Low-cost Ultrasonic Probe to Assess Wood Defects and Parameters

P. Mestre, *Member, IAENG*, A. Calçada, N. Carvalho, C. Serodio, *Member, IAENG*,
P. Couto, J. Matias, *Member, IAENG*, P. Melo-Pinto, J. Morais

***Abstract*—Wood is a natural material that due to its properties has been used for years in many applications such as construction and furniture industries. Being a natural material it is prone to defects which must be detected, preferably during the early stage of product production. Testing of wood pieces, to detect defects or to determine some of its properties, can be made using two types of techniques: destructive and non-destructive. For obvious reasons Non-Destructive Testing (NDT) is more desirable because pieces subject to testing do not suffer any change of its structure. One of the techniques that has been used in such tests is based on ultrasonic waves. In this paper it is presented a low cost ultrasonic probe that can be used to detect some defects on wood pieces. It is based on an FPGA which allows the development of a system with the performance of hardware based systems and flexibility of software based systems. The prototype was then tested successfully to detect some defects and to determine the dynamic module of elasticity (Ed) of wood samples. The obtained Ed values were compared with values obtained using mechanical testing.**

***Index Terms*—Wood, Ultrasounds, Modulus of Elasticity, FPGA**

I. Introduction

Wood is a material with excellent qualities for use as building material, which has been used for many years, for example, in the construction and furniture industries, due to its competitive price and its ease of handling[1].

Due to the fact that wood has its origin in living organisms, trees, it has some peculiar features on its structure, e.g., nodes, which can induce some changes on wood properties. Another characteristic of wood is that two wood samples may have different characteristics, even if they have origin on trees from the same species. Among the factors that influence these differences we can include the age of the tree, the soil or the climatic conditions [2], [3], [4]. This means that wood might have some defects and features that may compromise its use [1].

Detection of wood defects and assessment of its properties can be made using either destructive or non-destructive methods. The first are based on mechanical testing and the second uses methods that do not compromise the wood structure, allowing its utilization afterwards. It becomes evident why these last methods have an increasing interest.

Non Destructive Testing (NDT) are a result of the improvements on the techniques used to characterize materials, both from the mechanical and the quality points of view. It is possible to use such processes during the product production (specially at the start). According to [5], 80% of the defects of a product are corrected during the quality control and utilization phases.

One of the techniques used in NDT, that is becoming much used, is based on ultrasonic waves. This type of testing allows to determine mechanical and physical properties of wood, using easy to use and relatively low cost equipments.

In this paper it is presented a low-cost ultrasonic probe, based on FPGA, to assess the Modulus of Elasticity and detect some defects on wood pieces. It has been tested successfully in laboratory and the results were compared to those obtained using mechanical testing.

II. Assessing Wood Parameters using Ultrasounds

Using ultrasonic waves in Non-Destructive Testing started at the beginning of the 20th century when, in 1929, S. Sokoloff [6] published some tests. Nowadays this is one of the most used techniques in wood testing and it was first used by Sanyal and Gulati [7].

Some of the advantages of using ultrasounds include: tests can be made from the surface, because of the high penetration capability that is has in most of the materials; high accuracy in the detection and measurement of defects, even when they are very small in size such as small fissures. Furthermore it is very simple to use, it does not need any additional security measures and its use can be easily automated using, for example, microprocessors, microcontrollers and/or computers [8].

Manuscript received March 05, 2013.

P. Mestre is with CITAB/UTAD - Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal, and Algoritmi Research Centre, Guimarães, Portugal, email: pmestre@utad.pt

A. Calçada is with UTAD - University of Trás-os-Montes and Alto Douro, Vila Real, Portugal, email: ademar_calcada@sapo.pt

N. Carvalho is with UTAD University of Trás-os-Montes and Alto Douro, Vila Real, Portugal, email: nmmscvr@gmail.com

C. Serodio is with CITAB/UTAD - Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal, and Algoritmi Research Centre, Guimarães, Portugal, email: cserodio@utad.pt

J. Matias is with CM-UTAD - Centre for the Mathematics, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal, email:j_matias@utad.pt

P. Couto is with CITAB/UTAD - Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal, and Algoritmi Research Centre, Guimarães, Portugal, email: pcouto@utad.pt

P. Melo-Pinto is with CITAB/UTAD - Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal, and Algoritmi Research Centre, Guimarães, Portugal, email: pmelo@utad.pt

J. Morais is with CITAB - Centre for the Research and Technology of Agro-Environment and Biological Sciences, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal, email: jmorais@utad.pt

It was Voichita Bucur, one of the main researchers in the area of ultrasonic waves applied to wood testing, in the book *"Acoustics of wood"* [9] that presented the fundamental equations of ultrasound propagation in wood.

