Fiber-reinforced polymer (FRP)-bonded civil structures have been increasingly used in various construction fields, such as building, bridge, and tunnel. To maintain their designed mechanical performance, the integrity of interfacial bonding should be detected on a regular basis. From many recent laboratory studies, acoustic-laser technique is promising to be applied for identifying the presence of delamination or debonding in FRP-bonded civil structures. However, the defect detection performance of this technique towards real infrastructure encounters a challenging problem related to airborne vehicle noise as the number of cars circulating in urban area increases rapidly. In this study, we deal with the effect of vehicle noise on acoustic-laser technique when applying it in defect detection of FRP-bonded structures. Vehicle sound is found to not only raise the noise floor in measured frequency spectrum but also induce noise-related peaks (below 2000 Hz). Noise from a single passing vehicle causes greater reduction in signal-to-noise (SNR) ratio than that from a platoon of vehicle stream. Additionally, detecting large defect is more vulnerable to acoustic interference of vehicle noise than the small one. A quantitative function between the SNR and the noise level is set up to estimate the performance for defect detection in a construction area near the traffic flow. To handle the vehicle noise issue, a de-noising scheme is proposed and demonstrated for practical defect detection in the field.

1. Introduction

Mechanical performance of structures used in a variety of industries may be subject to degradation with age, due to factors of corrosion, stress concentration, and accidental impact [1–3]. With the advantages of high specific stiffness and strength, good damage tolerance, and excellent resistance to corrosion, FRP composites have been increasingly used for strengthening or retrofitting the deficient infrastructures all around the world. The FRP composites can significantly improve the mechanical capacities of building elements (e.g. columns, beams, slabs), bridge components (e.g. piers, girders, decks), or concrete tunnels. In FRP-bonded structural system, the integrity of interfacial bonding is crucial for effectiveness and efficiency of structural strengthening [4–6]. Recently, the integrity issue has been becoming more and more critical, as the delamination and debonding of FRP are often caused by poor workmanship during wet lay-up procedure, infiltration of moisture, and temperature variations. Hence, a reliable and cost-effective method is needed for defect detection towards the FRP-bonded structural system.
During the past few decades, a great amount of non-destructive testing (NDT) methods have been developed and demonstrated to be capable of collecting the defect information of layered composites like FRP-bonded systems. Many of NDT methods for structural identification are based on receiving the mechanical wave propagation through the structure, such as accelerometer instrumentation [7], impact echo method [8], acoustic emission technique [9], and ultrasonic tomography [10]. They are able to perform a precise interpretation of structural defect with satisfactory signal-to-noise ratio [11]. Nevertheless, sensors in these techniques are often mounted on the surface of structural element. This procedure restricts their widespread use in large-scale civil infrastructures and in the case where the mass of sensor is comparable to the mass of structural element to be tested [12–14]. Another problem associated with the mechanical-wave-based NDT methods is that they require substantial wiring work to collect the transducers with the data acquisition system [15]. Mounting and wiring a large structure with the transducers is typically a time-consuming task [16,17]. On the contrary, far-field and non-contact NDT methods avoid these problems and have attracted great attention in structural health inspection [18].

It is generally recognized that most of non-contact NDT methods depend on receiving the electromagnetic radiation from the tested object. Photoelectric sensor (also called photoreceiver) is primarily used for far-field and non-contact measurement, which has been adopted in acoustic-laser technique for defect detection [19]. Regarding the principle of this technique, acoustic wave is used to initiate the surface vibration of a tested object and laser beam is used to extract meaningful vibration characteristics of structural surface [20]. To interpret the physical signal of laser beam reflected from the object, the photoelectric sensor is used as a conversion device for collecting the light signal and transferring it into the electrical signal for further analysis. De-bonding defect or other imperfections at near surface region are likely to cause a significant increase in the vibration level, distinguishing the defect region from the intact region [21–23]. This feature can be identified by the modification of laser beam reflection and the resulting variation of electrical signal from photoelectric sensor. In comparison to conventional NDT methods, acoustic-laser technique features its advantages of non-contact measurement, cost-effective test, sensing over wide frequency bands, efficient sensor installation, and rapid data acquisition. Previous studies were carried out to adopt acoustic-laser technique with great success to evaluate the integrity loss in materials and structures. Experimental work was conducted to examine the sensitivity of acoustic-laser technique used in defect detection with considerations of several operational parameters including distance of acoustic excitation, sound pressure level, incident angle of acoustic excitation, and incident angle of laser beam [24,25]. Integrity of FRP-bonded concrete system was effectively evaluated by acoustic-laser technique [26–30]. Besides, this technique was applied to detect the near surface defect in wood beam [31] and tree trunk [32–34], and even inspect the bonding degradation of FRP-bonded wood composite under elevated temperature condition [35,36].

