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Non-contact imaging for surface-opening cracks in concrete with air-coupled sensors

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ABSTRACT

Rapid and accurate non-destructive evaluation (NDE) techniques are needed to assess the in-place condition of concrete structures. However the time and effort required to perform NDE tests using conventional surface-mounted contact sensors hinder rapid evaluation of large full-scale structures. The suitability of surface waves and non-contact sensing techniques to detect the presence of concrete defects is examined here. First, the ability to detect leaky surface waves in concrete with air-coupled sensors is demonstrated. Surface waves in a concrete slab specimen are generated by an electrically-controlled impact source. Next, the data and signal processing needed to improve leaky surface wave data, with respect to eventual application to velocity and attenuation images, are demonstrated. Finally velocity and wave attenuation data collected from a concrete slab specimen that exhibits surface cracking are presented. Test results show that the proposed energy ratio (attenuation) criterion is more sensitive to existence of cracks than the velocity criterion.

RÉSUMÉ

Les techniques rapides et précises d'évaluation non destructive (END) permettent d'évaluer la condition in-situ d'ouvrages en béton. Cependant, le temps et les efforts nécessaires pour effectuer ces essais non destructifs à l'aide de capteurs de contact conventionnels montés en surface empêchent une évaluation rapide des constructions à grande échelle. On étudie ici le caractère approprié des ondes de surface et des techniques de capteurs sans contact permettant de détecter la présence de défauts dans le béton. Tout d'abord, on démontre la capacité à détecter des ondes de surface perméable dans le béton au moyen de transducteurs à couplage par air. Les ondes de surface dans un échantillon de dalle en béton sont générées par un impact contrôlé électriquement. Ensuite, on démontre le traitement des données et signaux nécessaires à l'amélioration des données extérieures de vague, en ce qui concerne l'application finale des images de la vitesse et de l'atténuation. Enfin, les données des images de la vitesse et de l'atténuation produite à partir d'un échantillon de dalle en béton montrant la fissuration de la surface sont présentées. Les résultats des essais démontrent que le critère proposé pour le rapport d'énergie (atténuation) est plus sensible à l'existence de fissures que celui de la vitesse.

1. INTRODUCTION

Imaging is implemented in many fields of science and engineering and has been demonstrated to be a powerful tool for the interpretation of signal data. However the use of imaging for the evaluation of concrete structures has been limited, especially when stress wave (ultrasonic and acoustic) signal data are used [1-2]. Practical imaging is enabled by non-contact sensing techniques that provide rapid signal data collection, such as pulsed RADAR (GPR), thermography and radiography. However, these non-contact sensing techniques have limitations in that they either require expensive equipment (all) or have safety issues (radiography), or the results are not directly related to concrete's mechanical properties (GPR). Air-coupled sensing is a stress wave based non-contact NDE method that was developed in 1970s. Compared to the contact stress-wave based NDE methods, air-coupled sensing has advantages: the non-contact nature enables rapid scanning of large structures; and without surface coupling effects, consistent and reliable amplitude information can be obtained and used to study wave attenuation. Most stress wave based imaging techniques,

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such as UPV tomography, use only P-wave velocity information for image construction. However, previous research [3] showed wave attenuation is more sensitive to existence of defects in concrete than velocity. Therefore, the use of attenuation information and an air-coupled sensing technique is expected to improve the accuracy of flaw detection in concrete.

Air coupled sensors detect the acoustic wave fronts (air pressure variations), which leak from propagating waves in the solid material, without contact to the surface. The surface motion associated with passing surface waves is usually much larger than that of body waves, so it is likely that surface waves can be practically and rapidly detected in concrete using air-coupled sensors. Surface waves propagate along the surface and exhibit significant motion to a depth of approximately one wavelength below the surface [4]. If surface wave images are to be used for material non-destructive evaluation, the sensitivity of surface waves to the presence of defects in concrete must be established. Accordingly, the objectives of the work reported in this paper are:

(a) to demonstrate practical air-coupled detection of propagating surface waves in concrete having a normal unprepared surface in typical indoor acoustic conditions, and

(b) to evaluate the practicality of using leaky surface wave data for velocity and attenuation measurements to identify surface defects in concrete.

