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Non-destructive Testing of Wood Defects Based on Discriminant Analysis Method

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Abstract: The defects of wood samples were tested by the technique of stress wave and ultrasonic technology, and the testing results were comparatively analyzed by using the Fisher discriminant analysis in the statistic software of SPSS. The differences of defect detection sensitivity and accuracy for stress wave and ultrasonic under different wood properties and defects were concluded. Therefore, in practical applications, according to different situations the corresponding wood non-destructive testing method should be used, or the two detection methods are applied at the same time in order to compensate for its shortcomings with each other to improve the ability to distinguish the timber defects. The results can provide a reference for further improvement of the reliability of timber defects detection. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Wood sampling, Defect, Stress wave, Ultrasonic, Discriminant analysis method.

1. Introduction

Wood non-destructive testing technology is a new and comprehensive detection method, which can detect and evaluate the physical properties of wood, growth characteristics, mechanical properties, and wood defects without destroying the final value of the wood. Among the non-destructive testing method, any method has its own advantages and disadvantages, and the effects on wood defect detection are different. In addition, wood is a natural material and its properties are very complex. Under different wood properties (water content and density) and different defect types, shape, size and position of the distribution conditions, the accuracy and precision of wood non-destructive testing method have some differences, so the reliability of testing was different. The timber defects testing reliability problems can be seen as wood defects detection rate and misjudgment rate.

Discriminant analysis is an important statistical method. It is a multivariate statistical analysis method, and is used to determine the ownership of an objects based on its various characteristic values under the defined classification conditions. The basic principle is based on a certain criterion to create one or more discriminant functions, with large amount of data of the study object to determine the discriminant function coefficients to be determined and calculated discriminant index. Then what kind of a sample belonged to can be determined [1]. Therefore, the sample's misjudgment rate can be obtained by using discriminant analysis. In this study, the Fisher discriminant analysis was used to distinguish the different classes.

Since stress wave and ultrasonic can detect the wood detection accurately, so many researchers focus on studying these two waves, and a series of results have been achieved [2-8]. However, the sensitivity of the defect and defect detection reliability are different for two waves when the timber properties and the impact of external conditions are different. Therefore, each testing method has its own advantages and disadvantages. For the better application of stress wave and ultrasonic flaw detection on wood, these two detection methods must do in-depth research. At present, for both waves detection in wood properties comparative study is relatively rare, while the detection of internal defects in wood comparative studies have not been conducted.

2. Materials and Methods

2.1. Wood Samples

Elm is one of the popular tree species in the northeast of China; therefore the elm (*Ulmus rubra*) wood samples were used in this study. The elms were obtained from Fangzheng Forestry Bureau located in Heilongjiang Province, and then were delivered to the Wood Manufacturing Factory of Northeast Forestry University and processed to wood samples. The specifications for wood samples were 300 mm×50 mm (length × width × height). The moisture content of the wood samples is around 9 % due to the long time stored after being processed. The wood samples include intact samples and samples with defects, and the number for each type of wood samples was 16. Each group of wood samples was labeled before processing and testing in order to deal with the tested data easily. Wood defects include natural defects (such as wood cracks and decays) and artificial defects (holes and cracks) in this study.

Artificial defects were conducive to quantify the extent of the defect. The detail processing methods are as follows: From the intact wood samples, the diameter of hole with 10 mm and 20 mm were produced, and the number of holes ranges from 1 to 3, and the quantities of each type of holes were 16, and the locations of holes along the axis. In addition, a crack was sawn on the intact wood samples, and the depth of crack was 3 mm, and the shape of crack was arc. The locations of the holes and cracks are illustrated in Fig. 1.

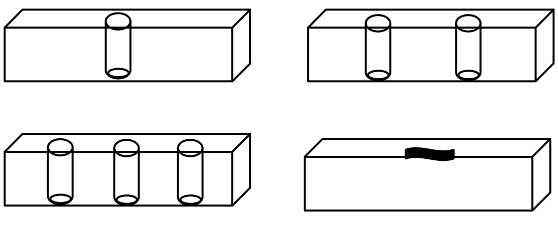


Fig. 1. Locations of holes and cracks.

2.2. Testing Method

2.2.1. Stress Wave Testing

A) Testing Method.

