress wave

Ultrasonic stress wave NDT technique is similar in many ways to the sonic wave approach except that it works at higher frequencies. For wood the most favorable frequency range is between 20 kHz and 500 kHz because of the high attenuation in wood. The acoustic velocity and acoustic attenuation coefficient is used as strength predictors, and the increase of transit time between two transducers can locate defects [8].

The ultrasonic method is very popular with homogeneous, nonporous materials [9] and most effective for manufacturing quality control of delaminated areas of laminate structures, due to the ability of ultrasonic wave to be concentrated in small areas. The most frequently ultrasonic methods are the *through transmission*, and *pulse-echo* methods [9, 10]. The *through transmission* method requires two piezoelectric transducers one emitter and one receiver being mounted on opposite side of the wood specimen. The ultrasonic signal, which meets a defect in its way, would be partly reflected and will be received by the transmitter, while the reduced signal by the receiver. The proportion of these two signals can be used to investigate the internal defect.

The *pulse-echo* method uses only one transducer serving both as transmitter and receiver of reflected pulses [11]. The ultrasound is affected both by environmental factors and wood characteristics such as moisture and grain. Thus, for example, the ultrasound is about three times faster along the grain direction than across it in solid wood [12]. This enables to detect defects, which involves changes in the grain direction.

2.4. Other methods

There are some other methods applied to examine and control the quality of wood and wood composites in a nondestructive way but their use is very limited. Here only we shall mention them:

Deflection method, employed mostly with lumber and pole type product. By this method the deflection is measured at a safe load level.

Electrical method in which the relation between moisture contents and electrical resistance of wood is used to detect the decay with in-situ examination.

Gamma radiation method or ***isotope method*** is employed to determine a trace element for quantifying the distribution of preservations in wood [13].

Penetrating radar method is used to detect and quantify the wood degradation at inaccessible locations.

X- Ray method, used mostly in laboratory environment or in production line for density measurements of wood. It is limited due to the bulky nature of the x-ray source.

It is seen from the above consideration that, from practical point of view, the ultrasonic methods seems to be most suitable method in many cases especially for quality control purposes**.** The information supplied by this method during production process can be used to stop the manufacturing before the process gets out of control.

The success of ultrasonic method depends mostly on the quality of piezoelectric transducers used as transmitter and receiver. Therefore, the present work reports on the results of the construction and characteristics of such a piezoelectric transducer specially designed for NDT of wood and wood structures.

3. Experimental

It is recognized that ultrasonic technique provides quick and reliable results in wood examination when ultrasonic properties samples are measured. One of the most important tools for such investigation is the piezoelectric transducer, which can work either as source or detector of ultrasounds. It can play equally both functions due to the reversibility of the piezoelectric effect and to the independence of the transmission and reflection constants with respect to the direction of the working discontinuities [14-24].

Efficiency for emitters and sensivity for receivers are the fundamental characteristics of ultrasound transducers and these qualities need to be maximized in order to get high efficiency transducers. Both are dependent on electromechanical coupling factor and some other dielectric, piezoelectric and elastic constants of the materials [25-27]. Mechanical quality factor Q_m determines the efficiency and bandwidth. Thus, for example, in pulse echo transducers the use of short ultrasonic pulses requires a very low Q_m for a compact impulse response. A low Q_m also ensures a good transfer of acoustic energy into the load, which implies the matching of acoustic impedance of transducer and the load [28, 29].

3.1. Design and construction of transducer

The most simple piezoelectric transducer consists of a disc (or cylinder) shaped piezoceramic element operating in one direction axis of polarization normal to the parallel faces.

This piezoceramic element is, in fact, the heart of any real transducer, since it produces the high frequency ultrasonic vibration in response to a short electrical pulse and on the other hand it receives the reflected high frequencies sound signals and transforms them into electrical signals. The vibrations of the end faces of such a disc resemble those of a piston like motions with adequate directivity and good separation of harmonics if the disc diameter is sufficiently large, compared to the thickness. On the other hand if lower frequencies are required then the thickness must be large enough so that the disc becomes inconveniently large.

