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ORIGINAL ARTICLE

Feasibility of ultrasonic spectral analysis for detecting insect damage in wooden cultural heritage

Jung-Kwon Oh · Jun-Jae Lee

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Abstract In cultural heritage, insect damage is one of the most serious damages, but conventional ultrasonic methods could not detect the early stage of insect damage because it is too small. In order to detect such small size damages, the analysis of attenuation is required, but elastomeric couplant and inconsistent contact condition of transducer make it difficult, in which only the elastomeric couplant is allowed to be applied to cultural heritage because of the paintings on the surface and the pressure employing transducers make effects on the attenuation measurement. Therefore, this study was aimed to investigate if the ultrasonic spectrum analysis can detect internal small hole, in which ultrasonic test was conducted with varied contact pressure. In this study, the diameter of drill hole was only 3 mm and this experiment was carried out under severely varied contact pressure. Nevertheless, spectral analysis with 2nd derivative pretreatment (Root mean square error of prediction, RMSE: 1.609) predicted the number of holes with much higher accuracy than the conventional methods (RMSE: 5.925). This result indicates that the spectral analysis has a high possibility in detection of insect damage in cultural heritage, even though contact condition is not consistent.

Keywords Ultrasound · Attenuation · Spectroscopy · Insect damage · Cultural heritage

J.-K. Oh · J.-J. Lee (✉)
Research Institute for Agriculture and Life Sciences, Department of Forest Sciences, Seoul National University, 6221 200 Bldng., 599 Gwanak-ro, Gwanak-gu, Seoul, Korea
e-mail: junjae@snu.ac.kr

Introduction

In wooden cultural heritage building, insect damage, such as termite damage, is one of the most serious problems. Usually, insects prefer early wood rather than latewood, because early wood is softer and easier to eat than latewood, and so insects make narrow and long tunnels from the ground to the top of the column. Because this hole can be a path of other biological attack and the damage can be expended, early detection is required for conservation of the building. But the early stage of the damage is quite small in a cross section.

Through-transmission elastic wave is very powerful tool to measure wood properties and internal state of wood. The wave speed traveling in longitudinal direction is related to modulus of elasticity (MOE) and density. Recently Yamasaki et al. [1, 2] developed a method of determining the MOE of timber using the stress wave propagation velocity without knowing the timber density for the cases that density is not easy to measure such as historic building. Also, the elastic wave technique provides valuable information on the internal state of wood. Also, the time of flight (TOF) is sensitive to the defects in wood [3]; based on this knowledge, TOF-based computed tomography (CT) was developed and commercialized for standing tree inspection (FAKOPP 3D Acoustic tomography, Fakopp, Hungary; PICUS Sonic tomography, argus electronic gmbh, Germany). The CT technology reconstructs cross section views by the filtered back projection (FBP) algorithm and TOF of waves passing through various paths in the cross section. This CT technique can provide higher detectability by inspection of more wave paths [4]. Nevertheless, this technology cannot detect early stage of insect damage because of its size. Kim et al. [5] reported that a 13 mm diameter defect or larger could be detected

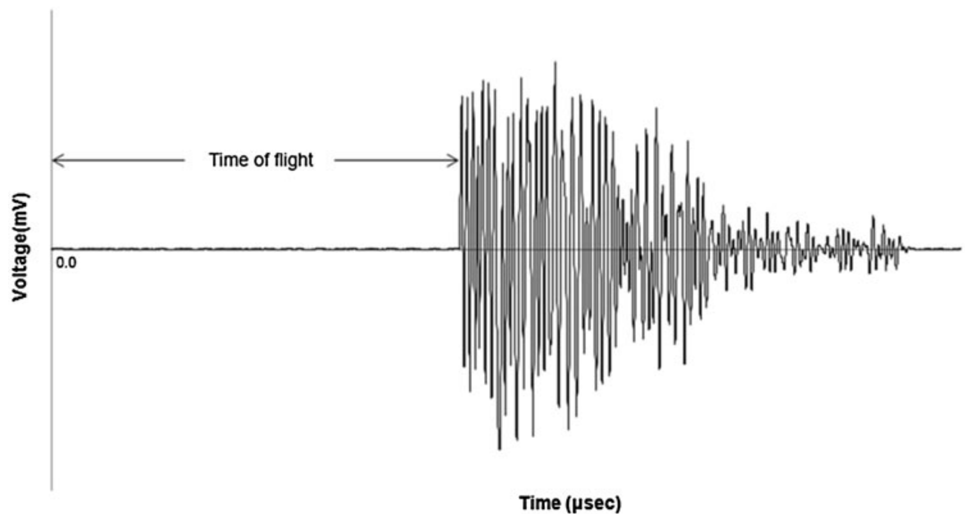

Fig. 1 Received signal of elastic wave traveling through wood

by TOF-based CT in which ultrasound was used, but the diameter of insect damage is smaller than 5 mm.

