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The sensitivity of acoustic-laser technique for detecting the defects in CFRP-bonded concrete systems

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Abstract This paper presents an experimental study to evaluate the sensitivity of acoustic-laser technique in defect detection. The technique is particularly useful towards the detection of near-surface defects in fiber reinforced polymer (FRP)-bonded concrete by vibrating the material with an acoustic excitation and measuring the vibration signals with a laser beam. However, relatively little is known about the sensitivity of acoustic-laser technique. More research work should be conducted to evaluate the effectiveness of the technique when adopted for defect detection. It is also important to investigate the limits of the technique performance with respect to varying operational conditions so as to determine ways of improving the detectability. For this purpose, operational conditions in terms of acoustic excitation and laser beam incidence are investigated for their effectiveness in detecting near-surface defects and a reliable defect detection scheme using our portable equipment is therefore recommended. This work provides a basis for further improving such technique which can be used in other engineering applications including quality control of materials and product development process.

Keywords Acoustic-laser technique · Defect ← · Detection ← · FRP-bonded concrete ≤ Sensitivity

1 Introduction

There are numerous non-destructive testing (NDT) methods for quantifying material condition in reinforced concrete (RC) structures. Acoustic emission (AE), radiography method, and radar (microwave) methodology are

1 some of the examples. AE methodology is based on detecting the elastic waves generated in materials due to plastic
2 deformation, crack expansion and other kinds of material degradation [1-4]. Proper analysis of the elastic waves can
3 provide information concerning the defects within a material. However, AE is a contact method, which requires
4 attaching transducers to materials in order to transmit and receive the acoustic signals [5]. Radiography method is
5 involved in using the short wavelength electromagnetic radiations (*i.e.* X-rays or neutron rays) which can be
6 absorbed by the materials as they penetrate through the medium [6]. The amount of the absorption is affected by the
7 density and composition of the materials. However, the method poses a radiation hazard towards the users. Radar
8 (microwave) methodology is based on electromagnetic waves within the radio frequency spectrum range (3 Hz - 300
9 GHz) for rapidly assessing a variety of characteristics in concrete structures [7-9]. A drawback to this technique is
10 that the received signals may be reflected from other regions of no interest due to the defocused microwave.
11 Apart from the non-destructive testing methods mentioned previously, acoustic-laser technique has emerged as a
12 promising method for detecting the near-surface defects in composite structures such as FRP-bonded concrete
13 structures. The method is particularly suitable for detecting the air voids, cracking, delamination, or debonding
14 under the FRP plate by vibrating the target with an acoustic excitation and characterizing the vibration behavior with
15 a laser beam. Under an adequate acoustic pressure, the defect areas can vibrate more significantly as compared to
16 the intact regions firmly bonded to the concrete. The analysis of the vibration signals measured in a frequency
17 spectrum can be used to identify the presence of a defect. Acoustic-laser technique offers numerous advantages
18 over the conventional NDT methods for damage evaluation. Compared to AE, the acoustic-laser technique is a non-
19 contact method which utilizes the acoustic waves propagating at a standoff distance from the object for vibration
20 excitation. The robust non-contact method is suitable to inspect the structures in locations where the operating
21 environments (*e.g.* high temperature, high tension) may be dangerous or prohibitive. The acoustic-laser technique
22 has the ability to detect the objects from relatively large distances due to the high concentration of the laser beam.
23 In contrast to the electromagnetic waves adopted by radiography method, acoustic-laser technique makes use of the
24 optical beam in the measurement which is less harmful to people. In addition, the acoustic-laser technique is
25 capable of detecting small defects because of the focused laser beam of which the radar (microwave) methodology
26 fails to achieve.

27 Previous work has proven the concept of the acoustic-laser technique for the detection of defects in FRP-bonded
28 concrete [10,11]. However, relatively little is known about the sensitivity of acoustic-laser technique when applied

1 in defect detection. It is important to investigate the limits of the technique performance with respect to varying
2 operational conditions (*e.g.* distance of acoustic source, sound pressure level, incident angle of acoustic excitation,
3 and incident angle of laser beam) so as to determine the ways of improving the detectability. The intensity of the
4 acoustic excitation is an important factor in the measurement sensitivity because it affects the amount of acoustic
5 waves radiating from the acoustic source towards the target. Sound pressure level (SPL) is another operational
6 parameter that states the level of acoustic excitation. Also, incident angle of acoustic excitation is considered to be a
7 parameter because decomposition of the acoustic pressure will occur if the acoustic excitation is obliquely incident
8 on the FRP surface. In addition to the parameters which are related to the acoustic excitation, the incident angle of
9 laser beam is another parameter that influences the measured response of a target. The objective of this paper is to
10 explore how these operational parameters affect the sensitivity of acoustic-laser technique for defect detection. The
11 operational conditions with varying distance of acoustic source, SPL, incident angle of acoustic excitation, and
12 incident angle of laser beam are measured, and their influence on the measured signals is evaluated in this study.
13 This paper will first describe the test specimen and describe the overview of the laboratory acoustic-laser technique
14 system. Then, an in-depth description of the operational parameters will be given. Experimental results will be
15 discussed to explain the effects of the operational parameters on the system performance of the acoustic-laser
16 technique. Based on our experimental results, the optimum ranges of the four concerned parameters will be
17 recommended, which can determine a reliable defect detection scheme using our portable equipment. Finally, the
18 highlights of this work and the future study will be outlined. The knowledge and findings provided in this paper
19 will be of prompt use in the structural health monitoring and nondestructive testing community.