While defect identification has been achieved by using acoustic-laser technique, previous investigations of this technique are mainly conducted in laboratory condition. As a matter of fact, the effectiveness of defect detection may be affected by the ambient mechanical noise when this technique is applied in field condition. In urban area, almost every moving vehicle makes some kinds of airborne mechanical wave (i.e. acoustic noise), deriving from the vibrations of running engine, transmission, bumping and friction of the vehicle tires with ground, wind effects, etc. When acoustic-laser technique is used, such airborne noise may reduce the signal-to-noise ratio (SNR) and decline the reliability of identifying the signal belonged to defect information. It is also noted that the engine noise, the transmission noise as well as the friction noise exhibits spectral peaks at certain frequencies [37–39]. These noise peaks may embed in the measured waveform, mislead the users to capture the dynamical characteristics of defect region, and thus place a fundamental limit on defect detection of the existing FRP-bonded structures in the field. While the number of vehicles circulating in urban area has constantly increased over recent years [40], research study with respect to the vehicle-induced airborne noise effect on the performance of defect detection by acoustic-laser technique is still rare. In order to promote the widespread use of this technique in real construction environments, it is important to understand how such vehicle noise influences its accuracy of structural defect detection and to suggest appropriate noise reduction methods to address this issue. Moreover, a quantitative function is worth being established to correlate the SNR with sound pressure level of vehicle noise. With this quantitative relationship, the criticality of noise effect on defect detection can be estimated and the de-noising factor is reasonably adjusted.

The objective of present study is to understand the vehicle noise effect on the performance of acoustic-laser technique for defect detection of FRP-bonded structural systems and to establish the appropriate de-noising scheme to reduce the noise effect. In the present research work, the FRP-bonded concrete panel with interfacial defect (between FRP and concrete) is fabricated. Firstly, the acoustic wave with frequency that matches the natural frequency of defect region is used as the input signal in acoustic-laser technique for defect evaluation. Then, the input acoustic source is incorporated with noises realistically recorded from vehicle flow for defect evaluation again. The electrical signals in time domain are recorded and their frequency spectrums are obtained by fast Fourier transfer (FFT). Results from acoustic-laser technique with and without vehicle noise are compared so that the noise impacts on defect detection are interpreted. Quantitative correlation of noise effect versus noise level is also investigated. Additionally, a de-noising method is proposed in this study to reduce the noise effect on defect detection with acoustic-laser technique. Based on this method, a de-noising scheme is established for practical defect detection to deal with noise reduction for different variables of vehicle movement.
2. Novelty of the proposed technique

Acoustic-laser technique is a kind of non-destructive testing method that combines the mechanical and electromagnetic waves for structural identification, vibration measurement and other characterization purposes. Previously, researchers have adopted the laser Doppler vibrometer in the acoustic-laser technique for defect evaluation of FRP-bonded structural system [28,41,42]. However, laser Doppler vibrometer is quite expensive for product itself and the maintenance cost. Besides, the big volume and heavy weight of laser Doppler vibrometer make this technique not portable enough in a narrow construction space. Due to this limitation, recent research group aims to improve this technique for defect detection. Compared to the use of laser Doppler vibrometer, the novelty of the present acoustic-laser technique is that some economical and small instruments (such as laser and photoreceiver) were adopted to form a more cost-effective measurement setup. It has been demonstrated from the latest studies that this proposed technique is sensitive, practical, portable, and efficient when it is used in defect detection in FRP-bonded structural systems [25–27]. Moreover, in the present work, a novel de-noising scheme is established in this acoustic-laser technique to handle the vehicle noise issue when the technique is applied in real construction site.

3. Experiment

3.1. Specimen detail

In this research, two carbon FRP (CFRP) bonded concrete panels with different dimensions of artificial defects were made. During the fabrication of concrete panel, type I ordinary Portland cement was used. For aggregate components, crushed stone with the density of 1550 kg/m³ and river sand with the density of 1460 kg/m³ were used. Besides, tap water was used to mix the raw materials in concrete production. The water-to-cement ratio and the mass ratio of river sand to crushed stone were 0.6 and 0.45, respectively. Dimension of the concrete panel was 300 mm (length) \times 300 mm (width) \times 50 mm (thickness). Air hole was made on top surface of concrete before FRP bonding, in order to produce the interfacial defects between FRP and concrete substrate. Defects with sizes of 25 mm \times 25 mm and 50 mm \times 50 mm were created in the two FRP-bonded concrete specimens, respectively.

3.2. Acoustic-laser technique

As stated in many previous articles, acoustic-laser technique utilizes both the mechanical and electromagnetic waves for detecting the near surface defects in layered composite system. Due to the presence of defect, the surface of local defect region under the mechanical wave excitation can be more easily deformed in comparison to the intact region where the interface between the FRP plate and the concrete substrate is firmly adhered. In terms of the mechanical wave excitation, acoustic wave is suitable to be used because of its no impairment to structure, stable loading, and easy control. When the FRP-bonded concrete panel is excited by external acoustic wave, the vibration of FRP surface is characterized by using laser beam as the surface motion can modify the laser reflection. In order to receive the optical signal and transfer it into electrical signal, photoreceiver was adopted. For storing the electrical signal in the form of digital signal, the data acquisition system was then employed in this technique. The electrical signals in time domain were recorded, which were then converted into frequency spectrum by FFT. From the frequency spectrum, it was able to capture the vibration information of defect region with natural frequency.

To determine the signal input used in acoustic-laser technique, the acoustic waves in the range of 0 to 20000 Hz were adopted to excite the two FRP-bonded concrete specimens, as shown in Fig. 1(a). Results are presented in Fig. 1(b) and (c). It is clearly observed that the natural frequency peak for smaller defect region (i.e. 25 mm \times 25 mm) locates at around 8000 Hz while the peak for larger defect region (i.e. 50 mm \times 50 mm) locates at around 1300 Hz.

