Research paper

Detection of Internal Holes in *Swietenia mahagoni* Disks Using a Stress Wave Device

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【Summary】

The objectives of this study were to evaluate the feasibility of detecting different sizes and positions of hidden defects in trees using a 2-sensor stress wave device. In addition, we attempted to evaluate the detection resolution of the stress wave method which was rarely discussed previously. Artificial holes were created in *Swietenia mahagoni* disks to imitate natural decay in a trunk and were then detected using stress waves. The results revealed that as the diameter of the artificial hole increased, the radial transit time of the disk increased. This increasing tendency was repeated in the relationship between the radial relative transit time (RT) and the relative hole diameter (RD) and was discordant in the tangential direction. The tangential RT was greatly influenced by the position of the hole: it was highly related to the RD when the hole was near the 2 sensors; while it is not related to the RD when the hole was far from the 2 sensors. We also found that detection resolutions of stress waves, defined as the diameter or area ratio when the radial velocity had decreased by 10%, were 0.29 and 8.4%, respectively. A tree was considered to be decayed when the relative velocity (RV) was < 0.9 and was considered hazardous when the RV was < 0.66 with a central hole. On the basis of the results obtained, it appears that a 2-sensor stress wave device allows the nondestructive inspection of the presence, size, and location of defects in trees and could be a cost-effective way to perform tree risk assessments.

Key words: detection resolution, nondestructive test, stress wave, *Swietenia mahagoni*, transit time, sound velocity.

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研究報告

以應力波儀偵測桃花心木圓盤內部孔洞之研究

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摘　要

本研究旨在探討以雙偵測器之應力波儀器預測樹幹內孔洞大小及位置之可行性，此外，更試圖探討此技術之解析度。為模擬自然界中內含腐朽空洞之樹幹，將桃花心木(*Swietenia mahagoni*)圓盤上鑿取三種不同位置之人工孔洞，並逐漸增加孔洞直徑，分別以應力波技術進行評估，以探究不同位置及大小之孔洞對於應力波在圓盤內傳遞表現之影響。試驗結果顯示，隨著孔洞直徑的增加，應力波穿透圓盤所需的時間亦隨之增加。應力波穿透缺陷材與健全材之相對時間比(RT)亦隨孔洞佔健全材之相對直徑比(RD)而明顯增加，此趨勢在徑向十分明顯，在弦向則深受孔洞位置影響：當孔洞位接近兩偵測器時，RT隨RD增加而增加；當孔洞位置遠離兩偵測器時，RT與RD呈不相關，意即徑向RT可做為預測孔洞大小之判斷指標，而弦向RT穿透時間率可做為預測孔洞位置指標而加以定位。由於音速降低10%為樹木腐朽之基準，故定義相對音速比(RV)達0.9時之孔洞為應力波的解析度，由結果得知對於中央孔洞之圓盤，應力波的解析度為相對直徑0.29(相對面積8.4%)。此外，由於RD達0.7時為危木之基準，故建議當被測樹之RV小於0.66時，該樹應列為危木並受適當管理。本試驗證實，雙偵測器應力波技術提供一可檢視立木內部缺陷存在與否、形態大小及定位之非破壞檢測法，且可作為樹木風險評估的有效工具。

關鍵詞：偵測解析度、非破壞試驗、應力波、桃花心木、穿透時間、音速。

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INTRODUCTION

Trees are under constant stress due to wounds and decay (Shigo 1979). Once a tree decays, its strength and value is greatly reduced, and in the long run, this leads to failure of the tree. This might also endanger the safety of people and has become a public safety issue. Therefore, there is a great need to effectively detect the location and size of decay in trunks, so that proper procedures can be taken to deal with the decayed tree to reduce the loss and damage that may occur.

