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A Study on Frequency Analysis Methods for Concrete Thickness Estimation by Impact Elastic-Wave Method

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ABSTRACT

In this study, difference of frequency analysis methods for concrete thickness estimation by the impact elastic-wave method was investigated with concrete plate specimens (concrete member of which the lateral dimensions are at least six times of the thickness). Four frequency analysis methods applied for concrete thickness estimation were fast Fourier transform (FFT), FFT for the waveform with the Rayleigh wave removed, the maximum entropy method and cross correlation method. As a result, it was revealed that cross correlation method demonstrated better results for all test cases of slab thickness and steel ball diameters than other methods investigated in this study.

Keywords. Non-destructive evaluation, Elastic-wave method, Concrete plate thickness, Maximum entropy method, Cross correlation method

INTRODUCTION

Impact elastic-wave method is a non-destructive testing method to estimate thickness of concrete members. In this method, it is necessary to identify a single peak corresponding to resonance frequency of primary wave (called P-wave) reflection between the parallel surfaces of concrete members. Thus, it is important to extract the targeted frequency component due to P-wave reflections. According to ASTM standard for the Impact-Echo Method (ASTM-C 1383-04, 2004), applicable concrete member is restricted to concrete plate-any concrete member of which the lateral dimensions are at least six times the thickness. On the other hand, according to the contact theory, it is important to select proper size of steel sphere to generate elastic wave with frequency component higher than the theoretical resonance frequency corresponding to concrete plate thickness. However, according to a previous study of the authors (Kamada *et al*., 2009), even if the above two requirements (size of concrete member and steel sphere) are satisfied, it is found that estimation of concrete thickness is not always easy because many peaks are often observed in the spectrum.

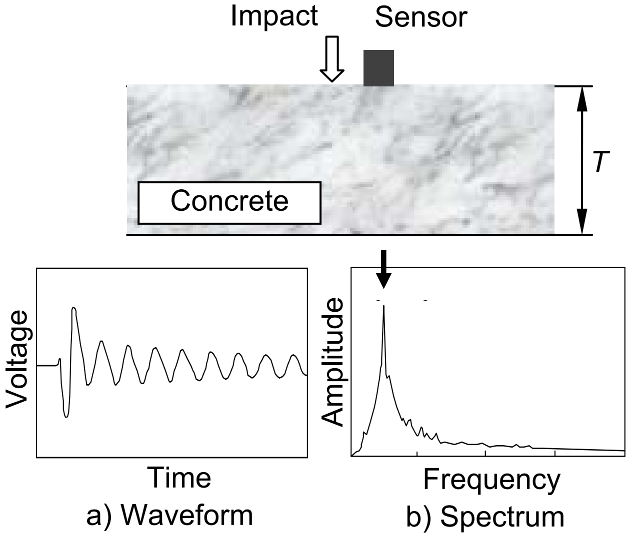
In order to solve the above problems, difference of frequency analysis methods for concrete thickness estimation by the impact elastic-wave method was investigated with concrete plate specimens (concrete member of which the lateral dimensions are at least six times of the thickness) by using steel spheres that could generate elastic wave with frequency component higher than the theoretical resonance frequency corresponding to the thickness of the target members in this study. Four frequency analysis methods applied for concrete thickness estimation were fast Fourier transform (FFT), FFT for the waveform with the Rayleigh wave removed , the maximum entropy method and cross correlation method.

PRINCIPLE OF ESTIMATION FOR CONCRETE PLATE THICKENSS BY IMPACT ELASTIC-WAVE METHOD

The principle of estimation for concrete plate thickness by impact elastic-wave method is shown in Figure 1. In this method P-wave is generated by tapping a steel sphere against the plate surface. The multiple reflection of P-wave between the parallel surfaces is measured by a sensor installed on the surface and frequency analysis for measured wave form is performed to obtain the peak frequency (f in Figure 1). Then, the thickness of concrete plate T can be estimated based on the peak frequency. The theoretical resonance frequency corresponding to the total thickness of the concrete plate can be calculated by the following equation (1) according to a previous study (Sansalone & Streett, 1997).