Since the requirement for wood and wooden structures investigation is a rather low frequency [30-32], because of the high wave attenuation in wood, the dimensions of the piezoceramic element would become so big that it will imply a high power generator to work at high voltages. In order to overcome these difficulties a “sandwich” type element can be proposed as piezoactive element. Such an element, made of a number of thinner discs, glued together and having the polarization directions in opposition is then tightly glued on a steel cylinder playing the role of backing material.

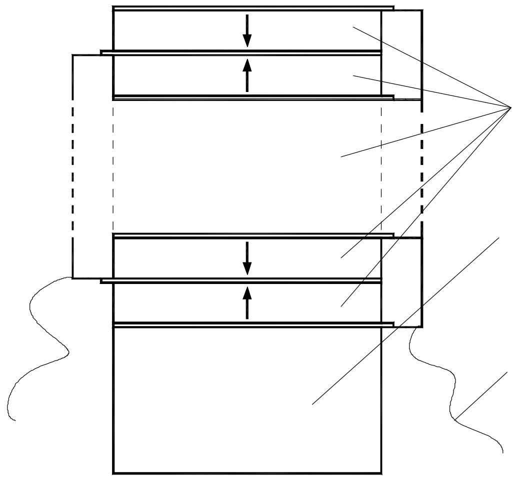

Fig. 1. The composite structure of transducer consisting of sandwich type piezoactive elements glued on a steel cylinder.

This composite structure made of a sandwich type piezoactive element and a steel cylinder (figure1) has two main advantages. One is that the electrical connection being disposed in derivation, each disc receives the whole **emf** of the driver, which is much smaller compared to the case of a single thick element and thus makes it possible le a considerable simplification of the electronics. The second great advantage is that one can chose the desired working frequency for the transducer simply by choosing the right number of thin piezoactive elements, since the resonance frequency for such a composite structure is a function of the number of thin piezoactive elements involved, as can be seen from figure 2, which illustrates the dependence of the resonance frequency of the number of thin disc of the sandwich structure. The experimental construction on which the measurements were carried out was made from discs of 20 mm diameter and 2 mm thickness, glued together one by one with the direction of polarization in opposition in a sandwich type structure.

They were next glued on a steel cylinder with a diameter of 20 mm and a thickness of 20 mm. The resonance frequency of the system was measured after each element was stuck. One can see that the resonance frequency decreases with increasing number of elements, following an estimated curve shown in figure 2. This curve can be described with a good approximation, by a fifth order polynomial of the form:

$$f = a + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5 \quad (2)$$

where a =85.01; b_1 = 301.25; b_2 = -199.79; b_3 = 48.54; b_4 = -5.21; b_5 = 0.21.

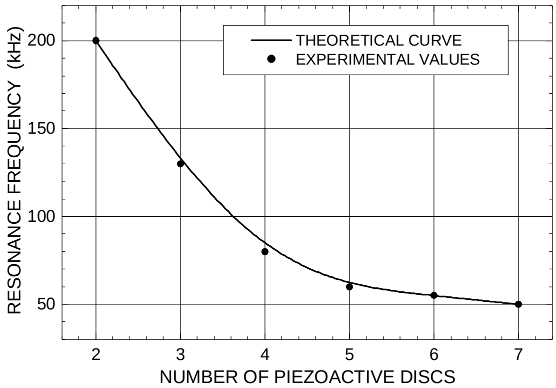

Fig. 2. The resonator frequency as a function of the number of thin piezoactive elements of the sandwich. The points show the experimental values of the sandwich active elements and the line illustrate the theoretical polynomial fit.

For the construction of the transducer we chose a structure with five piezoceramic active elements corresponding to a resonance frequency of 60 kHz. This proved to be a proper frequency for wood investigations [33]. The schematic view of the transducer is shown in Fig. 3.

