Wood defect detection using low acoustic impedance-based PZT transducers

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Abstract

Early detection of common defects in wooden structures is an important factor to avoid costly maintenance and improve the life expectancy of structures. A novel qualitative technique has been developed and evaluated for detecting near-surface abnormalities and defects in wooden structures. The proposed setup consisted of a piezoelectric ceramic lead-zirconate-titanate (PZT) transducer and an impedance evaluation board. This setup is cost-effective and can be easily employed over various wooden structures. The proposed setup was evaluated on a polymeric material with a debonding. The main experimental validations were conducted on wood specimens with unfilled carved cavities and also, putty-filled holes. In addition, the setup was tested for the poor gluing in a wooden specimen. The measured impedance for each location was recorded and normalized to the reference baseline. The proposed setup could detect the cavities and putty-filled regions successfully. It also could detect the approximate geometry of defects. The glued and unglued regions were detected as well.

Keyword: PZT transducer, low acoustic impedance transducer, structural health monitoring, defects in wood, nondestructive testing

Introduction

The history of using wood as a popular and easily accessible material is very old. It has been also used in making tools and furniture widely. Wooden products naturally have good mechanical properties (Green, Winandy et al. 1999), which make them an efficient and economical alternative compared to the other materials. Although the natural wood is still popular, the shortage of natural resources pushed the industry to fabricate and employ plywoods, particleboards, fiberboards and wood-based composites which have been grown fast in the last few decades (Maloney 1996, Ahmed 2005, Lo Castro and Fragnelli 2006). Wood applications are numerous including civil structures, furniture, interior paneling, construction materials, sports tools, and even small boats.

Different types of defects have been observed in wooden structures. In general, the main three categories of defects could be classified as, first the natural defects such as decay in wood, fungal attack, second the fabrication defects such as unglued regions or unexpected cracks and cavities and at last, the defects occurred during the operation like those caused by impacts or overloading (Erteld, Mette et al. 1964, Estevez, Fernandez et al. 1999). Defects could weaken the wooden structure and finally could lead to the severe collapse of structures. Nondestructive testing (NDT)

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techniques have comprehensive applications among different materials and wooden structures as well (Ross 2015). A wide range of NDT applications for wooden structures has been discussed already (Ross and Pellerin 1994, Smulski 2007, Liñán, Morales Conde et al. 2015). Among different NDT strategies, an ultrasonic inspection is a popular approach which evaluates the elasticity of the wood to find out the abnormalities in the structure (Bucur and Chivers 1991, Fang, Lin et al. 2017, Yang and Yu 2017). Despite reliable and consistent results, the ultrasonic technique needs trained operators to interpret the results. In the case of near-surface defects, using ultrasonic approach does not provide reliable data as well, because near-surface defects usually lay within the wavelength of propagated ultrasound waves and ultrasound will not be able to detect this type of defects easily (Dugnani 2013, Dugnani 2015). Other techniques like x-ray (Tomazello, Brazolin et al. 2008) need special equipment and safety issues remain a concern. Although ultrasonic inspection remains a popular technique, PZT transducers can be used for dynamic strain measurements as well (Yu and Giurgiutiu 2009, Zagrai, Doyle et al. 2010). In the case of strain measurements, PZT transducers may sit individually or in an array on the surface of the specimen to form piezoelectric wafer active sensors (PWASs) which help to localize the damage (Zhang 2005, Zagrai, Doyle et al. 2010). Embedded PZT transducers can capture the change of structural mechanical impedance to provide structural health monitoring (SHM) signals (Narayanan, Kocherla et al. 2017, Ai, Zhu et al. 2018). PZT transducers are usually excited in their thickness mode and require higher frequencies of excitation and interface matching layers to reduce the impedance mismatching depending on their size and material properties (Dugnani 2015). Employing the radial resonance mode provides several advantages over the thickness mode, including the lower resonance frequency and also, improved impedance matching (Dugnani and Chang 2008, Mohammadabadi and Dugnani 2019). Excited PZT transducers in their radial mode show a lower acoustic impedance which is matched with low acoustic impedance (LAI) of biological and natural materials like wood (Mohammadabadi and Dugnani 2013, Mohammadabadi and Dugnani 2019, Mohammadabadi, Gu et al. 2019). It has been shown that using LAI technique will provide a qualitative approach to detect abnormalities by measuring the change in acoustic impedance due to the defects. Although the accuracy of the qualitative LAI technique is not comparable with the quantitative approaches like ultrasonic or x-ray imaging, using LAI provides a basic understanding of the damages which helps to plan ahead and arrange further advanced inspections.