2. AIR-COUPLED WAVE DETECTION IN CONCRETE

Previous work has shown that leaky surface waves in concrete can be detected readily using microphones that act as air-coupled sensors [5]. Fig. 1 shows the schematic for air-coupled sensing. When a transient wave source is applied at a point on the surface of concrete, elastic waves propagate along the concrete surface and direct acoustic waves travel in air. The resulting motion at each surface point of the solid causes an acoustic wave to "leak" into the surrounding air. The superposed leaky waves that emanate from each point in motion form leaky bulk (P- and S-waves) and surface wave wavefronts. From wave motion theory, we know that the out-of-plane motion associated with surface waves is much larger than that of bulk waves. Therefore, leaky surface waves are more readily detected than leaky bulk waves. Because the velocity of surface waves in concrete is 5 to 8 times higher than that of direct acoustic waves in air, the leaky waves will arrive the microphone earlier than acoustic waves when the horizontal distance L is larger than $h\tan(\theta)$, as shown in Fig. 1, where h is the vertical distance between the air-coupled sensor and the concrete surface, and the leaky angle θ is determined by Snell's law.

Fig. 2 shows a typical signal detected by a microphone that was located 0.45 m above a concrete floor. The waves were generated by the impact of a small hammer. The test was performed in a lab with normal ambient noise level.

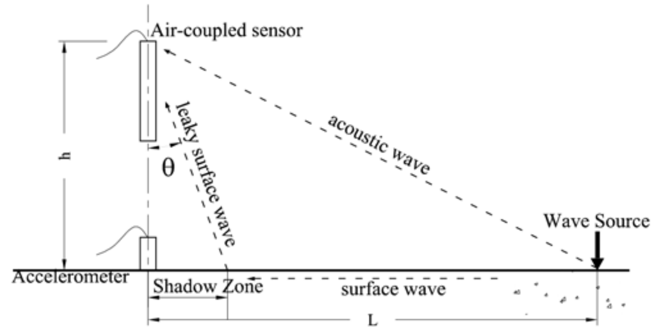

Fig. 1 - Non-contact surface wave detection scheme using an air-coupled transducer.

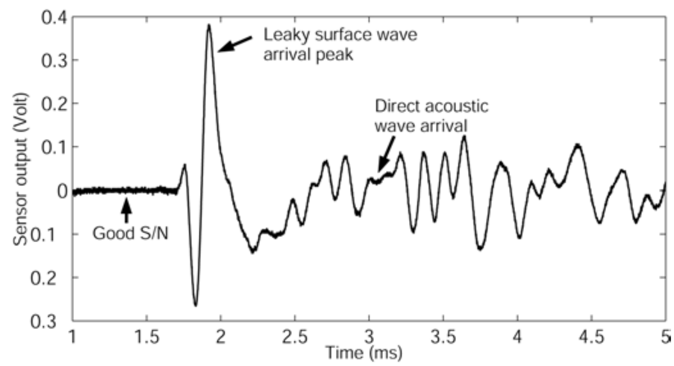

Fig. 2 - A typical signal detected by the air-coupled sensor located at L=1.0m, h=0.45m.

The signal shows a clear and sharp peak nearby the expected leaky surface wave arrival time. Good signal-to-noise ratio (S/N) can be observed. The effect of direct acoustic waves is very small owing to the highly-directional property of the microphone. Compared to the signal detected by a contact accelerometer (not shown in this paper, please refer to [5]) at the same sensed location, the non-contact signal has better S/N ratio, because accelerometers tend to amplify high frequency noise. In addition, body wave effects in non-contact tests are smaller than in contact tests.

The findings from previous work on air-coupled sensing in concrete by Zhu and Popovics [5] are summarized here:

(a) air-coupled transducers may be used to detect the leaky surface waves or guided waves propagating in concrete;

(b) air-coupled transducers are sensitive and tests can be performed over large distances up to 10 m, which is valuable for rapid scanning of large-scale structures;

(c) the signals collected by air-coupled transducers have high S/N ratio even after propagation over large distances;

(d) the highly directional feature of the microphone used in this research notably reduces the effect of the direct acoustic wave and ambient noise;

(e) for thin slab and plate structures the detected leaky waves propagate as dispersive Lamb waves, and for thick structures as Rayleigh waves.