Nondestructive testing, including vibration methods, acoustic emissions, tap-tone processes, stress waves, ultrasonic waves, microwaves, x-rays, neutrons, radiation, etc., has been applied to evaluate the physical properties of wood products and living trees, and also used to detect deterioration in trees (McCracken and Vann 1983, Huang 1986, Huang et al. 1993, 1997, Huang and Chen 1996, Chen and Huang 2004). Among them, sonic nondestructive test methods, the principle of which is that waves travel through intact wood faster than through decayed wood, are most often used. However, detecting different hole positions and the detection resolution with a 2-sensor stress wave method have never been examined. Therefore, the purposes of this study were to evaluate different locations and sizes of an artificial hole in *Swietenia mahagoni* disks using a 2-sensor stress wave device. Relationships among the relative hole diameter (RD), the relative transit time (RT), the relative velocity (RV), and the detection direction were examined. In addition, the detection resolution of the stress wave method is further discussed.

MATERIALS AND METHODS

To establish a databank for inner holes of trunks by stress waves, a log of *S. mahagoni* was sawn into cross-sectional disks (10 cm thick) at the Chungpu Research Center (Chiayi, Taiwan), and they were soaked in water before testing began. Moisture contents and diameters of the 3 test disks were respectively around 69~85% and 39~44 cm as shown in Table 1. A disk was tested using a 2-sensor stress wave device (Fakopp®, Agfalva, Hungary). As shown in Fig. 1, the start sensor probe was pinned 5 mm into 1 side of the disk and was defined as I, and the stop sensor was pinned counterclockwise perpendicularly into the other side of the disk and was defined as II. Stress wave signals were generated by knocking on the start sensor with a hammer, and the sound wave propagation time between the 2 sensors (T_{I-II}) was measured by a stress wave timer with microsecond precision. Then, the stop sensor was moved counterclockwise 90°, and the knocking and measuring process was repeated to obtain the other 2 transit times (T_{I-III} and T_{I-IV}) from the stop sensors at III and IV.

After the transit time of the intact disk was measured, a hole was created in the disk as an artificial defect to imitate natural decay in a trunk. Three hole positions, 1 central and 2 off-center, were created and were gradually enlarged at intervals of 2 cm in diameter (Fig. 2). Wood pieces with holes were collected and weighted (W) to calculate the moisture content of the disk.

Table 1. Moisture content (MC) and diameter of the disks

	MC (%)	D_{I-III} (cm)	D_{II-IV} (cm)
Type A	69	40.0	41.0
Type B	85	43.6	42.2
Type C	76	39.6	41.1

D_{I-III}, distance from I to III; D_{II-IV}, distance from II to IV.

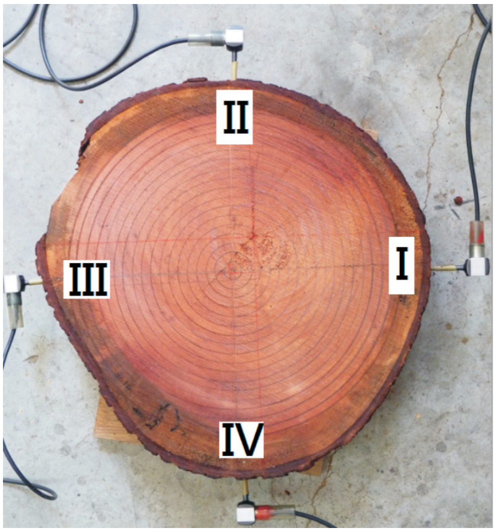

Fig. 1. Setup of transit time detection by the stress wave device.

The stress wave velocity (V) was calculated by dividing the distance between the 2 sensors (S) by the measured transit time (T), and other indicators such as the RD, the relative hole area (RA), the relative transit time for a disk with a hole to an intact disk (RT), the relative transit time for the tangential direction to the radial direction (RTr), the RV, and the moisture content (MC) were defined and calculated by the following formulae:

$V\ (m/s) = S/T;$ (1)

$RD = d/D;$ (2)

$RA\ (\%) = (d/D)^2 \times 100;$ (3)

$RT = T_d/T_i;$ (4)

$RTr = T_{90°}/T_{180°};$ (5)