Fig. 1. Identifying the natural frequency for the two defect regions by acoustic frequency sweeping from 0 to 20000 Hz: (a) frequency spectrum of acoustic signal with frequency sweeping, (b) frequency spectrum showing the natural frequency of 8000 Hz for 25 mm \times 25 mm defect region, and (c) frequency spectrum showing the natural frequency of 1300 Hz for 50 mm \times 50 mm defect region.
After determining the natural frequency for these two defects by frequency sweep test, the acoustic wave with 8000 Hz was adopted in acoustic-laser technique for detecting the 25 mm × 25 mm defect region, as illustrated in Fig. 2(a). In addition, another acoustic wave with 1300 Hz was adopted in acoustic-laser technique for detecting the 50 mm × 50 mm defect region, as shown in Fig. 2(b). By applying the acoustic wave excitation with specific dominant frequency, the resonance of surface vibration at defect region could be more paramount and the defect information could be extracted more sensitively.

3.3. Collection and analysis of vehicle noise

Vehicle noise on buildings can be divided into airborne and ground-borne noises. It has been found from some studies [43–45] that the ground-borne noise can be markedly reduced when the measurement site locates away from the road up to 30 m or so. In contrast, spreading of airborne vehicle noise in urban area is much more stable and remote. Only a reduction level of 15 dB is resulted when airborne vehicle noise transmits 250 m in distance [46]. Hence, we only considered and recorded the airborne noise from passing vehicles here in this study. Fig. 3(a) shows the schematic diagram of a building detected by acoustic-laser technique near the traffic road, representing the situation of defect detection under the influence of airborne vehicle noise. A passing vehicle can induce the acoustic noise that transmits towards the building away from the road. In this situation, the de-bonding region of FRP-bonded structural system can be stimulated by the air-borne noise, which affects the defect detection performance. In the field survey, we recorded the realistic air-borne noise from passing vehicle nearby the road site, as marked in Fig. 3(b).

Fig. 2. Acoustic input signals used in acoustic-laser technique for detection of defects with sizes of 25 mm × 25 mm and 50 mm × 50 mm, respectively: (a) frequency spectrum of acoustic input signal with 8000 Hz, (b) frequency spectrum of acoustic input signal with 1300 Hz.

Fig. 3. Description of noise effect on defect detection and collection of vehicle noise in field condition: (a) schematic diagram of building and setup of acoustic-laser technique near the traffic road and (b) map of place for collecting the real vehicle noise.
Generally, the vehicle noise comes from the vibrations of running engine, transmission, bumping and friction of the vehicle tires with ground, and wind effects. Such noise can induce certain characteristic frequency peaks which may contaminate the information of frequency peaks associated with defect in structure. In order to understand the feature of frequency components of vehicle noise, we recorded the realistic sound near a road site (Cornwall Street in Hong Kong) when the cars were passing by. Taking into account the factor of vehicle number, both the single vehicle noise (SVN) and the platoon vehicle noise (PVN) were recorded with the sampling frequency of 48 kHz. Given that the noise spectrum of SVN is affected by the vehicle speed, the running speed of single vehicle movement is recorded statistically. In this research, the vehicle noise coming from a bus was investigated as the representative of SVN, and the vehicle noise coming from a flow of various cars were explored as PVN. The frequency spectrums of these noises are presented in Fig. 4. It is clearly seen that the amplitudes of the noise pattern for both the SVN (with an average speed of 38.07 km/h) and PVN are more dominant in the low frequency domain less than 2000 Hz. Additionally, the frequency spectrum presents several pronounced peaks in this frequency range, which can be attributed to the engine and transmission vibrations at 50–500 Hz [37–39,47], and the tire-to-road friction at 500–1500 Hz [47,48]. The observations of noise pattern go in agreement with those results reported by the literatures [37–39,47,48]. These frequency peaks caused by the vehicle noise may significantly affect the accuracy of defect detection when the acoustic-laser technique is used in real building structures located in urban area. Thus, the effect of vehicle noise on defect detection should be evaluated and the method of reducing the noise effect is essential.

3.4. Test scenario

Three acoustic sources were produced respectively in acoustic-laser technique for defect detection: (a) acoustic input signal without vehicle noise, (b) acoustic input signal mixed with SVN, and (c) acoustic input signal mixed with PVN. Frequency spectrums among these three acoustic cases were compared so as to figure out how the vehicle noise affects the effectiveness of this technique for defect detection. More specifically, Table 1 lists the details of specimens and the sources of acoustic wave in the research work. Based on our investigation, the sound pressure level of vehicle noise near the road site can be up to around 70 dB. To examine the noise effect on defect detection, in the experiment the recorded vehicle noise with sound pressure level of 70 dB was emitted by loudspeaker. Meanwhile, the sound pressure level of acoustic input signal (1300 Hz or 8000 Hz) was 70 dB. As to the other operational settings, the distance between the loudspeaker and the test specimen was 50 cm. Besides, the incident angles of laser beam and acoustic excitation were 45° and 0°, respectively.

3.5. Investigation of noise level

Noise effect on defect detection can be increased with the increase in noise level produced by vehicle movement. In urban city, the noise level is dependent on the location near the road. Noise level at a longer distance away from road is decreased

![Fig. 4. Characteristics of recorded vehicle noise: (a) frequency spectrum of SVN and (b) frequency spectrum of PVN. Noise level is concentrated in the low frequency band below 2000 Hz. Both frequency spectrums depict some evident peaks in this frequency domain. These peaks can be derived from the running engine, moving transmission, and the contact of tires on the road.](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Acoustic sources Without vehicle noise</th>
<th>In the presence of vehicle noise</th>
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<tr>
<td>25 mm × 25 mm defect</td>
<td>8000 Hz</td>
<td>8000 Hz and SVN</td>
</tr>
<tr>
<td>50 mm × 50 mm defect</td>
<td>1300 Hz</td>
<td>1300 Hz and SVN</td>
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and its effect on defect detection of acoustic-laser technique can be attenuated. Here, the noise level was characterized by sound pressure level. In this study, an extra experimental work was carried out to investigate the quantitative correlation of SNR with different noise levels. The output noise level of SVN from loudspeaker ranged from 50 to 90 dB, with the interval of 5 dB. At each noise level, the 25 mm × 25 mm defect region was detected and the resulted SNR was plotted. Afterwards, trend of SNR versus noise level was obtained and quantified.

