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ORIGINAL ARTICLE

Improvement of robustness in ultrasonic attenuation spectroscopy for detecting internal insect damage in wood member of cultural heritage

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Abstract Insect damage is one of the most serious problems in conservation of wooden cultural heritage buildings. Because this damage is quite small in a cross section, it is difficult to detect by conventional ultrasonic techniques. In the previous study, ultrasonic attenuation spectroscopy showed a feasibility to detect this small defect. But to apply this method to real inspection, the robustness needs to be improved. For improving the robustness, this study focused on inconsistency of ultrasonic spectrum measurement. To minimize the inconsistency, Spectra-averaging pretreatment was attempted. Even though this pretreatment would provide the better robustness, it can also make a negative effect on the accuracy in the detection of small damage. Therefore, the influence of the pretreatment on the prediction was investigated in this study. By ultrasonic attenuation spectroscopy, the number of drill hole was predicted. When comparing the accuracy in prediction using the pretreated spectra from the prediction without the pretreatment, the accuracy was not lower than that without the pretreatment or the previous study. Therefore, it was concluded that the Spectra-averaging pretreatment does not make a negative effect on the prediction.

Keywords Ultrasonic attenuation spectroscopy · Termite damage · Cultural heritage · Wooden building · Non-destructive

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Introduction

Wood is a natural material and it can be deteriorated by various biological attacks. Various non-destructive techniques have been developed to detect these biological deteriorations. Comparing with many other techniques, ultrasonic technique has advantages; it is safer in inspection than radiation techniques and it is efficient in apparatus expense. Therefore, ultrasonic technique has been frequently used for various purposes in quality control of wood industry, inspection of timber buildings, measuring modulus of elasticity and so on. For each purpose, the experimental setup and analyzing algorithm can be chosen, such as ultrasonic-echo, through-transmission, air-coupled ultrasonic method and ultrasonic-computed tomography. Through-transmission method is the most common in detection of defects inside.

During traveling through wood, the wave transmission tends to be slow when there is defect in the wave path (Sandos et al. [1]). Therefore, the time of flight (TOF, 1/wave speed) is generally used to detect defects in wood. Heart rot in standing tree, decay in old member and cracks in wood were successfully detected [2].

Based on the sensitivity of TOF, recently more advanced techniques have been developed. When applying the through-transmission method, there are some limitations because its two transducers should contact the wood of inspection. Therefore, Hasenstab et al. [3] developed ultrasonic-echo system to detect defects in wood. It could detect and visualize cracks and knots in wood. Besides, the ultrasonic methods for wood generally require that the transducers are pressed with a well-controlled force onto the inspected sample. To remove this limitation, Sanabria [4] developed air-coupled ultrasonic system for detecting bonding failure in glulam. Because transducers do not need contact to wood, the effect of couplant on the receiving signal was reduced. In different point of view, the ultrasonic technique has been improved by combining computed tomography (CT) algorithm. Several researches on ultrasonic CT have been performed [5–7]. The CT reconstruction provides higher detectability than two transducer system and provides the information about location of the defects.

In wooden cultural heritage building, insect damage, such as termite damage, is one of the most serious problems. Because the insect damage can occur inside of wooden member, it is difficult to recognize the damage. Besides, the termite prefers early wood rather than latewood, because it is softer and easier to eat than latewood, as a result the insects make narrow and long tunnels in a longitudinal direction of wood member. In viewpoint of structural safety, the area of damage in a cross section is information of interest. In a cross section, the early stage of the damage is very small because the early wood is less than 5 mm in width. Based on the sensitivity of TOF on defects in wood, TOF-based CT was developed and this CT could detect larger than 13 mm diameter defects [5]. However, it did not show high enough detectability to detect the early stage of insect damages which is 3–5 mm diameter in a cross section.

