NUMERICAL EXPERIMENT ON DETECTING VOIDS IN CONCRETE BY SIBIE

Ninel Ata and Masayasu Ohtsu

Graduate School of Science and Technology, Kumamoto University, Kurokami 2-39-1, Kumamoto 860-8555, Japan

ABSTRACT

Impact-echo is known as a method for nondestructive evaluation (NDE) of defects in concrete structures. The method is based on detecting elastic waves which are generated by a mechanical impact and are reflected by internal defects and external surfaces. The resonance frequencies that can be identified in the spectrum are applied to estimate the presence and depth of defects in concrete. Thus, the method is available to evaluate voids in concrete structures. A variety of attempts have shown that identification of resonance frequencies due to voids has been marginally successful. This is because it is often difficult to extract particular peak frequencies only responsible for voids.

In order to identify the peak frequencies more clearly, the impact-echo is studied on the basis of elastodynamics and signal analysis. Theoretically, frequency responses of a specimen depend on the size of the member, the location of the void and P-wave velocity, because wave motions in concrete structures are characterized by material properties, incident waves, and the representative length. In order to improve the impact-echo, SIBIE (Stack Imaging of Spectral Amplitudes based on Impact-Echo) procedure has been developed. To investigate the performance of SIBIE theoretically, numerical experiments are conducted by the boundary element method (BEM).

1 INTRODUCTION

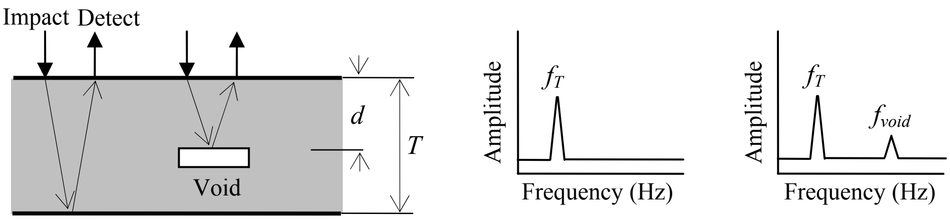
Impact-echo method is a method for nondestructive testing of concrete structures (Sansalone & Streett, [1]). Impact-generated elastic waves propagate through concrete and are reflected at internal defects and external surfaces. By using the resonance frequencies in the spectrum, the presence and the depth of defects are estimated. Although it is demonstrated that the technique is available to evaluate voids in concrete (Jaeger & Sansalone, [2]), still several limitations are reported in applications to concrete structures in service. Consequently, in order to identify voids or defects in concrete, SIBIE (Stack Imaging of Spectral Amplitudes Based on Impact-Echo) procedure has been developed (Ohtsu & Watanabe, [3]). Here, numerical analyses are conducted to confirm and study the performance of SIBIE.

2 IMPACT-ECHO METHOD

The impact-echo method consists of such three stages as applying an impact, detecting elastic waves, and identifying peak frequencies after FFT (Fast Fourier Transform) analysis of detected waves. Theoretically, frequency responses of a concrete slab containing voids depend on the size of the member, the location of voids and P-wave velocity. Concerning the frequency responses of concrete slabs, following relationships between the resonance frequencies due to reflections are known (Sansalone, [4]),

$$f_T = 0.96\frac{C_p}{2T}. \tag{1}$$

$$f_{void} = 0.96\frac{C_p}{2d}. \tag{2}$$



f_T : Resonance frequency of a plate thickness
f_{void} : Resonance frequency of a void

Figure 1: Frequency response of a concrete slab.

where f_T is the resonance frequency of a plate thickness T, f_{void} is the resonance frequency of a void in depth d, C_p is P-wave velocity and 0.96 is a shape factor determined from geometry. The presence of these resonance frequencies is illustrated in Figure 1. Concerning dynamic motions of concrete members, the dimensional analysis has been carried out (Ohtsu & Watanabe, [3]). Among such parameters as frequency *f*, characteristic length *L* and wave velocity *V*, a following non-dimensional parameter α, as a ratio of characteristic length *L* to wavelength λ, is obtained.

$$\alpha = \frac{fL}{V} = \frac{L}{\lambda} \tag{3}$$

In the case that α is larger than 1, it is found that the frequency response is significantly influenced by the characteristic length. Considering the case that α is equal to 1, *L* is replaced by the depth of a void *d* and *V* of P-wave velocity C_p, a following relationship is obtained.

$$f'_{\mathrm{void}} = \frac{C_p}{d}. \tag{4}$$

f'_{void} implies the existence of higher resonance frequency than f_{void} in eqn (2).