The propagation speed of longitudinal and transversal waves can be calculated by:

$$S_L = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \qquad (1)$$

$$S_T = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\mu)}} \qquad (2)$$

where:

- S_L - Speed of the longitudinal wave $[m/s]$;
- S_T - Speed of the transversal wave $[m/s]$;
- E - Modulus of elasticity $[Kg/ms^2]$;
- μ - Poisson Coeficient
- G - Shear module $[Kg/ms^2]$;
- ρ - Density $[Kg/m^3]$.

A. Inspection techniques

1) Reflection: The reflection technique, or, pulse-echo, is one of the most used in the industry. In this technique a burst of pulses is sent and then the returning echoes are detected. Some of its advantages include the fact that only one of the sides the a piece needs to be available and the capability of detecting the exact depth of possible defects on the wood piece. Usually it is used only one transducer, that transmits the pulse burst and the captures the echo signal [5].

Ultrasonic pulses are transmitted by the transducer, then, the ultrasonic wave propagates through the sample and as it crosses boundaries or discontinuities inside the material under test, with different acoustic impedances, it might be partially reflected [5]. All those reflections are then picked-up by the transducer and sent for processing.

It is possible to calculate the depth at which each reflection was generated, by measuring the time of propagation of the wave, Eq. 3:

$$d = \frac{S}{2T} \qquad (3)$$

- d - Depth $[m]$;
- S - Speed of sound $[m/s]$;
- T - Propagation time $[s]$.

2) Direct Transmission: Unlike the above presented technique, in direct transmission the wave that is captured by the receiveir is the transmitted wave and to the echoes. This means that two transceivers are needed, a transmitter and a receiver, and that they need to be placed opposite to each other. Two opposite sides of the piece under test must be available for this type of test.

The captured signal will therefore be different from the one obtained with the reflection technique because the transducer receives continuous waves and not echoes. One disadvantage of this technique is that, unlike the reflection method, the depth of possible defects or discontinuities cannot be determined. However it is still possible to detect them and their position and dimension [5].

Feature detection is made by analysing any changes on the amplitude of the received signal as well as by the propagation time of the ultrasonic wave travelling along the sample. Any change on the amplitude of the received signal is due to reflection, attenuation and dispersion of the wave caused by material features (including deffects) [5].

The propagation speed of the ultrasonic wave in the material under test is given by Eq. 4:

$$S = \frac{L}{T} \qquad (4)$$

Onde:

- L - Path length $[m]$;
- S - Speed of sound $[m/s]$;
- T - Propagation time $[s]$.

III. Proposed System

It is proposed in this paper a system (hardware and software) to obtain the time of travel and the wave form for ultrasonic waves in wood, using the direct transmission technique. Results are presented in A-scan mode so that the effects suffered by the wave while travelling through the wood pieces can be registered.

A. Hardware

As depicted in the diagram block presented in Fig. 1, the proposed system consists of a pair of ultrasonic transceivers (a receiver and a transmitter), signal amplifiers and a control and data acquisition unit that controls the ultrasonic signal and acquires data. This block also transmits the collected data to a computer.