As a source of elastic wave, stress wave and ultrasound are most commonly used in research on wood. Stress wave and ultrasound can be produced by a hammer hit and piezoelectric transducer, respectively. The two elastic waves travel at the same speed in wood, but the central frequency of stress wave is lower than ultrasonic wave. Because higher frequency wave can detect smaller defects, high frequency ultrasound is preferred in defect detection. However, ultrasound is attenuated while traveling through wood. Especially high frequency wave is more attenuated than low frequency wave [6]. Therefore, in reality, there is a limitation in increase of frequency.

Most of the elastic wave technology detects defects by TOF of the earliest received wave passing through the wood of interest. As Fig. 1 shows, there are many data point in received signal but only TOF is used for internal defect detection. In addition to TOF, attenuation is a parameter in wave transmission analysis that is influenced by internal defects, which is especially reflected in studies on non-wood materials [7, 8]. In the case of wood, Tallavo et al. [9] investigated attenuation according to the direction of the transducers and distinguished a deteriorated wood pole by statistical dissimilarities. Sandoz et al. [3] also investigated the relationship between induced saw cut depth and wave velocity, peak amplitude, and energy of the received signal. Several studies on attenuation have used peak amplitude and energy [9–11]. The results of these studies indicated that attenuation can be a good predictor in internal defect detection. Because TOF analysis cannot provide enough detectability to detect small insect damage, another predictor, attenuation, needs to be analyzed.

As a method to analyze attenuation, spectral analysis has been attempted. While wave travels through wood, it can be attenuated by absorption or scattering. Fundamentally, the wavelengths that are long (low frequency) relative to defect size are not affected by defects, but relatively short wavelengths (high frequency) are attenuated [12]. Chambers and Tucker [13] applied ultrasonic spectroscopy to bond-quality inspections of nozzles in a space shuttle; however, we found very few studies using ultrasonic spectroscopy on wood. Tiitta et al. [14] reported that the high frequency content of the signal is virtually absent and the amplitude of the peak frequencies is also substantially reduced. Jordan et al. [15] tried to classify wood species by the machine learning algorithm (neural network) of the ultrasonic technique, and showed possibility to use ultrasonic attenuation spectral analysis with the machine learning algorithm in order to obtain the micro-structure information.

In cultural heritage, non-destructive technique (NDT) needs to be carefully applied. Any harm is not allowed during inspection of cultural heritage. Because painting on its surface is also cultural heritage, any spots by liquid, even water, are not allowed during NDT testing. Therefore, elastomeric couplant is commonly used instead of liquid type couplant. When using this type of couplant, the pressure on transducers is another factor to affect receiving signals, especially attenuation. The attenuation analysis is much more sensitive than TOF-based model to these contact conditions. The use of elastomeric couplant and in-consistent contact pressure makes it difficult to use attenuation characteristics for internal defect detection. For analysis of attenuation in cultural heritage, an apparatus to press transducers with consistent pressure was developed which consists of shoe and spring [11]. Even this apparatus cannot provide consistent contact condition in perfect because of many unexpected test condition, such as various shapes of objects, surface condition and undesired spring deformation.

Existing TOF-based technique does not have sufficient detectability to detect the early stage of insect damage because it is quite small. Attenuation spectral analysis was expected to provide better detectability than the TOF-based technique. However, in case of NDT inspection on cultural heritage buildings, varied contact pressure can make a negative effect on the attenuation measurement, and in field application it is not possible to keep the pressure perfectly consistent. Therefore, in this study, through-transmission ultrasonic tests were carried out under severely varied contact pressure at every ultrasonic measurement. Prior to making attenuation spectral analysis model for detecting small defects, it was investigated in this study if attenuation spectral analysis can detect these small defects under varied contact pressure.