3.6. De-noising method

As the noise effect of vehicle transport may result in the reduction in signal quality regarding the defect information collected by acoustic-laser technique, the present study also proposed the effective de-noising scheme that could be adopted in real and practical conditions. The de-noising method was based on FFT filtering that reduced the noise components in measured data (i.e. output voltage with a period of time) from acoustic-laser technique. At first, the recorded vehicle noise was converted into a digital data set A with specific sampling rate. The data set A was transformed into the time–frequency waveform (spectrum A), as shown in Fig. 5(a). Meanwhile, the measured data from acoustic-laser technique was normalized into 0–1 range (i.e. data set B), by dividing the time-series of voltage with the maximum one. This procedure made the data sets A and B have the consistent magnitude of value. The normalized data was also converted into time–frequency waveform (spectrum B), as exhibited in the right parts of Fig. 5(b). To conduct the noise filtering, the spectrum A in the range of 0–2000 Hz was extracted and recorded, as indicated by the blue dash line. Reason for this selection was that noise was much more dominant in this range, as discussed in section 2.3. Then, as seen in Fig. 5(c), the spectrum region in the range of 0–2000 Hz to be de-noised was also captured in spectrum B. Noise filtering was conducted afterwards on this selected area and the de-noised outcome is shown in Fig. 5(d), namely the spectrum C. Finally, the spectrum C was converted back to the time-series of data and then transferred into frequency spectrum for further defect evaluation.

In practical application, the vehicle noises are more complicated due to the variation of vehicle type, vehicle speed, road material, etc. To deal with the noise effects on the field detection, the acoustic-laser technique is carried out with a period of time and a specific sampling rate. During this period, the surrounding vehicle noise is simultaneously recorded in the field and stored as an audio file. Then, the aforementioned de-noising method is applied. After each de-noising, the SNR is calcu-

![Fig. 5. Noise filtering procedures in time–frequency spectrums: (a) extracting the vehicle noise in the range of 0–2000 Hz during 1 s in spectrum A, (b) spectrum B with acoustic signal of 8000 Hz and vehicle noise, (c) locating the target area for de-noising in spectrum B, and (d) filtering the vehicle noise component and producing spectrum C.](image-url)
lated and compared with the desirable value (threshold). If the SNR is lower than the threshold, the de-noising factor is increased, and the de-noising process is conducted again. This de-noising cycle is repeated until the required SNR is reached, as described in Fig. 6. Apart from the vehicle noises from a moving bus and a flow of cars in the present investigation, based on this de-noising scheme, we can deal with the noise reduction in practice towards a certain traffic situation.

4. Physical model of de-bonding region under noise effect

To describe the noise effect on defect detection, we put forward physical or mechanical model of surface vibration at a de-bonding area in FRP-concrete composite structure, as shown in Fig. 7. The physical model is based on the theory of plate vibration [49,50]. In this model, the boundary condition of the de-bonding area is considered as four identical clamped sides, the FRP layer is deemed as isotropic plate and the air underneath the FRP plate is assumed to have no effect on surface vibration. With these hypothesizes, the governing equations of plate vibration of the de-bonding area are expressed in Eqs. (1) and (2), and its natural frequency is theoretically calculated by Eq. (3):

$$D \nabla^4 w + \rho_0 \frac{\partial^2 w}{\partial t^2} = 0$$  \hspace{1cm} (1)

$$D = \frac{E_y h^3}{12(1 - \nu^2)}$$  \hspace{1cm} (2)

![Fig. 6. Procedures of de-noising scheme for reducing the vehicle noise effect on the defect detection of FRP-bonded system by acoustic-laser technique. Note: the sampling rate \( x \) of data sets A and B should be the same as they are subjected to FFT filtering process. Setting the value of sampling rate in defect detection depends on the natural frequency of defect region to be evaluated. For instance, a sampling rate of 48,000 Hz can interpret the vibration with natural frequency of 24000 Hz, which indicates the smallest detectable defect with about 20 mm × 20 mm in size.](image-url)
where \( D \) denotes the flexural rigidity of FRP plate, \( E_Y \) denotes the Young’s modulus of FRP composite, \( h \) denotes the thickness of the FRP plate, \( \nu \) denotes the Poisson’s ratio of FRP composite, \( a \) denotes the length of de-bonding side, \( \rho \) denotes the...
density of FRP material, \( w \) denotes the transverse displacement of the plate as a function of spatial variables \( x, y, \) and time \( t \). \( \lambda \) is the frequency parameter, which is numerically solved by well-known Rayleigh-Ritz method [51]. The detailed procedures are described in the literature [52]. \( \lambda \) is numerically computed as 35.99 at mode (1, 1) [53], for the square plate with four clamped side. With the material properties of FRP composite (listed in Table 2) and the defect dimension, the calculation of natural frequency for the two defect regions is shown by Eqs. (4–6) below:

For 25 mm \( \times \) 25 mm defect region,

\[
D = \frac{3.8 \times 10^9 \times 0.00025^3}{12(1 - 0.33^2)} = 0.00555
\]

\[
f = \frac{35.99}{0.025 \times 0.025} \sqrt{\frac{0.00555}{1300 \times 0.00025}} = 7526.82 \text{ Hz}
\]

(4)

For 50 mm \( \times \) 50 mm defect region,

\[
f = \frac{35.99}{0.050 \times 0.050} \sqrt{\frac{0.00555}{1300 \times 0.00025}} = 1881.71 \text{ Hz}
\]

(5)

(6)

Based on this physical model, the de-bonding defect in the form of air hole or air gap between FRP and concrete can be effectively identified by the natural frequency. In our previous case study, the effectiveness of acoustic-laser technique for detecting both types (i.e. air hole and air gap) of de-bonding defect was examined and confirmed.

Based on the theory of plate vibration, the acoustic-laser technique can also be used to estimate the surface area \( (A = a^2) \) of defect, based on Eq. (7). Since the square defects in this investigation may not truly represent the existing defects in real condition, it is crucial to quantify the realistic shape and dimension of defect region by acoustic-laser technique. In this study, the measurement point is located at the center of defect region, and the natural frequency is obtained. Based on the previous experimental results from a study [25], the measured natural frequency keeps consistent if the measurement point is not at the center but still within the defect region. This observation indicates that acoustic-laser technique can be used for spatial scanning over the area of interest, with the purpose to confirm the shape and area of defect region.

\[
A = \frac{\lambda}{f} \sqrt[4]{\frac{D}{\rho h}}
\]

(7)

Using the natural frequency as the input signal of acoustic wave, the power spectrums of vibration response under pure acoustic input signal and input signal mixed with vehicle noise are expressed in Eqs. (8) and (9).

\[
P = S(f_i)
\]

(8)

\[
P = S(f_i) + N(f_a, f_b, f_c, \ldots, f_n)
\]

(9)

where \( P \) denotes the power spectrum, \( S(f_i) \) denotes the signal at frequency \( i \), \( N(f_a, f_b, f_c, \ldots, f_n) \) denotes the noise components at frequency \( a, b, c, \ldots, n \).

In the case of 25 mm \( \times \) 25 mm defect region, the natural frequency \( f_{25mm}^{25mm} \) is theoretically estimated as 7526.82 Hz. This is closed to the frequency sweep result, as indicated in Fig. 1(b) that shows the experimental value of about 8000 Hz. When an acoustic wave excitation with 8000 Hz is applied upon the de-bonding area, a straight and distinct signal peak at 8000 Hz could appear in the frequency spectrum. If airborne vehicle noise is included in the excitation, a few noise peaks may be initiated. As the vehicle noise dominates in the low frequency range below 2000 Hz, the noise would have little interaction with the signal of 8000 Hz, as illustrated in Fig. 7(a). In the case of 50 mm \( \times \) 50 mm defect region, the natural frequency \( f_{50mm}^{50mm} \) is theoretically estimated as 1881.71 Hz. This is roughly closed to the frequency sweep result, as indicated in Fig. 1(c). When a pure acoustic wave excitation with 1300 Hz is applied, it is expected that only a signal peak at 1300 Hz appears in the frequency spectrum. If the vehicle noise is included in the excitation, strong resonance noise peaks could be resulted, as schematically shown in Fig. 7(b). This is because the noise frequency is closed to the natural frequency of FRP plate vibration over defect region, causing resonance phenomenon.

| Material properties of FRP composite for 25 mm \( \times \) 25 mm and 50 mm \( \times \) 50 mm defect regions. |
|--------------------------------------|-----------------|-----------------|
| Young's modulus \( E_Y \) | 3.8 \( \text{GPa} \) |
| Poisson's ratio \( \nu \) | 0.33 |
| Density \( \rho \) | 1300 \( \text{Kg/m}^3 \) |
| Thickness \( h \) | 0.00025 \( \text{m} \) |
| Side length \( a \) | 0.025 (for small defect), 0.050 (for large defect) \( \text{m} \) |
5. Results and discussion

5.1. Vehicle noise effect on defect detection of FRP-bonded structural system

From acoustic-laser technique, the electrical signal with a period of time is recorded and transferred into frequency spectrum via FFT function $F(x)$ where $x$ is the output voltage signal. In this paper, the amplitude of the transformed data is presented. To start with, data collected from intact region (as a reference) of FRP-bonded concrete panel is shown in Fig. 8. It is observed that acoustic-laser technique receives little characteristic signals from the intact region under the acoustic excitation of 1300 Hz and 8000 Hz signal waves, respectively. This indicates that the intact region or the whole structural system is hardly affected by the presence of acoustic wave stimulation. The results from Fig. 8 indicate that vibration of the whole structure or intact region in this condition does not affect the performance of defect detection by acoustic-laser technique.