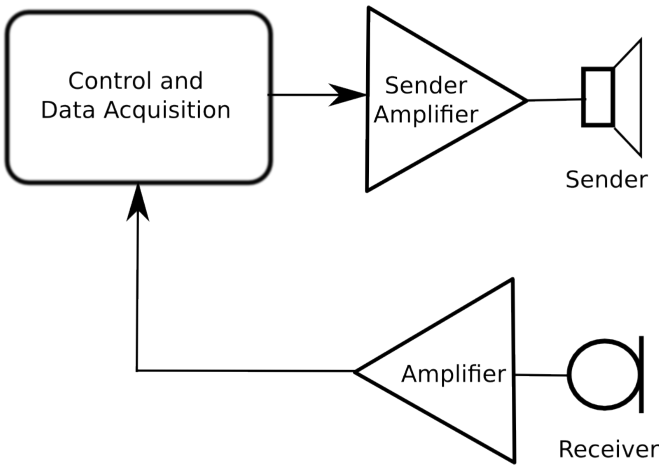

Figure 1. Diagram block of the proposed system.

The used ultrasonic transmitter and receiver are MA40E7S and MA40E7R from Murata, respectively. These are piezo-electric transducers ($PbTiO_3xPbZrO_3$) that operate at a frequency of 40KHz. Their main characteristics are [10]:

- Compact and light-weight;
- Good sensitivity and liability;
- Water-proof;
- Operate between -30^{o}C and 85^{o}C.

Pulses from the control unit to the ultrasonic transmitter are amplified using a simple Darlington pair and the analog signal from the receiver is amplified using a precision instrumentation amplifier, an AD624 from Analog Devices. The output of this amplifier is fed to the data acquisition block where it is recorded and pre-processed.

Two types of information are recorded by the data acquisition block: the ToF (Time of Flight) and the waveform. The first is calculated by detecting the arrival of the first wave of the ultrasonic signal. The received signal must be converted into a pulse, which can be done using a envelope detector and a voltage comparator, as in [11]. To record the waveform, the output of the amplifier is also fed into an Analog-to-Digital (ADC) converter.

To implement the control and data acquisition block two main options can the taken: use a microcontroller or develop a digital circuit. The first option might appear more flexible, because in a microntroller we can develop and modify its firmware according to the needs. However it might have some performance issues due to (unpredictable) time delays that firmware may impose. If the system is developed in hardware there will be no time delays due to processing time however it seems to be a less flexible option.

These issues can be overcome if this block is implemented using an FGPA (Field Programmable Gate Array). We have then the flexibility of firmware and the performance of hardware. For this project a Nexys2 FPGA board from Digilent, with a Xilinx Spartan-3E, was used to implement the prototype. Despite the fact that this specific FPGA was used, any FPGA with the enough number of gates can be used.

Because an FPGA was used it must be used an external ADC. For this project a 10-bit, 80Msps ADC (MAX1448) from Maxim was used. This ADC was selected because it has parallel interface (making the interface with the FPGA easier) and it has the enough speed to acquire the ultrasonic waveform.

For the prototype used in this paper, the sampling frequency is 1MHz which is enough for the used ultrasonic frequency (40KHz) and 4096 samples of the signal are recorded. These values are limited by the clock speed of the FPGA and the number of available gates.

A more detailed diagram block of the final prototype is presented in Fig. 2.

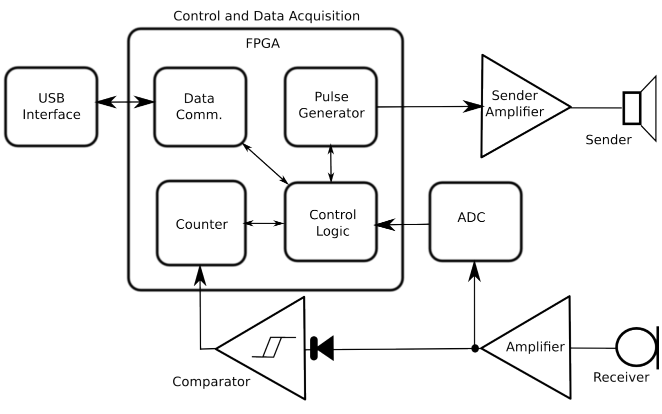

Figure 2. Diagram block of the proposed system.