Materials and methods

Experiments

Specimen preparation

Insects usually make small holes along the length of the wood members (Fig. 2a). Due to difficulty in obtaining insect-damaged timber, red pine (*Pinus densiflora*) round timbers without any biological deterioration were prepared, and drill holes were bored in the direction of the timber length from one end, in order to simulate insect damage, primarily termite damage (Fig. 2b). The diameter of the round timber was 96 mm.

The attenuation of the waves moving at the longitudinal direction is much smaller than in the other direction. If the specimen length was too short, then the waves could be repeatedly reflected at both ends. These repeatedly reflecting waves could have an unexpected effect on this study. The reflection of an end could not be avoided due to the limitation of the drill length; however, the reflection of the other end could be minimized. In this study, the long specimens were used without trimming (longer than 1300 mm). While traveling through the long specimen, the reflected wave could be fully attenuated; hence, it was expected that the undesired effects of the reflection at the other end could be minimized.

There must be large variation in ultrasound behavior between wood pieces. This variation can decrease the accuracy of final model. However, this study was intended to investigate if the spectral analysis can detect small defect under varied contact pressure to ensure transducers contact to wood. The variation between wood pieces can make it difficult to investigate the effect of contact condition. Therefore, only two specimens were prepared for the experiment, instead at each specimen, many spectrums were obtained under various contact conditions.

Ultrasonic test

In this study, two piezoelectric transducers (central frequency: 80 kHz, Kaijo Co. Ltd., Japan) were used to generate ultrasound and to receive the signal. These transducers had approximately 33 % bandwidth (54–106 kHz). A custom-made device and transducers were used to generate ultrasonic wave (central frequency 80 kHz, Kaijo Co. Ltd., Japan). The device has functions of pulse generator, amplifier, data acquisition and TOF calculator and TOF display. The raw voltage signals were transferred into laptop computer through an interface card (NI 5102, National Instrument Inc, USA). The full signal of through-transmitted waves were captured and recorded by LabVIEW software (LabVIEW, National Instrument Inc, USA) (Fig. 3). As a couplant, elastomeric couplant (Elastomer, Olympus Co., USA) was glued on both transducers. Generated ultrasound at transmitting transducers was

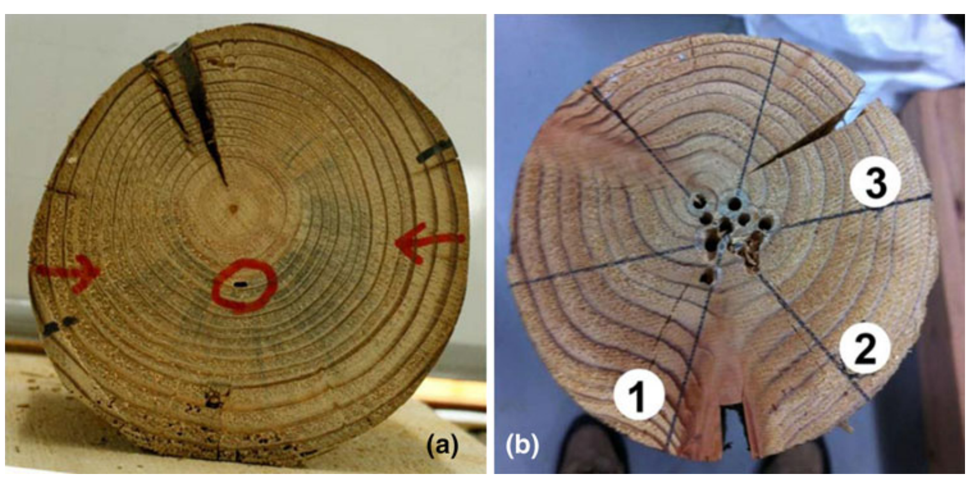

Fig. 2 Replication of insect damage by drill holes. **a** Hidden insect damage. **b** Artificial insect damage replicated by drill holes (number showed 3 paths of ultrasound in ultrasonic measurement)