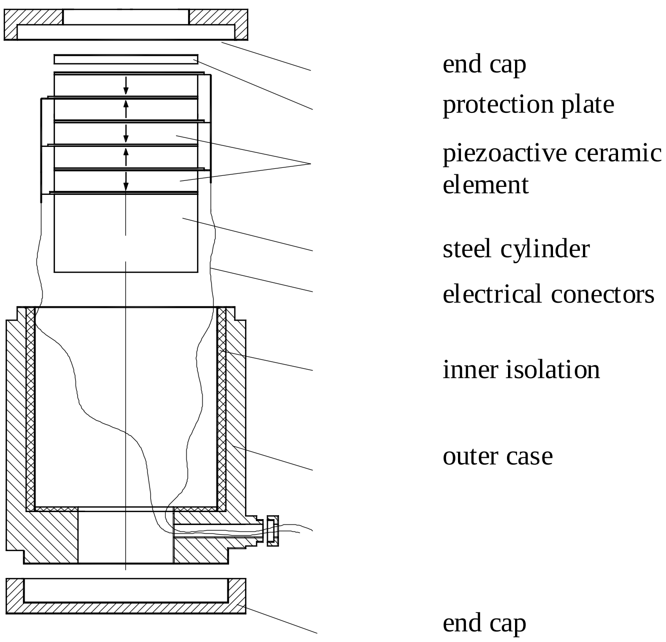

Fig. 3. Schematic view of the transducer illustrating the main parts of it.

The transducer produces longitudinal waves, which propagate into the outer space. Its vibration mode is the fundamental longitudinal vibration, proper to a cylinder. The ultraacoustic wave packets produced and emitted through the frontal part, via the protection disc, propagate into the wood specimen to be investigated and they are received by a similar transducer attenuated and distorted due to the defects of materials. The changes in the pattern of the emitted waves represent the encrypted structure of materials investigated.

3.2. Characteristics of transducer

The electrical characteristics of this transducer were determined by means of an impedance gain/phase analyzer type HP4194A. The electrical spectra are shown in figure 4.

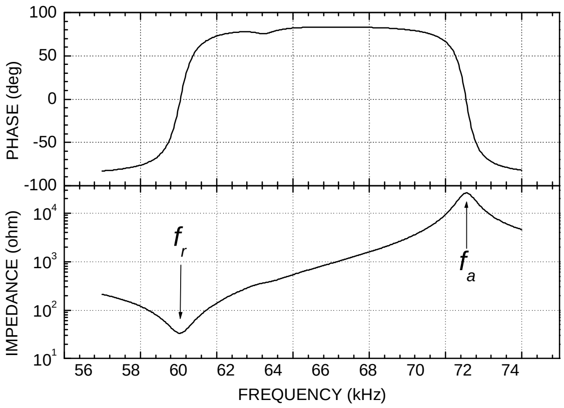

Fig. 4. The characteristics electrical spectra of the transducer showing the phase and impedance versus frequency

The resonance frequency is situated around 60 kHz with a minimum impedance of 22 ohms and the antiresonance frequency at 71 kHz with a maximum impedance of 28 kohms. Using these values one can simply calculate the quality factor Q by means of the formula:

$$Q = \frac{f_W}{\Delta f} \tag{3}$$

where f_w - is the working frequency which correspond to the resonance frequency f_r and $\Delta f = f_a - f_r$ is the bandwidth of the oscillation spectrum. The estimated value of Q was 5.5. There is another way to calculate Q by means of the formula:

$$Q = X / R \tag{4}$$

where X is the reactance and R the resistance of the electrical branch of the equivalent circuit of the transducer. The reactance is given by:

$$X = 2\pi f_\omega L - \frac{1}{2\pi f \omega C_b} \tag{5}$$

where L and C_b are the inductance and capacitance of the electrical branch of the equivalent circuit. The equivalent circuit with its characteristics, as determined by the impedance analyzer gave the following values: $\boldsymbol{R} = 30.4\Omega$, $\boldsymbol{L} = 9.94\boldsymbol{mH}$ and $\boldsymbol{C_b} = 1.5\boldsymbol{nF}$ so that the estimated value of Q was 5.44 in good agreement with the value estimated with (3).

As concerns the acoustical characteristics, they were determined by using a pair of transducers, one emitter and one receiver, and measuring the ultrasonic output by means of the gain phase analyzer. The transmitted ultrasonic wave within the working range is shown in figure 5. The shape of the acoustical spectrum is that of a product of two lorentzians, each corresponding to a single mode.

