NON-CONTACT DETECTION OF SURFACE WAVES IN CONCRETE USING AN AIR-COUPLED SENSOR

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Abstract. This research investigates air-coupled sensors used for non-contact NDT of concrete structures. An air-coupled sensor detects propagating leaky surface waves generated by a point impact event applied on the concrete surface. Compared to conventional body waves, leaky surface waves can be easily detected by the sensor due to the large out-of-plane motion of the waves. The computed velocity of the sensed leaky waves indicates the nature of the wave: Rayleigh surface waves are generated in the thick wall and Lamb waves in the thin slab. The study shows the potential of this sensing method for rapid inspection of concrete structures.

INTRODUCTION

There is growing concern about the deterioration of the world's concrete infrastructure. According to the 2001 ASCE Report card, the overall grade of American infrastructure is "D+", only a little improvement compared to the D"given in 1998. Much of this infrastructure is approaching or has passed its original design life. Therefore, it is necessary to search for advanced NDT techniques that will provide low-cost and reliable condition assessment to the existing infrastructure.

In recent years, various forms of acoustic imaging for concrete has been developed for application to mass concrete structures, such as dams [1-2] and structural members [3], with some success. Compared to other imaging techniques, such as radiography, GPR and infrared thermography, the results of acoustic wave tomography offer direct information related to material mechanical properties and are sensitive to the presence of damage and flaws. However, large amount of data are needed to construct an adequate image, and the requirement of surface coupling between sensors and tested structure make the data collection very time-consuming.

One approach to speed up the data collection process is to develop a non-contact ultrasonic test method. Laser ultrasonic techniques have been used to study the attenuation of Rayleigh waves in cement-based materials [4-5]. However, this technique involves expensive equipment, and the naturally rough surface of concrete requires surface treatment which hinders the field application of lasers. Air-coupled transducers have been widely investigated for many years. The main limitation for using an air-coupled transducer is the great impedance mismatch between air and concrete, which causes poor sensitivity and restricts most of wave energy from passing into concrete. However, there are many successful applications to guided wave detection in metal and composite materials [6].

The objective of this research is to study the possibility of using an air-coupled transducer to detect leaky surface waves in concrete. A series of tests performed on a thick concrete wall and a thin floor slab are presented in this paper.

EXPERIMENTAL WORK

Description of Leaky Wave Velocity Test

From wave motion theory, we know that the out-of-plane motion associated with the surface Rayleigh wave (R wave) is much larger than that of bulk waves. So, it's more possible to detect leaky R wave from concrete using air-coupled sensors. A Microphone is a kind of sensitive air-coupled transducer, which usually works in 0-20kHz frequency range and may be used to detect low frequency wave propagation in concrete.

The scheme for leaky wave detection using a microphone is shown in Fig.1. When a transient wave source is applied to the surface of concrete, elastic waves propagate along the concrete surface and direct acoustic waves travel in air. Because the velocity of R wave in concrete is 5~8 times higher than that of direct acoustic waves, at large distances, the leaky waves will arrive the microphone earlier than acoustic waves.

If the leaky angle θ is known, the R wave velocity can be obtained from the following equation

$$V_R = \frac{L - h\tan(\theta)}{t - h/V_a \cos(\theta)} \quad . \tag{1}$$

where, *t* is the leaky R wave arrival time, and *Va* is the acoustic wave velocity. We assume *Va*=344*m/s* at room temperature.

Test Set up and Procedure

The test set up for leaky wave velocity measurement in concrete is shown in Fig. 1. An instrumented hammer with a load cell at the tip is used to generate R waves and also