20

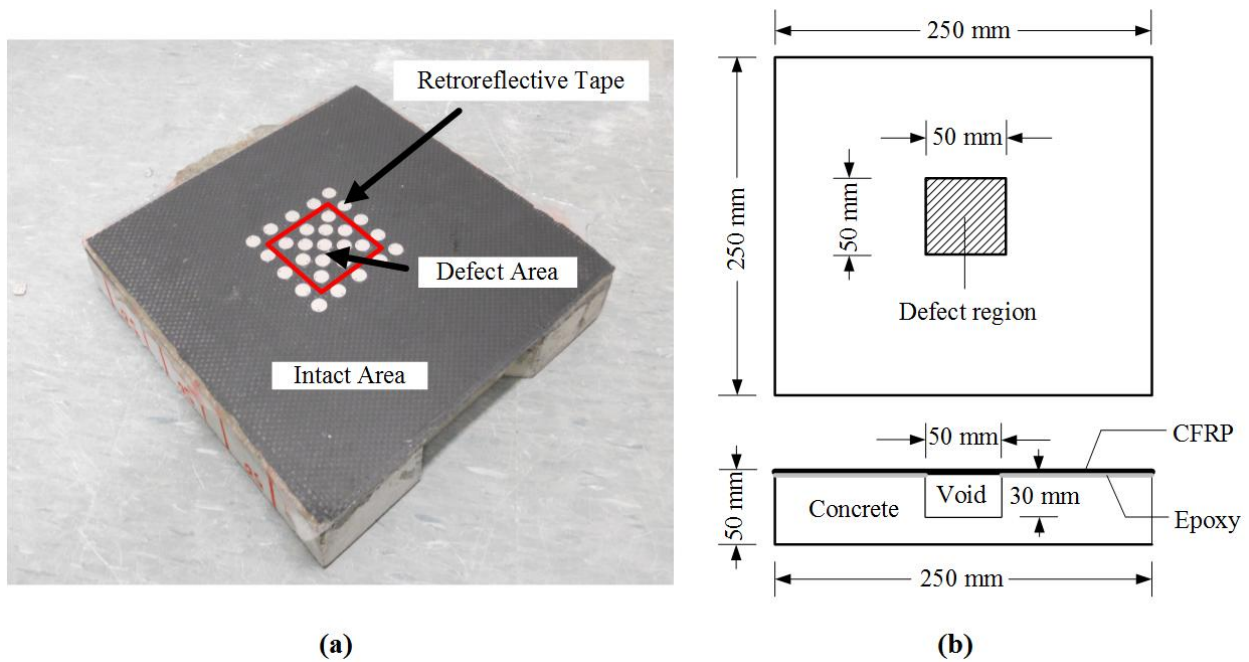
21 **2 Material and Methods**

22 2.1 Test specimen

23 A carbon fiber-reinforced polymer (CFRP)-bonded concrete panel was fabricated in the laboratory. The CFRP-
24 bonded concrete panel was made with an artificial defect (air block) by means of polystyrene foam. The polystyrene
25 foam was attached to a steel mold with the use of glass cement one day prior to the concrete casting. After
26 demoulding, the concrete was left in a humidity room for 28 days moist curing. Then, the polystyrene foam was
27 removed so that an air cavity was left in the concrete block. Finally, a CFRP plate was bonded to the concrete

1 surface through the use of a commercial epoxy resin. The bonding of the CFRP plate was undertaken through the
 2 wet-epoxy layup process and the detailed procedures can be found in the publication [12].
 3 The thickness of the CFRP sheet and the epoxy layer were 0.167 mm and 0.34 mm, respectively. The size of the
 4 concrete panel was 250 mm × 250 mm × 50 mm and that of the artificial defect was 50 mm × 50 mm × 30 mm. It
 5 should be noted that the defect size can affect the effectiveness of acoustic-laser technique for defect detection in
 6 FRP-concrete structure. If defect size is too small, the acoustic wave will not be able to excite the defect region.
 7 The defect size is commonly seen 10% - 20% of the side length of FRP-concrete structural element. Therefore, the
 8 defect area 50 mm × 50 mm was considered in this study as a representative size of defect, given that the CFRP-
 9 concrete sample has the area of 250 mm × 250 mm. The configuration of the CFRP-bonded concrete panel and the
 10 dimension of the artificial defect are shown in Fig. 1. Since the reflective laser beam may be scattered due to the
 11 roughness of the FRP surface, special surface preparation on the target was conducted by lamination of
 12 retroreflective tape. In this circumstance, a focused return signal from the target can be ensured.

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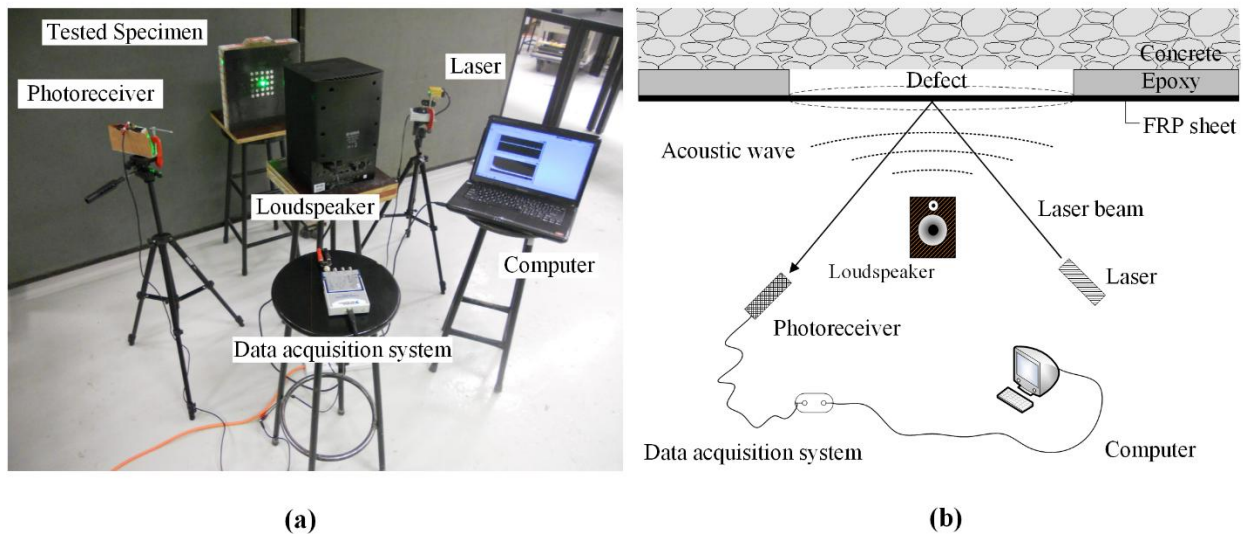
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15 **Fig. 1** The configuration of the CFRP-bonded concrete panel and the dimension of the artificial defect