Fig. 3 Schematic drawing of ultrasonic test set-up

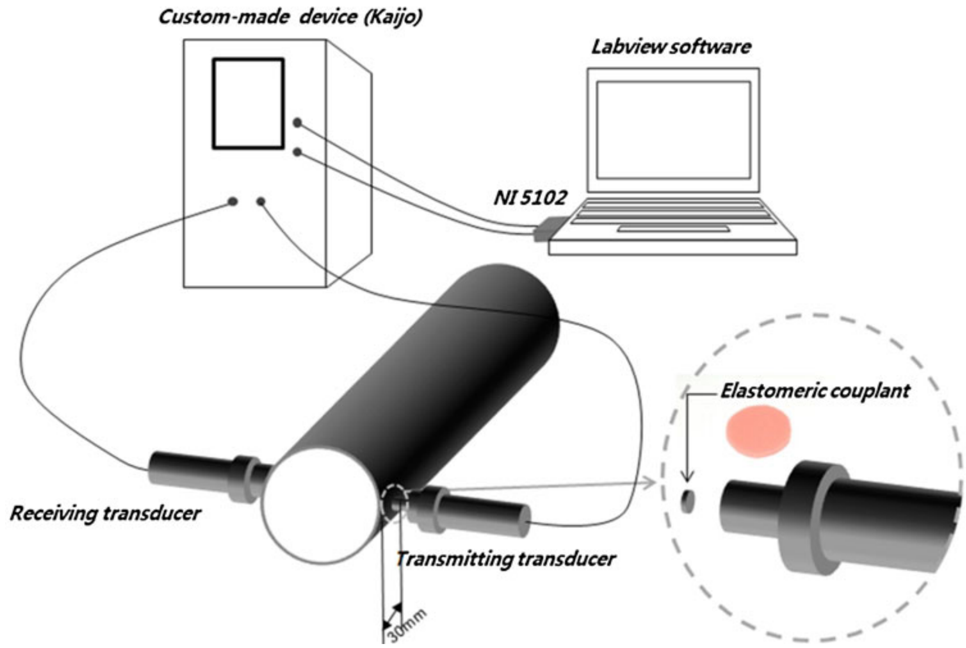

Fig. 4 Test set-up in order to obtain the ultrasonic waveforms

transferred into wood specimen after passing through elastomeric couplant. After traveling through wood specimen, the wave reached elastomeric couplant at receiving transducer and then the voltage of received signal was recorded by laptop computer.

At first, the ultrasonic test was carried out on the sound round timber in three directions as shown in Fig. 2b. The transmitting and receiving transducers were positioned at opposite sides of the specimen (Figs. 3, 4). Ultrasonic spectra were obtained in three direction (Fig. 2b). In each direction, 10 ultrasonic waveforms were obtained and the tested cross section was located 30 mm away from an end (Fig. 3).

In this study, elastomeric couplant was used, which made it possible to obtain ultrasonic signals without wetting the specimen by a liquid couplant. However, pressure on transducers was needed in order to ensure the transducers contact to wood. This pressure can affect the attenuation characteristics of the waves [16]. When applying the ultrasonic technique to real wooden members, it is difficult to maintain consistent pressure. To minimize the effect of contact pressure on attenuation measurement, Lee et al. [11] developed a spring apparatus which make it press transducers with a specific pressure. Theoretically this spring apparatus can provide consistent pressure at every measurement. However, it cannot perfectly control the pressure in real application, because of unexpected physical movement of spring and the inconsistent curvature of object. Therefore, the contact pressure was applied by hand to have varied pressure level, from low pressure to let the transducer touch on wood to high pressure (approximately 0.4 N/mm^2). Also, in order to obtain sufficient number of observations, transducers were detached and pressed again at every measurement. By these test procedures, 10 waveforms were obtained at a path, and the pressure of the 10 waveforms were not the same, even though they were obtained from the same path.

After obtaining 30 waveforms on a sound specimen, a 3 mm diameter hole was bored at the center of a cross section. Then, 30 waveforms were obtained at the cross section of interest. Then, a second hole of the same diameter was bored. The procedure of obtaining a waveform and boring another hole was repeated until the number of holes reached nine. All of the holes penetrated only early wood and were made as close to the center as possible. The holes were bored to a depth of 50 mm. Because holes were bored close to the center, ultrasound always passed through the holes. The contact area was 346 mm^2 (diameter of couplant was 21 mm).