In the FPGA are implemented four modules:

- Control logic - which upon request of the host computer starts the data acquisition cycle. It starts the pulse generator, starts the ToF acquisition, and acquires the data from the external ADC. At the end of the data acquisition cyle it sends data to the host computer thorough the data communications module;
- Counter - used to measure the ToF. It is reseted at the start of the pulse burst and stopped when the first pulse arrives;
- Pulse generator - generates the pulse burst that is sent to the transmitter;
- Data communications - which receives commands from the host computer and sends the acquired data to it.

The data communications module interfaces a Cypress CY7C68013A USB controller which makes part of the Nexys2 board.

B. Software

To interface the implemented data acquisition system it was developed a Java application (Fig. 3). This application allows the user to start the data acquisition cycle, download data and display it. The user can visualize the waveforms of both the pulse burst and the received ultrasonic wave, as well as the estimated value for the modulus of elasticity.

It is also possible to save data for later visualization and there is also an option to visualise the Fast Fourrier Transform of the received signal.

Interface between this application and the FPGA was made using Java Native Interface (JNI) and the Digilent's Adept SDK (Software Development Kit) libraries. These libraries are used both to send commands to the FPGA board to start the acquisition cycle and to collect data of the Time of Flight and the waveform.

IV. Numerical Results

In this section are presented some results obtained with the above presented system.

A. Sample Preparation and Used Methodology

Tests were made using *Pinus pinaster* samples divided into three groups:

- Laminated wood samples with transversal section of $2cm$ by $3cm$ and a length of $66,5cm$;
- Solid wood samples with transversal section of $2cm$ by $2cm$ and a length of $50cm$.
- Solid wood samples with transversal section of $2cm$ by $2cm$ and a length of $48cm$.

All samples were exposed to the air and were used only after reaching the moisture equilibrium.

To assess if the ultrasonic probe can be used to detect defects in wood pieces, the propagation speed was measured both in defect free samples and samples with visible defects. In some samples were also introduced some defects with a drill.

To acquire data the ultrasonic transmitter and receiver were placed in opposite ends of the sample under test. The data was recorded by the PC application and the ToF results were confirmed using a digital scope.

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

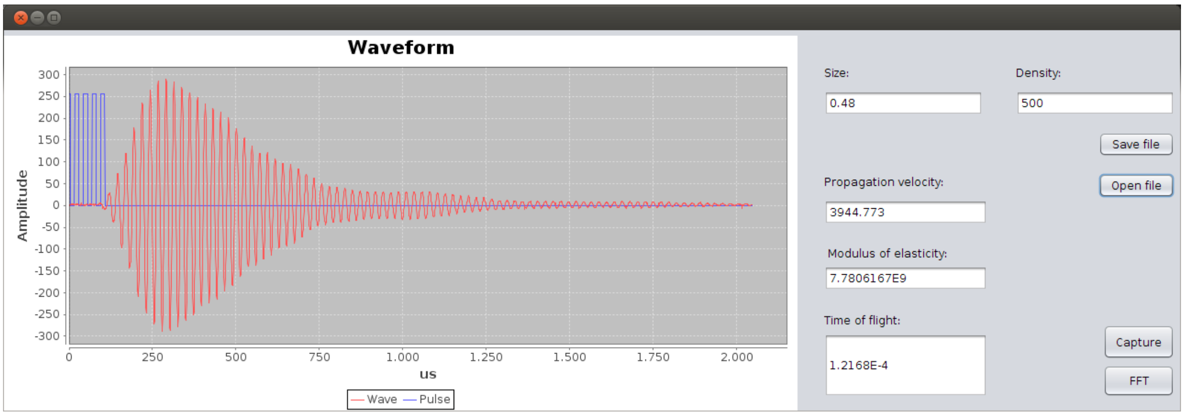

Figure 3. Screen-shot of the Java application developed to acquire and display data.

Due to he need for a good coupling between the transducers and the sample under test, an acoustic coupling medium (gel) was used, together with the device presented on Fig. 4. This device allows to perform the tests using a constant contact pressure of the transducers.

Figure 4. Device used to hold the ultrasonic transducers and maintain a constant pressure during the test.

B. Defect Detection

Obtaining two wood samples that are a perfect match is not possible, therefore a direct comparison between the results obtained for several wood samples cannot be made.