Fig. 9 presents the electrical signal in frequency domain for defect region with dimension of 25 mm $\times$ 25 mm. As the flick noise (also called 1/f noise [54]) from the photoreceiver is dominant in the low frequency zone between 0 and 150 Hz, the FFT data in this range are eliminated. According to Table 1, three cases of acoustic source are taken into account. Without the presence of vehicle noise, the FFT data at 8000 Hz appears a noticeable peak which reflects the vibration signal of defect region under the mechanical excitation of 8000 Hz acoustic wave. A flat noise floor across the frequency range except 8000 Hz is found, and the noise level is higher than that of intact region. This phenomenon is attributed to the effect of environmental white noise in laboratory on the defect region. Clearly, this noise level is relatively low and it does not exhibit distinct frequency peaks that may cause the false positive detection. In this study, we also collect more data of clean response for another two 25 mm $\times$ 25 mm defect regions. The level of the above three noise floors is averaged as 0.004665. In this work, the SNR is defined by the following Eq. (10):

$$\text{SNR} = \frac{S}{N}$$

where $S$ denotes the amplitude of FFT data at the corresponding signal frequency (i.e. 8000 Hz for 25 mm $\times$ 25 mm defect and 1300 Hz for 50 mm $\times$ 50 mm defect), and $N$ denotes the maximum amplitude of noise frequency peak in the range of 150–2000 Hz. Based on Eq. (10), the SNR for detection of 25 mm $\times$ 25 mm defect is calculated as 5.817, without the influence of vehicle noise. Fig. 9(b) presents the frequency spectrum of measurement data for 25 mm $\times$ 25 mm defect in the presence of SVN. It can be clearly observed that the noise floor in the low frequency domain (lower than 2000 Hz) is increased under the influence of single vehicle noise. To show clearer measurement data in low frequency domain, the spectrum zone in the range of 150–2000 Hz is extracted and enlarged as described in the grey spectrum pattern. In comparison to the clean response in Fig. 9(a), frequency spectrum with SVN has higher noise floor level of 0.006396. Besides, Fig. 9(b) plots several frequency peaks between 150 and 2000 Hz. Previous researchers have investigated the vibration frequency with respect to a general running car. The studies shown that fundamental vibration frequencies for car engine and transmission are typically distributed in the frequency band under 500 Hz [47] and frequencies for friction between tires and road are mainly located around 500–1500 Hz [48]. These research findings support the present measured frequency spectrum where the frequency peaks are induced by the SVN and they are probably associated with the fundamental frequencies of running vehicle. In addition to SVN, PVN also leads to higher noise floor level to an averaged value of 0.006867. Several frequency peaks also exist in Fig. 9(b) and (c). In comparison to the clean response, several frequency peaks that may cause the false positive detection. In this study, we also collect more data of clean response for another two 25 mm $\times$ 25 mm defect regions. The level of the above three noise floors is averaged as 0.004665. In this work, the SNR is defined by the following Eq. (10):

$$\text{SNR} = \frac{S}{N}$$

where $S$ denotes the amplitude of FFT data at the corresponding signal frequency (i.e. 8000 Hz for 25 mm $\times$ 25 mm defect and 1300 Hz for 50 mm $\times$ 50 mm defect), and $N$ denotes the maximum amplitude of noise frequency peak in the range of 150–2000 Hz. Based on Eq. (10), the SNR for detection of 25 mm $\times$ 25 mm defect is calculated as 5.817, without the influence of vehicle noise. Fig. 9(b) presents the frequency spectrum of measurement data for 25 mm $\times$ 25 mm defect in the presence of SVN. It can be clearly observed that the noise floor in the low frequency domain (lower than 2000 Hz) is increased under the influence of single vehicle noise. To show clearer measurement data in low frequency domain, the spectrum zone in the range of 150–2000 Hz is extracted and enlarged as described in the grey spectrum pattern. In comparison to the clean response in Fig. 9(a), frequency spectrum with SVN has higher noise floor level of 0.006396. Besides, Fig. 9(b) plots several frequency peaks between 150 and 2000 Hz. Previous researchers have investigated the vibration frequency with respect to a general running car. The studies shown that fundamental vibration frequencies for car engine and transmission are typically distributed in the frequency band under 500 Hz [47] and frequencies for friction between tires and road are mainly located around 500–1500 Hz [48]. These research findings support the present measured frequency spectrum where the frequency peaks are induced by the SVN and they are probably associated with the fundamental frequencies of running vehicle. In addition to SVN, PVN also leads to higher noise floor level to an averaged value of 0.006867. Several frequency peaks also exist in the low frequency domain lower than 2000 Hz, as shown in Fig. 9(c). Due to the wave interaction between the environmental white noise and vehicle noise, some tiny fluctuations in the noise floor are found in Fig. 9(b) and (c). The fluctuations may cause the small reduction in the noise floor at some frequencies. Therefore, in a certain frequency range, the spectral response of clean signal (Fig. 9(a)) is greater than Fig. 9(b) and (c). However, this uncertainty or tiny floor fluctuation does not have valid effect on the accuracy of defect detection. The vehicle-induced characteristic peaks in Fig. 9(b) and (c) are more critical to cause the false positive detection. Additionally, it is found that characteristic peaks produced by SVN are more evident than those from PVN. Due to the presence of vehicle noise, the SNR is much reduced and the low frequency peaks may cause the small reduction in the noise floor at some frequencies. Therefore, in a certain frequency range, the spectral response of clean signal (Fig. 9(a)) is greater than Fig. 9(b) and (c). However, this uncertainty or tiny floor fluctuation does not have valid effect on the accuracy of defect detection. The vehicle-induced characteristic peaks in Fig. 9(b) and (c) are more critical to cause the false positive detection. Additionally, it is found that characteristic peaks produced by SVN are more evident than those from PVN. Due to the presence of vehicle noise, the SNR is much reduced and the low frequency peaks may cause the false positive detection.
the nature frequency of defect region. In contrast, amplitudes of FFT data are significantly increased when SVN and PVN are included, especially for the low frequency domain. From the extracted graph in the range of 150 to 2000 Hz, some noise peaks clearly emerge. Similar to the detection case for 25 mm $\times$ 25 mm defect region, Fig. 10 reveals that characteristic peaks produced by SVN are more evident than those from PVN. Additionally, FFT data in the vicinity of 1300 Hz are significant. This observation is associated with the resonance of vibrating defect region under vehicle noise. Due to this effect, the signal peak is notably merged and thus the efficiency of peak detection is reduced. As compared to small defect with 25 mm $\times$ 25 mm in size, detecting the larger defect (50 mm $\times$ 50 mm region with low natural frequency) is more vulnerable to vehicle noise effect.