According to Herz's theory, the contact time T_c of a mechanical impact due to a steel-ball drop depends on diameter *D* of the steel-ball, and a simplified equation is given as (Sansalone & Streett, [1]),

$$T_c = 0.0043D. \tag{5}$$

The frequency, f_c, generated by the impact is,

$$f_c = \frac{1.25}{T_c}. \tag{6}$$

In order to be able to identify resonance frequencies f_T, f_{void} and f'_{void} in the frequency spectra, the upper-bound frequency f_c should cover all of them.

3 SIBIE PROCEDURE

The peak frequencies in the frequency spectra can consist of reflections from the boundary surfaces of the structure and those from the voids. In order to identify the locations of the reflectors, SIBIE (Stack Imaging of Spectral Amplitudes Based on Impact-Echo) procedure is developed. An analytical model is shown in Figure 2. The cross-section of a specimen is divided into square elements. First, the resonance frequencies due to reflections from the center of the

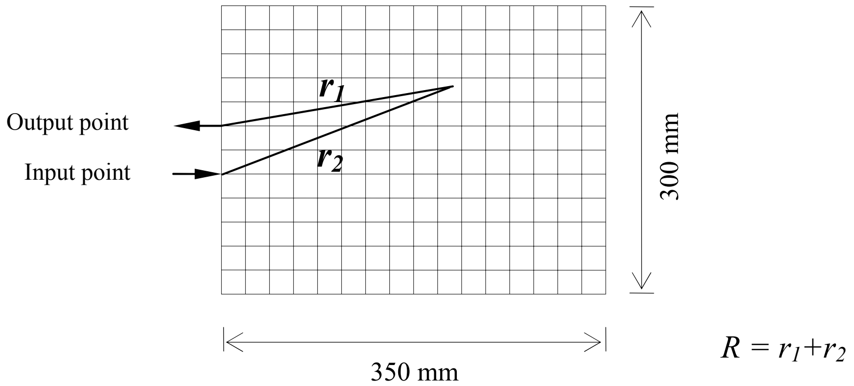


Figure 2: Spectral imaging model.

elements are computed. The travel distance from the input to the output via the center of the element is calculated as,

$$R = r_1+r_2. \tag{7}$$

The resonance frequencies due to reflections at the element are determined from,

$$f' = \frac{C_p}{R/2} \quad \text{and} \quad f = \frac{C_p}{R}. \tag{8}$$

In the frequency spectrum, corresponding amplitudes to the above frequencies are summed. Thus, the intensity of reflection at each element is determined. This scanning procedure is named SIBIE.

4 EXPERIMENT AND BEM ANALYSIS

A specimen containing a void was tested. Dimensions of the specimen are 350 mm x 300 mm x 500 mm and the diameter of the void is 30 mm. The impact-echo test was conducted at a cross-section from left and right sides as shown in Figure 3. Mechanical properties of concrete were tested at 28 days after moisture-curing in the standard room. Compressive strength was 39.1 MPa, Young's modulus was 27.3 GPa, Poisson ratio was 0.21 and the velocity of P-wave was 4340 m/s. The thickness resonance frequency f_T was calculated as 6.2 kHz from eqn (1). For the left impact case, the resonance frequencies of the void at 120 mm depth, f_{void} and f'_{void}, were found to be 18.1 kHz and 36.2 kHz, from eqns (2) and (4). For the right impact case, the resonance frequencies of the void at 200 mm depth, f_{void} and f'_{void}, were found to be 10.9 kHz and 21.7 kHz, respectively.