Further theoretical analysis also shows that the excitation effectiveness of leaky surface waves induced by an impact point load also depends on the impulse force duration [6]. Shorter impulse duration gives higher output pressure of leaky surface waves. For a typical impact source with peak amplitude of 1 kN, the generated air pressure of leaky surface waves increases from 0.1 to 1.0 Pa when the duration varies from 200 µs to 50 µs. This is approximately equivalent to a sound pressure level of 75 dB~95 dB; such pressure levels are high enough to be detected readily by a microphone.

3. EXPERIMENTS

To investigate the effect of surface-opening cracks on the velocity and attenuation of leaky surface waves, a 2-D scan test was performed on a concrete floor that contains surface-opening cracks. The results of experimental tests are reported here. The experiments were carried out at the Newmark Laboratory at the University of Illinois at Urbana.

3.1 Testing equipment

An electrically-controlled mechanical impactor is used to generate repeatable impulse forces. Experiments showed that the generated forces are consistent in amplitude and duration. The impactor operates on the basis of high speed tubular solenoids. The electrical trigger signal can be monitored for consistency and works as the trigger signal. The impulse energy can be adjusted and the impulse force duration is about 100 µs. The typical signal frequency range generated by the impactor is 0~25 kHz.

Highly directional microphones are used to detect leaky waves from the concrete. Direct acoustic waves are also detected. The microphone has the following nominal properties: end face diameter = 20 mm; length = 386 mm; flat frequency response range 0-20kHz; output sensitivity = 2.2 mV/µbar. The sensitivity of microphone is directional: at an angle 30° off from the central axis, attenuation at 6 kHz and 10 kHz are -7.5 dB and -10 dB, respectively. This feature helps reduce ambient off-axis noise. A phantom power supply is needed to power the microphone and amplify signals. In most cases, three microphones were used to collect data simultaneously. The outputs of microphones after amplification were calibrated to a consistent acoustic source. In this test, an airborne ultrasound transmitter was used as the calibration source. The microphones were mounted in line using a mounting system that allows accurate placement of the sensors with regard to sensor separation and height from the test surface. A photo of the multiple-sensor frame in use is shown in Fig. 3. The sensor frame maintains a constant microphone height and spacing. In this case three microphones were used with 40 cm spacing between each other and 67 cm height from the test surface. The impact source is applied at a surface point along the line defined by the three aligned microphones, and the spacing between the source and the first microphone is 80 cm. The propagating leaky waves generated by the source are detected by the microphones and are sent to separate channels of a digital oscilloscope. Each transient signal is collected for duration of 5 ms, and digitized with 4096 points at a sampling resolution of 1.2 µs. The digitized data are transferred to a computer using the GPIB interface system for storage and further analysis.

Fig. 3 - Experimental test set-up showing microphones and rack mount. The microphones in the photo have a fixed horizontal spacing of 40 cm.