In addition to the accuracy of NDTs, the cost of testing equipment remains an important factor as well. When monitoring the health of a structure like a bridge is critical, high-cost investment on some advanced NDTs makes sense, but obviously, clients are not willing to pay large amounts, sometimes several times higher than the products' price for NDT testing of regular wooden products. On the other hand, it is not easy to transfer extra-large wooden products to a laboratory for defect's testing as well. Hence it is clear that there is a potential gap for a cheap, reliable and user-friendly technique in the easy detection of specific defects in wooden structures. The novel proposed LAI technique in this research might cover a part of this demand by introducing a portable and easy-to-use technique.

Materials and methods

The LAI setup includes a ceramic PZT transducer, PZT-5A, with the resonance frequency of 245 kHz, diameter of 10 mm and thickness of 3.7 mm, manufactured by APC International Ltd (American Piezo Ceramics Ltd). The transducer was connected to an evaluation board, AD 5933, made by the Analog Devices Co, to analyze the measured impedance. A custom frame was designed, and 3D printed with the details discussed in previous studies (Mohammadabadi, Chamani et al. 2019, Mohammadabadi and Dugnani 2019).

As the proof of concept, two transparent pieces of regular polymethyl methacrylate (PMMA) with the size of 75 × 55 mm and different thickness of 5 mm and 3 mm were prepared. Both polymer specimens were sanded in the middle to mimic the debonding after gluing the specimens together. The size of the debonding area was 20 × 20 × 1 mm approximately, Fig. 2a. LAI technique was used to detect the debonding. The surface was gridded in 5 mm step size and the impedance was measured for each location.

In order to mimic the defects in wooden structures, a piece of commercial maple wood with a density of 386 Kg/m^3 was cut to the size of 205 × 135 × 15 mm. The specimen was carved to create different reference shapes by a handheld electric grinder. The depth of carving was 8 mm approximately. Then the surface of the specimen was covered by a thin wood veneer with a thickness of 2 mm and a density of 270 Kg/m^3. The veneer was glued to the specimen using a wood adhesive manufactured by Jinwande Adhesive Co. Finally, the specimen was covered by a self-adhesive vinyl film manufactured by Yong Feng Co. Before testing the LAI setup, the specimen's surface was gridded in 10 × 10 mm squares and the impedance was measured over the surface grid. The specimen was imaged by the x-ray technique to have a second inspection's method. Briefly, the x-ray was done by XY-2515 flaw detector manufactured by Liaoning Instrument Co. The specimen was under radiation for 210 seconds. The maximum applied voltage and the current across the x-ray tube were 250 kVP (peak kilovoltage) and 15 mA respectively. The focal spot size and the radiation angle were 44 mm and 40^o respectively. The focus film distance (FFD) was 600 mm.

As a different scenario, the previously carved specimen was filled and repaired by a putty manufactured by Shanghai Noon Decoration Materials Co, and then covered by the self-adhesive vinyl film. The putty-filled specimen was left in room temperature for several hours until the curing was completed. Then the surface was sanded and smoothed by a very fine sandpaper. Finally, the surface of the specimen was covered by a self-adhesive vinyl film. The density of the cured putty was 1640 kg/m^3. Same as the previous experiment, the surface was gridded in 10 × 10 mm squares and the impedance was measured over the surface grid.

Since using the adhesives is very common in wooden structures, it is usually possible that some surfaces do not receive sufficient adhesives during the production or repair. The unglued surfaces cause localized debonding defects which might lead to a complete debonding. Also, products may fail unexpectedly because of stress concentration at the unglued joints. A general type of unglued region in wooden products was mimicked by a maple wood specimen similar to the previous experiment. It was cut in size of 170 × 80 × 34 mm. Then it has been veneered by a thin wooden sheet with a density of 270 kg / m^3 and thickness of 2 mm. Half of the specimen was glued using the same adhesive as the previous experiment and half left unglued. The extra glue was removed, and specimens were pressed using a clamp at the room temperature for 24 hours. The impedance was measured over a line in the middle with the step size of 5 mm.