The impact stress wave method was used in the study. Two probes were nailed on both ends of the wood sample, and sensors were hanged on the probes (Fig. 2). When hitting the sensor by using a small hammer, stress wave was generated in the interior of the wood, and two sensors was used to induct the change of wave, and the propagation data was shown on the screen of the laptop. Based on the propagation time and velocity, the wood properties (such as modulus of elasticity and defects) were determined.

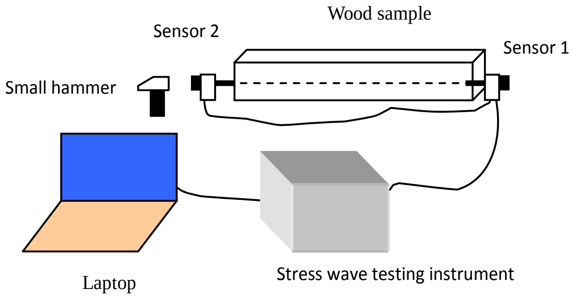


Fig. 2. Principle of testing wood defects using stress wave technology.

B). Testing system.

The stress wave detector ARBOTOM imported from Germany was used in the experiment. The ARBOTOM detector is mainly used to measure the internal situation of wood. The propagation velocity of stress wave and wood density is highly correlated, so the ARBOTOM can be used to collect the information of wood internal defects. Before testing, some parameter values should be input, such as the number of sensors, the distance of all sensors, the unit of distance, the height of sensors above ground, the PC port, filtering mode, the name of tree species, and so on.

2.2.2. Ultrasonic Testing

A) Testing Method.

In this paper, the so-called penetration method was used in the test. On one end of the wood sample, an emission transducer and ultrasonic pulse wave are localized and on the other end a receiving transducer is set up, so that the ultrasound can travel through the wood sample. The received ultrasonic signal is converted into electrical signal and amplified by an amplifier. By the simulated digital converter, the signal is converted into digital information and stored in a computer. After proper processing using specific procedures, we can obtain the ultrasonic parameters such as propagation time, velocity, and amplitude. Based on the propagation parameters, we can judge whether there are inner defects in the wood sample. The principle of testing wood defects using ultrasound is illustrated in Fig. 3.

B) Testing System.

The testing instrument used in the paper is RSM-SY5 ultrasonic tester made by Wuhan Institute of Rock and Soil Mechanics, China. The data collection software in the tester can adjust the testing parameters, signal collection mode, and storage and open functions of the signal. Meanwhile, the wave and frequency forms can be obtained together with the transit parameters including propagation time, velocity, and elastic modulus. These wave forms can be further analyzed and processed.

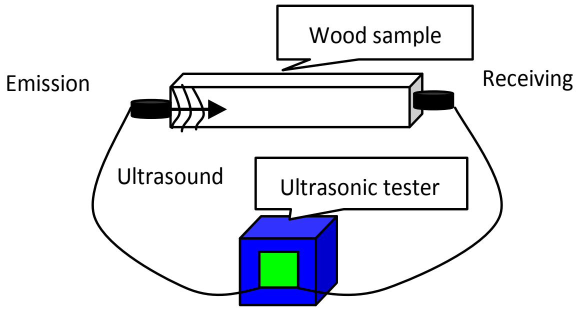


Fig. 3. Principle of testing wood defects using ultrasonic technology.

3. Results and Analysis

3.1. Effects of the Number of Holes on the Parameters and Dynamic Elastic Modulus for the Two Waves

The specimens were divided into four groups based on the number of holes with 20 mm diameter and intact samples. Each group contains 11 specimens. A total of 20 specimens will be judged with 5 specimens in each group. The specimen's moisture content, density, wave velocity and elastic modulus were used as the data index in the discriminant analysis. In order to facilitate the calculation, Let X1 represent moisture, X2 represent the density, X3 represent the velocity of propagation, and X4 represent the elastic modulus, and the discriminant analysis method in the multivariate statistical analysis software SPSS was used for the comparisons.

3.1.1. The Discriminant Analysis for Stress Wave Testing

Based on the Classification Function Coefficients (Fisher's Discriminant Function Coefficients) table, four groups of linear discriminant functions were derived as follow:
y1=-12.050-0.0768X1-38.286X2-44.329X3+85.322X4,
y2=-2.416-0.02444X1+19.061X2+22.348X3-38.041X4,
y3=-3.321+1.604X1+12.231X2+14.742X3-29.825X4,
y4=-5.092-0.577X1+1.463X2-0.134X3-5.092X4.