5.2. Quantitative estimation of vehicle noise

Vehicle noise effect on defect detection with acoustic-laser technique can be affected by the noise level. An increase in noise level results in higher noise floor and more obvious noise frequency peaks, which increases the possibility of detection.
errors. In view of this issue, we aim to quantify the relationship between the vehicle noise level and the SNR in acoustic-laser technique. It has been reported by a few literatures that increasing the sound pressure level can bring about exponential increase of structural plate vibration \[25,55,56\]. Due to this characteristic, it is interesting to determine the critical noise level (i.e. noise threshold) that has negligible impact on defect detection. Here, FRP-bonded concrete panel with 25 mm/C2/C25 mm defect was selected as the specimen in this investigation. As depicted in Fig. 11, when the noise level is up to 85 dB, the measured SNR is found to be less than 1. This means that the amplitude of noise frequency peak is higher than that of signal peak. At this noise level, a serious wrong detection outcome may be resulted in the practical application. Fig. 11 shows the SNR versus noise level from 50 to 90 dB, which confirms the decreasing trend. Based on our measured data, an exponential function is used to link the SNR with noise level, as expressed in Eq. (11).

\[
\text{SNR} = 5.854 \times Nl^{-4.135}
\]  

(11)

where SNR denotes the signal-to-noise ratio, \(Nl\) denotes the noise level. Using this equation, it is able to indicate the critical noise level where the noise effect is attenuated to a degree that can be ignored. For instance, if the SNR of 3.2 is required, the noise level is estimated as 55 dB. In practical defect detection, it would be feasible to acquire the noise level by sound level meter in the field, estimate the SNR with this quantitative model, and determine whether the de-noising procedure should be taken or not.

Fig. 10. Effect of vehicle noise on the performance of defect detection for 50 mm \(\times\) 50 mm defect by using acoustic-laser technique: (a) frequency spectrum of electrical response without vehicle noise, (b) frequency spectrum of electrical response in the presence of SVN, and (c) frequency spectrum of electrical response in the presence of PVN.
5.3. De-noising performance

As the vehicle noise can affect the effectiveness of acoustic-laser technique for defect detection of real FRP-bonded structural system, a de-noising method mentioned in section 3.6 is performed in this study. Fig. 12 shows the frequency spectrum

![Graph showing quantitative relationship between SNR and vehicle noise level.](image1)

**Fig. 11.** Quantitative relationship between SNR and vehicle noise level.

![Graphs showing noise reduction performance for SVN and PVN.](image2)

**Fig. 12.** Noise reduction performance by using the proposed de-noising method for detecting the 25 mm × 25 mm defect: (a) frequency spectrum of electrical response after de-noising for SVN, (b) frequency spectrum of electrical response after de-noising for PVN.
after noise reduction for 25 mm × 25 mm defect. Compared to Fig. 9(b) and (c), the noise floor is reduced, and the several noise peaks are lowered for both cases of SVN and PVN. Besides the de-noising result for 25 mm × 25 mm defect, the frequency spectrum after noise reduction for 50 mm × 50 mm defect is presented in Fig. 13. Results demonstrate that the noise floor in the low frequency domain is effectively reduced, the noise peaks are suppressed, and the resonance peaks in the vicinity of signal peak (at 1300 Hz) are effectively minified. The excellent de-noising performance enhances the accuracy of using the acoustic-laser technique in identifying the near surface defects of real FRP-bonded structural system near the roadway transport network. Increasing the de-noising factor can further eliminate the noise frequency peaks and improve the identification of signal peak, for example, the signal peak of 1300 Hz after de-noising as shown in Fig. 13. It should be noted that too large de-noising factor can overly reduce the noise floor below 2000 Hz. This is because the noise spectrum A below 2000 Hz has larger data value than the spectrum B from normalized data measured by acoustic-laser technique, as shown in Fig. 5(a) and (b). For instance, a de-noising factor of 50 can eliminate the most electrical response and result in the extremely high SNR value, as shown in Table 3. Other than the de-noising factor of 50, the de-noising factor of 20 is used in the procedure and the SNR of denoised response is calculated in this study. Tables 3 and 4 list the SNR values for detection of the two defect regions before and after applying the de-noising method with factors of 20 and 50. It can be found that the SNR after de-noising with factor of 20 is greater than the SNR before de-noising but reasonably lower than the SNR without vehicle noise. In practical detection, the threshold of SNR for clean response may be pre-determined, in order to provide the suggestion of selecting the appropriate de-noising factor.