Results and discussion

PMMA debonding

The impedance has been measured in twelve locations on the midline of the surface which four measuring spots located on the debonding. The other eight spots were located before and after the debonding area. The exploded view of the LAI transducer and the prototype of the system are shown in Fig. 1.

The same setup was used for the entirety of this study. The average magnitude of measured impedance at four spots away from the debonding region has been considered as the reference for the healthy part of the specimen. They were referred to as ΔZ_{nd} in the graph, which indicates ΔZ at 'non-defective' area. Other measured impedance values were normalized to the ΔZ_{nd}. The normalized measured impedance is shown in Fig. 2b. The measured impedance increased when the PZT transducer passed over the debonded area. Measured locations before and after the debonding area did not indicate any abnormality. The normalized impedance increased around 40% compared to the reference normalized impedance. As we discussed already, LAI technique is a qualitative technique, therefore we can claim that those locations with a significantly higher or lower measured impedance compared to the reference locations, contain abnormal structural objects like defects, cavities, etc.

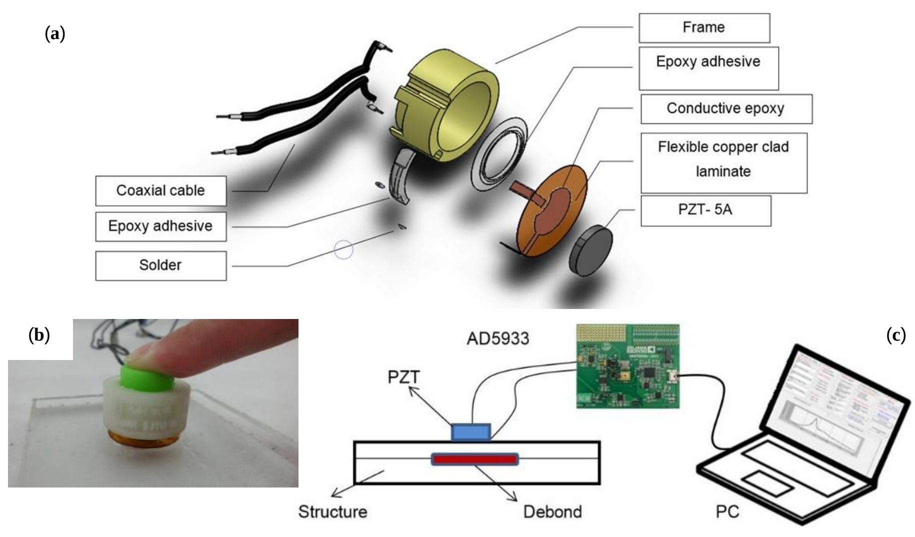

Fig. 1 Exploded view of LAI transducer (**a**), digital image of LAI prototype (**b**) and schematic view of the LAI setup (**c**) (Mohammadabadi and Dugnani 2019)

The approximate size of the defect was matched to the measured impedance in Fig. 2 as well. PMMA experiment validated the setup and provided the proof of concept to evaluate the LAI technique for wooden structures as well.