16

17 2.2 Experimental setup

1 The key instruments of the acoustic-laser technique consist of loudspeaker, laser, photoreceiver, data acquisition
 2 equipment, and computer. Fig. 2 shows the photograph and schematic diagram of the test setup of acoustic-laser
 3 technique. The principle of acoustic-laser technique is described as follows. The white noise emitted from the
 4 loudspeaker was used to excite the target to vibrate as it provides acoustic waves with a wide band of frequencies
 5 which may contain the resonant frequency of the FRP surface. A laser beam was used to measure the vibration of
 6 the target surface. The optical signals carried by the laser beam were transferred into the electrical signals via the
 7 photoreceiver. The vibration behavior of the target surface was characterized from the electrical signals as they
 8 contain the information of the surface vibration amplitude.
 9



10 (a) (b)
 11 **Fig. 2** Photograph (a) and schematic diagram (b) of the test setup of acoustic-laser technique
 12

13 The laser emitted a green optical beam with the wavelength of 532 nm and the spot size of 1.96 mm. The input
 14 voltage and the output power of the laser were 220 V and 100 mW, respectively. Specifications of the loudspeaker
 15 are given in Table 1. The photoreceiver used in our research is composed of two parts: silicon photodiode and
 16 amplification system. The silicon photodiode was used to collect the optical signal and transfer it into the electrical
 17 signal. The properties of the silicon photodiode are also given in Table 1. The amplification system was used to
 18 enlarge the electrical signals from the photodiode.
 19

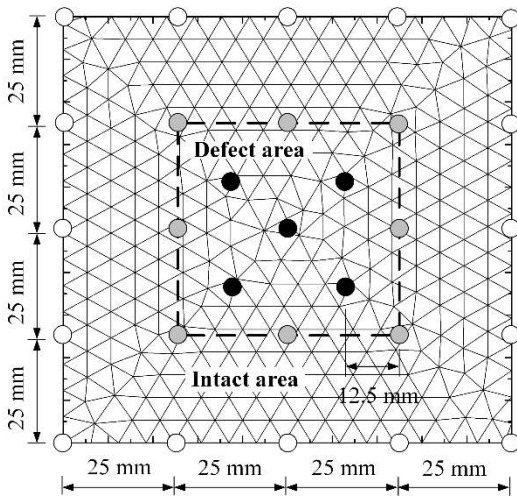
20 **Table 1** Specification of the loudspeaker and photodiode (From the manufacturer)

	Properties	Value	Unit
Loudspeaker	Crossover frequency	2500	Hz
	Overall frequency response	45 – 40000	Hz
	Maximum Output Level	125	dB
	Dimensions (W × H × D)	218 × 330 × 235	mm
	Weight	12.2	Kg
	Power Consumption	100	W
	Property	Value	Unit
Photodiode	Active Area Size	5.8 × 5.8	mm
	Reverse Voltage	5	V
	Operating Temperature	-20 – 80	°C
	Open Circuit Voltage	0.3	V
	Short Circuit Voltage	12	μA
	Dark Current	5	nA
	Terminal Capacitance	500	pF
	Peak wavelength	550	nm

1
2 In order to examine the capability of acoustic-laser technique to identify the presence of defect in the CFRP-bonded
3 concrete, scanned measurements over the defect region and the surrounding intact region were conducted. With the
4 laser moving on a tripod by manual adjustment, the surface of the defect region and the surrounding intact region
5 can be easily scanned. Fig. 3 depicts the schematic diagram of measurement points on the scanned surface over the
6 defect region and the surrounding intact region. For the intact region, the measurement points were at the
7 boundaries of the scanned surface. The measurement points inside the intact region were not considered in this
8 work because they make little difference in the defect characterization, since that FRP sheet is well bonded to the
9 concrete in intact region. For the defect region, the measurement points at the defect center, the defect boundaries
10 and inside the defect region were tested. In order to generate the contour map of the measurement signals, the
11 triangulation (shown as triangular element in Fig. 3) and the linear interpolation are employed.

12

- Measurement Point (Defect region) [] Defect boundary
- Measurement Point (Defect side)
- Measurement Point (Intact region) △ Triangular element



1
2 **Fig. 3** Measurement points on the scanned surface over the defect region and the surrounding intact region

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4 2.3 Operational parameters of the acoustic-laser technique

5 As previously mentioned, acoustic waves are used in the acoustic-laser technique for vibrating the surface of the
6 structures to be evaluated. The intensity of the acoustic excitation on the target is significantly influenced by the
7 following aspects. Distance of acoustic source can affect the amount of acoustic waves radiating from the
8 loudspeaker towards the FRP surface. SPL states the level of acoustic excitation. Incident angle of acoustic
9 excitation determines the decomposition of the acoustic pressure at the FRP surface. Therefore, several operational
10 parameters related to acoustic excitation are required to be studied including distance of acoustic source, SPL and
11 incident angle of acoustic excitation. Another parameter that should also be considered is the incident angle of laser
12 beam since the measured vibration signals are interpreted by the laser beam reflected from the target. The detailed
13 operational parameters of the acoustic-laser technique are outlined in the following Table 2.