So, to test the usability of our prototype to detect defects on wood samples, using the wave propagation speed, all the needed measurements were first made in defect free samples. Afterwards some defects were added to the samples and they were tested again. Any difference in the results will therefore be only a consequence of the defects and not any other feature of the wood sample.

1) Detecting Defective Adhesive Application on Laminated Wood: A first set of tests was made using laminated wood with defective adhesive application. These tests were made using three wood samples. While the first two samples did not have any visually detectable defect the third sample had noticeable defects induced by lack of glue.

The Time of Flight (ToF) using the direct method was measured for all the samples. Those measurements were made on the longitudinal direction and at three point along the sample. In table I are presented the results obtained for these tests. Since the first two samples had no defects, results obtained with them will be considered as reference values.

Table I
PROPAGATION SPEED IN LAMINATED WOOD SAMPLES WITH AND WITHOUT DEFECTIVE ADHESIVE (VALUES IN m/s).

Sample	S_{LL}	1st point	2nd point	3rd point
1.1	5038	811	789	833
1.2	5115	1333	1429	1363
1.3	4926	395	1111	375

For sample 1.3 it is noticeable a much lower propagation speed at the 1st and 3rd point, which correspond to points of the sample where it was noticeable the lack of adhesive. At the 2nd testing point no visible defect was found and it was chosen as a reference point. On the other samples there is no significant propagation speed difference between the chosen testing points, therefore confirming that there were no defective adhesive application on these samples.

Based on the results of this test we can conclude that the probe can be used in the detection of this type of defect.

2) Detection of Holes: This second set of tests consisted in detecting the presence of holes in the samples. For these tests were used samples with a length of $48cm$ and a transversal section of $2cm \times 2cm$. On sample 2.1 it was introduced a hole in the tangential direction and on sample 2.2 the hole was made in the radial direction.

Measurements of the ToF were first made without any hole and then it was used a drill to make a $6.5mm$ hole. This hole was gradually enlarged until it reached $16,5mm$, as the tests were being made. For the last set of measurement it was made a second $16,5mm$. During this process it was recoded the longitudinal propagation speed and the waveform of the received signal.

On table II are presented the results obtained for this set of tests. Observing these data it is noticeable that there is a decrease of the propagation speed as the size of the hole increases. Despite this change on the propagation speed, it becomes evident that it is only noticeable for relatively large

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table II
PROPAGATION SPEED ON THE SAMPLE FOR THE DIFFERENT HOLE DIAMETER (VALUES IN m/s).

	Diâmetro do furo						
Sample	no hole	6,5mm	9mm	12mm	14mm	16,5mm	2x16,5mm
2.1	4897,96	4897,96	4897,96	4848,49	4800	4800	4705,88
2.2	4848,49	4848,49	4848,49	4848,49	4848,49	4800	4615,39

defects. In the samples under test for holes greater or equal than $14mm$ (sample 2.1) and $16,5mm$ for sample 2.2.

This apparent lack of sensibility is related with the wavelength, which for the presented tests is approximately $122.5mm$. To decrease minimum defect dimension that can be correctly detected by the system the frequency of the ultrasonic wave must be increased.

3) Detection of Galleries: In this test galleries made by xylophagous insects were simulated on the samples. The samples used in this test that $2cm$ by $2cm$ of transversal section and length of $48cm$. To simulate the presence of the galleries several holes were made with a $4mm$ drill.

As for the previous test, the samples were first tested without any hole on it and then the number of holes was increased progressively. Data of the propagation speed and the waveform was recorded for every step. For every step 8 holes were added to the sample, 4 in the radial direction and 4 in the tangential direction, until a total of 40 holes was obtained.

Table III presented the results obtained for this test. As expected it is noticeable a decrease on the propagation speed as the number of holes increases. This technique can therefore be used in wood testing to detect detect the presence of this type of defect. Obviously that this detection can only be made if the sample was already analysed and there are previous values that can be used as a reference. This might not be applicable during the manufacturing process but can be used for example to periodically verify the integrity of wood beams.

C. Modulus of Elasticity

For this test were used solid *Pinus pinaster* samples ($2cm \times 2cm \times 50cm$) that had never been subject no any kind of mechanical testing. For comparison purposes a bending force test was also made, using a universal testing instrument, a Instron model 1125 (Fig. 5).