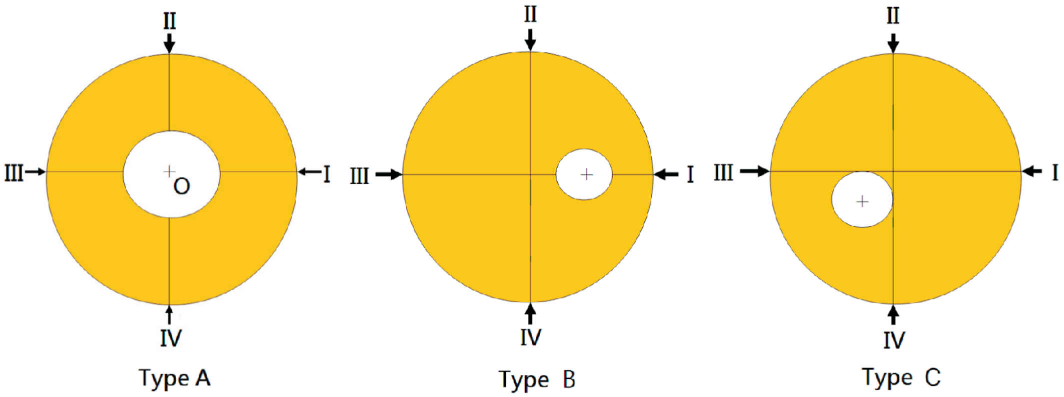

Fig. 2. Three types of hole positions in a disk. Type A, disk with a central hole; type B, disk with an off-center hole located between the start sensor and center of the disk; type C, disk with an off-center hole not located along any path among sensors.

$RV = V_d/V_i$; and (6)

$MC\ (\%) = (W-W_o)/W_o \times 100$; (7)

where S is the distance between the 2 sensors, T is the transit time between the 2 sensors, d is the hole diameter, D is the disk diameter, T_d is the transit time of a disk with a hole, T_i is the transit time of an intact disk, $T_{90°}$ is the tangential transit time, $T_{180°}$ is the radial transit time, V_d is the velocity of a disk with a hole, V_i is the velocity of an intact disk, and W_o is the oven-dry weight of collected wood pieces when different sizes of hole were created.

RESULTS AND DISCUSSION

Stress wave transit time for a disk with a central hole

The type A disk was created to imitate different extents of central decay in a trunk. Results of the stress wave transit time are shown in Table 2. The $T_{180°}$ increased as the hole diameter increased and therefore could be a preliminary indicator of the size of an internal defect in a trunk. This is because the generated sound waves propagate in a straight line in intact wood, while they have to go around the hole in decayed wood, and therefore it takes a longer time to reach the stop sensor. In contrast, the $T_{90°}$ increased only when the hole diameter was > 19.9 cm (RD, 0.49). The results revealed that the radial transit time was more sensitive than the tangential transit time.

Relationship of the RT with the RD

The relationship of the RT with the RD for 3 types of disks are shown in Fig. 3. The RT increased as the relative hole size increased. For a disk with a central hole, this tendency was obvious and sensitive in the radial direction, but was not obvious in the tangential direction especially when the RD was < 0.5 (Fig. 3A).

The radial RT in type B disks also increased as the RD increased and was also sensitive to the RD, while there were different performances among the 4 tangential directions (Fig. 3B). Since the hole located in the path from sensors I to III and was between quadrants I-II and I-IV, the RT from sensors I to II and from sensors I to IV increased abnormally; while the other 2 tangential RTs were not related to the RD.

Table 2. Effects of diameter of the central hole on the stress wave in a disc

d	RD	$T_{180°}$ (I to III)	$T_{90°}$ (I to II)	$T_{90°}$ (I to IV)
(cm)	(%)		(μs)	
0.0	0	271	198	211
2.1	5	279	202	210
3.9	10	284	201	210
5.8	14	288	205	211
8.0	20	291	205	212
10.0	24	297	202	211
11.8	29	301	204	212
13.7	33	309	205	210
15.5	38	312	205	212
17.7	43	327	205	211
19.9	49	337	206	212
21.8	53	352	212	217
23.9	58	366	219	219
25.7	63	379	223	223
27.8	68	403	229	225
29.9	73	428	241	235
31.8	78	460	255	250
34.0	83	511	283	273
36.2	88	564	318	288

d, hole diameter; D, disk diameter; $T_{180°}$, radial transit time; $T_{90°}$ (I to II), tangential transit time from I to II; $T_{90°}$ (I to IV), tangential transit time from I to IV.