14
15 **Table 2** The detailed parameters and their designed ranges in the experimental set up

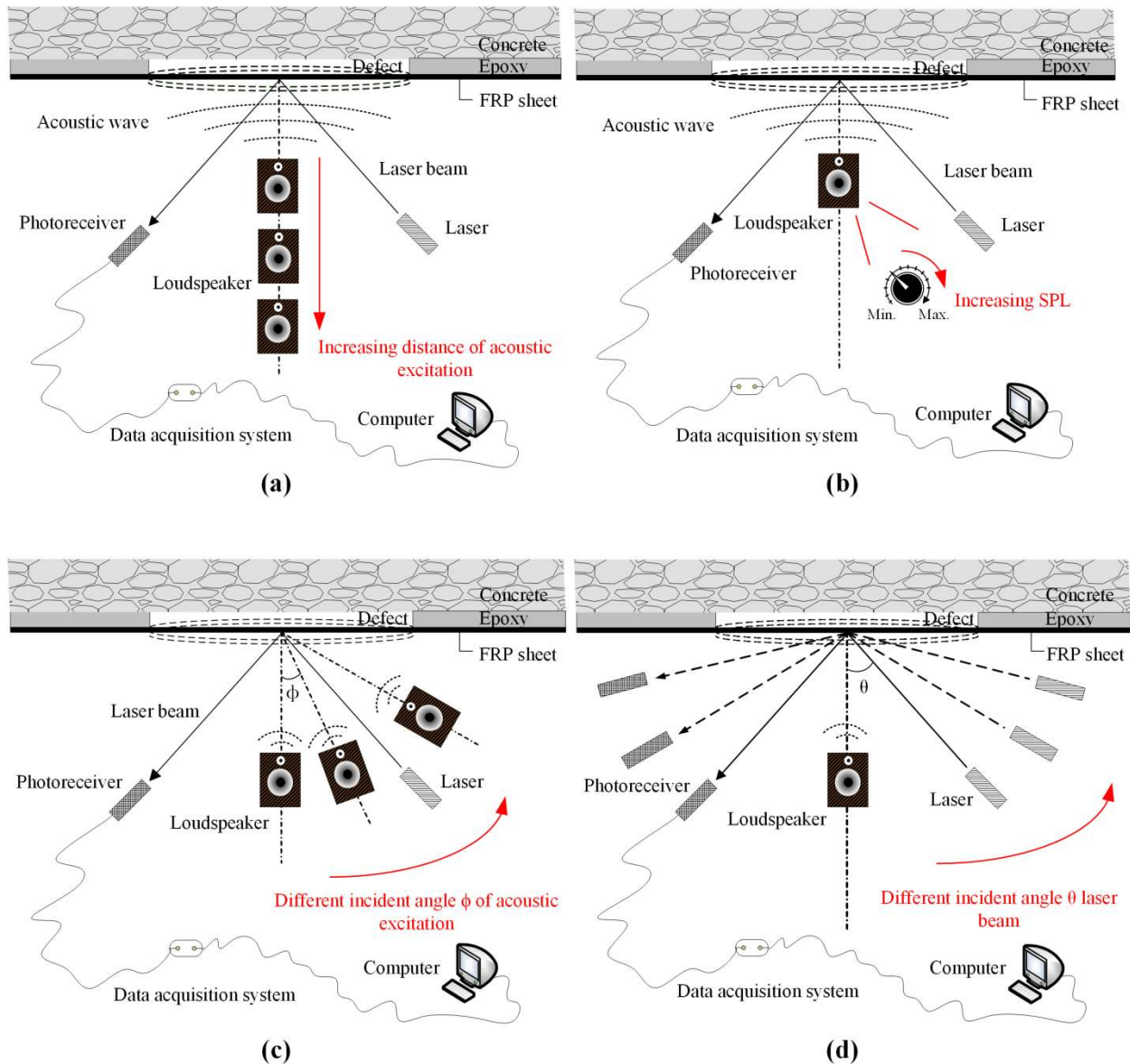
Parameters	Range	Unit
Distance of acoustic source	15 - 200	cm
SPL	55 - 125	dB
Incident angle of acoustic excitation	0 - 90	degree (°)
Incident angle of laser beam	15 - 90	degree (°)

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As shown in Fig. 4(a), distance of acoustic source refers to the distance between the loudspeaker and the CFRP-bonded concrete panel. The range of the distance started from 15 cm is due to the fact that laser beam will be blocked by the loudspeaker if the distance is too small. Due to the limitation of the working space in the laboratory, the maximum distance of acoustic source was set as 200 cm. SPL defines the measure of air pressure deviation caused by a sound wave, related logarithmically to the reference pressure of 20 μ Pa as given in Eq. (1). An SPL of 80 dB corresponds to an acoustic pressure of 0.2 Pa [13], while 120 dB SPL is equivalent to the pressure of 20 Pa, 100 times as much as the 80 dB. Fig. 4(b) shows the operational parameter of SPL for acoustic-laser technique. In the test, the volume on the loudspeaker was turned up so as to increase the SPL. Here, a sound level meter was used to measure the SPL. The background SPL in the laboratory was 55 dB. The largest SPL that can be produced by the loudspeaker in this experiment was 125 dB.

$$SPL = 20 \times \log_{10} \left(\frac{\text{sound pressure in Pascals}}{20 \mu Pa} \right) \tag{1}$$

Incident angle of acoustic excitation (ϕ) is the angle between the propagating path of acoustic wave and the normal line of target surface, as shown in Fig. 4(c). Incident angle of laser beam (θ) means the angle between the laser beam and the normal line of target surface, shown as Fig. 4(d). In our measurement, the incident angle of laser beam starts from 15° due to the presence of the loudspeaker. It is also noteworthy that the laser should not be placed too closed to the loudspeaker since the acoustic energy may excite the motions of laser.