The following functions were used to calculate the correct rate of back substitution and disriminant, where CRBS represents the correct rate of back substitution, and CRD represents the correct rate of disriminant.

$$CRBS = \frac{\text{the correct number of specimens of discriminant}}{\text{total number of specimens in each group}} \times 100\% \quad (1)$$

$$CRD = \frac{\text{the correct number of specimens to be determined}}{\text{total number of specimens to be determined in each group}} \times 100\% \quad (2)$$

According to Eqs. (1) and (2), the number of specimens correctly classified was 11, 9, 8 and 10 for the four groups of stress wave tested specimens, and the corresponding correct rate of back substitution was 100 %, 81.82 %, 72.73 %, and 90.91 %, respectively. The correct rate of disriminant for the specimens to be determined was $12/20\times100\% = 60\%$. The misjudgment rate for the four groups by using the stress wave testing is presented in Table 1.

Table 1. The misjudgment rate for the number of holes of specimens by stress wave and ultrasonic testing.

Groups	Stress wave testing				Ultrasonic testing			
	1	2	3	4	1	2	3	4
1	-	20 %	0	0	-	20 %	0	0
2	20 %	-	20 %	0	20 %	-	0	20 %
3	0	60 %	-	0	0	20 %	-	20 %
4	0	20 %	20 %	-	0	0	40 %	-

Based on the correct rate of back substitution, we can see that the correct rate of back substitution increased as the number of holes increased. There are misjudgment situations for these two groups: intact and one-hole specimens, two-hole and three-hole specimens, which illustrates that stress wave testing cannot accurately judge the specimens with fewer inner defects. However, the stress wave is able to distinguish the specimens with 3 holes and intact specimens.

3.1.2. The Discriminant Analysis for Ultrasonic Testing

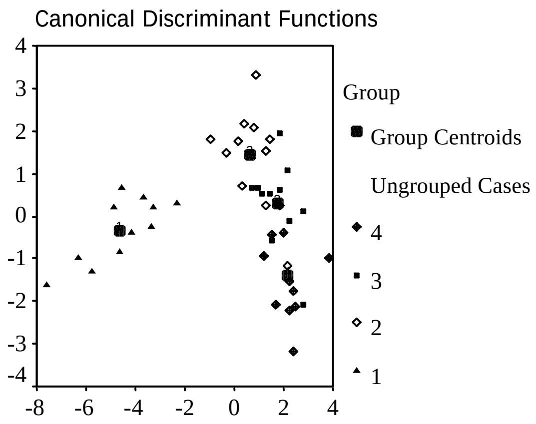
Based on the Classification Function Coefficients (Fisher's Discriminant Function Coefficients) table, four groups of linear discriminant functions were derived as follow:
y1=-9.177-0.415X1-22.251X2-27.553X3+52.680X4,
y2=-2.259+0.509X1+7.700X2+11.231X3-17.719X4,
y3=-2.881+1.690X1+10.061X2+13.187X3-24.747X4,
y4=-3.903-1.386X1+2.638X2+1.478X3-7.250X4.

Based on Eqs. (1) and (2), the number of specimens correctly classified was 11, 9, 9 and 10 for the four groups of ultrasonic tested specimens, and the corresponding correct rate of back substitution was 100 %, 81.82 %, 81.82 %, and 90.91 %, respectively. The correct rate of disriminant or the specimens to be determined was $13/20\times100\% = 65\%$. The misjudgment rate for the number of holes of specimens by using ultrasonic testing is presented in Table 1.

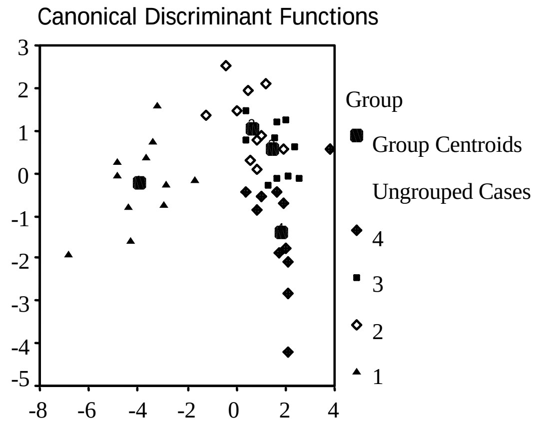
From the correct rate of back substitution, we can see that the correct rate of back substitution increased as the number of holes increased. There are misjudgment situations for these two groups: intact and one-hole specimens, two-hole and three-hole specimens.