In the through-transmission ultrasonic technique, the detectability can be governed by algorithm to analyze the received signal. The algorithm could analyze the wave speed (1/TOF) and/or the attenuation of wave during passing through the wood. The wave speed (TOF) is being used frequently because of its simplicity and sensitivity to defects. But the attenuation is barely used in detecting internal defects because of its complexity in analysis and inconsistency in measurement. Even though the attenuation analysis is not simple, the analysis of attenuation has been used in non-wood materials [8, 9]. In wood, Tallavo et al. [10] developed an index of TOF and attenuation to detect decay in wood pole. Sandos et al. [1], Lee et al. [11, 12]. reported that analysis of attenuation can be a good predictor in detecting defects in wood.

Because TOF analysis does not provide enough detectability to detect small insect damage, the analysis of attenuation would be a good opportunity to improve its detectability. Oh and Lee [13] investigated the feasibility of ultrasonic attenuation spectroscopy for detecting small defects in wood under inconsistent contact condition of transducers. They reported that the spectroscopic approach could improve the detectability and is possible to detect the small defects.

As well as accuracy, robustness is important in development of defect detecting method. Because the difference in spectrum between sound wood and defected wood is tiny, even small inconsistency can also cause misprediction. The inconsistency can be caused by inconsistent signal generating/receiving as well as inconsistent contact conditions. To improve the robustness of the ultrasonic spectroscopy up to applicable level, this inconsistency in measurements needs to be minimized.

To solve this inconsistency problem, a simple pretreatment was expected to minimize it, which is obtaining multiple spectra in the position of interest and then averaging the spectra to minimize the inconsistency. However, during this calculation certain important information can be erased by the pretreatment. Therefore, the influence of the pretreatment on the prediction was investigated in this study.

Materials and methods

Experimental apparatus and spectrum measurement

In this study, two custom-made piezoelectric transducers (central frequency: 80 kHz, Kaijo Co. Ltd., Japan) were used to generate ultrasound and to receive the signal. A custom-made pulse generator was used to generate an 80 kHz ultrasonic wave (Kaijo Co. Ltd., Japan) which also has a function of amplifier. The generated ultrasound has approximately 33 % bandwidth (54–106 kHz). The generated waves passed through the specimen and then the received signal was captured by a data logger (NI 5102, National Instrument Inc, USA) and the captured signals were stored by the LabVIEW (National Instrument Inc, USA). The diagram for the test setup is shown in Fig. 1. For couplant, elastomeric couplant (Elastomer, Olympus Co., USA) was glued on the surface of transducers as shown in Fig. 2.

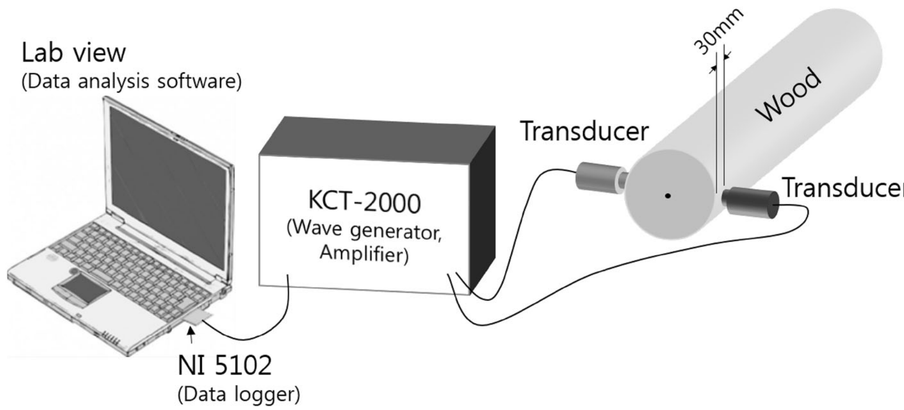
The captured signals (time-domain) were converted into frequency-domain spectra by a Fast Fourier Transform algorithm written in Matlab 2014a (Mathwork, USA).