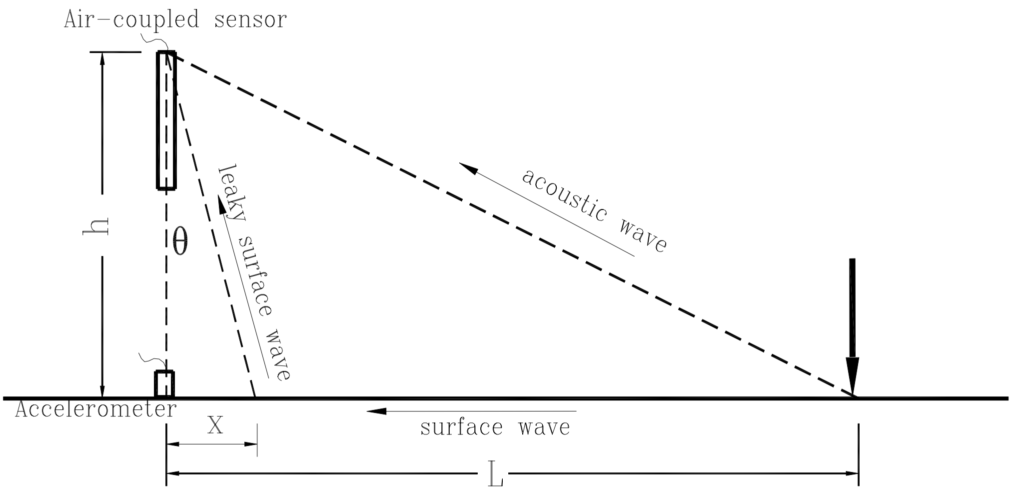


FIGURE 1. Non-contact surface wave detection scheme using an air-coupled transducer

works as a signal trigger. The typical signal frequency range generated by the hammer is 0-10kHz.

A highly directional microphone is used as air-coupled transducer to detect leaky waves from the concrete. Direct acoustic waves are also detected. The microphone has the following nominal properties: end face diameter = 20mm; length=386mm; flat frequency response range 0-20kHz; output sensitivity= 2.2mV/μbar. For off-axis angle 30°, the attenuation at 6kHz and 10kHz are 7.5dB and 10dB, respectively. This feature helps to reduce the effect of ambient off-axis noise.

To compare the signals obtained from contact and non-contact sensors, an accelerometer is placed on the surface right directly under the microphone. Properties of the accelerometer are: contact area = $25mm^2$; mass=0.7g; nominal voltage acceleration sensitivity = $1.02mV/(m/s^2)$; nominal ±10% flat frequency response over 1-25kHz; wax-mounted resonant frequency 75kHz.

The propagating waves detected by the microphone and accelerometer are sent to separate channels of a digital oscilloscope. Each transient signal is collected for a duration of 10ms, and digitized with 8192 points at a sampling resolution 1.2μs. The digitized data are transferred to a computer using the GPIB interface system for storage and further analysis.

The typical time domain signals detected by microphone and accelerometer are presented in Fig.2. The two signals are fairly similar except for the arrival time and high frequency content. By comparing the vertical axis scale, it will be noted that the signal sensitivity of the microphone is about 30 times that of the accelerometer, and the signal-to-noise ratio (S/N) for the microphone is also higher than that for the accelerometer. In this case, the corresponding off-axis angle α for the direct acoustic wave is 68°. The direct acoustic wave is not clearly seen at the expected time in signal of Fig.2(a). Thus, no