3.1.3. Comparative Analysis Between Stress Wave and Ultrasonic Testing

When the number of holes is fewer, the correct rate is lower for both waves based on the misjudgment rate for stress wave and ultrasonic detection, but the misjudgment rate is relatively lower by using the ultrasonic testing method. From the correct rate of specimens to be determined, the probability of detection using ultrasonic is greater than stress waves, which illustrates that ultrasonic is more sensitive than stress wave when testing the specimens with holes. The discrimination results figures (Fig. 4) also indicate that the grouping is better when using ultrasonic.



(a) Stress wave testing



(b) Ultrasonic testing

Fig. 4. Discrimination results for specimens with different number of holes by stress wave and ultrasonic testing.

3.2. Comparison of the Effects of the Size of Holes on the Two Waves

The specimens were divided into three groups based on the sizes of the holes. Each group contains 11 specimens. A total of 15 specimens will be judged with 5 specimens in each group.

3.2.1. The Discriminant Analysis for Stress Wave Testing

Based on the Classification Function Coefficients (Fisher's Discriminant Function Coefficients) table, three groups of linear discriminant functions were derived as follow:

y1=-3.719+1.565X1-13.435X2-10.729X3+22.296X4,
y2=-2.500-2.245X1+7.512X2+3.218X3-5.281X4,
y3=-4.333+1.275X1+0.721X2+2.962X3-8.349X4.

Based on Eqs (1) and (2), the number of specimens correctly classified was 10, 10 and 11 for the three groups using stress wave, and the corresponding correct rate of back substitution was 90.91 %, 90.91 %, and 100 %, respectively. The correct rate of disriminant for the specimens to be determined was 8/15×100%=53.3 %. The misjudgment rate for the specimens with different hole size by using the stress wave testing is shown in Table 2.

Table 2. The misjudgment rate for the specimens with different hole size by stress wave and ultrasonic testing.

Groups	Stress wave testing			Ultrasonic testing		
	1	2	3	1	2	3
1	-	20 %	20 %	-	20 %	20 %
2	20 %	-	40 %	20 %	-	40 %
3	20 %	20 %	-	20 %	0	-

It is noted that the smaller the size of holes, the lower the correct rate of back substitution based on the correct rate of back substitution. The judgment results are not very good for the specimens with hole size of 10 mm. The misjudgment rate was improved when the hole size increased to 20 mm, however there is still misjudgment situation. Based on the correct judgment rate for the specimens to be determined, the probability of correct classification was also low by using stress wave testing.

3.2.2. The Discriminant Analysis for Ultrasonic Testing

Based on the Classification Function Coefficients (Fisher's Discriminant Function Coefficients) table, three groups of linear discriminant functions were derived as follow:

y1=-3.252+1.391X1-7.108X2-7.752X3+13.875X4,

y2=-2.407-2.033X1+8.788X2+4.295X3-7.650X4,
y3=-4.043+0.992X1+0.239X2+4.149X3-7.586X4.

Based on Eqs. (1) and (2), the number of specimens correctly classified was 8, 11 and 11 for the three groups using ultrasonic testing, and the corresponding correct rate of back substitution was 72.73 %, 100 % and 100 %, respectively. The correct rate of disriminant for the specimens to be determined was 9/15×100 %=60 %. The misjudgment rate for the specimens with different hole size by using ultrasonic testing is shown in Table 2.

The judgment results are not very good for the specimens with hole size of 10 mm. Similar to the results using stress wave testing, the misjudgment was improved when the hole size was changed to 20 mm. The correct judgment rate of for the specimens (20 mm) to be determined was also higher by using ultrasonic testing.

3.2.3. Comparative Analysis Between Stress Wave and Ultrasonic Testing

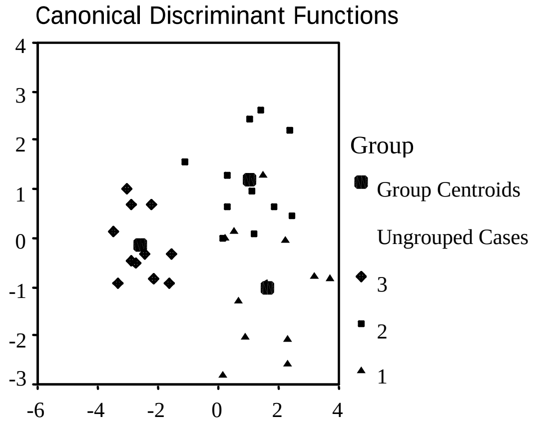
From the misjudgment rate for stress wave and ultrasonic detection, it is noted that when the size of the hole is smaller, the correct rate is lower for both waves. From the correct rate of specimens to be determined, the probability of detection using ultrasonic is greater than stress waves, especially for the specimens' holes with diameter of 20 mm. The discrimination results figures (Fig. 5) also indicate that the grouping is better when ultrasonic testing is applied.

