NON-CONTACT ULTRASONIC SENSOR FOR DENSITY MEASUREMENT AND DEFECT DETECTION ON WOOD
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Abstract: In this work the problem of measuring density and verifying structural integrity of wooden samples is approached by using non-contact ultrasonic transducers. The time of flight of the ultrasonic waves is measured in transmission mode using cross-correlation algorithms between emitted and received signals. Once known the times of flight, the propagation velocity through the wood, which is proportional to density, can be estimated. The conversion factor between velocity and density is experimentally established through a laboratory calibration. Moreover the non contact ultrasound technique is applied to detect the presence of knots by scanning the surface of the sample and measuring the integrated response proportional to signal energy.

Introduction: In last years great efforts have been made on the development of measurement and testing techniques for wood and wooden structures with the aim of predicting their characteristics and ensuring their performances. Many experimental methods have been investigated and, among the different approaches, particular attention has been devoted to ultrasonic measurement. However, wood is a naturally grown, anisotropic and heterogeneous material that makes the use of ultrasonic measurement systems very challenging. In fact several parameters, e.g. the wood fibres disposition and the humidity content, can make the ultrasonic signals complex and difficult to be analysed.

Nevertheless Non Destructive Techniques (NDT), mostly based on traditional contact ultrasounds application, have been widely applied in the evaluation of the wood quality in several characterization procedures, for diagnostic purposes and for the classification in working conditions. For instance, in order to evaluate the elastic modulus, the presence of defects and the bulk mass, a contact ultrasound system with waves propagating in the fibres direction can be used. A similar system, but with the waves propagating perpendicularly to the fibre direction, is utilized to detect the presence of wood rot directly on the tree. To determine the dynamic hardness and also the presence of wood rot an established measurement technique is the scleroscopy.

One parameter of great interest in the evaluation of the mechanical properties of wood is the density, that is related to the wood behaviour against environmental forces like wind, rain, gravity, snow, and other. The evaluation of this parameter permits also to detect wood defects like decay, insect damage, splits, checks, knots which change the wood density substantially.

Main limitations of traditional ultrasonic sensors are often connected with the contact and the coupling medium required to have a satisfactory SNR. As a consequence, one of the NDT measurement method used to locally evaluate the density is the X-Ray technique, which on the other side may present problems for use in industrial environment due to human exposure to radiations.

In this paper the development of a measurement system based on innovative non-contact ultrasonic sensors for density measurement and knots location is proposed. The methodology is discussed and preliminary results are presented. The use of non contact ultrasonic probes for this kind of analysis is a new approach that could allow to monitor the density during, for example, the working process.

Measurement technique: The developed experimental set-up is shown in Figure 1. The system is composed of two sensors, which can operate both as transmitter and as receiver. Therefore the system has two channels for data acquisition (with two amplifiers and two analog I/O boards), in such a way as to present four operation modes (two in reflection mode – one for each of the two sensors - and two in transmission mode – one used as transmitter and the other as receiver and vice-versa).

The boards for driving the ultrasonic probes are installed in a commercial industrial PC that performs generation, reception, acquisition and treatment of the ultrasonic signals acquired from the sensors. These signals will represent physical data such as the Time of Flight (time spent by the ultrasonic beam to cover the path) and Integrated Response (area underneath a selected transmission or reflection peak) of the
ultrasonic waves. In Figure 2 an example of the cross-correlation signal measured, in transmission mode, on a wooden sample, is shown. $T_c$ represents the time of flight of the first peak and $t_m$ is the difference between the ToF of the first and second peak. The arbitrary units are used because the information of interest is represented by the position of the peaks with respect to the time axis.

The probes are non-contact piezo-electric transducers (spherical focused probes with 12.5 mm active area diameter), operating at about 1.0 MHz. The signals used to drive the transducers are chirps (very fast sinusoidal sweeps in a limited frequency band), with amplitude, time duration and frequency content tuneable, in such a way as to optimise the ultrasonic wave propagation in the different materials.

To find the combination of settings that allowed to obtain the better signals for wood density measurement and knots location, several sets of parameters were tried leading to the following configuration:
- Central frequency: 750 kHz
- Bandwidth around the central frequency: 500 kHz
- Chirp Duration: 100 µs

In the performed tests the system operated in direct transmission mode, i.e. ultrasound travels from the transmitting to the receiving transducer through ambient air and the sample. In order to measure the time of flight, a cross-correlation algorithm is employed, which allows to determine the delays between emitted and received waves.

The system was used for two different purposes: to assess the density value of different kind of wooden samples and to detect the presence of knots. The measurement chain was optimized in order to have a satisfactory SNR (from 16 to 25 dB, depending on the wood) and a measurement time compatible with production requirements. In particular the distance and alignment of the sensors were carefully considered, as the losses at the interfaces (air-sample) significantly affect the achieved accuracy (see next section).