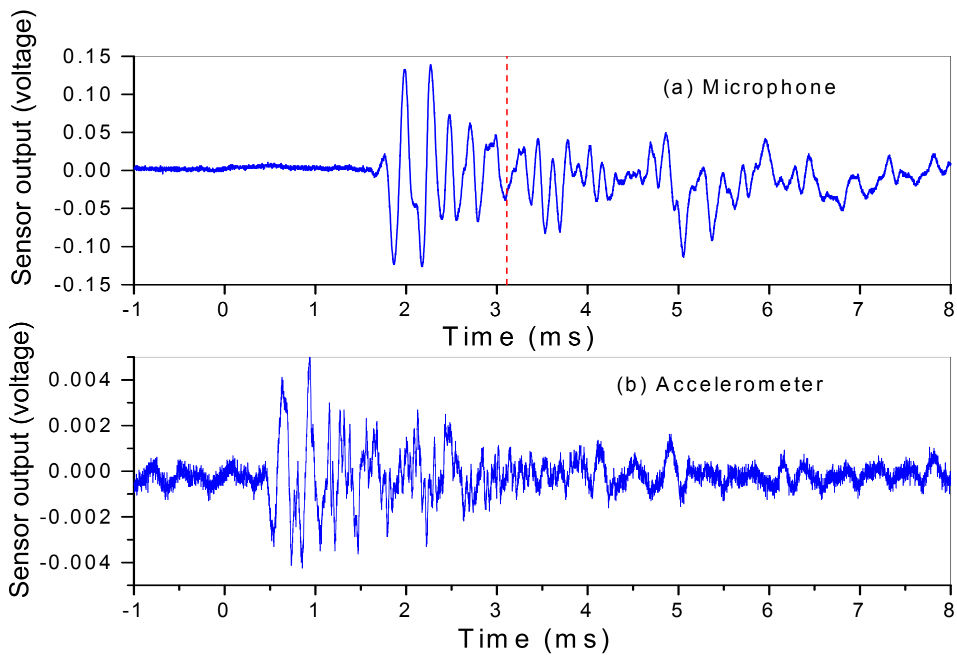
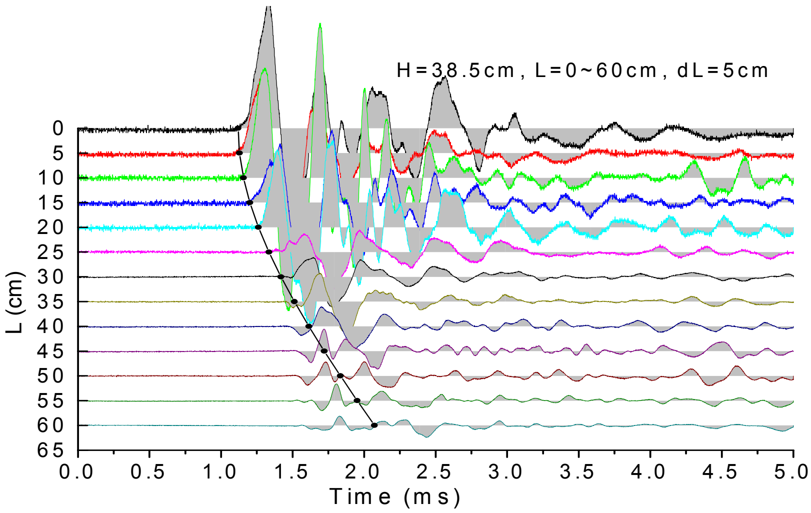


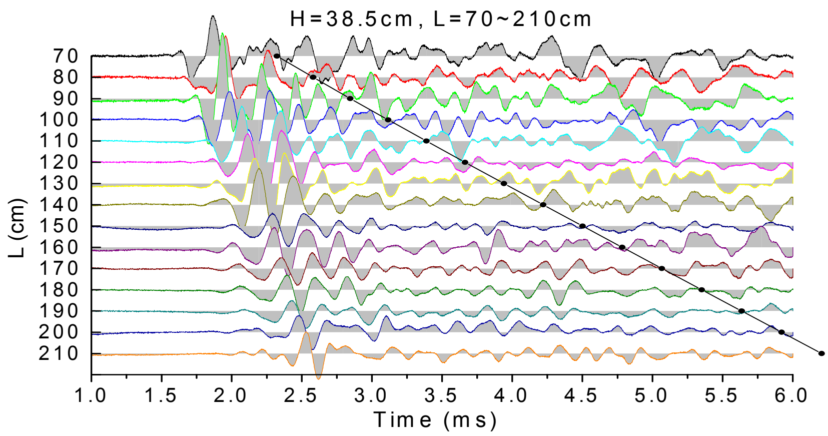
FIGURE 2. Comparison of signals from concrete collected by (a) microphone, h=38cm,L=100cm; (b) accelerometer, L=100cm; dashed line in (a) represents expected arrival time of direct acoustic wave.

special signal processing is needed to minimize the effect of ambient noise or the direct acoustic wave.