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

where, f is the theoretical resonance frequency corresponding to the total thickness of the concrete plate, C_p is wave propagation velocity of concrete, T is thickness of concrete plate.



a) Waveform b) Spectrum

Figure 1. Schematic diagram of the impact elastic-wave method

OUTLINE OF TEST

Specimens. Figure 2 and Figure 3 show concrete plate specimens used in this study. The concrete thickness was 150 and 280 mm, respectively. The lateral dimensions of all specimens were at least six times longer than the thickness. Table 1 and Table 2 show the mixture proportions of each specimen.

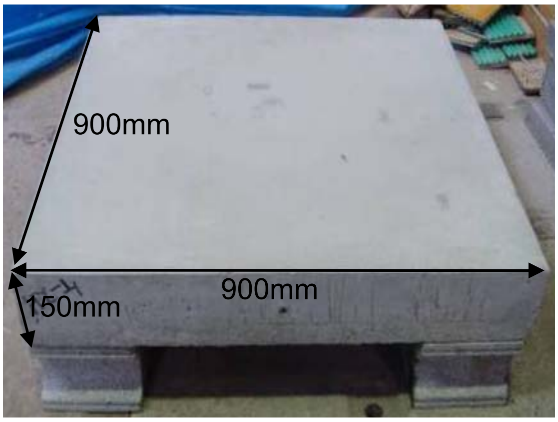


Figure 2. **Concrete plate thickness: 150mm**

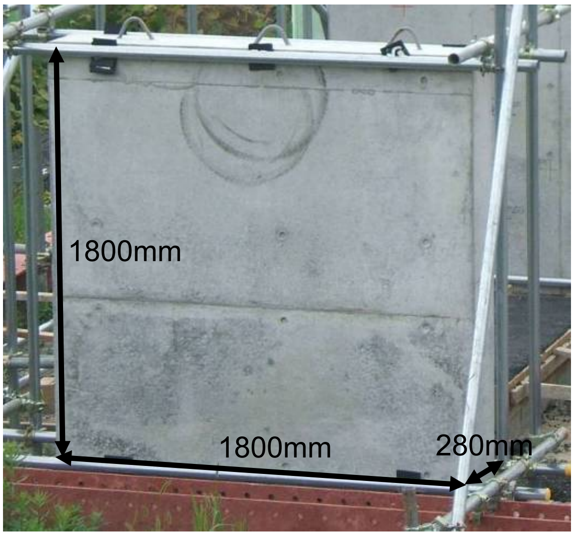


Figure 3. Concrete plate thickness: 280 mm

Measurement by impact elastic-wave method. Figure 4 shows the outline of measurement by the impact elastic-wave method. Elastic wave was applied at the center of the concrete specimens surface (900 mm × 900 mm in Figure2 and 1800 mm × 1800 mm in Figure 3). The receiving sensor was located 50 mm away from the point of elastic-wave input. In order to investigate the effect of varying frequencies of input elastic wave on the estimation of concrete thickness, steel spheres with five different diameters (3.2, 6.4, 9.6, 12.8 and 19.1 mm) were used. For receiving elastic waves, accelerometers with a flat frequency response in a range between 0.003 to 30 kHz were adopted.

Table 1. Mixture proportions of concrete (Concrete thickness : 150 mm)

G_{max} (mm)	W/C (%)	s/a (%)	Units (kg/m^3)				
			W	C	S	G	Admixture
15	64.0	55.9	216	338	925	748	3.600

Table 2. Mixture proportions of concrete (Concrete thickness : 280 mm)

G_{max} (mm)	W/C (%)	s/a (%)	Units (kg/m^3)				
			W	C	S	G	Admixture
20	53.0	45.5	191	360	758	948	3.971