Results: In order to obtain the density values of the test material, it is necessary to measure the ultrasound velocity through the material. In order to find a relation between velocity and density, a dedicated calibration must be performed using reference samples whose density was previously determined by measuring the volume by a calibre and the mass by a balance with a resolution of 0.01 g. The samples have dimensions typical of those in the production line during working progress. The thickness of the different samples used is in the order of 5-7 mm.

Several different kinds of wood were investigated. For each kind, about 4 or 5 samples at different density levels were used for calibration. In Table 1 the average reference density values of the samples calculated for each kind of wood are showed.
Figure 2: Example of transmission mode cross-correlation signal measured on a calibration sample. The first multiple reflection is used to determine time of flight through the sample ($t_m$)

<table>
<thead>
<tr>
<th>Wood</th>
<th>Reference density (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sycamore figured</td>
<td>567.7 kg/m$^3$</td>
</tr>
<tr>
<td>Maple</td>
<td>504.5 kg/m$^3$</td>
</tr>
<tr>
<td>Cedar</td>
<td>370.4 kg/m$^3$</td>
</tr>
<tr>
<td>Cherry wood</td>
<td>634.5 kg/m$^3$</td>
</tr>
<tr>
<td>Douglas wood</td>
<td>622.4 kg/m$^3$</td>
</tr>
<tr>
<td>Ash</td>
<td>679.8 kg/m$^3$</td>
</tr>
<tr>
<td>Iroko</td>
<td>645.9 kg/m$^3$</td>
</tr>
<tr>
<td>Mahogany</td>
<td>633.8 kg/m$^3$</td>
</tr>
<tr>
<td>Olive</td>
<td>720.2 kg/m$^3$</td>
</tr>
<tr>
<td>Oak</td>
<td>716.5 kg/m$^3$</td>
</tr>
<tr>
<td>Tulipwood</td>
<td>515.3 kg/m$^3$</td>
</tr>
<tr>
<td>Yellow pine</td>
<td>587.9 kg/m$^3$</td>
</tr>
</tbody>
</table>

Table 1: reference density

The uncertainty in the calculation of the reference density is in the order of 0.8-1% in controlled temperature conditions.

The propagation velocity was measured in three different points of each sample, by averaging on 200 readings. Then, the mean velocity value for each density level was calculated, in such a way as to obtain only one velocity value for each known density value. This one is an important step, as it aims to take into account also the dispersions in the results due to the non homogeneity in the reference samples, which could be significant. In fact, the density is a “local” quantity, that can easily present small variations from point to point of the same sample, whose density is therefore only “nominally” known.

The velocity of propagation through the sample is:

$$V_m = \frac{d_m}{t_m}$$

where $d_m$ is the sample thickness.

In this measurement process one important parameter to be considered was the humidity value as this influence the ultrasonic propagation velocity; since wood is a hygroscopic material it exchanges water vapour with the air and both its moisture content and its dimensions are controlled by the relative humidity of the surrounding air. For this reason we used dried samples that were stored and measured in an environment with a controlled humidity value. This allowed to consider the moisture content as constant for all the samples, thus making the influence of this interfering input negligible.

In the following figures some example of results are shown. In Figure 3 four samples of yellow pine wood were used to create the calibration line by least square interpolation; the dispersion of data with respect to the calibration line expressed as three times the standard deviation of the density is 1.35%. This uncertainty is affected by several interfering inputs as:

- temperature variation;
• fibres orientation;
• artefacts due to the averaging acquisitions in the borders of tiles;
• variation of thickness due to irregular cutting.

The considered density range is narrow, but it is representative of the real values of interest for practical applications. This requires an adequate sensitivity to correctly distinguish the different samples.

Then two new samples, not used to generate the calibration line, were measured by the proposed technique and by the reference method. The results are reported in Table 2, were it is shown that differences are below 1%.

![Figure 3: Calibration line for the yellow pine samples](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Reference density (kg/m³)</th>
<th>Measured density (kg/m³)</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow pine 1</td>
<td>589,017</td>
<td>589,970</td>
<td>0.16</td>
</tr>
<tr>
<td>Yellow pine 2</td>
<td>586,348</td>
<td>587,117</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 2: comparison between reference density and density obtained by the calibration curve for yellow pine samples

In Figure 4 the calibration line obtained for the olive wood samples is showed. In this case the uncertainty expressed as three times the standard deviation of density dispersion, with respect to the calibration line is 1.2%.