Although the R wave velocity can be obtained from Equation (1) if the leaky angle is known, large error will result because the arrival time of R wave is not easy to determine accurately. In addition, the leaky angle θ also needs to be determined from tests. Popovics et al. [7] proposed a method for one-sided R wave velocity measurement, which calculates the wave flight time between two receivers. Because the separation distance of the receivers is known, the R wave velocity can be obtained. The arrival time of R wave is taken as the arrival time of the first positive sharp peak in time domain signal. To improve accuracy of the measurement, a modified procedure is used in this research. Keeping the positions of microphone and accelerometer fixed, and the impact source is moved along a straight line over a distance *L*, with a spacing of Δ*L*. At each position, signals are collected and the arrivals corresponding to R wave peaks are recorded. A series of peak arrivals are plotted versus distance L, and fitted with a straight line. The velocity of R wave can be obtained from the slope of fitting line.

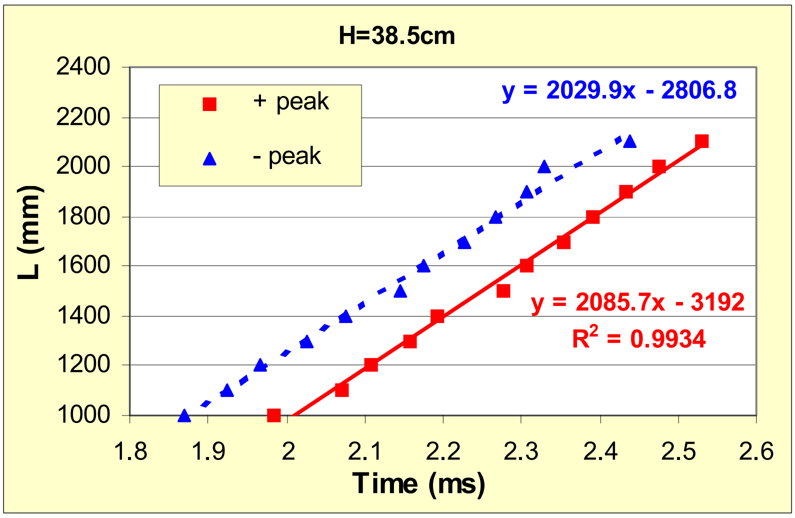


(a)

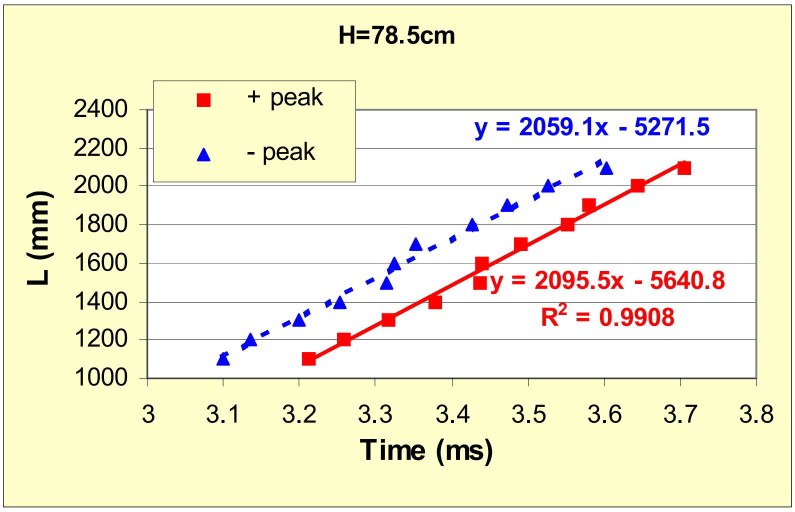


(b)

FIGURE 3. Waterfall plot of waveforms received by microphone for h=38.5cm, (a) L=0 to 60cm; (b) L=70 to 210cm. The solid line indicates expected arrival time of direct acoustic wave.



(a)



(b)

FIGURE 4. Measured leaky wave peaks arrival time vs. distance and fit lines for wall test (a) h=38.5cm, L=1000mm~2100mm; (b) h=78.5cm, L=1100mm~2100mm;the slope of fitting line represents surface wave velocity (unit: m/s).

Generally, *L* of 1m~2m with Δ*L* of 5cm ~ 10cm is used in the test.

EXPERIMENTAL RESULTS

Test results from a very thick concrete wall and a thin concrete floor slab are presented in this paper. The large difference of thickness used in the two tests enable us to study the possibility of using microphone to detect R waves and guided waves in plates.