Spectra-averaging (SA) pretreatment for increasing robustness

To investigate the consistency of received signal, the two piezoelastic transducers were contacted directly without wood (Fig. 3). By testing without any attenuating material between transducers, the consistency could be evaluated without effect of material. Because this type of signal does not contain any attenuation by object, generally it is called as non-attenuated signal. In this study, 23 non-attenuated signals were obtained.

Ultrasonic signal can be obtained by piezoelastic transducers. This piezoelastic transducer utilizes the piezoelastic phenomenon. The signal generated/received by transducer may be different by various inspection conditions such

Fig. 1 Test apparatus setup



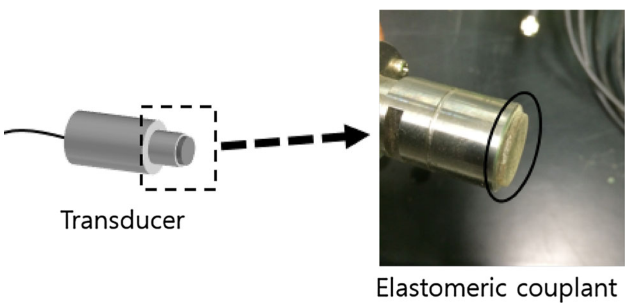


Fig. 2 Elastomeric couplant on transducers

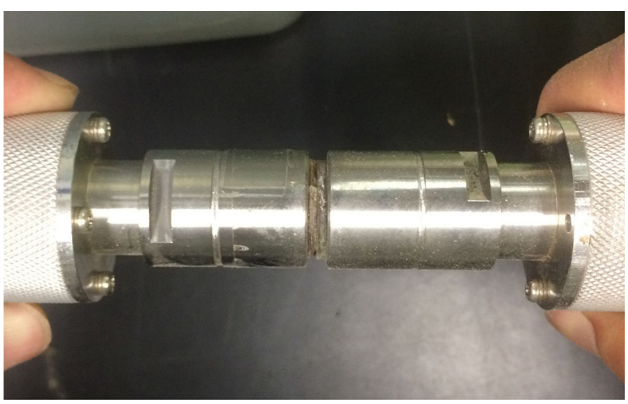


Fig. 3 Measurement of non-attenuated signal. Any attenuating materials were not between the dry couplants

as temperature and so on. To remove the influence of measuring condition at inspection, the received signals were converted into attenuation based on non-attenuated signals measured at the corresponding measuring condition (Eq 1).

$$A_f = -\ln\left(\frac{I_f}{I_{f,0}}\right) \tag{1}$$

where A_f is attenuation of frequency f. I_f and $I_{f,0}$ are the intensity of attenuated signal and non-attenuated signal at frequency f, respectively. The ln is natural log.

The non-attenuated signals were also converted into attenuation by Eq. 1. In this calculation, 13 non-attenuated signals were randomly chosen for the intensity of non-attenuation signal and the rest 10 signals were used as the intensity of attenuated signal in Eq. 1. Ideally the attenuation from this calculation must be zero for the full range of frequency because the non-attenuated signals were used in this calculation.

The SA pretreatment was defined as the average attenuation of a certain number of attenuation spectra (e.g. 10 spectra, Figs. 4, 5; Eq. 2). To investigate the effect of the pretreatment on the consistency in measurement, the 10 non-attenuated spectra were used for the analysis with averaged 13 non-attenuated spectra. To find the best frame size in SA treatment, 10 different SA frame sizes were investigated, where the SA frame size is the number of spectra to average (1 to 10 spectra). For each SA frame size, all spectrum for all possible combination was calculated. For example, in case of SA frame size 2, SA pretreatment averaged 2 spectra. In this case, there are 45 combinations available, when 2 spectra were chosen from the 10 spectra (e.g. Test1 and 2, Test1 and 3, etc. Eq. 2).