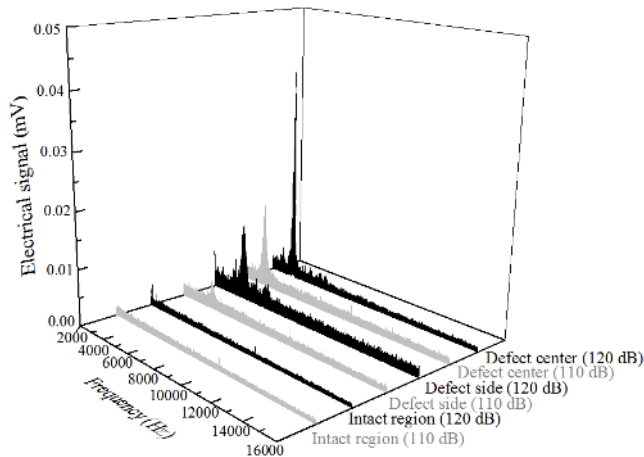
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 2 **Fig. 4** Sketch of the experimental set up with different cases of sensitivity studies: (a) distance of acoustic source; (b)
 3 SPL; (c) incident angle of acoustic excitation; (d) incident angle of laser beam

4
 5 **3 Results and discussions**

6 The electrical signals measured by the acoustic-laser technique contain the vibration information of FRP-concrete
 7 surface, and the signals can be presented in a time-domain waveform or in a frequency-domain spectrum. But in our
 8 measurement, a visual inspection of the original time series will not give any particular insight due to the complexity
 9 of the signals [14]. Therefore, in the present study, a fast Fourier transform (FFT) is adopted to map a recorded

1 time-domain waveform into frequency-domain spectrum. It is worth to point out that the flick noise (also called $1/f$
 2 noise) [15-19] always dominates in the frequency zone before 2000 Hz. Therefore, the signals in the frequency
 3 domain of 0 - 2000 Hz were eliminated. Fig. 5 illustrates the frequency spectrum of electrical signals measured in
 4 the intact region, the defect side, and the defect center. The distance of acoustic excitation is 20 cm while the
 5 incident angle of acoustic excitation and laser beam are 90° and 45° , respectively. Sound pressure levels 110 dB
 6 (marked grey) and 120 dB (marked black) are exhibited in Fig. 5. It can be found that the amplitude of electrical
 7 signals is quite small for the intact area. But in terms of the defect center, there is a sharp peak at the frequency of
 8 about 3670 Hz which may indicate the presence of damage. It is also noteworthy that the electrical signals for the
 9 defect side have a peak response with the same resonant frequency as that of the defect center, but the peak
 10 amplitude is decreased. In the following discussion, the peak amplitude of the electrical signals (at 3670 Hz)
 11 obtained from the frequency spectrum is recorded and presented.

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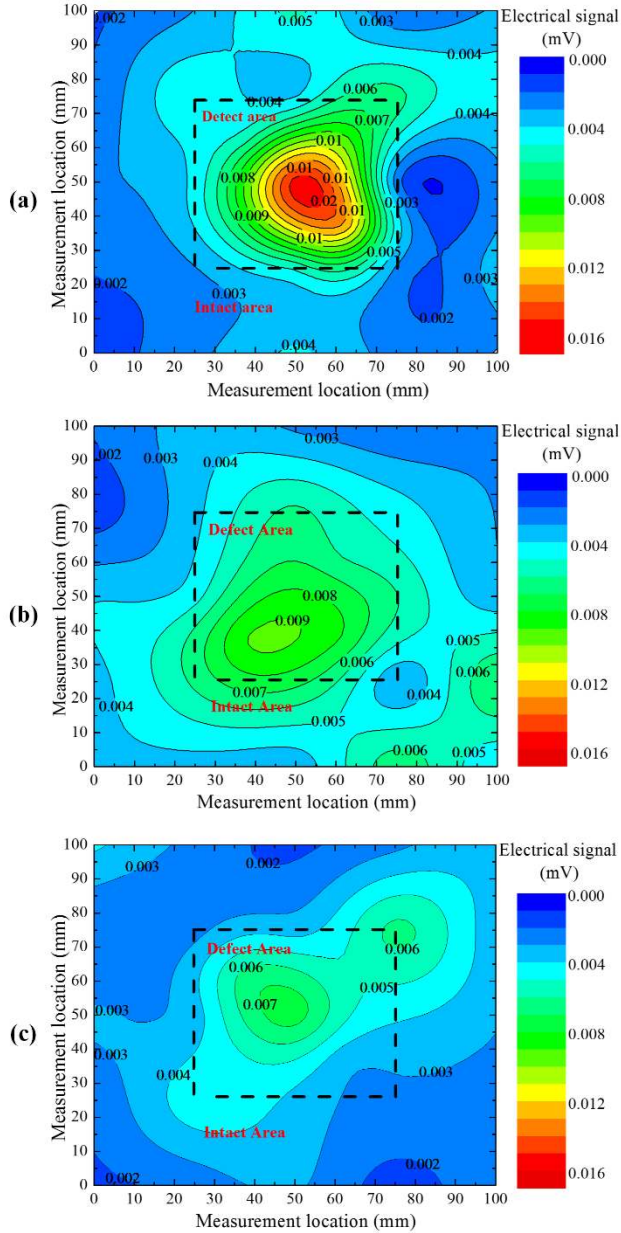
14 **Fig. 5** The typical measurement response of the intact region, the defect side, and the defect center in the frequency
 15 spectrum

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17 In order to assess the ability of acoustic-laser technique to locate the defect and characterize the defect size, a
 18 scanning image that reveals the electrical signals over the defect region and the intact region is plotted in Fig. 6. In
 19 Fig. 6, distances of acoustic excitation including 20 cm, 40 cm, and 60 cm are plotted respectively. The SPL is 110
 20 dB and the incident angle of laser beam is 45° . It is found from Fig. 6(a)-(c) that the signals within the defect region
 21 are much more significant than the intact region. The comparison among the Fig. 6(a), (b), and (c) suggests that an

1 increase in distance of acoustic excitation lowers the difference of vibration amplitude between the defect region and
2 the surrounding intact region.