Modeling to detect internal defects

Pretreatment

All of the waveforms obtained were converted from the time-domain to the frequency-domain by the Fast Fourier Transform (FFT, Matlab R2012a Mathworks USA).

The contact condition of transducers such as pressure and surface conditions was not controlled on purpose so it must be varied. Instead, two pretreatments were applied to minimize the effect of the contact condition: two types of scaling and two types of derivative (1st and 2nd derivative).

As the first scaling pretreatment, the maximum amplitude of the frequency-domain spectrum was identified, then all of the amplitude components for each frequency were divided by the maximum amplitude (Eq. 1). The second scaling pretreatment was performed by scaling based on the received wave energy, in which the received wave energy was calculated using Eq. 2, and all of the amplitude components for each frequency were divided by the energy (Eq. 1).

$$A^*(f) = \frac{A(f)}{k} \tag{1}$$

$$E = \int_f A(f)\,\mathrm{d}f = \sum_f A_f \tag{2}$$

where, $A(f)$ is the amplitude at a specific frequency of f and $A^*(f)$ is the scaled amplitude at a specific frequency of f. The term k is the maximum amplitude of the frequency-domain or the received energy (E).

Savitzky and Golay (S. Golay) [17] derivative was applied to scaling-pretreated spectrum. This pretreatment is based on performing a least squares linear regression fit of a polynomial around each point in the spectrum to smooth the data. The derivative was then the derivative of the fitted polynomial at each point. The derivative math pretreatment is often used to reduce the nonzero bias in near-infrared spectroscopy [18]. The derivative was calculated with 5 point (1667 Hz) segment smoothing by linear fitting by Matlab software.

Partial least squares (PLS) regression analysis

In this study, the PLS regression analysis was used as a model to detect small defects. The PLS regression program was written in Matlab (R2012a, Mathworks USA) and the program was verified by commercial software, The Unscrambler (CAMO software, ver. 9.7).

The degree of deterioration was evaluated by the number of drill holes which were bored to replicate insect damage. In the PLS model, the number of holes was used as a dependant variable. As independent variables, frequency domain attenuation (362 data) was used. In order to find the best set of independent variables, 3 conventional parameters (wave speed, energy and maximum amplitude) were added in the independent variable set of attenuation spectrum. The four sets of different independent variables were prepared as shown in Table 1. In addition, to the attenuation spectrum, three kinds of scaling pretreatments (without scaling, Maximum-amplitude-based scaling and energy-based scaling) and 3 kinds of derivative pretreatments (without derivative, 1st derivative and 2nd derivative) were applied. In total, 36 independent variable sets were tested (3 scalings, 3 derivatives and 4 independent variable sets).

As a training dataset, 300 datasets were randomly selected out of 600 datasets and the remaining 300 datasets were used for validation (twofold validation). Each 36 model was optimized by the accuracy in validation. The 36 modeling cases were compared with each other in accuracy of validation and the best model was chosen, where

Table 1 Independent variables in the statistical model used to detect the number of holes in wood

Model	Independent variables	Number of independent variables
M1	Spectrum[a]	362
M2	M1 and wave speed	363
M3	M2 and energy	364
M4	M3 and max. amplitude	365

[a] Frequency-domain

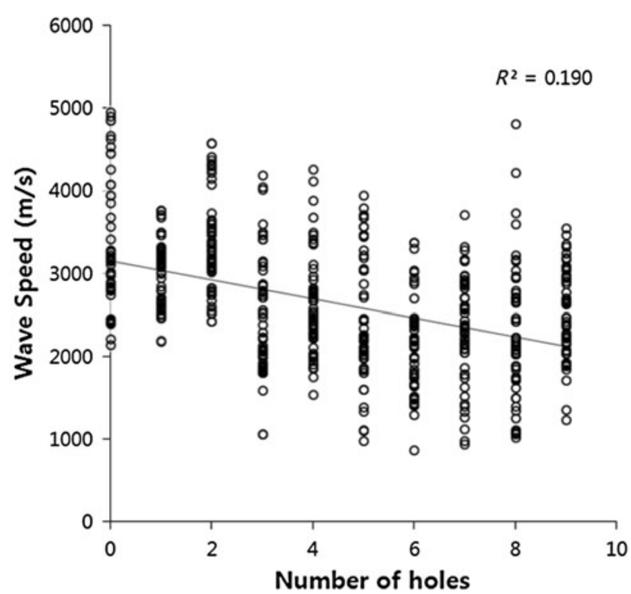

Fig. 5 Relationship between wave speed and the number of holes

Table 2 Accuracy in prediction of the number of holes by conventional parameters

	Accuracy	
	R^2	RMSE
Wave speed (1/TOF)	0.190	5.925
Energy	0.220	5.395
Max. amplitude	0.105	8.374
Spectrum[a]	0.582	1.858