Aluminum bullets were shot at the impact point and elastic waves were detected by two accelerometers at the detection points as shown in the figure. Fourier spectra of accelerations were analyzed by FFT (Fast Fourier Transform). Sampling time was 4 μsec and the number of digitized data for each waveform was 2048. The diameter of the aluminum bullet was 8 mm and from eqns (5) and (6) the upper bound frequency of the bullet was calculated as 36.3 kHz. Thus, the upper bound frequency of the bullet of 8 mm in diameter could cover both frequencies f_{void} and f'_{void}.

By using the frequency spectra obtained from the impact test, SIBIE analysis was performed. Cross-section of the specimen was divided into square elements, of which the size was selected as 10 mm. In order to investigate the performance of SIBIE, numerical analyses were carried out by applying the two-dimensional dynamic boundary element method (BEM).

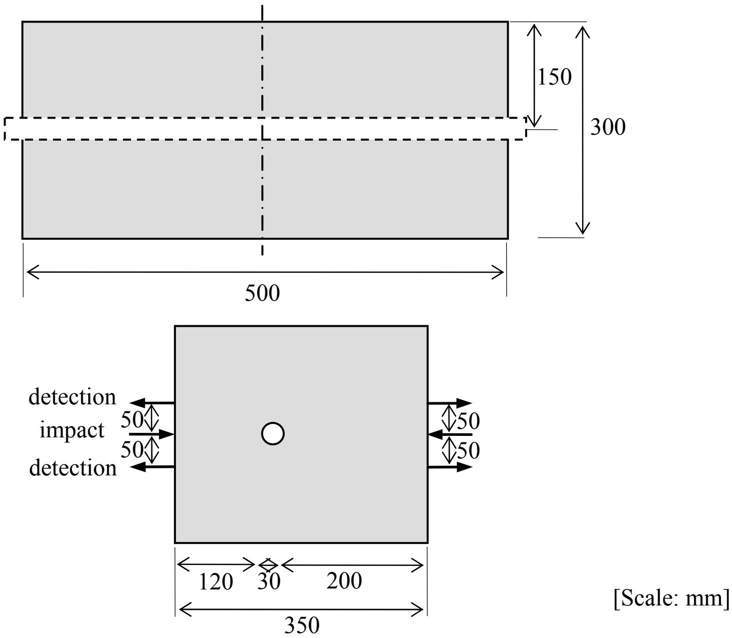


Figure 3: Cross section in the impact test.

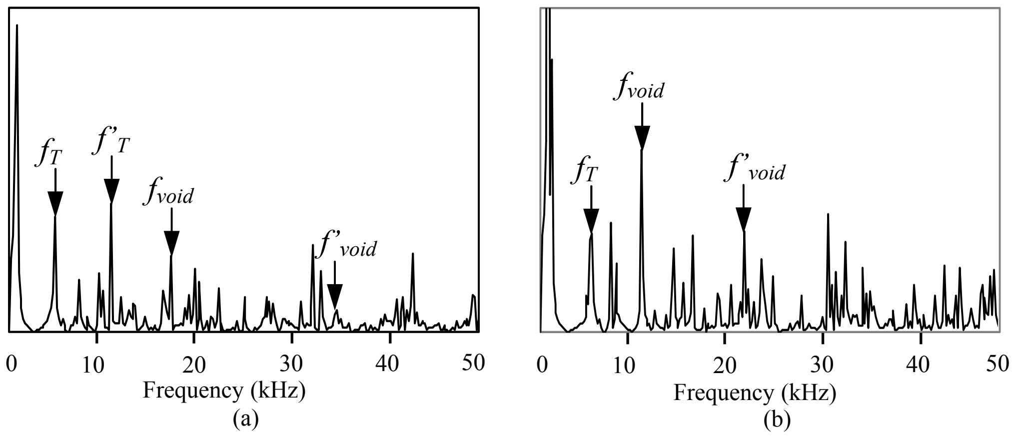


Figure 4: Frequency responses by BEM analysis; (a) impact from the left and (b) impact from the right side.

