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Estimation of Surface-Crack Depth by Stack Imaging of Spectral Amplitudes in Ultrasonic-Echo

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ABSTRACT

The impact-echo method is improved as the SIBIE procedure by visualizing a cross-section image, instead of identifying only peak frequencies in the frequency spectra. In the current SIBIE procedure, elastic waves are generated by shooting an aluminium bullet and detected by using an accelerometer. According to the latest studies, however, it have come out that the input-output system employed is not able to cover the high frequency range enough to detect shallow flaws such as surface cracks in concrete. In order to circumvent this drawback, AE sensor which has the wider range of frequency response than the accelerometer is employed for both generating and detecting elastic waves. By applying the ultrasonic-echo system, the depths of surface cracks are estimated in repaired and reinforced concrete. Thus, the SIBIE procedure is improved as applicable to detect surface cracks in concrete.

Keywords. Concrete, Surface Crack, SIBIE, Ultrasonic-Echo, NDT

INTRODUCTION

Recently it is getting urgent to inspect aging concrete structures in service, because they are no longer maintenance-free. In most cases, it is not an easy task to know concrete properties and detect internal defects in the structures in service. Consequently, nondestructive testing (NDT) of concrete from the surface of the structures is in critical demand. The impact-echo method is well known as one of NDT techniques for concrete structures (Sansalone and Streett, 1997). When an impact force is given to the one point on the surface of concrete, elastic waves propagate in concrete. Then the waves reflect at defects and waveforms are detected at the other point. After FFT (Fast Fourier Transform) analysis is applied to a recorded waveform, a frequency spectrum is obtained. By interpreting the peak of this frequency spectrum, the presence and the location of defects are able to be estimated. Because the frequency spectra, however, often contain many peak frequencies, a post-analysis named "Stack Imaging of Spectral Amplitudes Based on Impact-Echo (SIBIE)" has been developed to obtain a visualized cross-sectional image (Ohtsu and Watanabe, 2002).

In SIBIE procedure, a short and strong impact of wide frequency range is so desired that the impact generated by an aluminium bullet is developed. In this concern, it is realized that the frequency ranges of the impact and the accelerometer are not enough wide and high to detect shallow defects. To this end, by applying wideband AE sensors as input-output devices of the SIBIE procedure, an applicability to determination on the depths of shallow surface cracks is studied.

PRINCIPLES AND TECHNIQUES

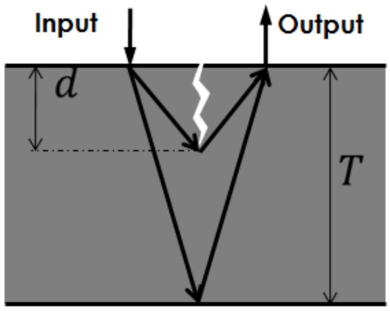
Impact-Echo method

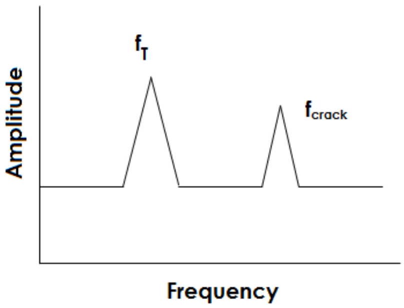
In the impact echo method, elastic wave are generated by a short duration mechanical impact. When the elastic wave is driven into a cracked concrete member, paths of the elastic waves are shown in Fig. 1. Frequency spectrum is identified after Fast Fourier Transform (FFT) analysis of an obtained waveform detected at the output point. Theoretically, peak frequencies could appear at f_T and f_{crack}, corresponding to the thickness of the member, *T*, and the depth of a surface crack, *d*, respectively,

$$f_T = C_p / 2T \tag{1}$$

$$f_{crack} = C_p / 2d \tag{2}$$

where C_p is the velocity of P-wave.





(a) Impact-echo method (b) Frequency spectrum idealized.

Figure 1. Resonant (peak) frequencies in a cracked concrete member.