3



4

5 **Fig. 6** The contour plot for the electrical signals over the defect region and the intact region with different distances
6 of acoustic excitation: (a) 20 cm, (b) 40 cm and (c) 60 cm

7

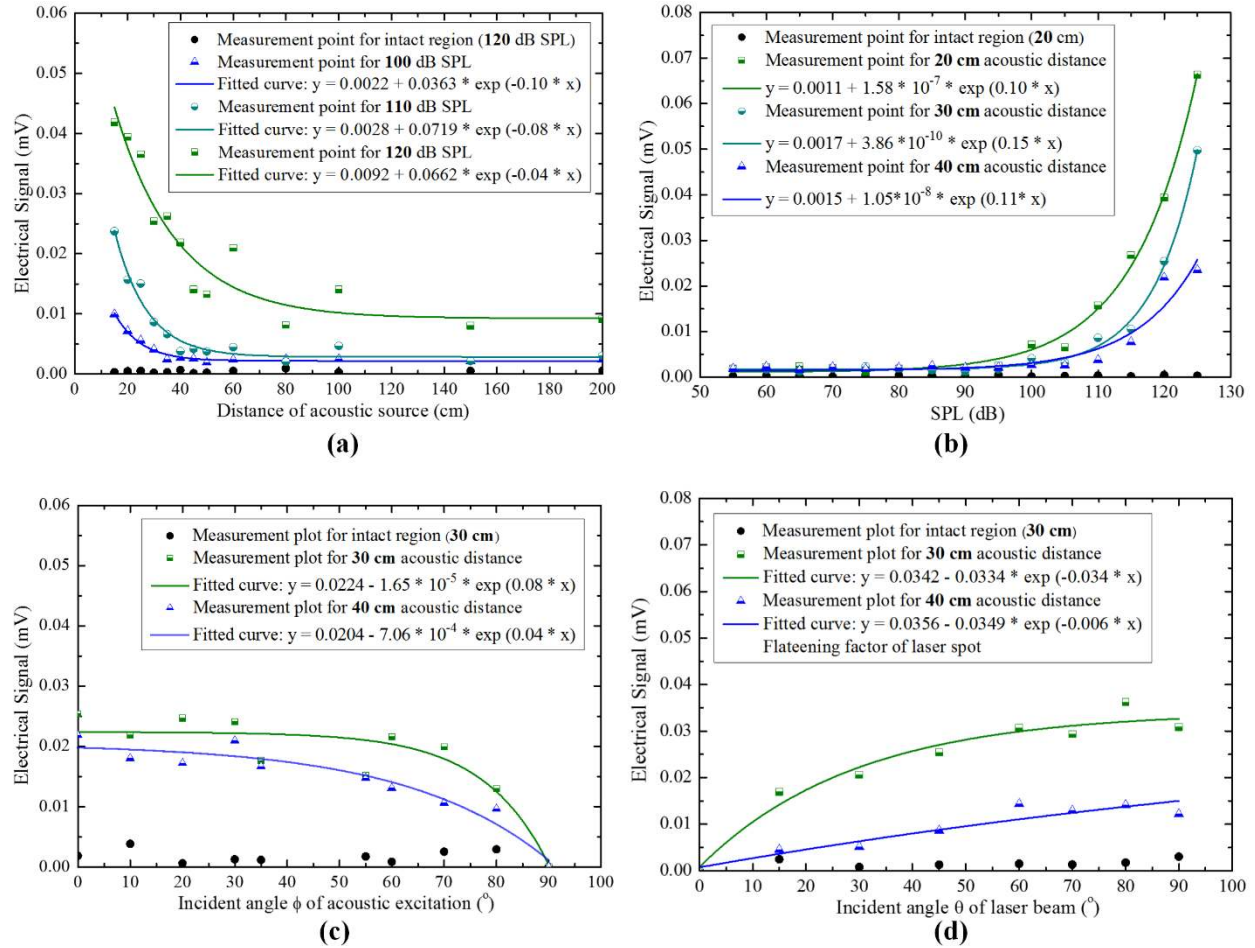
8 The effects of the operational parameters on the sensitivity of the acoustic-laser technique are displayed in Fig.7.

9 The measurement data collected from the defect center is plotted in this figure. Fig. 7(a) describes the amplitude of

1 electrical signals at resonant frequency (3670 Hz) plotted against distance of acoustic excitation, with three sound
2 pressure levels 100 dB, 110 dB, and 120 dB. The incident angle of laser beam is kept as 45° and incident angle of
3 acoustic excitation is kept as 90°. As seen from Fig. 7(a), measurement results with three sound pressure levels 100
4 dB, 110 dB, and 120 dB, showing a similar trend. The amplitude for the defect area decreases with an exponential
5 pattern as the loudspeaker is positioned more and more distant. The phenomenon is attributed to the reduction of the
6 acoustic pressure loading onto the FRP surface. In Fig. 7(a), the distances of acoustic excitation between 15 cm and
7 40 cm can ensure high sensitive measurement response, which are recommended by this paper for the practical
8 application of acoustic-laser technique. Since the down trend pertaining to the distance of acoustic excitation is
9 attributed to the declining acoustic pressure on the object, the following Fig. 7(b) presents the experimental results
10 of electrical signals against the SPL. It is found that the amplitude goes up with an increase in the SPL, in which the
11 trend as well follows the exponential manner. Based on the results in Fig. 7(b), it is suggested that SPL higher than
12 100 dB provides more electrical response as compared to that less than 100 dB. To obtain the reliable measurement
13 results with acoustic-laser technique, the loudspeaker should be turned on at least 100 dB. .