3.3. Comparison of the Effects of the Defect Types on the Two Waves

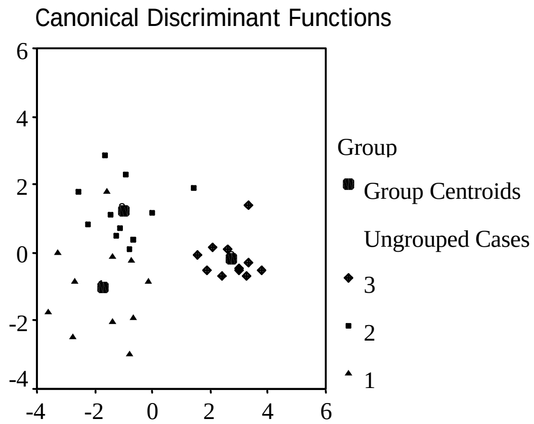
Wood defects include decay, hole, and crack. In the study, all the specimens were divided into four groups based on defect types and intact wood. A total of 11 specimens have defects and another 10 specimens are intact wood. Twenty specimens will be judged, with 5 specimens in each group. The moisture content, density, wave velocity, and elastic modulus of the specimens were used as data index in the discriminant analysis method. The stepwise discriminant method in the multivariate statistical analysis software is used to discriminate the types of defects.

3.3.1. The Discriminant Analysis for Stress Wave Testing

After stepwise discriminant, wood moisture content was removed from the input data, which illustrated that the discriminant ability by using wood moisture content was less significant. That is to say, the impact of wood moisture content on the judgment of timber defects is smaller compared with other three data index. After discriminant analysis, the number of specimens correctly classified was 9, 9, 7 and 8 for the four groups with different types of defects, and the corresponding correct rate of back substitution was 81.82 %, 81.82 %, 63.6 % and 80 %, respectively. The correct rate of disriminant for the specimens to be determined was 13/20×100 %=65 %. The misjudgment rate for the types of defects of specimens by using the stress wave testing is shown in Table 3.



(a) Stress wave testing



(b) Ultrasonic testing

Fig. 5. Discrimination results of size of holes by stress wave and ultrasonic testing.

Table 3. The misjudgment rate for the types of defects of specimens by stress wave and ultrasonic testing.

Groups	Stress wave testing				Ultrasonic testing			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1	-	0	0	0	-	0	0	20 %
2	0	-	40 %	0	20 %	-	20 %	20 %
3	0	40 %	-	0	0	40 %	-	0
4	40 %	20 %	0	-	0	20 %	0	-

Based on the misjudgment rate for different defect types using stress wave detection, it is noted that it is easy to misjudge between intact specimens with speciments with crack, or between speciments with decay and with hole. For the former case, it is possible that the stress wave propagation may not pass the crack part, therefore it will be the same as the intact wood. The latter case showed that the sensitivity is high for both decayed and holed wood when using stress wave testing. However, the stress wave can judge whether there is any defect in the wood specimens or not.

3.3.2. The Discriminant Analysis for Ultrasonic Testing

After stepwise discriminant, the wood moisture content data index was also removed. It means that the impact of wood moisture content on the judgment of timber defects is smaller compared with other three data index. After the analysis, the number of specimens correctly classified was 10, 10, 9 and 8 for the four groups with different types of defects, and the corresponding correct rate of back substitution was 90.91 %, 90.91 %, 81.82 % and 80 %, respectively. The correct rate of disriminant for the specimens to be determined was 13/20×100 %=65 %. The misjudgment rate for the types of defects of specimens by using the ultrasonic testing is shown in Table 3.

From the misjudgment rate for different type of defects using ultrasonic detection, it is easy to misjudge between specimens with decay and holes, which illustrates that the sensitivity is high for the decayed and holed wood tested by ultrasonic. Similar to stress wave testing, ultrasonic can also judge whether there is any defect in the wood specimens or not.