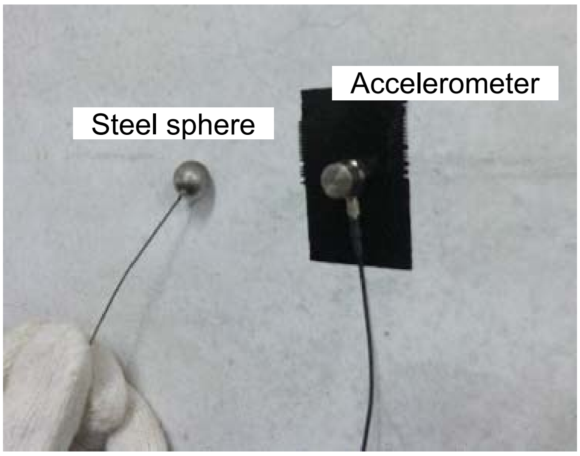


Figure 4. Measurement by impact elastic-wave method

The signals received by the sensor were recorded in a digital oscilloscope as acceleration versus time signals with 2 μs [= Δt] sampling time for 5000 samples [= N]. Four frequency analysis methods applied for concrete thickness estimation to verify effect of frequency analysis methods on estimation of concrete plate thickness were fast Fourier transform (Method I), FFT for the waveform with the Rayleigh wave removed (Method II), the maximum entropy method (Method III) and cross correlation method (Method IV).

RESULTS OF MEASUREMENT AND DISCUSSIONS

Method I. Figure 5 shows the frequency spectra calculated by FFT. The arrows indicate the theoretical resonance frequencies of P-wave corresponding to the thickness of the each specimen (thickness 150 mm: f_1 = 13 kHz, thickness 280 mm: f_2 = 7.1 kHz).

In the frequency spectra in the cases with concrete thickness of 150 mm, a peak is clearly identified nearly at the position of f_1 at all the steel sphere diameters. Nevertheless, in the case of a steel sphere of 3.2 mm diameter, multiple peaks with the almost the same intensity as f_1 are also observed in frequency range higher than f_1.

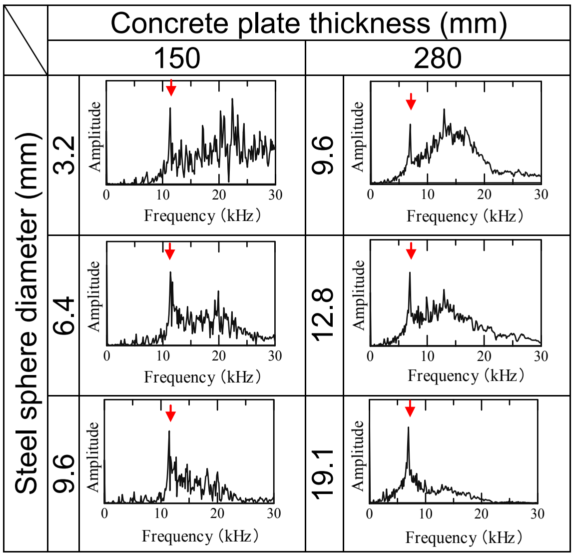


Figure 5. Frequency spectra calculated by Method I

On the other hand, in the frequency spectra obtained from concrete thickness of 280 mm, a peak clearly appears nearly at the position of f_2 like the case of concrete thickness of 150 mm. However, in the case of a steel sphere of 9.6 mm diameter, a peak with the intensity larger than f_2 appears at the position of approximately 13 kHz.

According to the above results, even in the cases when the steel sphere diameter was selected to obtain frequency component higher than the theoretical resonance frequency corresponding to concrete plate thickness, it was revealed that concrete thickness estimation from the peak frequency with the maximum intensity in frequency spectrum was difficult. It was considered that frequency component by multiple reflection might be reduced in waveforms due to the attenuation of elastic wave by selecting too small diameter of steel sphere. Similar findings were obtained in a previous study of the authors' (Kamada *et al.*, 2009).

Method II. The frequency spectra calculated by FFT for the waveform with the Rayleigh wave removed is shown in Figure 6. According to Figure 6, a peak is clearly identified nearly at the position of f_1 and f_2 at all the diameters of steel sphere respectively. Moreover, compared with the frequency spectra shown in Figure 5, the frequency component higher than the theoretical resonance frequency f_1 and f_2 corresponding to concrete plate thickness attenuate. However, a peak with the almost same intensity as f_1 and f_2 still appears. Therefore, same as Methods I, it was difficult to estimate the concrete thickness from the peak frequency in the frequency spectrum.