[a] Validation result of PLS analysis with 362 independent variables (M1 in Table 1)

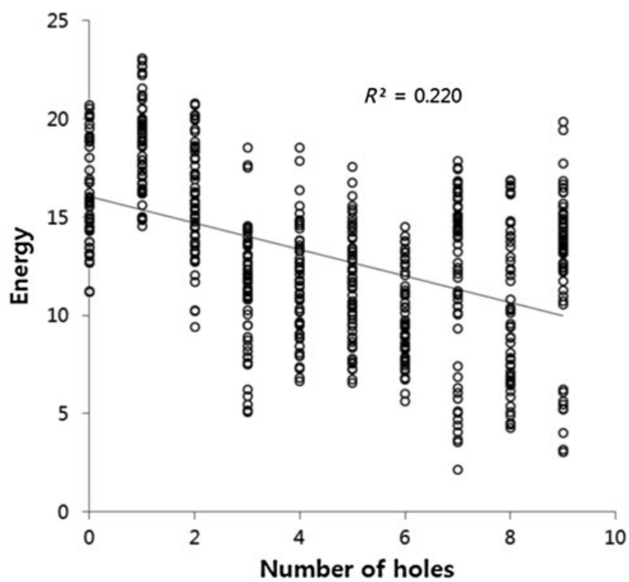

Fig. 6 Relationship between the received energy and the number of holes. (Energy: amplitude integral of frequency-domain spectrum)

accuracy of the validation was evaluated by root mean square error of prediction (RMSE, Eq. 3).

$$\mathrm{RMSE} = \sqrt{\frac{\sum (N_{\mathrm{predicted}} - N_{\mathrm{measured}})^2}{n}} \quad (3)$$

where, $N_{\mathrm{predicted}}$ is predicted number of drill holes, N_{measured} is measured number of drill holes and n is number of observations.

Results and discussions

Prediction by existing predictors

Wave speed is one of the best predictors to detect internal defects. Figure 5 showed the relationship between the wave speed and the number of holes in this study; however,

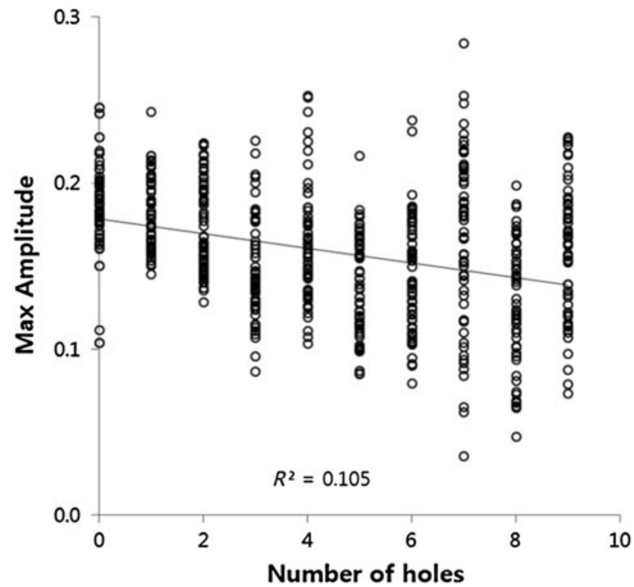

Fig. 7 Relationship between the max. amplitude and the number of holes

the coefficient of determinant was only 0.190 (RMSE: 5.925 in Table 2).

Several researchers have reported that the energy of the received signal and maximum amplitude are sensitive to the defects [10, 11, 19]; however, in this study, the accuracy of these parameters was also very low as shown in Figs. 6 and 7 and Table 2.