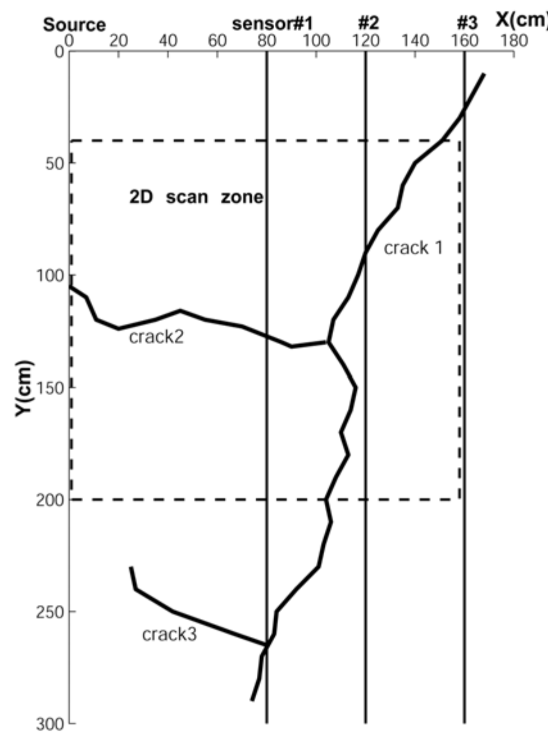

Fig. 4 - Concrete floor slab with surface-opening cracks. Impact point and three microphone locations are shown for Y scan (y=0-290cm). 2-D scan zone is in the range of x=0-160cm and y=40-200cm.

3.2 Testing setup

An existing concrete floor slab was identified for testing. A map of the floor slab specimen, showing crack locations, microphone and impact positions and scan lines is shown in Fig. 4. This slab has some regions that are apparently defect-free and other regions that contain individual tightly-closed surface cracks. The thickness of the slab varies between 180 mm to 210 mm, as determined by the impact-echo method. The surface wave velocity determined by SASW method is 2250 m/s. The surface of the concrete is smooth. No extra treatment or preparation was applied to the surface, and the leaky wave tests were carried out in ambient acoustic noise conditions. Three in-line microphones were used simultaneously to collect data from a single impact event.

Two 1-D scan tests were performed on the floor. First the microphone mounting frame was aligned along x direction and moved in y direction, and a series of 30 parallel linear data sets were collected in the region of x=0~160 cm and y=0~290 cm, with 10 cm spacing in y direction between each data set. Because the scanning line is along y direction, this scan pattern is defined as y-scan. For each data set, the impactor trigger signal and three leaky wave signals were collected. This scan configuration provides paths with no cracking between microphones #1 and #3 (y = 0~30 cm), cracking only between #1 and #2 (y = 140~220 cm), cracking only between #2 and #3 (y = 40~80 cm) and cracking among several regions. The x-scan test was performed in the region of x = 0~160 cm and y = 40~200 cm. The microphone mounting frame was aligned along y direction and moved in x direction. The impact point and microphone locations are along y = 40 cm, 120 cm, 160 cm and 200 cm, respectively.

3.3 Data processing and imaging

The leaky surface wave velocities C_{LR} and attenuations were used to construct 1-D scanning images. Along each scan line, the leaky wave velocity C_{LR} is determined from the delay in the arrival time of the first large positive peak in the leaky wave signal between two adjacent microphone locations with known separation (40 cm). For the region of x = 0-80 cm (y-scan case), C_{LR} is determined from the initiation of leaky surface waves measured by microphone #1. Therefore, for the y-scan configuration, there are 3*30 = 90 velocity data obtained in total. The obtained velocities were then normalized with respect to the crack-free region leaky surface wave velocities C_{LR} = 2250 m/s. The normalized velocities were used to construct a leaky surface wave velocity scan image.

The attenuation was calculated based on the leaky surface wave pulse energy ratio between the leaky wave signals detected by two adjacent microphones. The detailed flow chart that illustrates energy ratio calculation is shown in Fig. 5. The energy ratio is used instead of peak amplitude ratio is because the pulse energy is less affected by dispersion, which distorts waveforms during wave propagation and makes amplitude measurement unreliable. For each scan line, a Hanning window is first applied to the raw signals to extract leaky surface wave signals, where the length of Hanning window is determined by the impact force duration. The root-mean-square (RMS) of each windowed signal is then calculated and denoted as A_1, A_2 and A_3, where the subscripts 1~3 represent microphones #1~#3. The definition of RMS is

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}\ , \tag{1}$$

where n is number of points in the collected signal x_i. The attenuation of leaky surface waves can be expressed as the energy ratio between adjacent microphones, *i.e.*,