To compare the consistency, mean of absolute value for all the spectra of all combination (Mean(ABS)) was calculated for each SA frame size. Also standard deviation of all the spectra of all combination (Stdev) was calculated for each SA frame size (Eqs. 3, 4). The consistency was evaluated by the Mean(ABS) and Stdev. The minimum SA frame size was decided by comparing the Mean(ABS) and Stdev of SA pretreated spectra between SA frame size.

$$A'_f = \frac{\sum_s A_f(s)}{S} \tag{2}$$

where, A'_f is SA pretreated attenuation at frequency f in choosing S spectra. $A_f(s)$ is attenuation at frequency f of sth spectra in choosing S spectra.

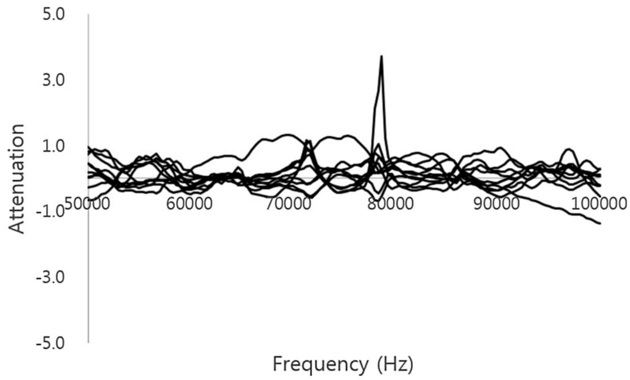


Fig. 4 Fluxation in attenuation of non-attenuated signal (when contacting directly transducers without wood)

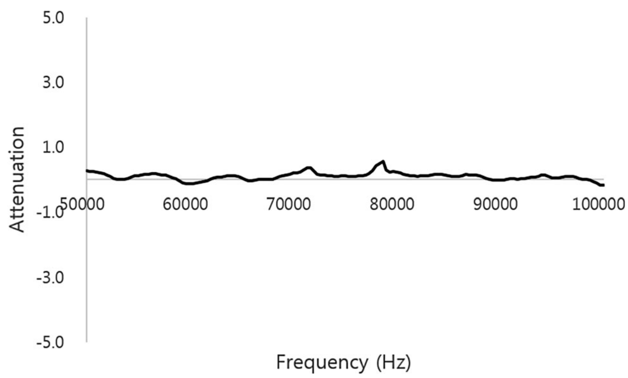


Fig. 5 SA pretreated attenuation spectrum of non-attenuated signal (SA frame size: 10)

$$\mathrm{Mean}\,(\mathrm{ABS}) = \frac{\sum_{f}\sum_{c}\left|A'_{c,f}\right|}{F \times C} \quad (3)$$

$$\mathrm{Stdev} = \sqrt{\frac{\sum_{f}\sum_{c}\left(A'_{c,f} - \mu(A')\right)}{F \times C}} \quad (4)$$

$$\mu(A') = \frac{\sum_{f}\sum_{c}A'_{c,f}}{F \times C} \quad (5)$$

where $A'_{c,f}$ is SA pretreated attenuation for frequency f of cth combination. The C and F are the number of possible combinations and frequencies, respectively. The $\mu(A')$ is the average of all SA pretreated attenuation for all combination and all frequency.

Influence of spectra-averaging pretreatment on prediction

Because the pretreatment can remove some important information for the internal defect detection, the SA pretreatment can make a negative effect on the prediction (decreasing the accuracy of the prediction). Therefore, the influence of SA pretreatment was investigated.

Specimens and artificial defect

Red pine (*Pinus densiflora*) is the most frequently used species in Korean heritage building. Because this species has very low insect resistance even in heartwood, insects make a serious hidden damage in the red pine wood member even in heartwood.

In this study, 6 red pine round timbers without any biological deterioration were prepared. The diameter of the round timber was the same as each other as 96 mm and length was approximately 1,300 mm. Moisture content was approximately 12 % (8–14 %).