The varied contact condition may be one of the reasons of the low accuracy of the conventional parameters and these low accuracies indicate that conventional parameters under varied contact conditions may not detect such small diameter damages in cultural heritage. Besides, the defect size in this experiment was very small. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected; in case of 80 kHz ultrasound traveling in perpendicular to the grain direction, larger than 10 mm defect can be detected but the size of the hole in this study was only 3 mm diameter.

Spectral analysis and attenuation

Effects of pretreatments

Originally, the scaling pretreatment was intended to remove the effects of the varied pressure used to make transducer contact to wood. However in most cases that the scaling process was applied, the accuracy was lower than that in the model without scaling pretreatments (Table 3). Figure 6 shows a relationship between the energy and the number of holes. Even though coefficient of determinant

Table 3 Accuracy in prediction of the number of drill holes, according to model

Model	Derivative pretreatment	Scaling pretreatment					
		Not applied		Based on max. amplitude		Based on energy	
		R^2	RMSE[a]	R^2	RMSE	R^2	RMSE
M1	Not applied	0.582	1.858	0.564	1.897	0.590	1.839
	1st derivative	0.637	1.731	0.635	1.736	0.625	1.759
	2nd derivative	0.673	1.642	0.615	1.781	0.658	1.679
M2	Not applied	0.590	1.840	0.528	1.974	0.566	1.891
	1st derivative	0.647	1.706	0.638	1.727	0.644	1.714
	2nd derivative	0.686	1.609	0.642	1.718	0.675	1.637
M3	Not applied	0.595	1.829	0.549	1.929	0.531	1.966
	1st derivative	0.662	1.671	0.629	1.748	0.647	1.707
	2nd derivative	0.670	1.651	0.647	1.707	0.677	1.633
M4	Not applied	0.563	1.900	0.549	1.929	0.544	1.940
	1st derivative	0.642	1.718	0.630	1.747	0.637	1.730
	2nd derivative	0.668	1.655	0.636	1.734	0.676	1.635

[a] Root mean square error

was only 0.220, it indicates that the energy is one of the important predictors for defect detection and the received signal was more attenuated with the increase in the number of holes. The scaling pretreatment removes the difference in overall attenuation regardless of the number of hole by dividing all of the spectrums by the maximum amplitude or energy. Losing this important predictor (overall attenuation) seemed to lower the accuracy. Even though the scaling pretreatment removed the effect of varied contact condition of transducers, the effect seems to be smaller than the contribution to the prediction of overall attenuation. Therefore, we concluded that the scaling pretreatment was not appropriate for modeling internal defect detection.

Another pretreatment, the derivative, increased the accuracy. From M1 to M4, the 2nd derivative showed approximately 10 % higher accuracy than the analysis without derivative pretreatment. This derivative is very common pretreatment in spectral analysis which can remove noise by smoothing effect and reduce the nonzero bias [18, 20]. The nonzero bias can be caused by varied contact condition such as surface condition and contact pressure employing the transducers. The overall received energy (received signal integral) can be varied by applied contact pressure and surface condition. This non-uniformity of received energy can drop the accuracy of the model as well as robustness. The derivative pretreatment leads to focus on relative change rather than the amplitudes at each frequency. Because this experiment used severely varied contact condition on purpose, the received energy must be very varied. Based on the comparison of RMSE between models, the derivative pretreatment seemed to effectively reduce the effect of contact condition. Besides, the spectrum must have some noise and S. Golay derivative pretreatment smoothes the spectrum, as a result the noises are removed. The effect of contact condition and noise reduction seemed to be the reason why derivative pretreatment increased the accuracy. The 2nd derivative showed higher accuracy than 1st derivative. The increase of accuracy (lower RMSE) can also be explained by the same reason (contact condition and noise removing effect).

As Table 3 shows, the best model was M2 model with 2nd derivative pretreatment. This model showed lowest RMSE (1.609) but most of sound wood was misclassified into a couple of holes (Fig. 8b), even in training set (Fig. 8a). It is likely that knots or cracks close to ultrasound path made this misclassification. As Fig. 2b shows, the specimens contained some knots and cracks. To distinguish insect damage from cracks or knots, further researches are required. In addition, 9 hole was underestimated by the PLS model as shown in Fig. 8b. All holes except the first hole cannot locate on the exact line between the two transducers. Especially, the case of nine holes has more possibility that some holes were located too far from the direct line between the two transducers.