Fig. 13. Noise reduction performance by using the proposed de-noising method for detecting the 50 mm × 50 mm defect: (a) frequency spectrum of electrical response after de-noising for SVN (b) frequency spectrum of electrical response after de-noising for PVN.
5.4. Discussion on the de-noising application in practice

In this work, we have investigated the frequency characteristics of airborne noise recorded from a moving single car (i.e. bus) and a platoon of cars, and their effects on the defect detection of FRP-bonded structural system by acoustic-laser technique. In practical application, there is a need to distinguish whether the frequency peak is from defect region or intact region. To figure out this, frequency sweep testing that determines the range of natural frequency for the defect region is conducted. When the signal peak measured by acoustic-laser technique is confirmed by frequency sweep testing, the de-noising method is then applied to end up with the signal and noise peaks. In reality, different types, brands and speeds of vehicle running on the road can result in different frequency components and thus lead to different features of noise peaks in the frequency spectrum measured by acoustic-laser technique. For instance, the vibrating car engine with higher rotation speed leads the vehicle sound to higher pitch. In this case, the noise peaks locate at larger frequency domain. Additionally, road discontinuities or type of road materials like cement, stone, and asphalt can affect the frequency component of friction sound. Our proposed de-noising technique, as described in Fig. 6, is promising to handle these complicated factors of in-situ vehicle noise spreading in urban area.

It is worth mentioning that the interpretation or recognition of signal and noise peaks measured by acoustic-laser technique is carried out by human experts. In this manner, the signal processing and the defect evaluation of large-scale FRP-bonded civil engineering structures are still not swift enough. This issue may be addressed by the use of artificial intelligence that can simulate the human perception ability for object detection. Recently, deep learning approaches via convolutional neural networks, a class of machine learning methods in the field of artificial intelligence, have been increasingly used in computer vision for automated damage detection of civil infrastructures [15,57–59]. It is attractive to integrate the deep learning algorithms into acoustic-laser technique for automated classification of signal and noise peaks. In addition, the labeled box data (pixels in height) at signal and noise locations are collected and expected to estimate the SNR. With the aid of deep learning methods, the present de-noising analysis would be more efficient.

6. Conclusion

Ability of acoustic-laser technique for defect detection in FRP-bonded structural system has been demonstrated in previous laboratory studies. When using this technique in the field, environmental vehicle noise can bring about critical challenge for the effectiveness of defect detection. The present study figures out that airborne noise either for SVN or PVN is dominant at relatively low frequency zone (less than 2000 Hz) and several characteristic peaks appear in the noise frequency spectrum. As the vehicle noise is present during defect detection, noise floor in the measured frequency spectrum (less than 2000 Hz) is increased notably. Signal-to-noise ratio is significantly reduced in the presence of vehicle noise. Moreover, several noise peaks are obvious in the frequency spectrum, which are thought to associate with the engine and transmission vibrations, and the contact of tires on the road. Such noise peaks can disturb the reliability and accuracy of identifying the natural frequency peak related to vibration of defect region. Our study also finds that noise peaks from single vehicle noise are more evident than those from platoon vehicle noise. Detection of large defect (with natural frequency smaller than 2000 Hz) is more vulnerable to vehicle noise. A quantitative correlation between the SNR and the noise level is established for assessing the criticality of vehicle noise effect. The research work also establishes the de-noising method to overcome the problem linked to noise effect on defect detection. The de-noising performance reveals that noise floor is declined within

### Table 3

SNR for detecting the 25 mm × 25 mm and 50 mm × 50 mm defects without vehicle noise, with vehicle noises, and after de-noising (de-noising factor of 50).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>SNR</th>
<th>Before de-noising</th>
<th>After de-noising</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without vehicle noise</td>
<td>SVN</td>
<td>PVN</td>
</tr>
<tr>
<td>25 mm × 25 mm defect</td>
<td>5.817</td>
<td>1.165</td>
<td>3.222</td>
</tr>
<tr>
<td>50 mm × 50 mm defect</td>
<td>5.441</td>
<td>1.468</td>
<td>3.682</td>
</tr>
</tbody>
</table>

### Table 4

SNR for detecting 25 mm × 25 mm and 50 mm × 50 mm defects without vehicle noise, with vehicle noises, and after de-noising (de-noising factor of 20).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>SNR</th>
<th>Before de-noising</th>
<th>After de-noising</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without vehicle noise</td>
<td>SVN</td>
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<td>50 mm × 50 mm defect</td>
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<td>1.468</td>
<td>3.682</td>
</tr>
</tbody>
</table>
2000 Hz, several appreciable noise peaks are minified, and signal-to-noise ratio is increased. In the field application, a de-noising scheme is suggested when attempting to handle different conditions of vehicle noise such as vehicle type, vehicle size and road surface material.

7. Future work

Further studies on this subject are recommended for improving the feasibility and efficiency of handling the noise issue. On the one hand, in order to examine the feasibility of the proposed de-noising scheme in practice, additional field investigations or ground truth measurement will be conducted in various conditions of vehicle transport. Examples of such conditions are: (a) single moving sedan, truck, or motorcycle, (b) a flow of moving vehicles in single lane, double or multiple lanes, and (c) cement-based, stone-based, or asphalt-based road. With these field investigations, the feasibility of the proposed de-noising scheme may be examined. On the other hand, the vehicle noise may also cause the extra vibration of instruments of acoustic-laser technique, for example, the laser and photoreceiver. Such vibration can result in the errors of defect detection with this technique. It is worth figuring out whether the vehicle noise leads to significant vibration of devices and thus low accuracy of measurement. In addition, development of supporting frame for insulating the vibration of devices in acoustic-laser technique is meaningful.

Credit authorship contribution statement

Qiwen Qiu: Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. Denvid Lau: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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