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As Published: <https://doi.org/10.1007/s00226-018-1016-z>

Publisher: Springer Berlin Heidelberg

Persistent URL: <https://hdl.handle.net/1721.1/131445>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Health assessment of tree trunk by using acoustic-laser technique and sonic tomography

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Abstract

An innovative tree defect detection scheme, which combines acoustic-laser technique and sonic tomography, is studied. A new sensor distribution can be adopted based on the near surface response detected by acoustic-laser technique, and a more reliable image of the tree trunk can be observed by sonic tomography. By using such hybrid detection scheme, the near surface defects (bark detachment, cracks, decay) can be revealed at the early stages of defect development. The accuracy of defect detection during advanced tree risk assessment is therefore highly improved. As a newly developed detection technique for detecting the near surface defect in tree trunk, the measurement results of acoustic-laser technique in tree trunk are comprehensively discussed, especially towards the detectable depth beneath the tree surface. The experimental results demonstrated that a newly developed acoustic-laser technique can identify the presence of near surface defects in a tree trunk that are normally overlooked in conventional sonic tomography measurements with random distribution of sensors.

1. Introduction

Development of defects in wood may reduce the mechanical strength of tree stems and branches. Such reduction in mechanical strength can increase the likelihood of tree failure and pose risks to humans in urban districts (Mattheck and Breloer 1994). From 1960 to 2007, out of 128 outdoor education activity related deaths in United Kingdom, 10.93% of them were due to falling trees (Brookes 2007). To avoid such accidents, the health condition of trees is needed to be monitored by robust methods. To assess the quality of living trees and wood logs, several non-destructive testing (NDT) methods have been proposed, such as static bending techniques, transverse vibration techniques, attenuation of X-ray or Gamma-ray, Pilodyn tests, impact hammer test and sonic/ultrasonic tomography (Najafi et al. 2017; Wang et al. 2002; Wang 2013; Watanabe et al. 2013; Ritschel et al. 2014; Kim et al. 2015; Gilbert et al. 2016). The static bending and transverse vibration techniques are particularly suitable for timber beams, but it is hard to be adopted in assessing standing trees (Allison and Wang 2015). Pilodyn test requires pins to penetrate into core wood, and it only focuses on the single measurement point which cannot provide comprehensive understanding of the tree cross-section (Ross and Pellerin 1994). The use of X-ray or Gamma-ray in tree monitoring is reported neither portable nor practical in field assessment, and more importantly, the method poses a radiation hazard towards the users (Wang et al. 2004; Büyüköztürk and Yu 2009; Yu et al. 2013). Among these methods, sonic tomography is considered as one of the most efficient methods to detect the internal voids and decay of trees or wood logs, and it has been widely adopted in field measurements (Chuang and Wang 2001; Gilbert and Smiley 2004; Brazee et al. 2011; Guntekin et al. 2012; Li et al. 2012; Pereira-Rollo et al. 2014; Gilbert et al. 2016; Chen and Guo 2017; Espinosa et al. 2017; Liao et al. 2017a). Sonic tomography is a technique that is used to produce an image of the internal structure of a solid object by recording differences in speed of acoustic wave transmission. The velocity of acoustic wave transmission reduces significantly in decayed or deteriorated wood compared with sound wood, so that internal defects can be detected by the prolonged wave transmission time in such area (Bodig 2001; Deflorio et al. 2008; Zhang et al. 2011; Arciniegas et al. 2014; Li et al.

2014, 2015; Du et al. 2015; Liao et al. 2017a). Some commercial tree tomography instruments, for example Picus Sonic Tomograph, Arbotom and Fakopp, have been developed to reconstruct the tomograms of tree cross-section using this principle (Gilbert and Smiley 2004; Grabianowski et al. 2006; Liang and Fu 2012; Visalga et al. 2016). However, the accuracy of sonic tomography is subjected to several parameters, such as the applied frequency, inversion technique, and arrangement of measurement points (Divos and Divós 2005). Moreover, in practice, the measurement points of sonic tomography are usually evenly distributed around the cross-section of the trunk. The even distribution of sensors leads to a lower density of sonic wave transmission path at the boundary of cross-section than that at the xylem of tree, which reduces the accuracy of sonic tomography in detecting the near surface defects and cracks. Near surface crack initiates at the area suffering from high local stresses, which may be caused by internal decay or attack from external forces (Mattheck and Breloer 1994; Aoyagi et al. 2014). The near surface cracks and defects can develop into the xylem of the trunk, and further adversely affect structural stability through extension into the wood of the tree. In addition, the presence of near surface cracks tends to facilitate entry of pathogens and insects and can increase the likelihood of tree failure and associated risks. Therefore, the presence of near surface defects should be detected as early as possible to prevent risks associated with the development of near surface defects.