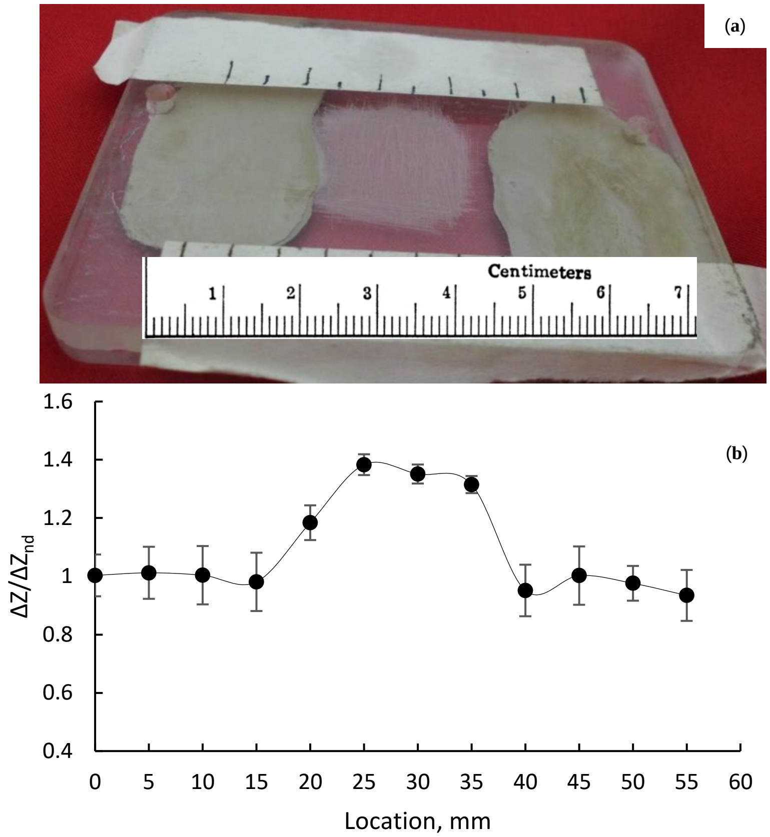

Fig. 2 PMMA specimen with debonding (**a**), Normalized impedance ($\Delta Z/\Delta Z_{nd}$) versus the location of transducer, mm (**b**)

Carved wood specimen

The preparation of wooden specimen is shown in Fig. 3 which shows steps from carving to the finished specimen.

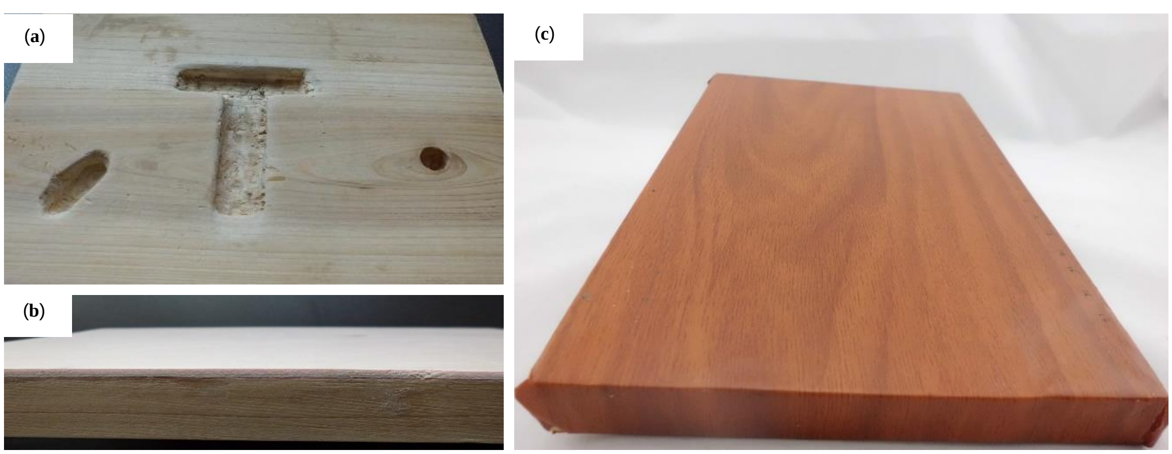

Fig. 3 Carved wood in different shapes (**a**), Gluing veneer to the carved specimen (**b**), Covering the specimen with a wood grain self-adhesive vinyl film

Using the LAI setup, the impedance was measured over the grid surface of the specimen and collected data were processed with the Microsoft Excel. The peak value of impedance has been found and stored for each location. Impedance values have been normalized to the reference impedance of PZT transducer with the free excitation in the air, ΔZ_0. The normalized impedance increased as the PZT transducer passed over the defect's region. The LAI setup successfully detected the presence of defects and their approximate shapes as well. The results are shown as a surface contour plot in Fig. 4a. The normalized impedance increased from the range of 0.8-0.83 for the healthy part of the specimen to the range of 0.83-0.85 for the regions with defects. In order to check the agreement of measurement with the actual defects, results were superimposed on the surface of the specimen, shown in Fig. 4b. The specimen was imaged by x-ray and the defects were visible in the x-ray image as well, Fig. 4c. As a qualitative technique, LAI worked well in the detection of defects but as expected, it did not provide any information about the depth, type, and severity of defects.