Method III. Figure 7 shows the frequency spectra calculated by maximum entropy method (MEM). As well as Figure 5, a peak is clearly identified nearly at the position of f_1 and f_2.

Moreover, comparing Figure 5, 6 and 7, by using MEM as the frequency analysis methods, it turns out that the form of the peaks become sharp and the intensity of the frequency component in other frequency bands become low. However, it can be seen some cases with a peak frequency as strong as f_1 and f_2. Therefore, it was difficult to estimate the concrete thickness from the peak frequency in the frequency spectrum as with the case of method I and II.

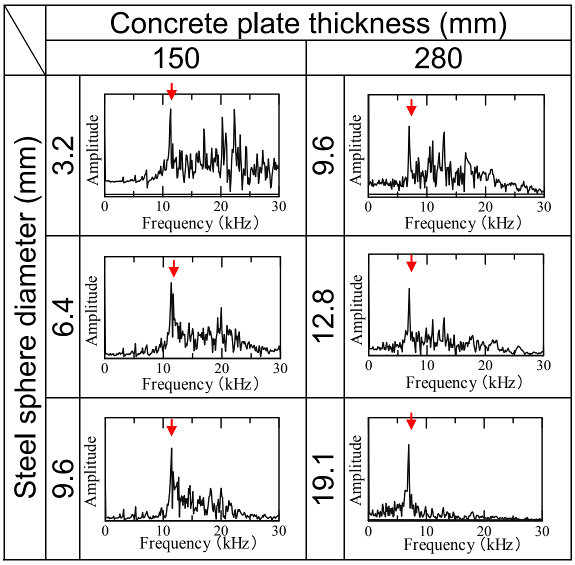


Figure 6. Frequency spectra calculated by Method II

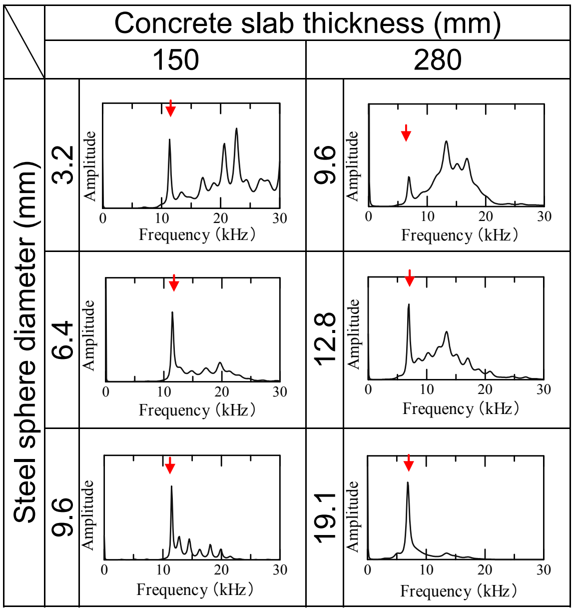


Figure 7. Frequency spectra calculated by Method III

Method IV. An example of a received waveform is illustrated in Figure 8. Figure 9 shows expanded waveform of wave front of the example waveform indicated in Figure 8. One wavelength illustrated in Figure 9 is equivalent to waveform of P-wave with one trip through concrete plate. This portion is defined as an "initial waveform". The cross correlation function was computed from between the received waveform and the initial waveform in the received waveform by the equation (2).