One of the solutions to improve the accuracy of sonic tomography in detecting near surface defects is to arrange sensors intensively at defect location, so that more sonic waves can transmit across defect location, and near surface defects can be recorded more comprehensively. To achieve the accuracy improvement by adopting such targeted distribution of sensors, it is needed to develop a suitable technique that can pre-locate the near-surface defects in trees. Acoustic-laser technique has been demonstrated as an effective method for detecting the near surface defects in composite structures (Lau 2013; Lau and Qiu 2016; Qiu and Lau 2016, 2017; Yu et al. 2016). The acoustic-laser technique makes use of acoustic excitation generated by loudspeaker to vibrate the object and the laser beam to measure the vibrational frequency response to determine the physical characteristics of a

material. The difference in the response signal could identify whether the material is intact or defective (Chen et al. 2015; Qiu and Lau 2015). In the presence of acoustic wave pressure, the surface vibration of a tree trunk is excited. The surface vibration under acoustic excitation is intensified when a near surface wood decay is present. Although acoustic-laser technique cannot directly reconstruct the image of defect shape and area in a tree, it can indicate the location of near surface defect, and sonic tomography can subsequently be used with respect to the targeted defect location to study the shape and area of the defect in the tree. The ability of the hybrid method combining acoustic-laser technique and sonic tomography for defect detection could be beneficial to tree risk assessment, providing more precise information on defects under the bark.

The objective of this study is to develop an advanced non-destructive method, *i.e.* acoustic-laser technique for near surface defect detection in tree, and to combine it with conventional sonic tomography as a comprehensive tree detection scheme to better assess tree health condition. The hybrid method combining acoustic-laser technique and sonic tomography can identify both the internal and near surface defects in a tree trunk without affecting its biological activity. The basic principle of the acoustic-laser technique is to pre-locate the near surface defect, and sonic tomography is responsible for measuring the shape and area of the defect in the tree cross-section. Experimental study was first carried out using acoustic-laser technique on trunk samples with defect depths of 5 to 25 mm to determine the maximum depth of defect that can be detected by this technique. The trunk samples were excited with white noise generated by a loudspeaker, and surface vibration characteristics of defects in different depths were analyzed by Fast Fourier Transform (FFT) algorithm, in order to find out the relationship between natural frequency of defect region and defect depth. Sonic tomography was employed subsequently on the same sample to measure the defect area, location and relative strength loss in the trunk sample. The measurement results using hybrid method combining acoustic-laser technique and sonic tomography were compared with the traditional tree monitoring method to show its superior performance. Moreover, to improve the applicability of proposed method to further field measurement, the

potential improvements according to limitations at laboratory-test stage are discussed and proposed.

2. Material and methods

2.1 Details of tree specimens

The experimental specimens used in the study were 200 mm long trunk sections, namely specimen A and specimen B, which were cut from a *Cinnamomum camphora* log in Hong Kong. The moisture contents of specimen A and specimen B were 12.45% and 12.87%, respectively. The diameters of the approximate circular shaped cross-section were 300 mm for both specimens. Three artificial defects were made in specimen A with thickness of 5 mm, 10 mm and 15 mm, respectively. It should be noted the defect with thickness of 5 mm was made between bark and sapwood, which can be regarded as bark detachment. Two artificial defects were made in specimen B with the thickness of 20 mm and 25 mm, respectively. It should be indicated that the defect size can affect the effectiveness of acoustic-laser technique for defect detection. If the defect size is too small, the acoustic wave will not be able to excite the defect region and such small defects will be considered insignificant. All five artificial near surface defects were designed with the same area of 90 mm $\times$ 70 mm as a representative size of defect, whose area was approximately 5% of the side surface of the trunk sample. The photograph and schematic diagram with the specimens and defect arrangement are shown in Fig. 1.