SIBIE Procedure

Since it is not easy to identify the resonance peak frequency in the frequency spectrum, the SIBIE procedure have been developed. This is a post-processing technique for impact-echo data. In the procedure, first, a cross-section of concrete is divided into square elements as shown in Fig. 2. Here, resonance frequencies due to reflections at each element are calculated from,

$$f_R = C_p / R \tag{3}$$

$$f_{r_2} = C_p / r_2 \qquad (4)$$

Spectral amplitudes corresponding to these two resonant frequencies in the frequency spectrum are summed up at each element as shown in Fig. 3. Thus, reflection intensity at each element is estimated as stack image.

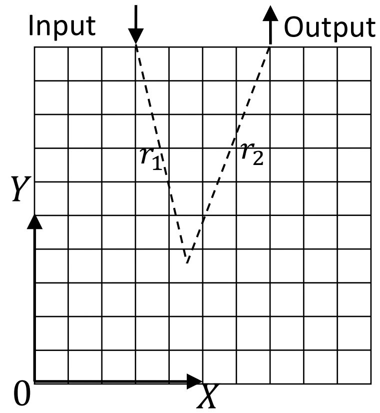


Figure 2. SIBIE imaging model.

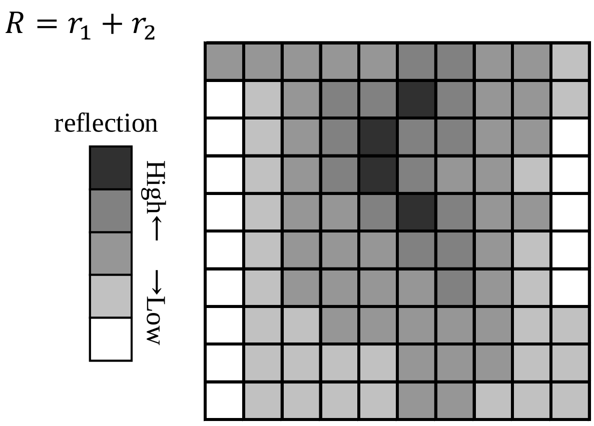
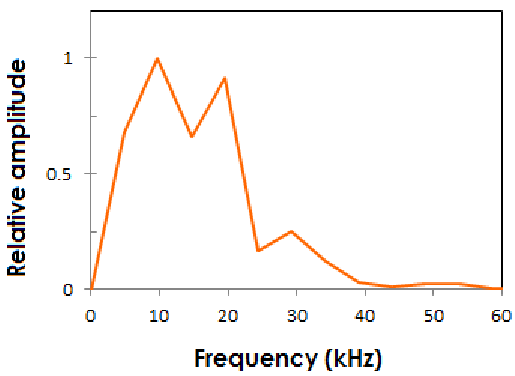


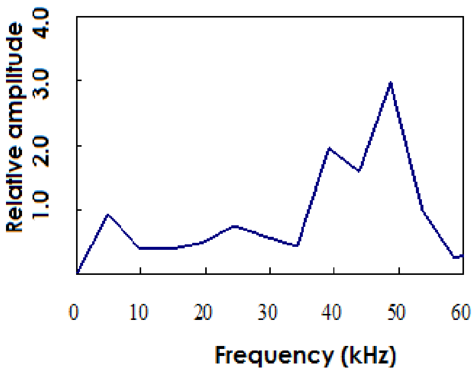
Figure 3. Example of SIBIE result.

Ultrasonics and Sensor calibration

According to the latest studies, it have come out that the input-output system employed is not able to cover the wide and high frequency range enough to detect shallow defects. In order to circumvent this drawback, AE sensor which has the wider range of frequency response than the accelerometer is employed for both generating and detecting elastic waves. In the previous study (Ohtsu and Watanabe, 2002), an aluminum bullet of 8 mm diameter and 17 mm length was shot at an impact point with compressed air (0.05 MPa) via a compressor. The frequency contents of the impact are clarified on the basis of Lamb's solution shown in Fig. 4 (a) (Ohtsu, Sonoda and Yamada, 2012).



(a) Impactor response



(b) Relative response of the accelerometer

Figure 4. (a) Frequency response of the impactor and (b) the response of the accelerometer over that of the vibrometer.