5 RESULTS AND DISCUSSION

Frequency spectra of the waveforms were analyzed by FFT (Fast Fourier Transform). In Figure 4, theoretical frequency spectra for the left and right impact cases by BEM are given. As indicated with arrows, the resonance frequency f_{void} for the impact from the left side is observed at approximately 17.2 kHz, while the thickness frequency f_T is observed at approximately 5.2 kHz. In Figure 4 (a), other peak frequencies are also observed as f'_T and f'_{void}. In Figure 4 (b), the spectrum

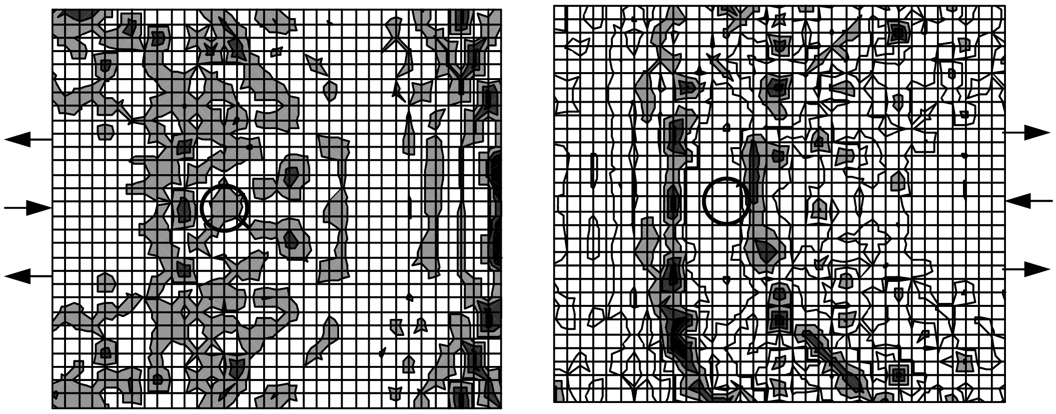


Figure 5: Results of SIBIE analysis for the left and right impact cases.

for the impact from the right side is given. The resonance frequency f_{void} is observed at approximately 10.9 kHz, while the resonance frequency f'_{void} is observed at approximately 22.2 kHz. The thickness resonance frequency f_T is observed at approximately 5.7 kHz.

Using the frequency spectra in Figure 4, SIBIE analysis was performed. Results for both impact cases are shown in Figure 5. The dark color corresponds to the high intense regions due to the presence of such reflectors as the void and the boundary surface. Arrows show the impact and the detection locations. It is clearly seen that the high intense region for the left impact case is observed at 120 mm depth in front of the void, while for the right impact case it is observed at 200 mm depth in front of the void.

In order to confirm the performance of SIBIE theoretically, by applying BEM analysis, stress and deformations were determined, at the frequencies corresponding to peak frequencies. The stress distribution of a cross-section for the left impact case with driving frequency f_{void} of 17.2 kHz is shown in Figure 6. For the case of impact from the right side, the driving frequency is f_{void} of 10.9 kHz. As it can be seen from the figures, the darker color regions of high stresses are observed at the outer boundaries of the sample and in front of the void. This confirms that reflections really occur at the boundaries and around the void.

Deformations due to the impact of driving frequency f_{void} for both impact cases are shown in Figure 7. Large deformations due to reflections are observed around the void. Thus, it is clarified that the high intense regions in Figure 5 are associated with the resonance frequency due to reflections.

6 CONCLUSION

Frequency spectra of a concrete slab containing a void are obtained by applying the impacts from two sides of the specimen. Because it is difficult to identify the peak frequencies only from the spectra, to identify voids or defects in concrete visually SIBIE (Stack Imaging of Spectral Amplitudes Based on Impact-Echo) procedure is developed. By the BEM analysis the performance of SIBIE is studied.

It is confirmed that the void is effectively visualized. The stress distribution and dynamic deformations at the peak frequency f_{void} demonstrate the presence of reflections at the void. Thus, the applicability of SIBIE procedure is theoretically confirmed.