The relationship of the radial RT with the RD in type C disks agreed with type A and B disks in that the radial RT increased as the RD increased, while there were also large differences in performances among the 4 tangential directions. Since the hole was in the III-IV quadrants, the RT from quadrants III to IV increased abnormally. On the contrary, the RT from other 3 quadrants were not related to the RD until it exceeded 0.6. This again suggests that the relationship between the RT and RD can be used to predict the size of the hole in the radial direction and the position of the hole in the tangential direction.

Stress waves travel through intact wood faster than through damaged wood; therefore, the stress wave velocity is considered an indicator of tree decay. According to Divos and Szalai (2002), when the measured velocity decreased by 10% of the average (reference) velocity, then there may be a hole or decay. In other words, when the ratio of T_d/T_i (RT) is > 1.11, it means that the trunk is probably decayed. Therefore we defined the detection resolution for the stress wave method as the corresponding diameter ratio or area ratio when the wave velocity decreased by 10% or the transit time increased by 11% compared to intact wood especially when the hole was located between the 2 sensors. As shown in Fig. 3A, an assistant line (a) was drawn: when RT was 1.11, then the ratio of d/D (RD) was 0.29. It appears that a defect could only be detected when the RD exceeded 0.29 or the RA exceeded 8.4% for a disk with a central hole. That is to say, the detection resolution

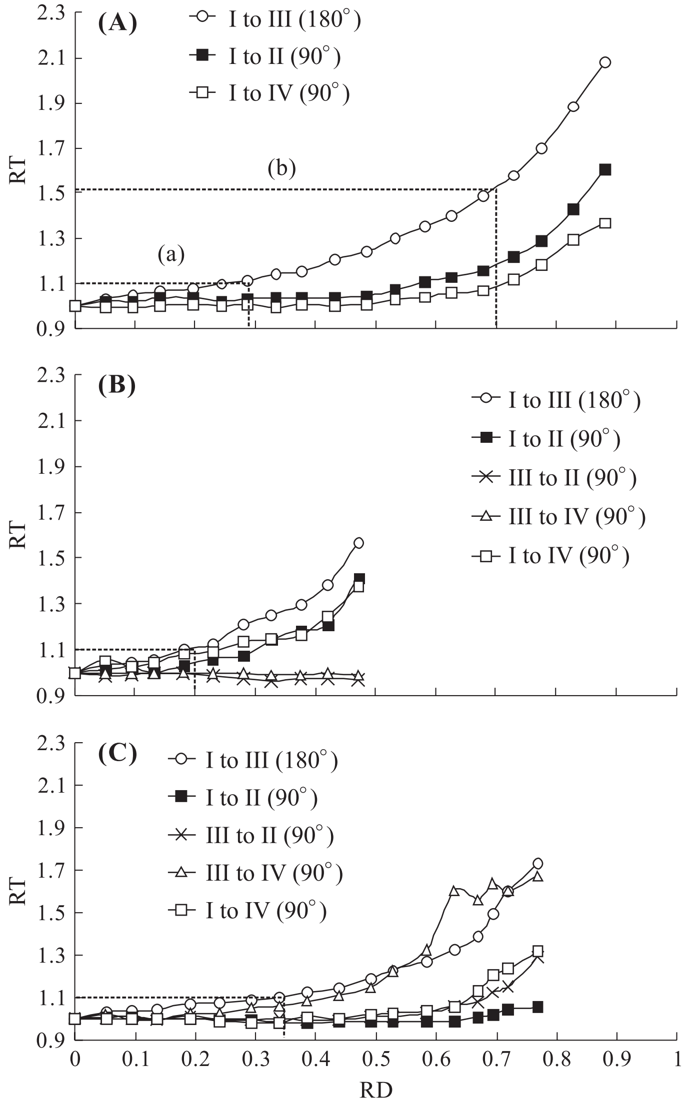

Fig. 3. Relationship of the relative transit time for a disk with a hole to an intact disk (RT) and the relative hole diameter (RD) for (A) a disk with a central hole, (B) a disk with an off-center hole located between the start sensor and center of the disk, and (C) a disk with an off-center hole located in any one of the quadrants.