It is found that the frequency range could cover up to 30 kHz. For detection, an accelerometer of the wide-band was employed. In order to estimate the frequency response of the accelerometer, relative response between a frequency spectrum of the accelerometer and that of a Laser-Doppler vibrometer was determined at Lamb's problem setting (Ohtsu and Alver, 2009). A result is illustrated in Fig. 4 (b). The response of the vibrometer is known to be flat up to 50 kHz. It is realized that the frequency response of the accelerometer increases over 30 kHz due to the effect of resonance.

These results lead to the fact that the conventional impact-echo system is not applicable to shallow surface cracks, because peak frequencies could appear in the range higher than 30 kHz. Consequently, AE sensors (UT100, PAC) are introduced as input and output sensors. In this case, the frequency response obtained in an experiment is significantly affected by frequency characteristics of the sensor. Since the wide-band senor in the high frequency range is not generally of such flat response that compensation of the sensor response might necessary. The response is theoretically presented in the following convolution integral,

$$u(t) = s(t) * a(t) \quad (5)$$

where, $u(t)$ is the detected wave by the sensor, $s(t)$ is the impulse response of the sensor and $a(t)$ is the elastic-wave generated at the surface. After applying FFT analysis to Eq. 5, frequency contents of the elastic-wave, *A(f)*, are derived from,

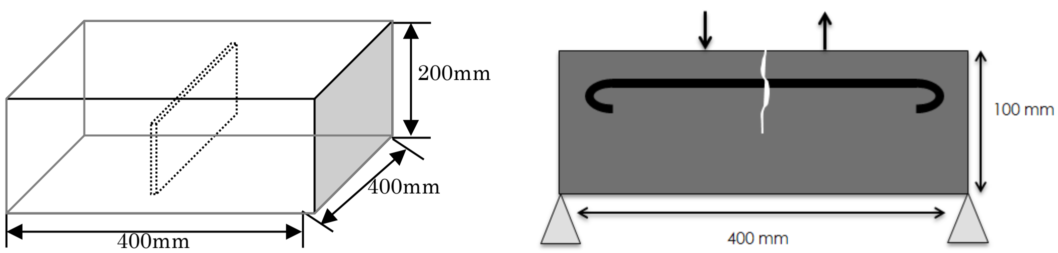
$$A(f) = U(f)/S(f) \quad (6)$$

Here, *U(f)* is obtained by the experiment, and *S(f)* is determined by a face-to-face test of sensors.

EXPERIMENTS

Specimens

Two types of concrete specimens were employed. Mixture proportion of concrete is given in Table 1. Plain concrete specimens are of dimensions 400mm×400mm×200mm. Modeling an imperfectly-repaired crack, styrene boards (2mm×400mm×120mm) is inserted as illustrated in Fig. 5 (a). Repaired depths are 50mm for Specimen I and 70mm for Specimen II. A reinforced concrete specimen with a crack is made after preloading. This is Specimen III of dimensions 400 mm x 100 mm x100 mm shown in Fig. 5 (b). Reinforcement was applied with a deformed bar of 13 mm diameter (D13) at 30 mm cover thickness. The depth of the surface crack was visually estimated as around 70 mm.



(a) Specimens I and II (b) Specimen III

Figure 5. Two types of specimens (Specimens I, Specimen II and Specimen III).

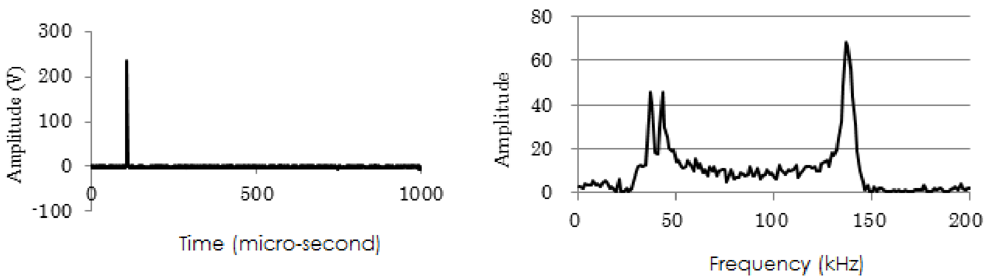
Table 1 Mixture proportion of concrete

Maximum gravel size (mm)	Water-to-cement ratio W/C (%)	Weight per unit volume (kg /m^3)				Slump (cm)	Air (%)
		Water	Cement	Sand	Gravel		
20	55	165	300	800	1109	8	5