With the sample placed on the testing machine, the propagation time was measured. Based on this value the longitudinal propagation speed of the sample was then calculated. Afterwards a bending force was applied to the sample at crosshead speed of 5mm per second.

With the collected data MOE was calculated using Eq. 5:

$$E_L^a = \frac{1}{4b}\left(\frac{L}{h}\right)^3 \frac{F}{f} \quad (5)$$

Onde:

- h e b - Dimensions of the transversal section;
- L - Distance between supports;
- F/f - Initial slope of the bending.

Using data collected with the ultrasonic probe, the dynamic modulus of elasticity was calculated using Eq. 6:

Figure 5. Sample being tested using the developed probe and a universal testing instrument.

$$S = \sqrt{\frac{Ed}{\rho}} \quad (6)$$

Onde:

- S - Propagation speed $[m/s]$;
- Ed - Dynamic modulus of elasticity $[N/m^2]$;
- ρ - Density $[Kg/m^3]$.

In table IV are presented the numerical results obtained for this test. This table presentes the calculated values for the sample density, the static modulus of elasticity and the dynamic modulus of elasticity.

For a better comparison between the MOE and Ed it is also presented, Fig. 6, the comparative plot of the obtained results for these parameters.

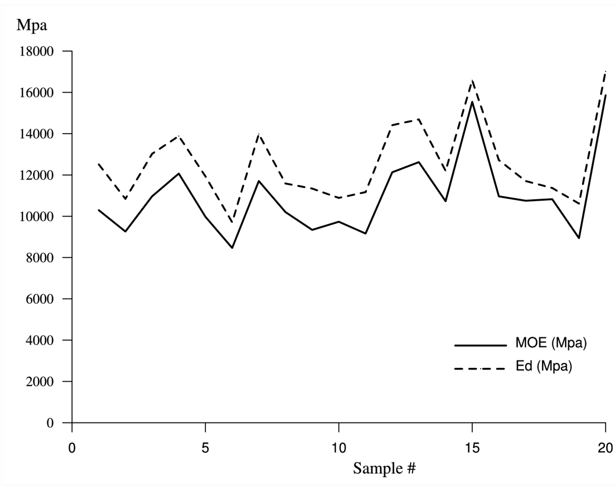

Figure 6. Comparison between the obtainedMOE and Ed values.

ISBN: 978-988-19252-8-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table III
PROPAGATION SPEED OBTAINED FOR THE SIMULATION OF THE GALLERIES (VALUES IN m/s)

	Number of holes					
Sample	no hiles	8 holes	16 holes	24 holes	32 holes	40 holes
3.1	4979,17	4927,84	4843,94	4747,72	4619,25	4514,55
3.2	5106,38	5000	4948,45	4848,49	4687,5	4597,70

Table IV
VALUES OF DENSITY, MOE AND Ed FOR THE SAMPLES USED IN THE TEST.

Sample	Dens.(Kg/m^3)	MOE (Mpa)	Ed (Mpa)
4.1	572,95	10296,37	12510,92
4.2	469,19	9259,88	10844,81
4.3	618,94	10970,17	13023,84
4.4	522,52	12063,58	13883,52
4.5	486,95	9975,5	11933,76
4.6	559,31	8466,74	9710,16
4.7	559,19	11704,36	13979,63
4.8	482,15	10200,76	11585,69
4.9	529,05	9341,94	11339,38
4.10	556,11	9736,75	10887,89
4.11	580,5	9161,95	11166,9
4.12	531,08	12129,72	14406,47
4.13	552,93	12622,51	14691,39
4.14	478,24	10729,11	12198,76
4.15	611,3	15539,37	16582,57
4.16	604,49	10963,85	12719,57
4.17	496,64	10749,65	11703,27
4.18	473,04	10825,9	11366,66
4.19	522,99	8937,91	10611,86
4.20	601,33	15858,77	17013,64

As it was already concluded by Divós et. al. [12], the values for Ed are higher than those for MOE. Observing Fig. 6 it can be concluded that although not equal in value, the plot for both terms are very similar (with an almost constant offset between them). In fact the correlation between these values is $0,9372$.