using a 2-sensor stress wave device for a central hole disk was 0.29 in RD or 8.4% in RA. The detection resolution for types B and C could also be determined by drawing assistant lines in Fig. 3B and C and were 0.2 of the RD (or 4% of the area ratio) and 0.35 of the RD (or 12% of the area ratio), respectively.

In addition, according to Mattheck and Bethge (1993), when the RD is > 0.7, the tree has a potential to fail in the field and is considered a hazard. An assistant line (b) was drawn in Fig. 3A: when the RD was 0.7, then the RT was around 1.5. This means that if the measured transit time is 1.5-times larger than that of the reference intact disk, the tree is potentially hazardous and should be properly treated.

Relationship of the relative velocity in an intact disk and the RD

The calculated velocities for intact disks A, B, and C were 1439, 1527, and 1475 m s^{-1} in the radial direction and 1351, 1471, and 1364 m s^{-1} in the tangential direction, respectively, and this agrees well with measurements from other experiments. By transferring the Y-axis from the RT to the RV (Fig. 4), the same detection resolutions as noted previously were also obtained. An assistant line (a) was drawn in Fig. 4A: when the RV was 0.9, then the ratio of the RD was 0.29; and an assistant line (b) was drawn in Fig. 4A: when the RD was 0.7, the RV was around 0.66. This means that when the measured velocity is 0.66-times smaller than the reference disk, then the tree is potentially hazardous and should be properly treated. A practical conclusion is that for a disk with a central hole, when the RV is < 0.9, the trunk is probably decayed; when the RV is < 0.66, the trunk should be considered a hazardous tree.

Relationship between the RT in the tangential direction to the radial direction and the RD

Relationships between the RT in the tangential direction to the radial direction (RTr) and RD are illustrated in Fig. 5. The RTr decreased as the RD of the disk increased. For type A, the RTr of an intact disk was around 0.7~0.8, and it decreased to 0.52~0.56 as the RD increased to 90%. The RTr for a type B disk also decreased with an increase in the RD except for the RTr from I to II and that from I to IV. The RTr for an intact disk was around 0.6~0.9, and it decreased to 0.4~0.8 as the RD increased to 50%. The RTr for disk C also decreased with an increase in the RD except for the RTr from III to IV. The RTr for an intact disk was around 0.6~0.9, and it decreased to 0.4~0.6 as the RD increased to 90%. The RTr from III to IV was abnormally high and could be used to detect the position of the hole. There were certain variations in RTr values among types A, B, and C. These arose from the irregular shape of the disks. Since sensors were pinned at 4 perpendicular positions around the disk instead of at equal distances from each other, this caused the

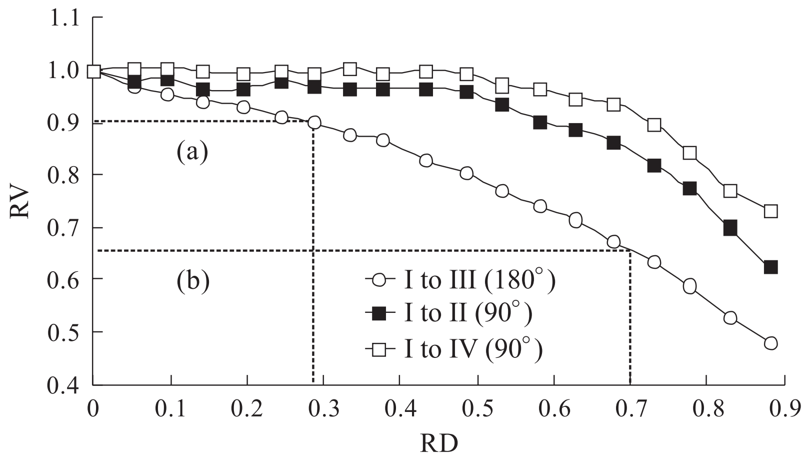

Fig. 4. Relationship of the relative velocity (RV) and the relative hole diameter (RD) for a disk with a central hole.