Insects usually make small tunnels along the length of the wood members (Fig. 6a) and they attack earlywood first because it is softer than latewood. Due to difficulty in qualifying insect damage in wood, drill holes in a cross section at the end were made to simulate the termite damage, which were bored in the direction of the timber length (Fig. 6b). All of the holes penetrated only early wood. The insect damage located at center of the cross section would make more serious problem because it would be more difficult to identify by the sense of human. Therefore, the first hole was made as close to the center as possible. Then the following holes were made as close to the first hole as possible. All holes were located in a straight path between the transducers. The diameter of a drill hole was 3 mm and it was drilled 50 mm in depth.

Ultrasonic attenuation spectroscopy

For obtaining the ultrasonic spectra for sound wood, a test set of ultrasonic measurement on each specimen was performed for each specimen. The two transducers were touched on wood specimen with 180° at angle. The point to measure was 30 mm away from a cross section as Fig. 1 shows. For a specimen, 10 through-transmission ultrasonic signals were measured. After sixty signals (6 specimens and 10 measurements) were obtained for the sound wood, a drill hole was made at center of the path between transducers. Another test set of ultrasonic test on each specimen was performed for the second damage level (1 drill hole). After the test sets of second damage level were done, one more hole was added in the path for the next damage set. This procedure was repeated until the number of holes reaches 6. In total, 420 signals were obtained, which was 7 damage levels (sound and 1 to 6 drill holes), 6 specimens and 10 signals for a test set. Each signal was converted into attenuation by Eq. 1. The 10 attenuation spectra for a test set were averaged. In total, 42 SA pretreated attenuation spectra according to damage level were prepared.

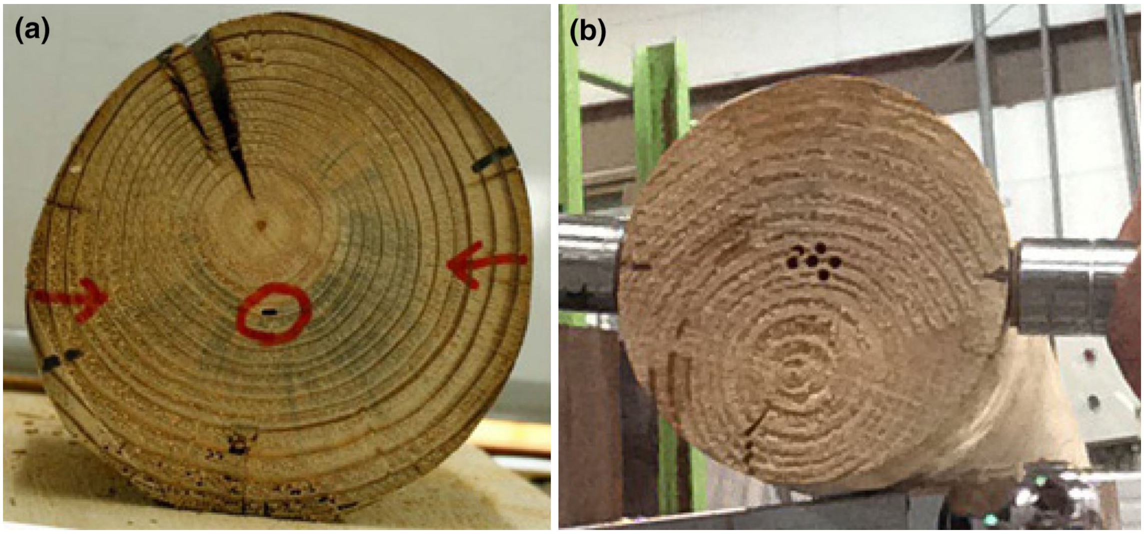


Fig. 6 Insect damage and artificial defects to simulate insect damage. **a** Insect damage, **b** artificial defect)