Feasibility of ultrasonic spectral analysis in detecting internal defects of cultural heritage

In terms of accuracy, the use of attenuation by spectral analysis significantly increased the accuracy in detecting small defect in wood. The TOF showed 5.925 of RMSE but spectral analysis showed much lower error of prediction (1.858 of RMSE). When wave speed and spectrum were used together as independent variables (M2 in Table 3), the

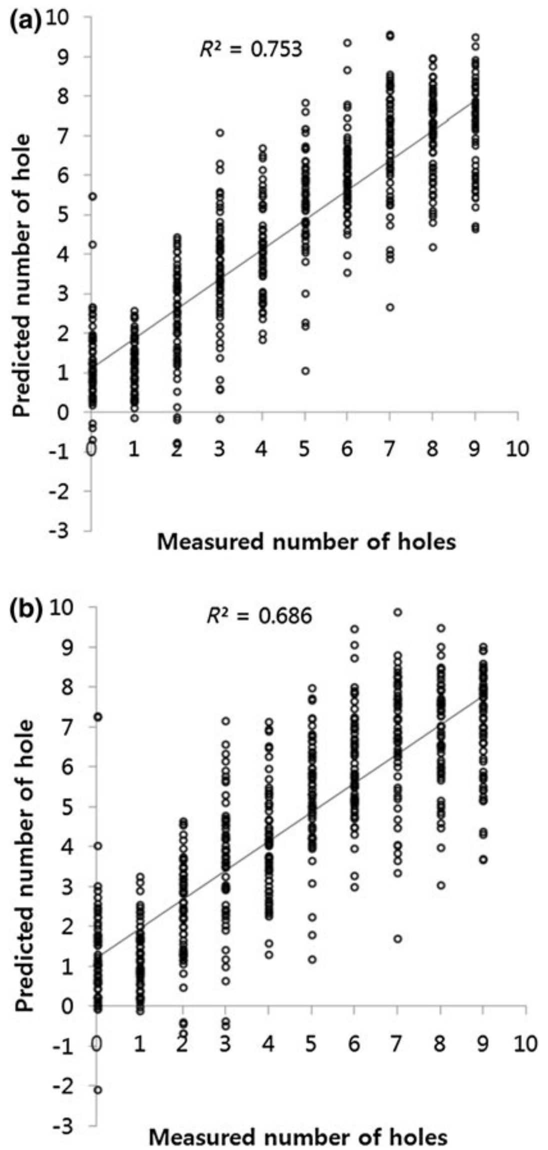

Fig. 8 Prediction of the number of holes by PLS with the attenuation and wave speed (M2, 2nd derivative, scaling pretreatment was not applied). **a** Training set, **b** validation set

RMSE decreased to 1.840. In addition, 2nd derivative pretreatment lowers the RMSE up to 1.609. This error of prediction was much lower than conventional parameters (Table 2). This comparison demonstrated that the attenuation spectral analysis would be worth in internal defect detection in NDT inspection of cultural heritage building.

Conclusions

Insect damage is one of the most serious damages in cultural heritage. In the early stage, the insect makes a small tunnel along the length of wooden member. This small diameter hole is too small to detect by conventional methods. In order to detect such small deterioration, attenuation needs to be analyzed but non-uniform contact condition of transducers makes it difficult. On purpose, the transducers were contacted to wood with varied pressure at every measurement and the number of 3 mm diameter drill hole was predicted by PLS regression. From this test set-up, this study investigated if spectral analysis can detect internal small diameter hole under non-uniform contact pressure of the transducers.

To remove the effect of contact condition, two pretreatments were applied. Out of the two, scaling pretreatment was not effective but derivative pretreatment showed approximately 10 % higher accuracy than the models without the pretreatment. Because derivative pretreatment makes the model be developed based on relative change rather than amplitude at each frequency, the derivative pretreatment seems to effectively reduce the negative effect of non-uniform contact condition on attenuation analysis.

In this study, the diameter of drill hole was only 3 mm and this experiment was carried out under very severely varied contact pressure. Nevertheless, the spectral analysis showed higher accuracy (RMSE: 1.609) than conventional method (RMSE: 5.925). Based on this result, it was concluded that the spectral analysis has a high possibility in detection of internal insect damage in cultural heritage.

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