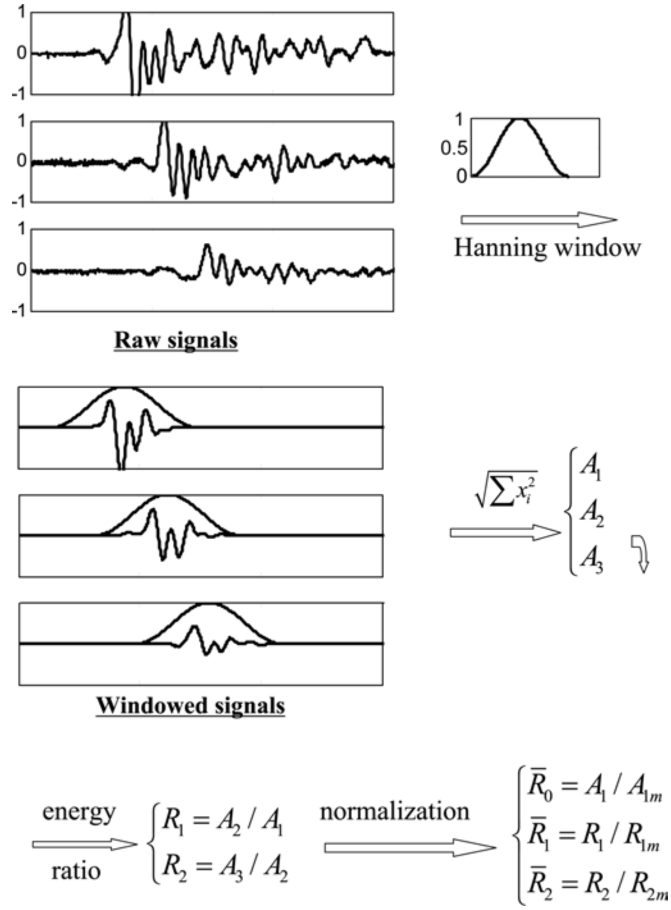

Fig. 5 - Flow chart for leaky surface wave energy ratio calculation. A_1~A_3 represent the RMS of each windowed signal detected by microphones #1~#3. A_{1m}, R_{1m} and R_{2m} are the RMS and energy ratios obtained from crack-free regions. The normalized values are used for image construction.

$R_2 = A_3 / A_2$ and $R_1 = A_2 / A_1$. Larger energy ratio indicates higher transmission and less attenuation. R_1 and R_2 are further normalized with respect to the energy ratio obtained in crack free regions. For the region between the impact point and microphone #1, because no energy ratio can be obtained, A_1 is normalized with respect to A_{1m} obtained from the crack free region.

To construct a 2-D scan image, the normalized x-scan and y-scan parameters at the same position are summed to give a normalized 2-D parameter.

4. RESULTS AND DISCUSSION

4.1 1-D and 2-D scan imaging

Fig. 6 shows the y-scan leaky surface wave velocity and energy ratio images. Dark regions indicate low velocity or transmission. The actual crack positions are also superimposed on the images for comparison. It can be seen that the velocity image has low contrast, which indicates that leaky surface wave velocity C_{LR} is relatively insensitive to existence of cracks. In addition, the low velocity regions do not match the actual crack position