Fig. 1 (a) Arrangement of artificial defects in specimen A; (b) arrangement of artificial defects in specimen B; (c) schematic diagram for boundary condition of real defects located inside a tree trunk. Prior to the measurement by acoustic-laser technique, the top surface of the tree trunk was bonded with a woodblock by using strong glue to make sure that the

rectangle plates at the defect region have 4 sides fixed.

2.2 Description of acoustic-laser technique

The basic principle of acoustic-laser technique for tree defect detection is that the acoustic waves are applied on the tree trunk to initiate its vibration, and the surface vibration variation between intact region and defect region is distinguished by laser beam. The measurement set-up of the acoustic-laser technique includes laser, loudspeaker, photoreceiver, data acquisition system, and computer. Table 1 lists the functions and properties of each instrument in the measurement system of acoustic-laser technique.

Fig. 2 Experimental details of using acoustic-laser technique for tree detection: (a)

photograph of experimental set-up and working situation, (b) input signal of white noise (with frequency approximately ranging from 0 Hz to 20000 Hz) emitted by loudspeaker, (c) measurement points for specimen A, and (d) measurement points for specimen B.

During the test, the loudspeaker was placed 20 cm in front of the tree trunk, and the laser beam was emitted towards the tree surface with an incident angle of 45° . In this technique, white noise (with a flat frequency spectrum when plotted as a linear function of frequency) was used for structural excitation. The frequency of white noise used in this study ranged from approximately 0 Hz to 20000 Hz, as shown in Fig. 2(b). Compared with traditional structure excitation methods, such as impact hammer, the acoustic wave was used as the vibration source which can be produced at a distance in front of the tree. The non-contact excitation ensured the propagation of a laser beam without being blocked. Moreover, it can provide consistent excitation to the object. The energy imparted to the object and the frequency of excitation can be controlled by designing the input of acoustic resources, which can better monitor vibration characteristics of the object compared with impact excitation. On the other hand, the optic-electronic sensor utilized in the photoreceiver was a silicon photodiode (Qiu and Lau 2018). The maximum relative sensitivity of the photodiode was formed when the wavelength of laser light was around 550 nm, from the specification of a photodiode product (LXD66CE-G). In order to obtain a sensitive response of this photoreceiver, the commercially available laser was adopted that emitted green light with 532 nm wavelength. The green laser beam was also commonly used in both scientific and industrial measurements (Konno et al. 2000). Data acquisition system (NI USB 9162) was used to collect the electrical signal from the photoreceiver, with a sampling frequency of 50000 Hz.

Since the surface of the tree trunk was quite coarse and this could seriously scatter the reflected laser beam, sand paper was used to polish the surface at measurement point in order to fix a retroreflective tape on the tree surface tightly, as depicted in Fig. 3. It should be noted that in field applications, more appropriate retroreflective tapes with excellent ability of

bonding to tree surface should be used to avoid surface treatment.

Fig. 3 Surface treatment of a tree trunk before the measurement of acoustic-laser technique: (a) before surface treatment; (b) after surface treatment; (c) tree surface laminated with a retroreflective tape

Table 1 Instruments in acoustic-laser technique and their corresponding functions

Item	Function
Loudspeaker	Providing the source of acoustic waves (white noise with frequency approximately from 0 Hz to 20000 Hz and sound pressure level of 120 dB).
Laser	Producing the laser beam with resolution of 3 mm and wavelength of 532 nm.
Photoreceiver	Collecting the reflected laser beam from tree trunk and transferring the optical signal into electrical signal.
Data acquisition system (NI USB 9162)	Collecting the electrical signal from photoreceiver with the sampling rate of 50000 Hz and the period of 5 seconds
Labview software	Visualizing the electrical signals (voltage) in time and frequency domains

2.3 Description of sonic tomography

PiCUS Sonic Tomography (Argus Electronic GmbH, Rostock, Germany) was used for

cross-section measurement of each specimen. The device consisted of twelve sensors, and eight of them were magnetically attached to the pins tapped into the bark and sapwood. Figure 4 shows the PiCUS sonic tomography package used in the study and the installed system on the trunk sample for measurement. For each specimen, the sonic tomography measurement was conducted three times with different arrangement of sensors. For the first two times, sensors were evenly arranged around the circumference with variation of the location of each sensor to avoid the singularity of measurement results. Sensors were arranged denser at defect area according to measurement results from acoustic-laser technique for the third measurement.