Impact-Test by AE Sensor

P-wave velocity is a key parameter in the impact echo method. By performing the ultrasonic test in through-transmission direction, P-wave velocities of the specimens were obtained at the day of experiments, as 4319 m/s for Specimen I, 4538 m/s for Specimen II and 4422 m/s for Specimen III.

To generate elastic waves, the electric signal was charged into AE sensor (UT1000; PAC). The electric impulse driven by a signal generator is shown in Fig. 6 (a). To detect elastic waves, AE sensor (UT1000) was also employed. Input and output sensors are attached with 100 mm interval across the centerline of the specimen.



(a) Electrical impulse (b) Sensor response by face-to-face

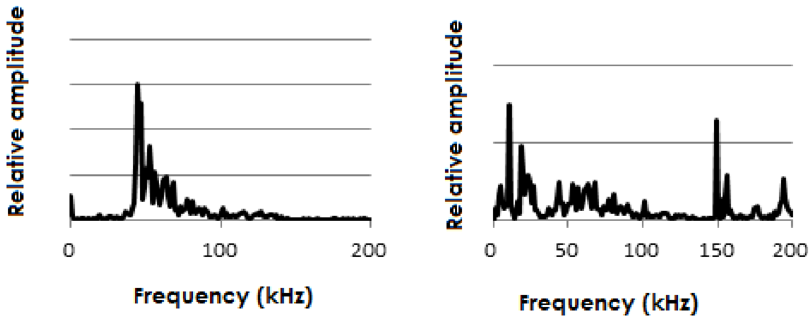
Figure 6. (a) Signal driven and (b) sensor response in ultrasonic test.

After detection of elastic waves, Fourier spectra of elastic waves were analyzed by Fast Fourier Transform (FFT). Sampling time was 0.4 μsec for digital recording and the number of digitized data for each waveform was 2048. In order to estimate the frequency response of the sensor, both of input and output AE sensors are attached as face-to-face. Then, the electric signal in Fig. 6 (a) was charged into the one. A frequency spectrum of the wave motion detected by the other is shown in Fig. 6 (b). Although AE senor (UT100) is known as wide-band and of fairly flat response, particular peak frequencies are observed around at 40 kHz and 140 kHz.

RESULTS AND DISCUSSION

Frequency Spectra obtained

Frequency spectrum obtained in Specimen I is shown in Fig. 7 (a). As can be seen, a peak frequency is observed at around at 40 kHz, which is in good agreement with the peak frequency observed in Fig. 6 (b). Consequently, in the case that the spectrum is applied to the SIBIE procedure, false intense zone might be identified. In order to compensate the sensor response, frequency spectrum in Fig. 7 (a) is divided by the sensor response in Fig. 6 (b), based on Eq. 6. A result is shown in Fig. 7 (b). It is observed that the peak frequency around at 40 kHz disappears.



(a) Original frequency spectrum (b) Compensated spectrum

Figure 7. Frequency spectra of Specimen I.

Results of SIBIE Analysis for Repaired Crack

The SIBIE procedure is applied to these compensated spectra of Specimen I and Specimen II. Results are shown in Fig. 8. In the analysis, the frequency range to be analyzed is set to 10 kHz–80 kHz, based on the frequency spectrum in Fig. 7 (b). In both Specimen I and Specimen II, it is found that the repaired depths are clearly identified.