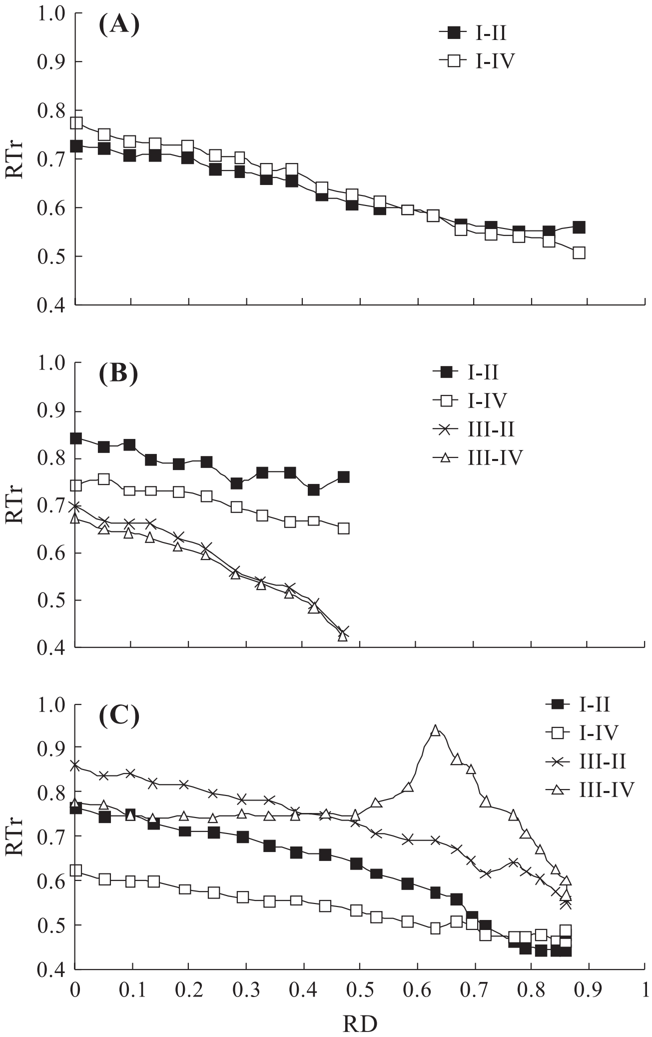

Fig. 5. Relationship of the relative transit time in the tangential direction to radial direction (RTr) and the relative hole diameter (RD) for (A) a disk with a central hole, (B) a disk with an off-center hole which located between the start sensor and the center of the disk, and (C) a disk with an off-center hole located in any one of the quadrants.

width of the annual rings and specific gravity of the 4 quadrants to differ and led to disagreements among tangential velocities. Generally speaking, the trunk of coniferous trees is round, and variations of the RTr are small; while the trunk of broadleaf trees is more irregular, and variations in the RTr are greater. When the stress wave method is applied in the field, the RTr should be detected from all 4 quadrants, and the smallest RTr values should be used to evaluate the size of the hole.

Commercial stress wave tomography emphasizes that the detection resolution can be increased by increasing the number of sensors. For example, the resolution of 8-sensor tomography is 5% of the area ratio, and it decreases to 2% for 32 sensors. In this study, we proved that the resolution of the stress wave device was independent of the number of sensor but depended on whether or not the hole was located between the sensors.

What problems have to be faced when the stress wave method is applied to living trees in the field?