Fig. 4 (a) PiCUS sonic tomography package; (b) installation of the system on the trunk sample

The circumference and distances between measurement points were measured by PiCUS caliper, and the measured data was used as input to reconstruct the shape of the cross-section. After measuring the geometrical data of the trunk sample, sonic tomography measurement was carried out by tapping each pin using the hammer sequentially. The acoustic wave transmission time between each two sensors was recorded and transferred into velocity matrix through the measurement process at each location. The velocity of acoustic waves in wood was altered at the defect or decay area, indicating the health condition of the trunk at corresponding location. After obtaining the completed velocity matrix, tomography was constructed for each cross-section by PiCUS Q73 software to evaluate the accuracy of the sonic tomography results.

2.4. Analytical model of defect detection in tree trunk by acoustic-laser technique

With respect to a tree trunk, the surface wood layer can be motioned with different vibration modes under acoustic excitation. In defect region, the surface wood layer is considered as vibrating wood plate. According to the theory of plate vibration, the local natural frequency of the wood layer at defect region can be quantified, given that several assumptions are made. Initially, the defect region is rectangular and the air gap underneath the wood plate has little effect on the measured natural frequency. In addition, the surface wood layer is treated as isotropic material. For a surface wood layer in defect region with boundary condition of four sides fixed, its vibration behavior can be described by the following Eq. (1) (Soedel and Qatu 2005; Liao et al. 2017):

$$D\nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} = 0 \quad (1)$$

where $w = w(x, y, t)$ is the transverse displacement of the wood plate as a function of spatial variables x , y , and time t . D is flexural rigidity of the wood plate, which is related to Young's modulus E , wood thickness h , and Poisson's ratio ν of wood material, as expressed by Eq. (2).

$$D = \frac{Eh^3}{[12(1 - \nu^2)]} \quad (2)$$

The resonant frequency of this wood plate can be determined by the following Eq. (3) (Soedel and Qatu 2005):

$$f = \frac{\pi^2}{a^2 b^2} \sqrt{\frac{DK}{\rho N}} \quad (3)$$

where K is expressed by Eq. (4); N is 2.254, which is frequency coefficient for rectangular plate with all sides clamped; a and b are the side lengths of the rectangular wood plate; f is the resonant frequency. Eq. (3) enables us to identify the presence of near surface defect in the tree trunk by using acoustic-laser technique. Besides, it is even able to assess the extent of

defect, according to Eq. (5) which is derived from Eq. (3).

$$K = 0.0468 + 0.340 \left(\frac{a}{b}\right)^2 + 1.814 \left(\frac{a}{b}\right)^4 \quad (4)$$

$$A = a^2 b^2 = \frac{\pi^2}{f} \sqrt{\frac{DK}{\rho N}} \quad (5)$$

In previous studies, the theory of plate vibration is adopted in acoustic-laser technique for analyzing the delamination, debonding, air gap and some other sub-surface defects in FRP-bonded composite systems (Lau 2013; Qiu and Lau 2015, 2016; Yu et al. 2016). When applying the acoustic-laser technique to tree detection, it should be noted that the analogy between the dynamic response of damaged trees and the dynamic behavior of plates and shells depends on the locations of defect inside the tree trunk. The theory of plate vibration can be used to analyze the vibration response of defect region with thin surface layer. As the thickness of the tree surface layer at the defect region increases, the dynamic response may no longer be treated as plate vibration behavior since the rotation and shear effects within the plate should not be neglected. In this view, the present study investigates the maximum depth of defect that can be effectively evaluated by acoustic-laser technique.