In this study, the degree of deterioration was evaluated by the number of holes. In the statistical model, the number of holes was used as a dependent variable and the spectra were used as independent variables. Partial least square (PLS) regression model was used for predicting the number of hole with twofold validation. In regression analysis, the prepared 42 spectra were divided into two groups as a training set and validation set. Using these 21 SA pretreated attenuation spectra, regression coefficient of the PLS regression was decided. With the regression coefficient, the number of holes of validation set was predicted. The best regression model was decided as the model showing the lowest Root mean square error of prediction (RMSEP, Eq. 6) for validation set. All analysis was done by a program written in Matlab (R2014a Mathworks USA) with statistical toolbox. The written program was validated by a commercial software, Unscrambler (CAMO Software AS, ver. 9.7).

$$E_{\mathrm{RMSEP}} = \sqrt{\frac{\sum (N_{\mathrm{Predicted}} - N_{\mathrm{Measured}})^2}{n}} \quad (6)$$

where E_{RMSEP} is root mean square error of prediction (RMSEP). The $N_{\mathrm{Predicted}}$ and N_{Measured} are the predicted number of hole and the measured number of hole, respectively. The n is the number of testing.

To investigate the influence of SA pretreatment on the prediction, additionally, a regression analysis was performed with original spectra without SA pretreatment. The number of data was 10 times larger than the SA pretreatment (420 spectra). The regression analysis with the 420 spectra was also performed by twofold validation and PLS regression in the same manner as the SA pretreatment.

Results and discussions

Consistency of non-attenuated spectra

In SA pretreatment, the consistency of attenuation was expected to be affected by the SA frame size, which was defined as the number of spectra to average in SA pretreatment in this study. Therefore, the pretreated spectra of 10 SA frame size (averaging from 1 to 10 spectra) were calculated on non-attenuated spectra. The consistency for a SA frame size was evaluated by the Mean(ABS) and Stdev (Eqs. 3, 4).

As Fig. 7 shows, as the SA frame size increases, the Mean(ABS) of the pretreated spectra decreased. This indicates that SA pretreatment makes non-attenuated spectra close to zero for full range of frequency. It needs to be noticed that the ideal non-attenuated spectrum is zero in full range of frequency. Also the standard deviation (Stdev) of the pretreated spectra decreases as the SA frame size

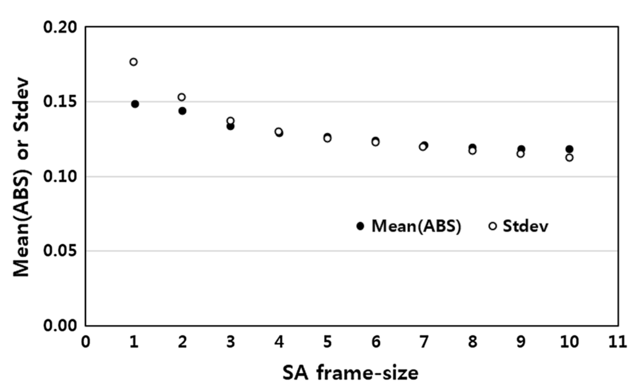


Fig. 7 Consistency according to SA frame size of SA pretreatment

increases (Fig. 7). This means that the SA pretreatment makes the non-attenuated spectrum more consistent.

From Fig. 7, the Mean(ABS) and Stdev of the pretreated spectra did not keep decreasing. More than 9 SA frame size seems to be appropriate to minimize the inconsistency of transducers. Figure 4 shows the attenuation spectra of non-attenuated signal before SA pretreatment. The fluxation was minimized by SA pretreatment with frame size 10 (Fig. 5).