Based on the above presented results it can be concluded that the prototype presented in this paper can be used to calculate wood parameters, such as MOE, without the need to submit the samples to deformation tests. One of the advantages of it is the fact that the wood will not suffer any change on its structure. Therefore the samples used on the tests can be used in any other application.

V. CONCLUSION

In this paper it was presented a prototype for a low-cost ultrasonic probe, using 40KHz ultrasonic transducers and an FPGA. The objective of this probe is to assess some wood parameters, such as the Ed, and to detect some types defects that can occur in wood samples.

There were made three sets of tests to detect defects on wood pieces and one set of tests to assess the Ed parameter value. It was possible to detect defects on the glueing process of laminated wood, by detecting a decrease on the propagation speed of the ultrasonic wave on defective areas of the sample under test. This speed decrease was also observed when the prototype was used to detect holes in the samples.

Regarding the determination of Ed, the used wood samples were also subjected to mechanical testing, and the obtained data corroborate that it is possible to use the proposed low-cost system to assess this parameter.

Using this technique, wood samples are not subject to any mechanical stress. They can therefore be used in further testing, during research, or be used in final products, in the case of industrial applications. Furthermore it has also the advantage of being a fast technique, when compared for example with the set-up time needed to make a test with an universal testing instrument.

ACKNOWLEDGEMENT

This work is supported by European Union Funds (FEDER/COMPETE - Operational Competitiveness Programme) and by national funds (FCT - Portuguese Foundation for Science and Technology) under the project FCOMP-01-0124-FEDER-022696.

REFERENCES

[1] K. A. McDonald, R. H. Falk, and M. P. Mallory, “Nondestructive testing of wood products and structures: state of the art and research needs.” *Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory*, pp. 137–147, 1990.

[2] B. Voichita and R. Patrick N.J., “Dynamic elastic anisotropy and nonlinear in wood and rock,” *Elsevier ScienceB. V., Utrasonics*, vol. 36, pp. 813–824, 1998.

[3] J. G. Haygreen and J. L. Bowyer, *Forest Products and wood science: Na Introduction. 2ed.* Iowa State University Press, Ames, Iowa, 1989.

[4] F. K. Bechtel and J. R. Allen, “Methods of implementing grain angle measurements in the machine stress rating process,” vol. Sixth Nondestructive Testing of Wood Symposium. Washington State University, Pullman, WA, 1987.

[5] R. Stößel, “Air-coupled ultrasound inspection as a new non-destructive testing tool for quality assurance,” Ph.D. dissertation, Universität Stuttgart, Holzgartenstr. 16, 70174 Stuttgart, 2004. [Online]. Available: http://elib.uni-stuttgart.de/opus/volltexte/2004/1622

[6] S. Sokoloff, “Zur frage der fortpflanzung ultraakustuscher schwingungen in verschiedenen koerpern,” pp. 454–461, 1929.

[7] A. S. Sanyal, S. N.and Gulati, “Compressive strength of timber by ultrasonic pulse technique,” *Indian Forester, Dehra Dun, India*, vol. 105, no. 2, pp. 180–185, 1979.

[8] J. Blitz and G. Simpson, *Ultrasonic methods of non-destructive testing*, ser. Non-destructive evaluation series. Chapman & Hall, 1996. [Online]. Available: http://books.google.com/books?id=d3WWect9zQEC

[9] V. Bucur, *Acoustics of Wood*, 2nd ed. Springer, 2006.

[10] “Ultrasonic sensor, aplication manual,” Murata Manufacturing Co. Ltd., Tech. Rep., (2008).

[11] P. Mestre, C. Serodio, A. Azevedo, H. Correia, I. Bentes, and C. Couto, “Filling rate assessment of recycling containers using ultrasonic transducers,” *Measurement*, vol. 44, no. 6, pp. 1084 – 1095, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0263224111000923

[12] F. Divós and T. Tanaka, “Acta silvatica et lignaria hungarica,” *Construction and Building Materials*, vol. 1, pp. 105–110, 2005.