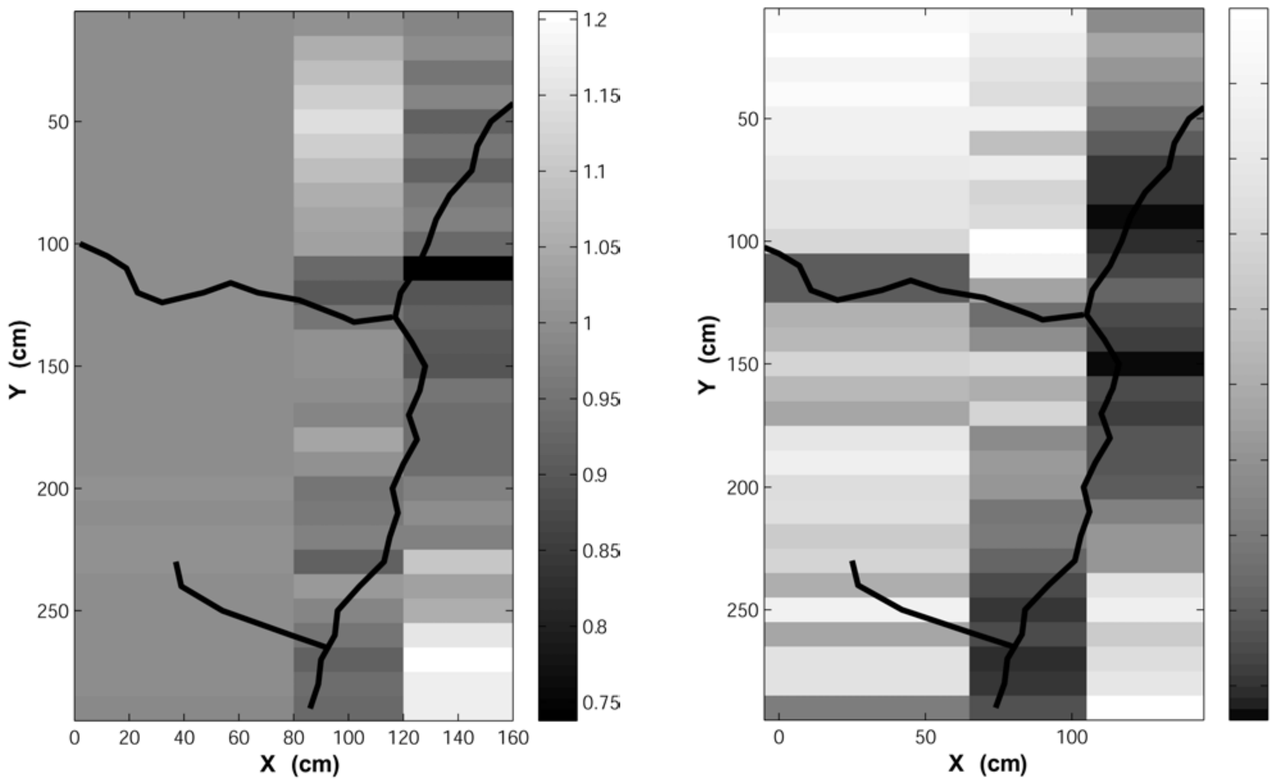

Fig. 6- Leaky surface wave y-scan images (a) normalized velocity; (b) normalized energy ratio. Dark regions represent low velocity or transmission. The actual crack positions are superimposed on the images for comparison.

well. On the contrary, the energy ratio image shown in Fig. 6(b) has clear and sharp contrast, and the dark regions agree well with the actual crack positions. Therefore, we can reach the conclusion that leaky surface wave energy ratio is a more sensitive criterion for crack indication than velocity. This result can be explained by surface wave propagation theory. In these tests, a relatively low frequency (5 kHz~25 kHz) impact source is used, which excites leaky surface waves with wavelength around 10~50 cm. Even for deep cracks that penetrate through the floor slab (20 cm), leaky surface waves can still propagate through the crack via sub-layers, but with energy loss. Therefore, leaky surface wave velocity is not as affected by existence of cracks as energy ratio.

The x-scan leaky surface wave energy ratio image is shown in Fig. 7. It can be seen that crack #2 has been clearly identified by low energy ratios, because the wave propagation direction is perpendicular to the crack. In region of y = 140~180 cm, crack #1 is nearly parallel to wave propagation direction, so it is difficult to identify the crack in this image. However, the accuracy can be improved by combining two images obtained from the different scanning directions. By summing the normalized x-scan and y-scan parameters at the same position, a 2-D scan image can be constructed, as shown in Fig. 8. The 2-D image clearly shows locations of all cracks as regions of low transmission.