Influence of averaging pretreatment on the prediction

The SA pretreatment showed the increase of consistency in the previous clause, but this pretreatment can decrease the accuracy of the prediction about the insect damage because some effective information in spectra might be removed by averaging treatment. To investigate the influence of the pretreatment on the prediction, the number of drill hole was predicted by the same ultrasonic attenuation spectroscopy as the previous study [13], which consists of Fast Fourier Transform and PLS regression analysis. Different from the previous study [13], derivative and scaling pretreatment was not applied; instead the SA pretreatment (10 SA frame size) was used in this study. To compare the difference in accuracy according to use of the SA pretreatment, the same spectroscopic analysis was also performed without SA pretreatment, where the number of observations was 420.

Figure 8 shows that the SA pretreatment provided much lower Root mean square error of prediction (RMSEP) than the case without SA pretreatment (Fig. 9). From this result, it was concluded that the pretreatment does not make a negative effect on the prediction. Rather than negative effect, the accuracy increased by the SA pretreatment. The reason seems to be that the SA pretreatment removed some noise. Figures 8 and 9 show the prediction of validation set by the spectroscopic model with/without the SA pretreatment. The SA pretreatment (RMSEP: 1.44) showed more accuracy than the case without the SA pretreatment (RMSEP: 2.02).

The previous study [13] reported that the spectroscopic model without SA pretreatment could predict the number of holes with RMSEP of from 1.609 to 1.974 which was much more accurate than the wave speed (RMSEP: 5.925). The result of this study with SA pretreatment showed 1.44 of RMSEP and it was also even more accurate than the previous study.

From this study, it was concluded that the SA pretreatment could provide higher consistency without decreasing the accuracy in prediction.

Conclusions

As one of the efforts to improve the robustness of ultrasonic attenuation spectroscopy for detecting small defect in wood, the SA pretreatment was attempted in this study. This pretreatment was expected to increase the robustness, but it needs to be checked whether it decreases the accuracy of the prediction or not.

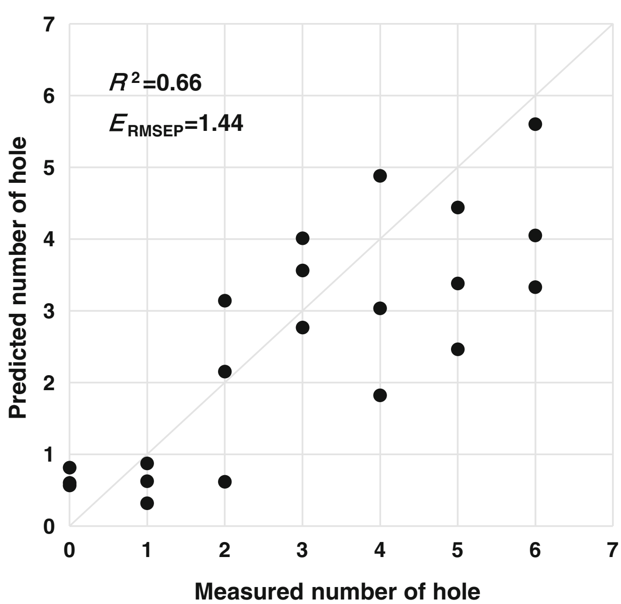


Fig. 8 Prediction of the number of holes by spectroscopic model with SA pretreatment (SA frame size: 10, validation set). R^2 coefficient of determinant, E_{RMSEP} root mean square error of prediction