![Figure 4: Calibration line for the olive wood samples](image)

Knots location: the presence of knots in the wooden tiles can create problems during the production process.
for different reasons. The first one is aesthetic since the knots appear with a different colour and present often cracks. The second one is due to their greater hardness with respect to the stem of the tree that makes the manufacturing more difficult. The last one is related to their use for construction purposes, the presence of knots in this case can affect the mechanical resistance.

The data are acquired by the non-contact ultrasonic measurement system and exported from the acquisition system to a PC through a serial port and acquired and processed using a software developed in LabView environment.

To achieve a 2-D spatial sampling over the investigated area with tuneable steps in both the directions, a motion workbench is realised by an automatic mechanical system composed of supporting structures, slides and motors. The control is done by the use of a parallel port from the second PC, that controls an electronic circuit. Motors managed by this circuit delivers motion directly to the probes with a spatial resolution of 2 mm in both directions.

![Probes motion workbench](image)

Figure 5: Probes motion workbench

With the LabView software it is possible to estimate the integrated response and the time of flight relative to the first peak in transmission mode, in one measurement it is possible to evaluate both density and presence of defects. Results achieved are shown in the following Figures.

![Images](image)

Figure 6: (a) Integrated response; (b) Time of flight; (c) picture of the examined sample
The map of the integrated response is normalized and represented in arbitrary units because the information that is needed in order to detect the presence of knots, is the difference between the IR values of the different measurement points over the scanning grid.

It is possible to notice that in presence of defects like knots or thickness variation, both the Integrated Response (IR) and Time of Flight (ToF) maps changed. The ToF decreases, as a result of the greater concentration of material in the knot, and increases in regions where the fibres present a lower compression (typically for young wood or around the knots). The IR, instead, decreases in presence of knots and also in presence of non compressed fibres. This leads to a non intrusive investigation, where the variation of both IR and ToF maps can be used to correlate with these dishomogeneities. From the performed measurements, it was possible to notice that better results in terms of knots identification, were achieved by using as diagnostic parameter the IR. This is due to the fact that in most cases the IR values decrease significantly thus leading to a better representation of dishomogeneities like knots. In Figure 6 the obtained IR (a) and ToF maps (b), and the wooden sample(c) are shown. By comparing the results it is possible to notice that in the IR map there is a better definition of this kind of defects, thus allowing a validation of the diagnostic method.

In Figure 7 the map of the IR obtained for a different sample is shown; it possible to notice that the system was able to detect not only the presence of two visible knots in the front side but also the knot located in the back side of the same sample.

Figure 7: (a) Knots on the front side of one of the maple samples; (b) Knot on the back side of the same sample; (c) map of IR obtained by ultrasound system

Figure 8: (a) map of IR obtained by ultrasound system; (b) map of temperature obtained by thermography; (c) mahogany sample
In order to have a further validation of the proposed method, samples without any visible defects were examined with two different measurement systems, the non-contact ultrasounds and the infrared thermography.

In Figure 8 the results of the two different examination techniques obtained for a sample of mahogany wood without any visible defect are shown. The use of these systems allowed to have a better characterization of the defects and the measurement method: in fact, the ultrasounds can detect the presence of an anomaly inside the material, the thermography can give information about their nature by outlining their different thermal capacity.

The wooden sample under inspection is uniformly heated by an infrared quartz lamps and measured by an infrared camera (FPA micro-bolometric sensor, 320x240 pixels, resolution < 0.08 °C) in reflection mode. As shown from the comparison of Figure 8 (a) and (b), the IR ultrasonic map presents two main regions with significant gradients, which could be representative of the presence of discontinuities. It is not possible to assess if these are due to a lack of material or to the presence of a knot since both of them would generate a decrease in the energy signal.

However, possible defects in those parts of the sample are confirmed by the analysis performed by infrared thermography. The two areas are highlighted, in Figure 8 (b), in one case by a higher temperature (left), in the other (right) by a lower temperature. This reveals a different nature of the two defects (different thermal capacity of the inclusions), and confirms the validity of the ultrasonic based proposed method.

**Conclusions and future results:** In this paper, an original measurement method for density evaluation and defect detection in wood samples is proposed. The method is based on piezo-electric non-contact ultrasonic probes, which allow to have a complete non-intrusive inspection of the sample during production processes. The measurement system was tested on samples of twelve different kinds of woods with satisfactory results. The problem of the dependence of the density from the moisture content of the wood was addressed by using dried samples stored in an environment with controlled humidity value, thus making possible to consider this interfering input as negligible.

The density was measured with an uncertainty in the order of 1-2%.

In addition, structural defects, such as knots, were correctly identified also when internal and non-visible. A comparison with results from infrared thermography allowed to validate the achieved results.

**Bibliography**