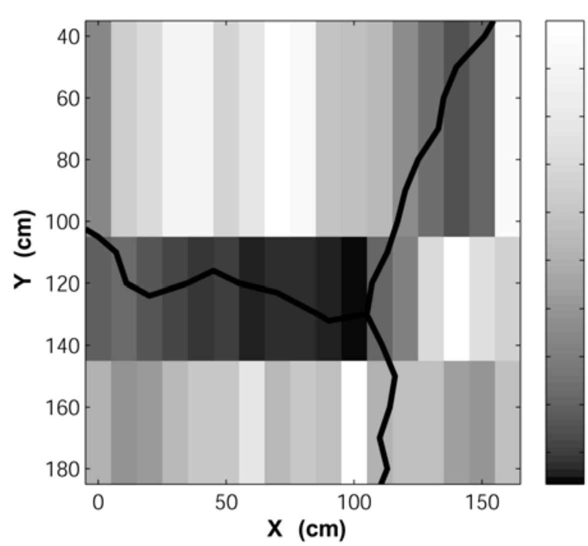

Fig. 7- Leaky surface wave x-scan energy ratio image. The actual crack positions are superimposed on the image for comparison.

4.2 Shadow zone effect

From Fig. 1, it can be noticed that, when source-to-sensor spacing $L < h\tan(\theta)$, no leaky surface wave can be detected. The region $h\tan(\theta)$ is called the shadow zone. This shadow zone makes data analysis more complicated, since the image should be corrected for shadow zone size.

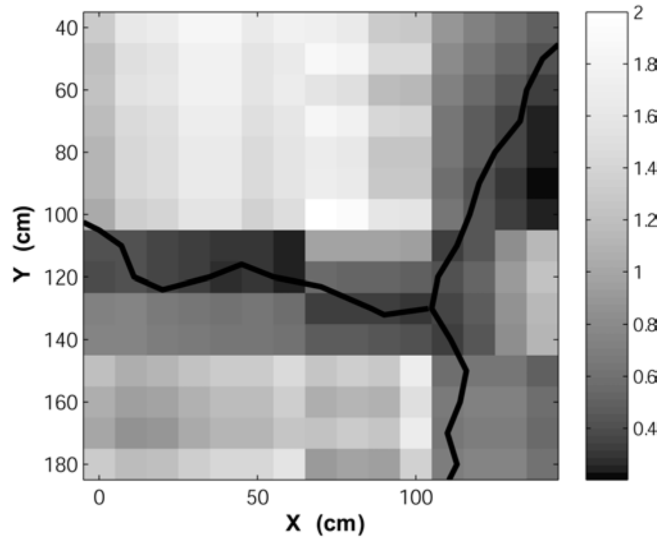

Fig. 8- Leaky surface wave 2-D scan energy ratio image. The actual crack positions are superimposed on the image for comparison.

For 2-D imaging, it should be corrected in both directions. In this test, h = 76 cm and $\theta = 8.8°$, which gives a shadow zone size of 12 cm. Because the leaky angle θ is relatively stable, which varies around 8 to 10 degrees for normal concrete, the only way to minimize shadow zone size is to reduce microphone height *h*. Smaller *h* also helps separate leaky surface waves from acoustic waves, which enables small source-to-sensor spacing and improves the imaging resolution. The sensing element of the microphone used in this test is 36 cm from the tip; therefore the minimum *h* we can obtain with this type of microphone is 36 cm. To reduce *h*, smaller microphones will be tried in future experiments. A new microphone frame will also be designed to improve portability and test efficiency.

4.3 Further applications

This preliminary study shows the potential to use leaky surface waves to detect and image surface-opening cracks. Further theoretical and experimental research is needed to extend this technique to subsurface defect detection. For surface-opening cracks, depth determination is of the most interest. A surface wave transmission method proposed by Song *et al.* [7] shows good reliability for crack depth measurement in concrete. Due to the similarity between propagation of leaky surface waves and of ordinary surface waves, the same technique can be applied to air-coupled sensing. Based on the same argument, leaky surface wave detection can also be applied to other surface waves based measurements, such as the SASW method.

5. CONCLUSIONS

In order to make use of leaky surface waves for velocity or attenuation imaging of concrete structures, the signals must be reliable and consistent. Signal processing can be applied to achieve this requirement. Test results show that the proposed energy ratio (attenuation) criterion is more sensitive to existence of cracks than the velocity criterion. In addition, the energy ratio criterion is reliable even when dispersion occurs during wave propagation. To improve imaging accuracy and resolution, 2-D scanning is needed.

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