Wall Test

The concrete wall used in this test is a reaction wall for structural testing. The wall has a thickness of 915mm. The P wave velocity obtained from impact-echo test is 3833 m/s, and the corresponding R wave velocity is 2100m/s, assuming Poisson's ratio ν=0.2.

To clearly show the wave motion variation trends with increasing distance *L*, waterfall plots are used to display the signals in cascade form with a step of Δ*L*. The expected arrivals of direct acoustic wave are also plotted on the waterfall plot to show the effect of acoustic waves. Fig.3 (a) and Fig.3 (b) show waterfall plots of signals collected by microphone, for height h=38.5cm. For small distance, such as L<20cm, the arrivals of the waves show very good agreement with direct acoustic wave arrivals, as shown in Fig.3(a). With increasing of distance L, the acoustic wave arrival curve begins to deviate from the initial arrivals of collected signals. For large distance L=70cm ~210cm, as shown in Fig.3(b), the effect of direct acoustic wave decreases, and the leaky waves arrive first and dominate the waveform. The leaky R wave peak arrivals are plotted vs. distance in Fig.4 (a) and the resulting R wave velocity is 2086m/s with a confident of correlation of 0.9934.

Fig.4(b) shows the test results for microphone height h=78.5cm, with other parameters same as before. Using the same data processing method, the resulting R wave velocity is 2092m/s. This value is very near to the value shown in Fig.4(a) and the result of impact-echo test.

If a group of waves are dispersive, the phase velocity depends on the wave frequency. As a result, the waveform will change its shape during propagation. To study the dispersion characteristics of the leaky R waves, the arrivals of first negative peaks are also plotted against distance for L>1m, which are shown in Fig.4(a) and Fig.4(b). It can be seen that, there is very little difference between the slopes of positive peaks and negative peaks fitting line; these lines are nearly parallel. This nature indicates the wave group travel at same velocity, and there is little or no dispersion in the leaky wave. According to wave motion theory in half space, the R wave dispersion is negligible when the wavelength is smaller than plate or layer thickness. In this case, the thickness of reaction wall is equal or less than the wavelength of detected R wave, which is in a range of 0.2m~1.0m corresponding to the frequency spectrum of wave source. Therefore, we expect little or no dispersion in this case.

Floor Slab Test

The thickness of the floor is 95mm, and the bottom of the slab appears totally debonded from the sub-layer. The P wave velocity from impact-echo test is 4000m/s, and R wave velocity 2250m/s, assuming Poisson's ratio ν=0.2.

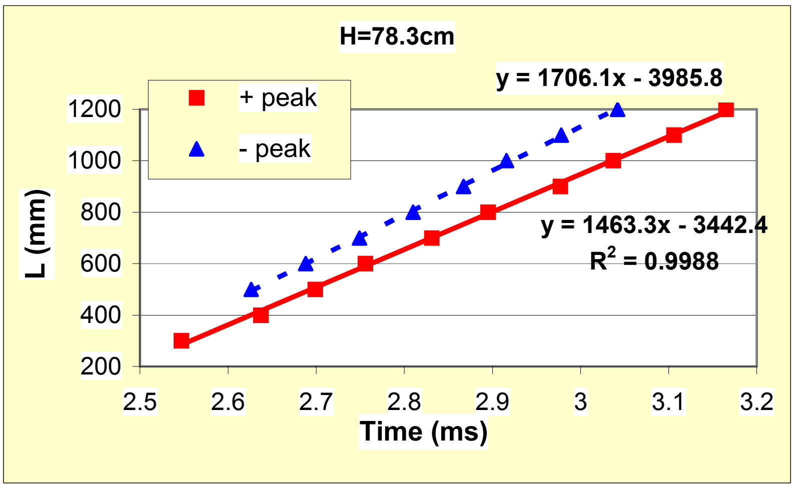


FIGURE 5. Measured leaky wave peaks arrival time vs. distance and fit lines for floor slab test with h=78.3cm, L=300mm~1200mm.