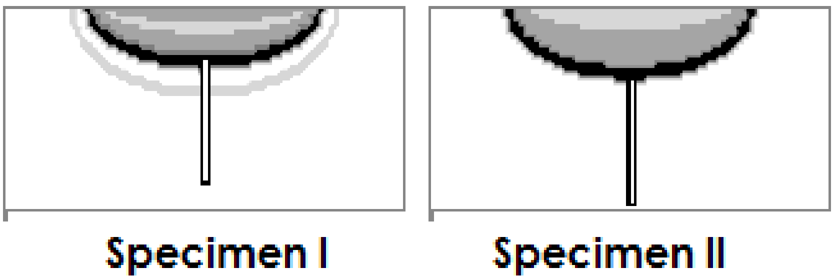
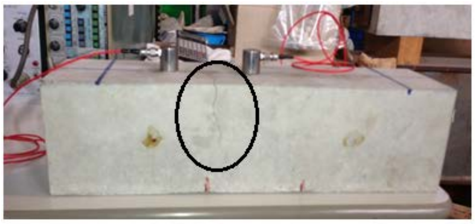


Figure 8. SIBIE results for Specimen I and Specimen II(10kHz-80kHz).

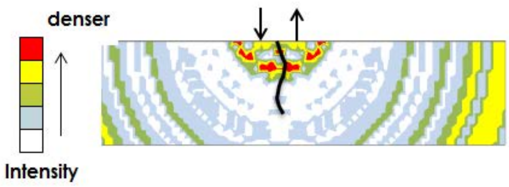
Result of SIBIE analysis in reinforced concrete

Results of the SIBIE analysis in Specimen III are given in Fig. 9. As seen in Fig. 9 (a), the surface crack of around 70 mm depth is observed, although the actual depth of through-thickness is unknown. Because we are interested in the depth of the surface crack, the upper limit of the frequency range was set to 40 kHz. In this case, the compensation of the sensor response is not inevitable, as found in Fig. 6 (b). A result in the frequency range from 10 kHz to 40 kHz is shown in Fig. 9 (b). High reflection at 30 mm is intensely observed, which is in remarkable agreement with the cover depth of reinforcement.

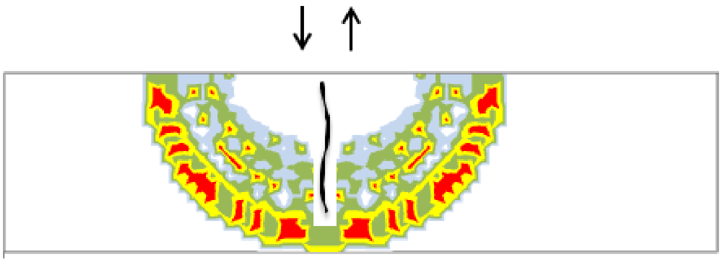
Since the depth of the surface crack is not clearly identified, the frequency range of the analysis is set to 20 kHz – 40 kHz in order to delete the high intensity zone due to reinforcement. A result is shown in Fig. 9 (c). The depth of the surface crack is obviously identified. This implies that the effect of reinforcement can be separated by shifting the frequency range in the SIBIE analysis.



(a) Test of reinforced concrete



(b) SIBIE result from 10 kHz to 40 kHz.



(c) SIBIE result from 20 kHz to 40 kHz

Figure 9. Results of SIBIE analysis in reinforced concrete with a surface crack.

CONCLUSION

In the present SIBIE procedure, the impact generated by an aluminium bullet is developed. It is realized that the frequency ranges of the impact and the accelerometer are not enough wide and high to detect shallow defects. To this end, by applying wideband AE sensors as input-output devices of the SIBIE procedure, an applicability to determination on the depths of shallow surface cracks is studied as ultrasonic SIBIE.

The technique was applied to estimate the surface cracks repaired. Since the frequency range to be covered in the analysis was set to 10 kHz to 80 kHz. Compensation of the sensor response was to be necessary. By analyzing compensated spectra in the SIBIE procedure, the repaired depths are successfully identified.

In the case of the reinforced concrete, the compensation of the sensor response is not inevitable. According to the case of the frequency range from 10 kHz to 40 kHz, high reflection at 30 mm depth was intensely observed, which is in remarkable agreement with the cover depth of reinforcement. Since the depth of the surface crack was not clearly identified, the frequency range of the analysis was shifted to 20 kHz – 40 kHz. This is because the high intensity zone due to reinforcement is deleted. Then, the depth of the surface crack is successfully identified. This implies that the effect of reinforcement can be separated by shifting the frequency range in the SIBIE analysis.

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