In fact, the transit time measured by stress waves varies due to many factors such as different tree species, ages, moisture contents, and even the season when detection is carried out. Therefore, the calculated velocity is also influenced by these factors. In order to minimize the influences of these factors, one can obtain the transit time and velocity from an intact disk before creating an artificial hole in the lab, so that relationships among the RT, RV, and RD can be obtained. Based on this, we could predict whether a tree was decayed or hazardous. When detecting defects in a living tree by the stress wave method in the field, one is unable to obtain the transit time and velocity from the living tree when it was intact. One can only get replacement data from neighboring trees or use average data from live trees. Results from these varied substitutes tend to be overestimated and can lead to misleading results. For example, the radial velocity of fir is around 1000~1600 m s^{-1}, and its average velocity is 1300 m s^{-1} (Wang et al 2005) which already exceeds the velocity by 10%. Therefore, when a tree is deemed to be hazardous by the stress wave method, further investigation should be conducted with an incremental borer or a resistograph. On the other hand, when one estimates the size of a hole by the RTr, which does not involve data from an intact tree, it is recommended to measure the RTr from 4 quadrants, since certain variations will still exist. The RTr can help one distinguish whether the hole belongs to type A, B, or C, and the size of the hole can further be estimated.

CONCLUSIONS

Artificial holes in *S. mahagoni* disks were detected by a 2-sensor stress wave device at 4 perpendicular positions around the periphery of a disk in this study. The following results were obtained. The radial transit time of the disk can be a preliminary indicator of the size of the hidden hole. The radial RT can be an indicator for predicting the size of the hole, and the tangential RT can be an indicator for predicting the location of the hole. For a disk with a central hole, when the RV is < 0.9, the trunk is probably decayed; when the RV is < 0.66, the tree is supposedly hazardous. In conclusion, the size and position of a hole can be detected by a 2-sensor stress wave device, and its detection resolution was 0.29 for the RD or 8.4% of the RA. A 2-sensor stress wave device is a fast, cost-effective, and easy to carry and operate non-destructive instrument. It provides direct information without requiring special software or parameters. This makes it very suitable for foresters to manage forests in a flexible way.

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LITERATURE CITED

Chen SS, Huang YS. 2004. Basic study on monitoring internal holes in logs using ultrasonic waves. Taiwan J For Sci 19(2):165-71.

Divos F, Szalai L. 2002. Tree evaluation by acoustic tomography. 13th International Symposium on Nondestructive Testing of Wood. 2002 Aug 19-21; University of California at Berkeley, Berkeley, CA. p 251-6.

Huang YS. 1986. Measurement of vibration properties and dynamic viscoelasticity of wood. Bull Taiwan For Res Inst no. 468. Taipei, Taiwan: Taiwan Forestry Research Institute. 13 p. [in Chinese with English summary].

Huang YS, Chen SS. 1996. Estimation of moisture content change in wood by tap tone nondestructive testing. Taiwan J For Sci 11(4):367-72. [in Chinese with English summary].

Huang YS, Chen SS, Chang CC, Ho YM. 1997. Application of ultrasound for detection wood decay on standing tree of *Casuarina equisetifolia*. Q J Chin For 30(4):445-50. [in Chinese with English summary].

Huang YS, Chen SS, Chi SC. 1993. Feasibility of the evaluation of log quality by using nondestructive test method. Bull Taiwan For Res Inst New Series 8(1):85-98. [in Chinese with English summary].

Mattheck CG, Bethge KA. 1993. Detection of decay in trees with the Metriguard Stress Wave Timer. J Arboricult 19(6):374-8.

McCracken FI, Vann SR. 1983. Sound can detect decay in standing hardwood trees. New Orleans, LA: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. 6 p.

Shigo AL. 1979. Tree decay - an expanded concept. Washington, DC: US Department of Agriculture, Forest Service. 68 p.

Wang X, Wiedenbeck J, Ross RJ, Forsman JW, Erickson JR, Pilon C, Brashaw BK. 2005. Nondestructive evaluation of incipient decay in hardwood logs. General Technical Report FRL-GTR-162. Madison, WI: US Department of Agriculture, Forest Service. 11 p.