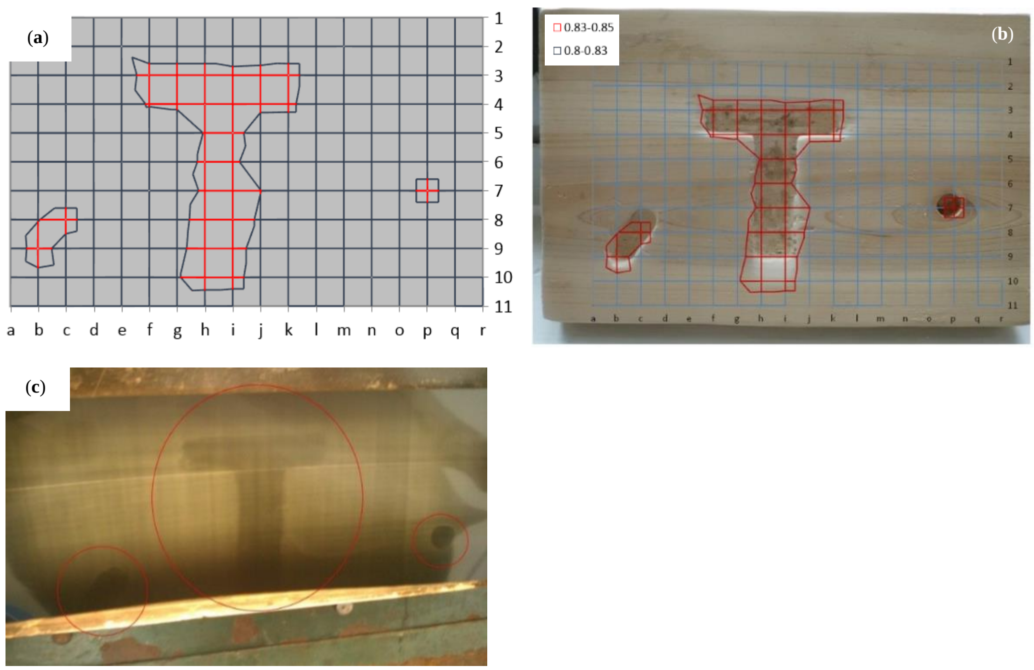

Fig. 4 Contour surface plot of normalized impedance, $\Delta Z/\Delta Z_0$ (**a**), Superimposition of contour surface plot of normalized impedance ($\Delta Z/\Delta Z_0$) and wooden specimen (**b**), x-ray image of carved wooden specimen (**c**)

Putty-filled wood specimen

The putty-filled specimen and the finished product are shown in Fig. 5. Since the surface was sanded after putty filling, covering with a thin layer of self-adhesive vinyl film concealed the defects which are shown in red circles.

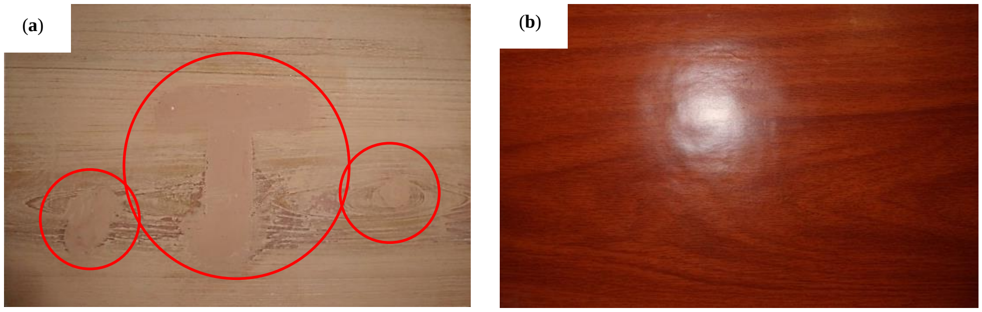

Fig. 5 Putty-filled and surface-sanded specimen (**a**), Covering the specimen with a wood grain self-adhesive vinyl film (**b**)

The general steps of impedance measurement were the same as the previous experiment. The surface of the specimen was gridded, and impedance at each location was measured. The measured impedances were normalized to the free excitation's impedance of PZT transducer in the air, means without loading and not in touch with any surface ($\Delta Z/\Delta Z_0$). The final processed data are shown in a contour surface plot in Fig. 6a. Previous studies (Mohammadabadi, Chamani et al. 2019, Mohammadabadi and Dugnani 2019) discussed that the shifting of the resonance frequency of PZT transducer for LAI technique provides another tool to detect the defects. It was also mentioned that the frequency shifting is not a consistent and reliable approach. However, in the case of the putty-filled wood specimen, the frequency shifting approach could detect the concealed defects successfully. The surface plot of frequency shifting is shown in Fig. 6b.