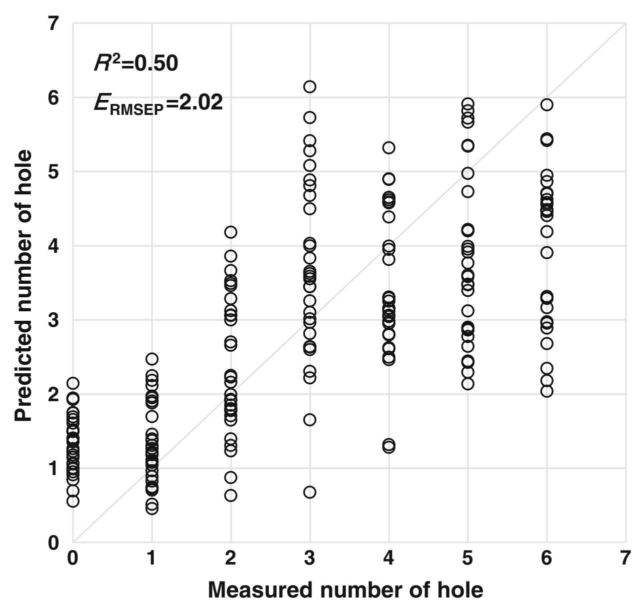


Fig. 9 Prediction of number of hole by spectroscopic model without SA pretreatment (validation set). R^2 coefficient of determinant, E_{RMSEP} root mean square error of prediction

In this study, the SA frame size was optimized with non-attenuated spectra. More than 9 spectra were recommended as SA frame size. To investigate the influence of the SA pretreatment on the prediction, the number of holes was predicted with the SA pretreatment (frame size: 10) by partial least square regression. The accuracy (RMSEP: 1.44) was not lower than the previous study and the case without the SA pretreatment. Therefore, it was concluded that the SA pretreatment could provide higher consistency without negative effects on the accuracy in the detection of small defects in wood.

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References

1. Sandoz JL, Benoit Y, Demay L (2000) Wood testing using acoustoultrasonic. In: Proceedings of world conference on timber engineering (oral), 7/31-8/3, 2000, Whistler Resort, Canada. http://timber.ce.wsu.edu/resources/papers/7-5-5.pdf. Accessed 16 Sept 2013
2. Wang X, Allison RB (2008) Decay detection in red oak trees using a combination of visual inspection, acoustic testing, and resistance microdrilling. Arboric Urban For 34:1–4
3. Hasenstab A, Hilbert G, Frühwald K (2011) Using an ultrasonic echo technique to inspect the structure of a pumice brick vault in a church. In: Proceedings of nondestructive testing of Mat. and Struc., Istanbul, 15–18 May 2011, pp 1123–1129
4. Sanabria SJ (2012) Air-coupled ultrasound propagation and novel non-destructive bonding quality assessment of timber composites. Dissertation (Diss. ETH No. 20404), ETH Zurich, Switzerland
5. Kim KM, Lee JJ, Lee SJ, Yeo H (2008) Improvement of wood CT images by consideration of the skewing of ultrasound caused by growth ring angle. Wood Fiber Sci 40:572–579
6. Divos F, Szalai L (2002) Tree evaluation by acoustic tomography. In: Proceedings of the 13th international symposium on nondestructive testing of wood, University of California, California, 19–21 August 2002, pp 251–256
7. Schubert S (2007) Acousto-ultrasound assessment of inner wood-decay in standing trees: possibilities and limitations. Dissertation (Diss. ETH No. 17126), ETH Zurich, Switzerland
8. Aduda BO, Rawlings RD (1996) Spectral analysis of acousto ultrasonic waves for detect sizing. NDT&E Int 94:237–240
9. Jeong H, Hsu DK (1995) Experimental analysis of porosity induced ultrasonic attenuation and velocity change in carbon composites. Ultrasonics 33:195–203
10. Tallavo F, Cascante G, Pandey MD (2012) A novel methodology for condition assessment of wood poles using ultrasonic testing. NDT&E Int 52:149–156
11. Lee S, Lee SJ, Lee JS, Kim KB, Lee JJ, Yeo H (2011) Basic study on nondestructive evaluation of artificial deterioration of a wooden rafter by ultrasonic measurement. J Wood Sci 57:387–394
12. Lee SJ, Lee S, Pang SJ, Kim CK, Kim KM, Kim KB, Lee JJ (2013) Indirect detection of internal defects in wooden rafter with ultrasound. J Korean Wood Sci Technol 41:164–172
13. Oh JK, Lee JJ (2014) Feasibility of ultrasonic spectral analysis for detecting insect damage in wooden cultural heritage. J Wood Sci 60:21–29