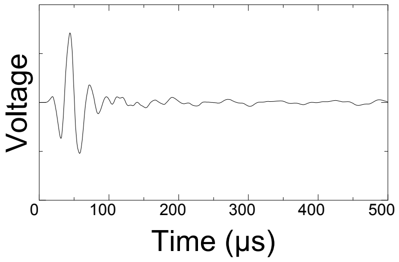


Figure 8. Received waveform

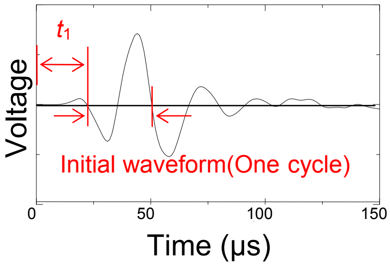


Figure 9. Expanded initial waveform

$$R(\tau)=\frac{\sum_{t=t_1+\tau}^{T+\tau}\left\{y_1(t)-\overline{y_1(t)}\right\}\left\{y_2(t-\tau)-\overline{y_2(t-\tau)}\right\}}{\sqrt{\sum_{t=t_1+\tau}^{T+\tau}\left\{y_1(t)-\overline{y_1(t)}\right\}^2}\sqrt{\sum_{t=t_1+\tau}^{T+\tau}\left\{y_2(t-\tau)-\overline{y_2(t-\tau)}\right\}^2}} \tag{2}$$

where, τ [μs] is time lag (τ: 0, 2, 4, $\cdots$, $N\Delta t$-t_1-T), $y_1(t)$ is a received waveform, $y_2(t$-$\tau)$ is an initial waveform, t_1 is the arrival time of first break in $y_1(t)$ or $y_2(t$-$\tau)$ (refer to Figure 9), T [μs] is computed by multiplying the cycle of the initial waveform by 10, bar is the average value of $y_1(t)$ or $y_2(t$-$\tau)$ in t=t_1+τ ~ T+τ, $R(\tau)$ is a cross correlation coefficient in the time lag τ. A cross correlation function (τ versus $R(\tau)$) is calculated by substituting each τ in to the equation (2).

The frequency spectra calculated by MEM for the cross correlation function are shown in Figure 10. In all frequency spectra, a single peak appears nearly at the position of f_1 or f_2, respectively. It is confirmed simultaneously that frequency component except the single peak become extremely small. Within the limits of the test cases (thickness of concrete member and diameter of steel sphere) in this study, it was possible to obtain a single peak corresponding to the concrete thickness. Thus, it was allowed to estimate of concrete thickness from the peak frequency with the maximum intensity in frequency spectrum.

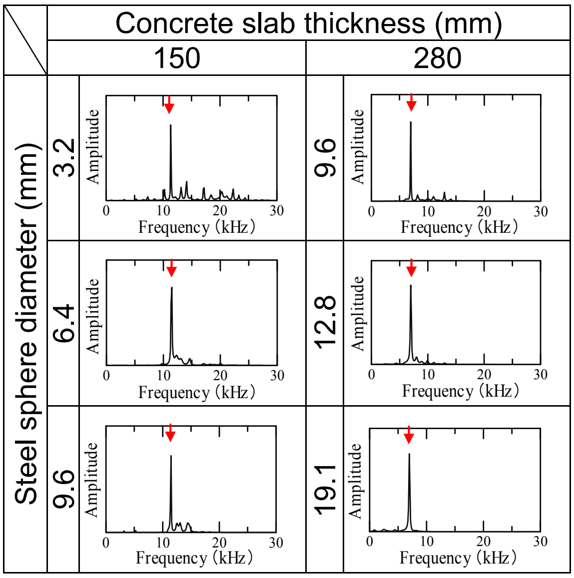


Figure 10. Frequency spectra calculated by Method IV

CONCLUSIONS

Results obtained are summarized as follows:

(1) In the frequency spectra calculated by Method I, II and III, a peak was identified nearly at the position of the theoretical resonance frequencies of P-wave corresponding to the concrete plate thickness. However a peak with large intensity appeared in the other position. Therefore, it was difficult to estimate the concrete thickness only from the peak frequency of the maximum intensity in frequency spectrum calculated by these methods.
(2) In the frequency spectra calculated by Method IV, a peak was clearly identified nearly at the position of the theoretical resonance frequencies of P-wave corresponding to the thickness only.

(3) According to above mentioned results ((1) and (2)), within the limit of this study, it was effective to use cross correlation method as a frequency analysis method for the estimation of the concrete thickness only from the peak frequency of the maximum intensity in frequency spectrum.

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