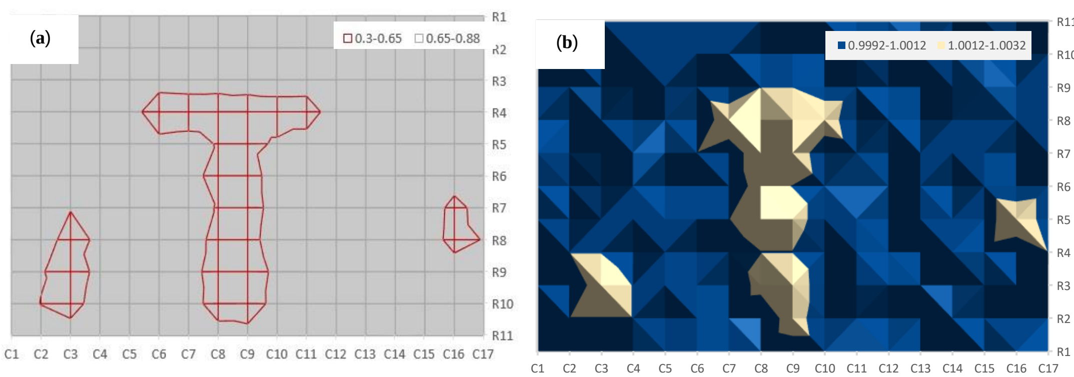

Fig. 6 Contour surface plot of normalized impedance, $\Delta Z/\Delta Z_0$ (**a**), Contour surface plot of normalized frequency, f/f_0 (**b**)

The normalized impedance increased to the range of 0.65-0.88 over the defects from the range of 0.3-0.65 over healthy part of the specimen. This difference provided the ability to distinguish the defects from the other parts of the specimen clearly. The approximate shapes of the defects were obtained as well. In the shifted frequency plot, the normalized values increased to the range of 1.0012-1.0032 over the defects from the range of 0.9992-1.0012 over the healthy part of the specimen. The change in shifted frequency was small compared to the noticeable change in the measured impedance, therefore we preferred to evaluate the specimens based on the measured impedance.

Glued wood specimen

The specimen's preparation and the finished product are shown in Fig. 7. Half part of the specimen was glued, and the other half did not have any glue.