The test setup is same as that for the previous wall test. The test results for microphone height of h=78.3cm are shown in Fig.5. Some difference can be seen between the results from the floor slab tests and wall tests. First, the slope of the line fitted to the first positive peak in signal is much lower than the expected R wave velocity, and the apparent group velocities is only 1463m/s to 1706m/s. Second, the positive peak fitted line is not parallel to the negative peaks fitted line. The results suggest there is dispersion in the detected leaky wave. Because the thickness of the slab is relative small compared to the wavelengths of leaky waves, the half space theory is no longer valid for this case. Therefore, it's possible that one or several guided wave (Lamb) modes are excited, which are determined by the frequency content of wave source. Due to the one-side excitation method, the A_0 mode lamb wave is usually the easiest mode to excite [6].

According to elastic wave theory [8], the Rayleigh-Lamb frequency equation is given by

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq} \ . \tag{2}$$

wherein

$$p^2 = \frac{\omega^2}{C_P^2} - k^2, \ q^2 = \frac{\omega^2}{C_S^2} - k^2 . \tag{3}$$

where, k is wave number, Cp and Cs are P-wave and S-wave velocity, respectively. Solve Equation (2), we can obtain the phase velocity dispersion curve. Group velocity can be obtained from

$$C_g = \frac{d\omega}{dk} \ . \tag{4}$$

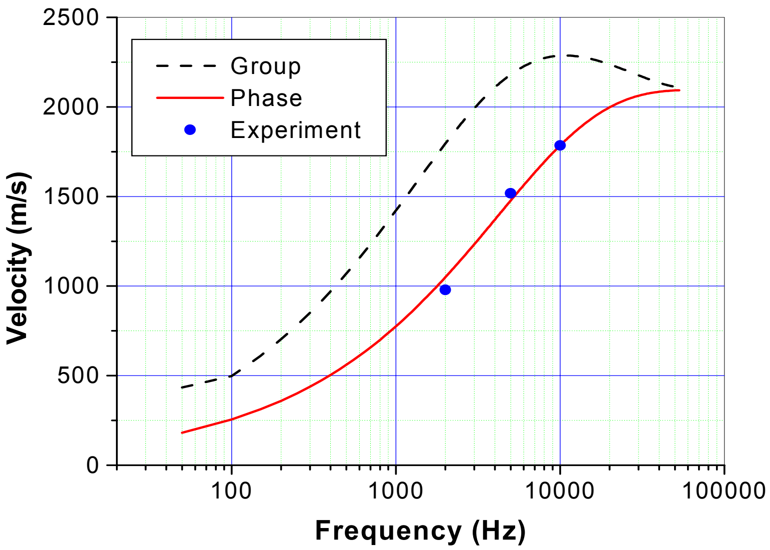


FIGURE 6. Lamb wave velocity dispersion curve (A_0 mode) for slab thickness 95mm with P wave velocity V_P=4000m/s.

The A_0 mode Lamb wave phase and group velocity dispersion curves are shown in Fig.6, assuming P wave velocity 4000m/s, Poisson's ratio ν=0.2 and plate thickness h=95mm. It can be seen there is apparent dispersion in the frequency range of 100Hz ~ 10kHz, which is also the frequency range of the wave source used in this test. If we let the collected signals pass through a series of band-pass filters, then apply the above mentioned peak fitting method to each group of filtered signals, phase velocities can be obtained for each frequency band. The experimental results for 2kHz, 5kHz and 10 kHz are shown in Fig.6. It can be seen, the experimental data agree with theoretical dispersion curve very well, which indicates that Lamb waves (A_0 mode) are excited and detected in the thin slab.

CONCLUSIONS

Based on the data presented in this paper, the following conclusions are drawn.

1. Air-coupled transducers may be used to detect the leaky surface waves or guided waves propagating in concrete.
2. Air-coupled transducers are more sensitive than the commonly used contact accelerometers. Tests can be performed over large distances up to 10m, which is valuable for rapid scanning of large-scale structures.
3. The signals collected by air-coupled transducers have high S/N ratio even for large distance detection. The highly directional feature of the microphone used in this research notably reduces the effect of the direct acoustic wave and ambient noise.
4. By investigating the leaky wave velocity, it's found that R-waves are generated in thick wall and lamb plate waves in thin slab, which agrees with elastic wave motion theory. This test method shows good potential for non-contact non-destructive detection and rapid scanning and imaging of concrete structures.

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