2.5 Integration of acoustic-laser technique and sonic tomography

The ability of sonic tomography to detect internal defects has been demonstrated in current literature by many researchers (Deflorio et al. 2008; Brazee et al. 2011; Guntekin et al. 2012; Du et al. 2015). The internal condition within the measured cross-section can be evaluated by the velocity of acoustic wave transmission in the cross-section of a trunk. Velocity of the acoustic wave transmission in wood is determined by two mechanical properties, namely, elastic modulus and wood density. Their relationship can be expressed in the following formula:

$$v = \sqrt{\frac{E}{\rho}} \quad (6)$$

where v is the velocity of acoustic wave, E is the elastic modulus of the wood and ρ refers to

the density of the wood.

Based on this method, the accuracy of reconstructed tomography is sensitive to the density of acoustic wave path within the cross-section. For the internal xylem area, the acoustic wave paths are denser than the area near bark and sapwood of the cross-section, so the ability of sonic tomography to detect near surface defects is much lower than that to detect internal defects. As illustrated in Fig. 5 (a) and (b), the white line refers to the path of acoustic wave influenced by the defect. There is little acoustic wave transmission influenced by the near surface defect. However, when the defect is located at the internal area of the cross-section, much more paths of the acoustic wave transmission are affected by the defect (ten in this case), so that the defect can be modeled more accurately than the near surface defect.

Fig. 5 (a) Near surface defect detected by sonic tomography; (b) internal defect detected by sonic tomography; (c) near surface defect detected by sonic tomography with the targeted distribution of sensors. The white lines are the paths of acoustic wave affected by defect and the black lines are the paths of acoustic wave transmission not affected by defect

To improve the accuracy of sonic tomography in detecting near surface defects, it is proposed that the distribution of the sensors can be adopted according to the measurement results of acoustic-laser technique. As shown in Fig. 5 (c), when a near surface defect is detected by acoustic-laser technique, sensors are distributed denser at the corresponding location. The numbers of the acoustic wave transmission path influenced by the defect increase to seven, so that the accuracy of sonic tomography in detecting near surface defects can be significantly improved in terms of defect size and location.

3. Results and Discussion

3.1 Detectable thickness of near surface defect in trunk using acoustic-laser technique

The measured electrical response describing the vibration behavior of tree surface can be plotted in time or frequency domain. Figure 6 shows the measurement signals of acoustic-laser technique in the time domain, with different defect regions with 5-25 mm deep and intact regions (point A1, A6 and B5). From the electrical signals in time domain, the big difference of the signal amplitude between the defect regions with 5-15 mm depth and the intact regions can be observed. However, signal difference between the defect regions with 20-25 mm depth and the intact regions is not remarkable. Based on Fig. 6, Table 2 lists the maximum amplitude value with different defect and intact locations. It can be noticed that the maximum amplitude values for 20 mm and 25 mm depth are close to those of intact regions. In this case, 15 mm is considered as the critical depth for more conservative defect detection by this technique.

Table 2 Maximum amplitude value with different defect and intact locations.

Measurement Point	5 mm	10 mm	15 mm	20 mm	25 mm	A1	A6	B5
Max. Amplitude	0.68	0.35	0.47	0.13	0.07	0.06	0.06	0.16

In order to characterize the natural frequency of a tree trunk with the presence of defect, the measured electrical signals in time series were transferred into frequency spectrum by FFT analysis. In this article, the amplitude of the transformed data by $F(x)$ is presented where x is the collected voltage signal. Since the existence of flick noise (also called $1/f$ noise, in the frequency zone between 0-500 Hz) can affect the signal analysis of tree defect, the signals in this range are eliminated (Erturk et al. 2005, 2007). Figure 7 shows the amplitude of signals in the frequency domain for intact region and defect regions with different locations. It can be clearly shown that the amplitudes of signals for intact regions (point A1, A6 and B5) are small, lower than 0.0004. This observation is also found for other measurement points (A3, A7, B1, B2, B3, B7 and B8) in intact regions. In contrast, the obvious frequency peaks can be found from the measurement results of the defects with depths of 5, 10 and 15 mm. It can also be found that the amplitudes for defect regions with 5-15 mm depth are much larger (almost 10 times) than those for defect regions with 20 and 25 mm depth as well as those for