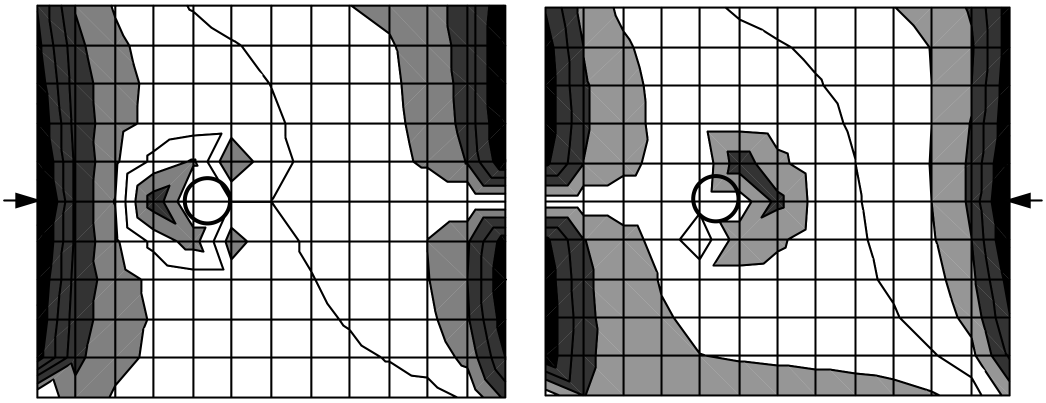


Figure 6: Stress distribution of the cross section by BEM analysis of (σ_{xx}) at f_{void}= 17.2 kHz for the left and f_{void}= 10.9 kHz for the right impact cases.

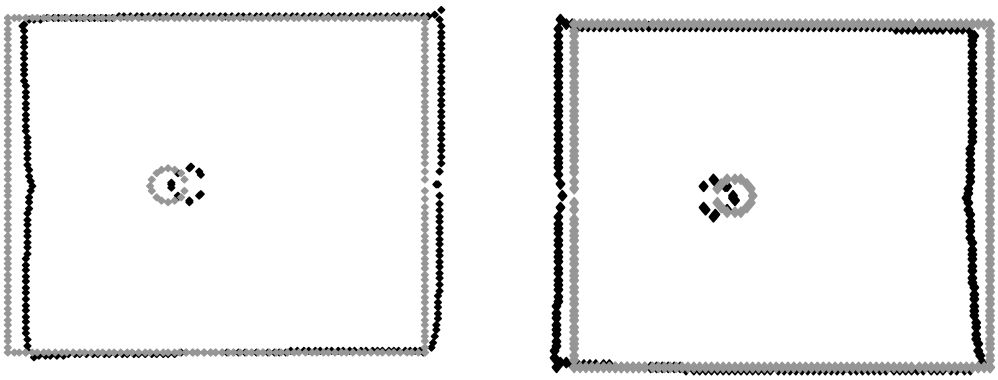


Figure 7: Deformations of the cross section by BEM analysis at f_{void}= 17.2 kHz for left and f_{void}=10.9 kHz for right impact cases.

7 REFERENCES

1. Sansalone, M.J. & Streett, W.B., Impact-echo, Ithaca, NY Bullbrier Press, 1997.
2. Jaeger, B.J. & Sansalone, M.J., Detecting voids in grouted tendon ducts of post-tensioned concrete structures using the impact-echo method, ACI structural journal, 93(4): 462-472, 1996.
3. Ohtsu, M. & Watanabe, T., Stack imaging of spectral amplitudes based on impact-echo for flaw detection, NDT & E international, 35: 189-196, 2002.
4. Sansalone, M., Impact-echo: The complete story, ACI structural journal, 94(6): 777-786, 1997.
5. Watanabe et al., Detecting voids in reinforced concrete slab by SIBIE, Construction and building materials, In press, 2003.
6. Carino, N.J., The impact-echo method: An overview, National Institute of Standards and Technology, 2001.