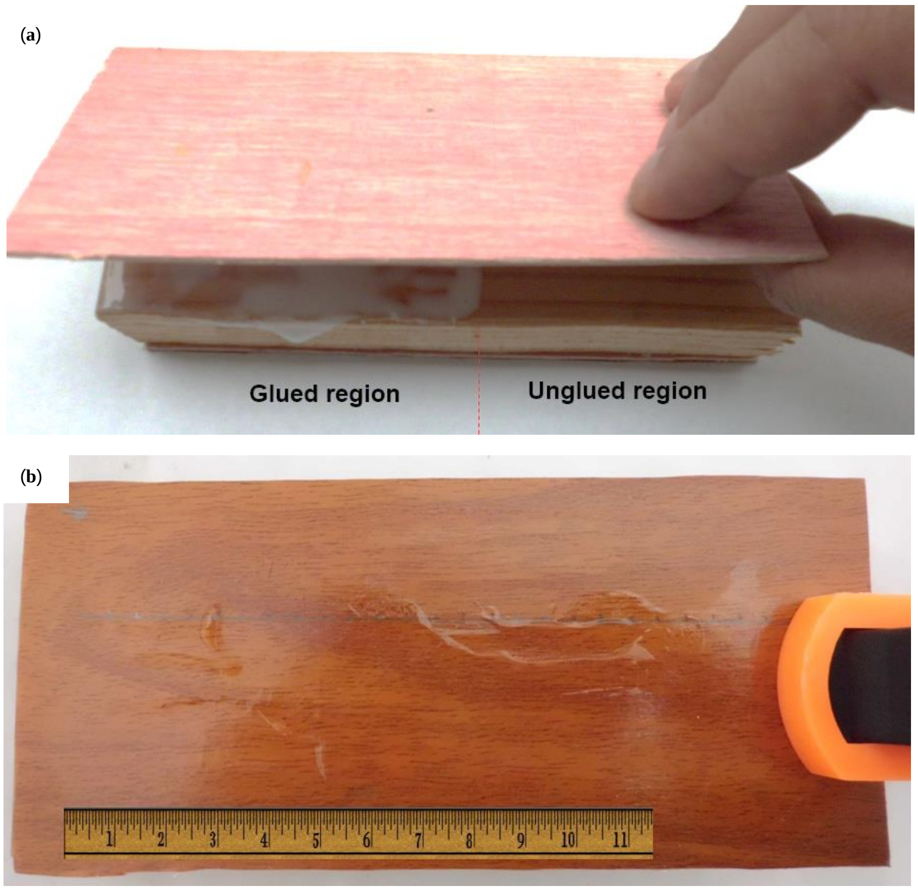

Fig. 7 Glued and unglued regions (**a**), Covering the specimen with a wood grain self-adhesive vinyl film (**b**)

The impedance measurement was done over a longitudinal midline with the step size of 5 mm. Same as the previous experiments, the measured impedance, ΔZ, was normalized to the free excitation's impedance of the PZT transducer without any load, ΔZ_0. The results are shown in Fig. 8. The ruler in Fig. 7b shows the size scale. Based on the ruler scaling, the glued region located in distance 0 to 90 mm approximately. Over the glued region, the normalized measured impedance was changing from 0.8 to 0.86 while the normalized impedance over the unglued region increased to the range of 0.87 to 0.9. If we assume that the lack of adhesives could be a defect in the structure, the LAI technique could detect this type of defect successfully. It should be considered that the LAI technique is a qualitative approach and can be employed for near surface defects. In this experiment, the gluing process had been done manually and it was highly possible that the glue was not uniformly distributed over the surface. It can be said that as an influencing factor of non-uniform gluing, the impedance plot did not show a linear trend over the glued region.

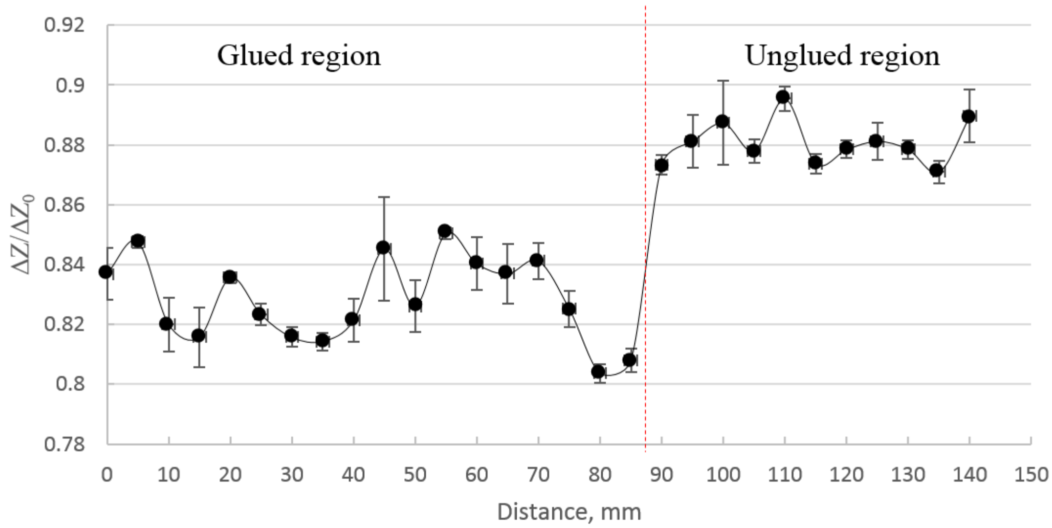

Fig. 8 Normalized impedance ($\Delta Z/\Delta Z_0$) versus location, mm over glued and unglued regions

Conclusions

Efficacy of a novel technique in the detection of defects in maple wood specimens was studied. It has been shown that LAI method provides a qualitative tool for detecting the near-surface abnormalities in LAI materials, especially wooden structures. As a proof of concept, the setup was evaluated for a polymeric specimen and then, several experiments on wood specimens were conducted. It was shown that the change in measured impedance due to the presence of abnormalities like cavities, putty-filled regions or unglued surfaces can be used as a preliminary inspection in LAI materials before employing the advanced and costly quantitative inspections. The approximate geometry of defects was obtained as well. Although LAI technique is a simple and qualitative approach, it proved its efficacy for certain types of defects without providing detailed information about the defects like depth, type or severity of defects.

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