intact regions. Although some frequency peaks can be found for defect regions with 20 and 25 mm depth when the scale of value at vertical axis is up to 0.0003, the natural frequency is not clearly identified. This means that the acoustic-laser technique can detect the defects in a tree trunk with maximum depth of 15 mm. With increasing thickness of the wood layer, the signal peak is located at higher frequency. Based on the theory of plate vibration, it can be understood that the flexural rigidity of the vibrating wood plate is reduced with the reduction in wood thickness, as expressed in Eq. (2) (Lau 2013; Chen et al. 2014, 2015; Cheng and Lau 2014). The reduced flexural rigidity can lead to a lower natural frequency of plate vibration, as expressed in Eq. (3) (Lau 2013; Chen et al. 2014, 2015; Cheng and Lau 2014). Therefore, the defect region with 5 mm depth from surface indicates lower flexural rigidity, so that the resonant frequency of this defect is smaller than that of the other defects. Table 2 lists the comparison of natural frequency of wood surface layer between the measured and theoretical values. The deviation between two values is less than 20%, indicating that acoustic-laser technique can approximately capture the natural frequency of near surface defect in the tree trunk.

As to frequency spectrum of defect region with 15 mm depth, many peaks are found in the range of 4000-6000 Hz, as shown in Fig. 7(c). This may be associated with the heterogeneous effect of wood when the thickness of the tree surface layer at the defect region increases. The frequency of 4860 Hz corresponding to the maximum amplitude of signal is selected as the representative natural frequency. This frequency value of 4860 Hz is close to the theoretical value of 4655 Hz, as listed in Table 3. As can be seen in the vertical scale of Fig. 7(d)-(h), all the signal amplitudes are significantly reduced in comparison to Fig. 7(a)-(c). Many frequency peaks found in Fig. 7(d)-(h) are probably related to noise instead of signal. Natural frequencies for defect regions with 20 mm and 25 mm depth are not clearly observed. In this case, the acoustic-laser technique is considered not sensitive to detect deep defects. It should be noticed that for the 5 mm depth defect, the surface layer mainly consists of bark, whose theoretical natural frequency should be calculated based on the material property of bark. It is reported that the elastic modulus of bark can be taken as 50% of that of wood and the density of bark can be taken as 0.24 g/cm^3 , so that the theoretical natural frequency could

be calculated accordingly (Upadhyaya et al. 1987; Niklas 1999; Antony et al. 2015).

By using this technique, the near surface defect inside the tree trunk can be identified, which gives indication for sonic tomography to optimize the defect location and area.

Fig. 6 Measurement signals in the time domain: (a) at point A8 of defect region with 5 mm

depth, (b) at point A4 of defect region with 10 mm depth, (c) at point A2 of defect region with 15 mm depth, (d) at point B4 of defect region with 20 mm depth, (e) at point B6 of defect region with 25 mm depth, (f) at point A1 of intact region, (g) at point A6 of intact region, and (h) at point B5 of intact region

Fig. 7 Measurement signals in the frequency domain: (a) at point A8 of defect region with 5 mm depth, (b) at point A4 of defect region with 10 mm depth, (c) at point A2 of defect region with 15 mm depth, (d) at point B4 of defect region with 20 mm depth, (e) at point B6 of defect region with 25 mm depth, (f) at point A1 of intact region, (g) at point A6 of intact region, and (h) at point B5 of intact region.

Table 3 Measured and theoretical natural frequency for wood surface layer at defect region

Defect location	Measured natural frequency	Theoretical natural frequency	Deviation
5 mm	1150 Hz	1097 Hz	4.61%
10 mm	2110 Hz	2534 Hz	16.73%
15 mm	4860 Hz	4655 Hz	4.40%
20 mm	Not found	7168 Hz	Not available
25 mm	Not found	10018 Hz	Not available

3.2 Hybrid measurement method using acoustic-laser technique and sonic tomography

In common practice of sonic tomography measurement, sensors are evenly distributed around the circumference of the tree trunk. However, the sensitivity of detection at near bark area will be questionable as aforementioned. To improve the sensitivity of sonic tomography in detecting the near surface defect, acoustic-laser technique is adopted. The measurement results show that the defects with a depth less than 15 mm from bark can be detected and located. Although the results from acoustic-laser technique cannot show comprehensive information on the health condition within the tree trunk in terms of defect area, it provides a guideline for the distributions of sensors in sonic tomography measurement.