3.3.3. Comparative Analysis Between Stress Wave and Ultrasonic Testing

From the correct rate of back substitution and the corresponding discrimination results figures (Fig. 6) for stress wave and ultrasonic detection, it is noted that the testing reliability is better when ultrasonic is used to detect wood decay and holes. In addition, from the misjudgment rate, there are misjudgments between wood decay and holes for both waves; however the misjudgment rate is smaller for ultrasonic testing. It is not quite different for both waves to detect wood cracks, which may be due to the fact that wave propagation didn't pass the wood cracks.

4. Conclusions

The testing results of elm wood specimens by using stress wave and ultrasonic detection were analyzed by using discriminant analysis method in SPSS statistical software, and the following conclusions can be drawn from the study:

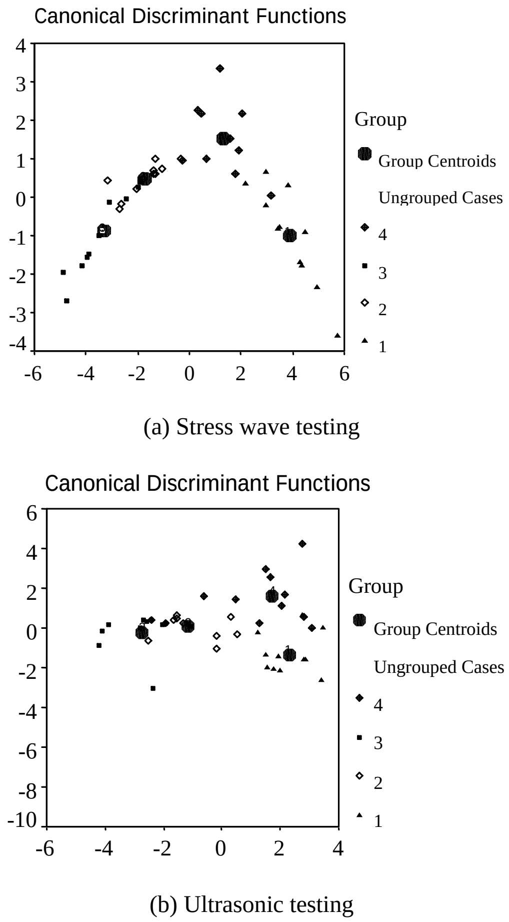


Fig. 6. Discrimination results of type of defects by stress wave and ultrasonic testing.

1) The correct judgment rates were 60 % and 65 % for stress wave and ultrasonic testing decayed wood specimens, respectively. With the increase of decay, the probability of detection using ultrasonic increased more significantly compared to stress waves, which indicated that ultrasonic is more sensitive to severe decay than stress wave when testing the holed specimens.

2) Ultrasonic showed very good sensitivity of detection on larger holes. In the experiment, the correct rates of judgment were 53.3 % and 60 %, respectively, for stress wave and ultrasonic testing wood specimens with holes. The testing reliability for both waves was low for the specimens with 10 mm holes, while the reliability was greatly improved for ultrasonic testing when the diameter of holes increased to 20 mm.

3) For the identification of defect types, both stress wave and ultrasonic were able to distinguish whether there are defects within the wood specimens or not. However, it is not very significant for the distinction between holes and decay, especially for stress wave detection. The misjudgment was small when either stress wave or ultrasonic was used to detect the specimens with severe decay and holes, and the discriminant accuracy rate can reach 80 % for both waves, especially for ultrasonic. The grouping

situation was not very good for crack detection discriminant, which illustrated that the surface crack detection reliability was not very good both waves.

Due to the limited number of wood samples tested, there may be some derivations in the statistical analysis. Therefore, it is recommended that multiple tree species and different wood defects can be considered in the future study. In addition, there may be errors during in the experiment, including the measurement error and human error. Because the impact force is not the same when using the mall hammer to hit the sensors, so there is a great influence on the accuracy for the stress wave detection. For ultrasonic testing, the quality of gap coupling between wood and ultrasonic probe will have impact on the testing results. In order to reduce the error, the instrument itself should be able to transmit and receive signal during the stress wave testing process, which will reduce the influence of human factors. In addition, if coupler is not needed, its impact will be reduced and there will be no pollution on wood products, which will enlarge the application of this technology in non-destructive testing of wood products.

Acknowledgements

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