The data from this figure allow calculating the relative bandwidth at 1.5 dB under the resonance peak and the corresponding Q number with the formula:

$$Q = \frac{\omega}{\Delta\omega_{1.5dB}} = 50 \qquad (6)$$

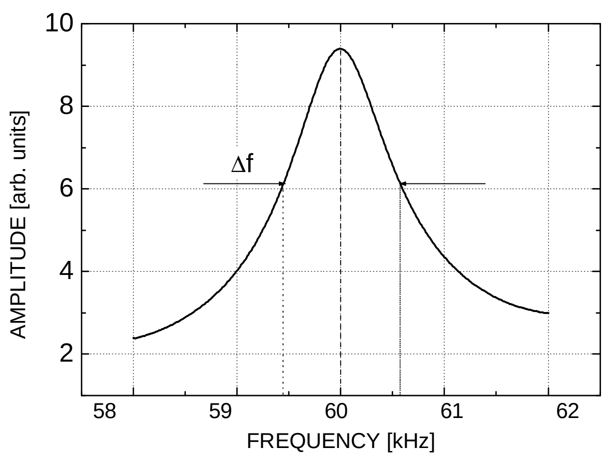

Fig. 5. The characteristic acoustical spectrum of a pair of transducer working in the trough-transmission arrangement

Using the experimental values for ω and $\Delta\omega_{1.5dB}$ we obtained for Q a value of 50 which seems a reasonable value for a pair of transducers working in tandem conditions.

4. Testing of transducer

The transducer described can be successfully used in NDT of wood and wooden structures either in the *through transmission* or *pulse-echo* arrangements. The first arrangement requires two transducers mounted on each side of the tested sample while the latter only one which serves both the transmitter and receiver functions and it measures only the reflected pulse. This method is extremely valuable *in-situ* measurements where access to both surfaces of the tested samples is impossible [34].

Though the acoustic ultrasound method is versatile and efficient in many cases for wood investigation, its utilization is not so widespread because of the necessity of using efficient couplants for transducers.

In case of fixed transducer on the sample surface, good physical contact is simply assured by means of applied pressure and proper grease, but in case of continuous scanning of larger surfaces the water proved to be a good couplant and submersible transducers are needed or dry contact rollers in order to avoid immersion [35].

As it was already mentioned the propagation of ultrasound in wood is affected by moisture content, and grain direction [36]. Thus the velocity of ultrasound increases with increasing moisture and it is faster along the grain direction than across it, this making possible to detect the defects which involves changes in the grain direction such as knots, or discontinuities in the cell structure. Biological degradation and wood structure integrity can also be detected by ultrasonic technique especially decaying in the incipient range. Integrity of wood structure can also be evaluated with acoustic emission and acoustic ultrasonic techniques. In the case of blue laminated beans, for example, the integrity between laminates and finger jointed elements could be investigated [37, 38]. The connection between the adhesive parameters and the ultrasonic events are not well understood, but the experiments showed lower stress levels for brittle than for flexible adhesives with this technique, while the emission from the weakly bonded ones are mainly masked.

To test the efficiency of our transducers we made some preliminary simple evaluation of ultrasound velocities in timber samples of pine wood, ash and elm of cubic shape with edges parallel and normal to the direction of internal fibbers. The samples were made from dried wood but the exact moisture for each sample was not entirely known since the experiments were only intended to test the transducer. Anyhow, the measurements made along and normal to the wood fiber confirmed the anisotropy of the sound velocities and values of these anisotropies from 1.4 up to 2.7 were recorded for different wood samples.

A systematic investigation concerning the sound velocity in different solid woods or laminates and evaluation of different mechanical properties (bending, compression and tensile strength) by NDT measurements with the discussed transducers is now in progress and the relevant results should be published as soon as they will come out.

5. Summary

The main NDT methods used to evaluate the quality and properties of timbers were presented with special emphasis on ultrasonic ones. The relevance of the ultrasonic investigations depends on the nature and quality of the piezoelectric transducer used. Therefore, a sandwich type piezoelectric transducer working at 60 kHz was designed and constructed for wood inspection and NDT investigations. The transducer is a composite structure made of five piezoceramic discs of 20 mm diameter and 2 mm thickness glued together, with polarization in opposite directions and then glued on a steel cylinder which plays the role of backing material. The transducer can work either in the *through transmission* or *pulse-echo* arrangement. Some preliminary measurements of sound velocity in different wood samples were made and the sound anisotropy along and normal to the wood fibers were confirmed.

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