In order to study the effect of sensor distribution on accuracy of sonic tomography in detecting the near surface defect, sonic tomography measurements were carried out three times for both specimen A and specimen B. In the first two tomographs, sensors are evenly distributed with different locations to avoid the singularity, and then sensors are distributed with a spacing of 40 mm in the defect area detected by acoustic-laser technique, and distributed with a spacing of 150 mm at location where no defects are detected. The

measurement results of sonic tomography for specimen A are shown in Fig. 8.

Fig. 8 Sonic tomography results for specimen A: (a) photography with defects with a thickness of 5 mm, 10 mm and 15 mm, (b) and (c) sonic tomography result with evenly distributed sensors, which cannot detect any defects, and (d) sonic tomography results with sensors intensively distributed at defect location. Sensors are arranged with a spacing of 40 mm at targeted defect area, and defects with a thickness of 10 mm and 15 mm are detected in sonic tomography results.

As shown in Fig. 8 (b), the sonic tomography with evenly distributed sensors cannot detect any defects, and the measurement results show the cross-section can be regarded as intact. By further adjusting the location of sensors with even distribution, there is still no defect detected. The minimum velocity of acoustic wave transmission in the cross-section is larger than 80% of the maximum velocity, which indicates that no defect or decay is detected, as shown in Fig. 8 (c). In the third sonic tomography measurement for specimen A, the image

shows that both the defect with thickness of 10mm and 15mm are shown in the tomograph. The maximum of the measured acoustic wave transmission velocity in the sonic tomography is 1276 m/s. The velocity of defect area is from 70% to 80% of the maximum wave transmission velocity, which indicates that the wave transmission is affected by the defect at corresponding location. However, the defect with 5 mm thickness is not detected, which can be regarded as the bark detachment. This is because in the sonic tomography measurement, the pins are tapped through the bark and sapwood for each measurement point. The acoustic wave transmission starts at tip area of each pin into the core wood, and bark detachment cannot be measured since the signal of such area cannot be detected. To further evaluate the improvement of accuracy of sonic tomography, a comparison is made based on the actual defect area and defect area measured in sonic tomography. For each defect, the defect area is 720 mm² by simplifying the defect area as rectangular. The area where acoustic transmission velocity is less than 1020 m/s in this sample is regarded as defect area according to the calculation from PiCUS Q73 software, and the results are shown in Fig. 8 (d). Table 3 shows the comparison result between actual defect area and sonic tomography measurement results.

Table 3 Sonic tomography measurement values for specimen A

Specimen	Defect depth	Defect area	Measured minimum		Measured defect area	Accuracy
	H (mm)	A ₁ (mm ²)	velocity	V _{min} (m/s)	A _s (mm ²)	
Specimen A	5	9		1187	0	-
	10	720		1006	1100	47.2%
	15	720		823	800	83.3%

As shown in Table 3, the defects with thickness of 10 mm and 15 mm are detected by sonic tomography, and the detected defect areas are 1100 mm² and 800 mm², respectively. The accuracy of the sonic tomography results for each defect is calculated according to the defect area measured in tomography and their actual area, which are 47.2% and 83.3% for each defect. The measurement results show a significant improvement by using the hybrid method combining acoustic-laser technique and sonic tomography in detecting the near surface

defect.

The sonic tomography measurement results for specimen B are shown in Fig. 9. In Fig. 9 (b) and (c), it is shown that the velocity of acoustic wave transmission within the entire cross-section is larger than 80% of its maximum value, which indicates that no defect is detected by the system. To further evaluate that whether targeted distribution of sensors at defect area can improve accuracy of sonic tomography results when detecting the near surface defects, the sensors are distributed with a spacing of 40 mm at the defect with a depth of 20 mm and evenly distributed with the spacing of 150 mm at location where no defects are detected by acoustic laser technique. The sonic tomography measurement results are shown in Fig. 9 (d).