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1
2 **Fig. 7** The amplitude of electrical signals versus: (a) distance of acoustic source; (b) SPL; (c) incident angle of
3 acoustic excitation; (d) incident angle of laser beam

4
5 Following attention is placed on the effect of incident angle of acoustic excitation on the sensitivity of acoustic-laser
6 technique. Fig. 7(c) shows the amplitude of electrical signals versus the incident angle of acoustic excitation. From
7 0° to 90°, the vibration amplitude (3670 Hz in the frequency spectrum) decreases with the incident angle. The
8 mechanism may be due to the decomposition of the acoustic wave if the acoustic excitation is not in the direction
9 perpendicular to the FRP surface. In this case, if the loudspeaker is positioned at a normal angle ($\phi = 0^\circ$), the
10 acoustic excitation will be the greatest. Based on the results in Fig. 7(c), incident angle of acoustic excitation
11 smaller than or equal to 60° can achieve a satisfactory signal strength.

12 Fig. 7(d) depicts the effect of incident angle of laser beam on the measurement response. As found in the Fig. 7(d),
13 vibration amplitude develops at an increasing rate with increase in the incident angle of laser beam. A possible

1 mechanism contributing to the **increasing signals** is that the larger incident angle of laser beam leads to the bigger
2 translating distance between the paths of reflected laser beams, as shown in Fig. 8(a). Image that a laser beam is
3 normally incident on the surface of the vibrating FRP plate, the path of the reflected laser beam does not change. In
4 this case, no evident response is expected to be measured. From Fig. 7(d), it is recommended that the incident angle
5 of laser beam larger than 30° gives a high sensitivity for acoustic-laser technique. However, too oblique incidence
6 of the laser beam leads to the **distortion** of the laser spot on the FRP plate which may **lead to** an inaccurate
7 measurement, as shown in Fig. 8(b). Here, a flattening factor ρ is used to examine the **distortion level** of laser spot
8 resulting from the oblique incidence, which is defined by Eq. (2):

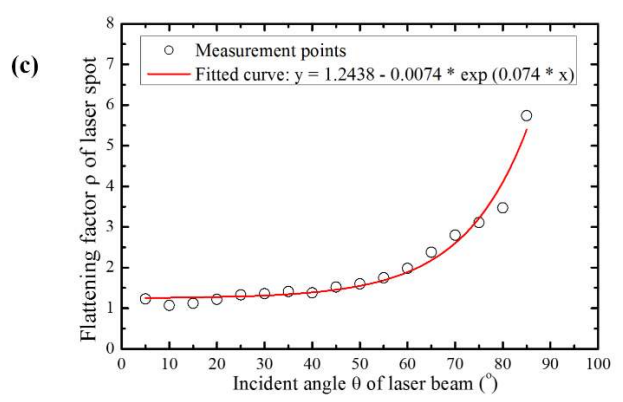
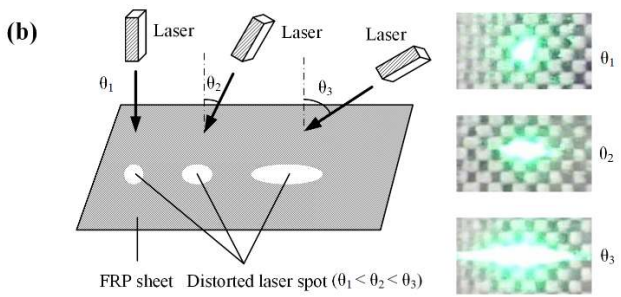
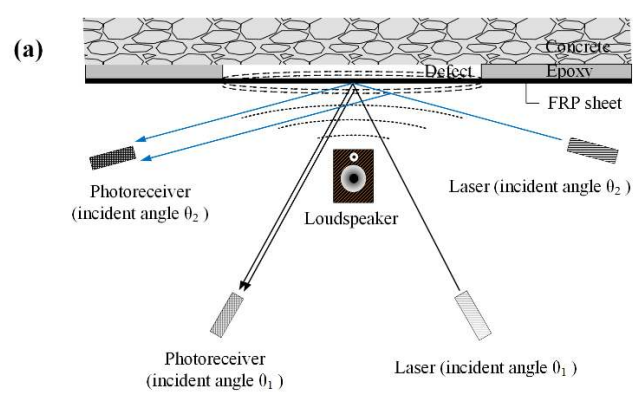
$$\rho = L(\theta)/L_0 \quad (2)$$

9
10
11 where $L(\theta)$ is the length of the laser spot at incident angle θ , L_0 is the initial length (1.96 mm) of the laser spot at
12 normal incidence ($\theta = 0^\circ$). From the definition, the flattening factor ρ is 1 when the laser beam is normally incident
13 on the FRP surface. The flattening factor ρ is measured in our experiment and is depicted in Fig. 8(c). It is
14 observed that from $0^\circ - 60^\circ$, the ρ increases slightly and the value remains in the range of 1 - 2. **But the increasing**
15 **rate of ρ is accelerated when the incident angle increases from 60° to 90° .** When $\theta = 75^\circ$, the length of the laser spot
16 is about three times ($\rho = 3$) as big as the initial length of 1.96 mm. The laser spot with excessively elliptical shape
17 can exacerbate the receiving errors of the photoreceiver. From the above discussion, the incident angle of laser
18 beam is suggested **to be** $30^\circ - 60^\circ$ as it can provide a sensitive measurement response as well as **achieving** an
19 accurate detection of defect.