Fig. 9 Sonic tomography results for specimen B: (a) Photograph with defects with a thickness of 20mm and 25mm, (b) and (c) sonic tomography result with evenly distributed sensors, which do not detect any defects, (d) sonic tomography results with sensors arranged with

spacing of 40 mm at defect with 20 mm depth and spacing of 150 mm at defect with 25mm depth.

The maximum velocity measured in Fig. 9 is 1473 m/s. By regarding the area with a velocity of less than 80% of its maximum value as defect area, the sonic tomography results show that both defects can be detected as shown in Fig. 9 (d). A comparison between measurement results with different locations of sensors for the two defects is shown in Table 4.

Table 4 Sonic tomography measurement values for specimen B

Specimen	Defect depth	Defect area	Measured minimum	Measured defect area	Accuracy
	H (mm)	A (mm ²)	velocity $V_{\min}$ (m/s)	A_s (mm ²)	
Specimen B	20	720	1171	900	63.9%
	25	720	970	110	15.2%

The measured defect areas using sonic tomography for the two defects were 900 mm² and 110 mm², respectively. By applying targeted distribution of sensors, more acoustic wave paths are influenced by the defect with 20 mm depth and recorded by sensors, so that the defect area and location can be analyzed more comprehensively compared with the defect with 25 mm depth, which is measured by normally distributed sensors. The accuracy of the measurement results increases from 15.2% to 63.9% by distributing the sensors denser at defect location, which significantly improves the ability of sonic tomography to monitor trees, especially to detect near surface defects.

4. Conclusion

Both acoustic-laser technique and sonic tomography were carried out to inspect near surface defects in tree trunk. The results show that the near surface defect with a depth less than 15 mm under the bark can be well identified with acoustic-laser technique, and the natural frequency of defect region agrees well with analytical model. It is demonstrated that

acoustic-laser technique is a robust method for tree health monitoring, which is capable of detecting the bark detachment in a tree trunk as well. Meanwhile, the accuracy of sonic tomography in detecting the near surface defect can be significantly improved by distributing sensors in the same manner as in acoustic-laser technique. It is recommended that acoustic-laser technique should be carried out first to determine bark detachment and near surface defect in tree trunk. Then, the sonic tomography can be used with both even distribution and targeted distribution of sensors in order to assess tree health condition comprehensively.

The major theme of this study is the validation of acoustic-laser technique in tree defect detection and its combination with conventional sonic tomography technique. To further extend the method in this study to field measurement, improvements are suggested according to the limitations found from laboratory experiment as below:

- The use of acoustic-laser technique seems not efficient enough at this laboratory-testing stage. The instruments of laser, loudspeaker and photoreceiver are set up separately when conducting the tree assessment, which requires a lot of time for defect detection. Given that the instruments of laser and photoreceiver have features of low cost, small size and lightweight, improvements can be made to combine all the instruments into one machine so that the volume of acoustic-laser technique system is largely reduced. In this case, the measurement can be more portable and the set-up can be easier.
- The measurement by acoustic-laser technique at this stage is carried out at a localized point rather than a scanned surface, which is not efficient enough for assessing large tree trunks. It takes around 20 to 25 minutes to measure one cross-section including 8 measurement points using acoustic-laser technique. To improve the feasibility of this technique in field test, it is encouraged to design the sensor array in acoustic-laser technique so that each measurement can be performed with multiple points. This can significantly improve the efficiency and speed of tree assessment by acoustic-laser based approach.

Acknowledgements

The authors are grateful to the support from Innovation and Technology Commission through the Innovation and Technology Fund (ITF) with the Project Reference No. ITS/116/15. The authors would also like to appreciate the support from Croucher Foundation through the

Start-up Allowance for Croucher Scholars with the Grant No. 9500012, and the support from the Research Grants Council (RGC) in Hong Kong through the Early Career Scheme (ECS) with the Grant No. 139113.

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