20 Exponential function $y = a_0 + b_0 * e^{c_0x}$ is adopted to fit all the measurement points and the fitted results are
21 satisfied, as shown in Fig. 7. This function can give us the indication that the acoustic-laser technique is very
22 sensitive in a certain value range of the operational parameters. For instance, the sensitivity of the acoustic-laser
23 technique is not changed much when the sound pressure level is smaller than the 100 dB, but the sensitivity can be
24 changed dramatically between the 100 dB and the 125 dB. Based on this, we are suggested that the sound pressure
25 level should be kept constant at each time when we repeat the detection of the same target or we detect several
26 targets. Note that a slight modification of SPL can lead to the big difference of the results. From the fitted results,
27 the value of the coefficient b_0 for distance of acoustic excitation or sound pressure level is positive ($b_0 > 0$), which

1 indicates that the amplitude of the measurement signals could be increased limitlessly when the parameters are
 2 altered in certain range. For instance, the measurement signal is 0.0071 mV when the SPL is 100 dB. When the
 3 SPL is changed to 120 dB, the measurement signal is increased to 0.0394 mV which is 5.55 times as that of 100 dB.
 4 SPL higher than 120 dB can even leads to larger signal (e.g. 0.0664 mV with 125 dB). However, for parameters
 5 related to incident angles the coefficient b_0 is negative ($b_0 < 0$), which implies that the measurement signals cannot be
 6 increased as much as we expected. For instance, the maximum measurement signal for incident angle of acoustic
 7 excitation could be reached is about 0.02 mV. Therefore, the distance of acoustic excitation and SPL will be the
 8 more important parameters to be considered if an increase of the measurement sensitivity is attempted.

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10

1 **Fig. 8** Effects of incident angle of laser beam on: (a) reflected path of laser beam; (b) laser spots projected on the
2 FRP sheet with different incident angles of laser beam; (c) flattening factor ρ of laser spot versus incident angle of
3 laser beam

4

5 **4 Conclusion and future work**

6 The present work focuses on the sensitivity of acoustic-laser technique when applied to inspect the defects in FRP-
7 bonded concrete system. A series of parametric studies are conducted to investigate the performance of the
8 laboratory system under different operational parameters. The paper provides a reference for further research and
9 practical application of the acoustic-laser technique. The following conclusions can be drawn from the experimental
10 work:

- 11 1. Acoustic-laser technique has a series of advantages for defect detection. For the FRP-bonded concrete panel
12 used in our research, the electrical signals of the defect region appears a sharp peak at the frequency of 3670 Hz,
13 which indicates the presence of the defect.
- 14 2. The results of scanned measurement on the defect region and the surrounding intact region demonstrate that the
15 vibration within the defect region is much more significant than that of the intact region. It is experimentally
16 proved that acoustic-laser technique can identify the location and size of defect in the FRP-bonded concrete
17 structure.
- 18 3. Four different operational parameters, namely, distance of acoustic excitation, SPL, incident angle of acoustic
19 excitation, and incident angle of laser beam are found to have considerable effects on the sensitivity of the
20 measurement results. The acoustic-laser technique is effective for defect detection when each of the concerned
21 parameters falls in a certain range. In order to achieve the sensitive and reliable defect detection by using the
22 acoustic-laser technique, the distance of acoustic excitation should be no more than 40 cm; the SPL should be at
23 least 100 dB, the incident angle of acoustic excitation is suggested as 90° , and the incident angle of laser beam
24 is suggested to be within the range of $30^\circ - 60^\circ$.

25 The performance of the acoustic-laser technique has been demonstrated by laboratory measurements on an
26 artificially damaged specimen. Further investigation of the technique is required before this technique is commonly
27 practiced in the site or outdoor environment. Some future research directions upon the acoustic-laser technique are
28 listed as follows:

- 1 1. According to the experimental results in this study, higher SPL provides more sensitive measurement response by
2 the acoustic-laser technique, but too high SPL can induce the health problems (*e.g.* hearing impairment and
3 hypertension) [20] to the users who perform the test. Such high SPL may also lead to the significant vibration of
4 the laser and photoreceiver, which makes the results inaccurate. Another issue of using the loudspeaker is that
5 the acoustic energy emitted from the loudspeaker is significantly dissipated in case when the distance of the
6 acoustic source exceeds 200 cm. Therefore, sensitivity of the acoustic-laser technique is very low when the
7 distance is more than 200 cm. An elegant solution to those issues involves in using the parametric acoustic array
8 (PAA) that can provide more focused and powerful acoustic energy over the conventional loudspeaker [13,21].
9 Future work will focus on studying the effectiveness of PAA as an acoustic source for improvement of acoustic-
10 laser technique.
- 11 2. During operations with acoustic-laser technique, the eye safety associated with the use of laser beam is concerned.
12 A study [22] has reported that high power laser can lead to serious injury of the retina, the body tissue which is
13 most vulnerable to laser radiation. It is meaningful to choose a laser with lower power which can reduce the
14 accident injuries of eyes. However, it is essential to evaluate the laser power level for its effect on the sensitivity
15 of acoustic-laser technique.
- 16 3. In the experiment, the operational parameters (*i.e.* distance of acoustic source, sound pressure level, incident
17 angle of acoustic excitation and incident angle of laser beam) are regarded as the independent variables. After
18 having the knowledge of these variables, the coupled effect of the operational parameters will be investigated in
19 the future study.
- 20 4. Noise is another issue to be addressed for acoustic-laser technique. As mentioned before, flick noise always
21 dominates in the frequency zone before 2000 Hz. Such unwanted signal wrapping may lead to the non-effective
22 measurements of the defects having the resonant frequency within 0 - 2000 Hz. Future work will improve the
23 signal-to-noise ratio (SNR) either by upgrading the quality of the electrical devices (*i.e.* photoreceiver and laser)
24 or by the use of filtering techniques such as wavelet de-noising algorithm.

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