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DETECTION OF INTEGRITY AND THICKNESS OF CONCRETE STRUCTURES BY TIME WINDOW MEM METHPD

by

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Abstract

Theoretical consideration and experimental analyses for the detection of the thickness and internal flaws of the concrete plate applying the impact echo methods are described in this paper. As the frequency analyses methods, FFT, auto power spectrum analysis and maximum entropy methods are examined. As a result of the experimental analysis, the time weighted or time window MEM spectrum analysis shows a good performance to detect the internal flaws of the concrete structures.

Keywords: Impact echo method, Integrity test, NDT, Elastic wave, MEM analysis

1. Introduction

Many of the infrastructures made from reinforced concrete have been constructed to maintain the well being of modern society. Recently in Japan, we have had accidents where a part of a concrete structure breaks away; therefore the question on the integrity of the concrete structures was raised.

Ultra sonic methods and the impact echo method (Sansalone, 1988) are well known as nondestructive testing methods for integrity and thickness detection of concrete structures.

In the case of the ultra sonic method, there are some disadvantages, that is, time consuming surface treatment of the concrete be measured is necessary to make the ultra sonic waves penetrate into the concrete structure and the waves may be dispersed by discontinuities in the concrete structures like reinforcing bars and aggregates.

On the other hand, there are no such disadvantages in the impact echo method because lower frequency waves are used. Steel balls are commonly used as the impactors to introduce the transient stress waves into the test materials. According to the ASTM-C-1383, it is recommended that the period of the surface wave becomes almost equal to the period of the multiple reflections of P waves between the plate boundaries when the mass of the impactor is chosen.

However, if the suitable size of the impactor is chosen for the thickness of the test materials, this size of the impactor might be larger than the suitable size for detecting internal flaws in the materials. As shown in ASTM, there are two different characterized frequencies, one is deduced from the period of the surface wave (it is same as the period of the impact pulse) and the other is the resonant frequency of the plate boundaries.

This fact means that if the smaller or larger size of the impactor is chosen, unexpected interpretations may arise in the process of frequency analysis, because more than one of the high-amplitude peaks in the frequency spectrum may be produced. And also no methods are provided to separate the frequencies of internal flaws and the resonant frequency of the plate for the Impact-echo method if there are some reflectors in the concrete plate.

To avoid the unexpected effects of the impactor size in frequency spectrum of measured waves, we examine following two measuring and analyzing methods: (a) the method to use the "time window cross correlation function" for detecting the time when multiple reflections of P waves are dominant and (b) the method to use different sizes of impactors and then to average power spectrums obtained from each trial measured at same point. And also, we examined several signal analysis methods to find out what method is suitable for the thickness and flaws detection of the concrete plate.

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As a result of the examination, the maximum entropy method (MEM) is recommended for analyzing the frequency spectrum instead of the FFT method. In this paper, the theories and the analytical results of the experiments are described.

2. Tow points measurement method

Figure-1 shows a schematic illustration of the impact echo method. The impact pulse is introduced by dropping a small steel ball onto the surface of the concrete plate. The surface vibration of the concrete plate by the impact pulse is measured by accelerometers vertically attached to the surface of the concrete plate. By the impact, though P waves, SH, SV waves and surface waves are mainly generated in the concrete plate, reflected P waves and surface waves are dominant because the measuring axis of the accelerometers are vertical to the testing surface.

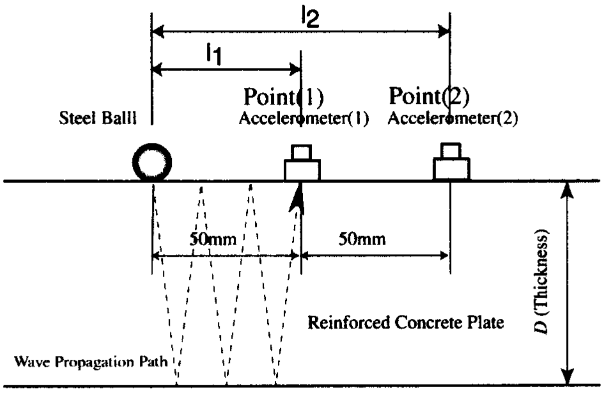


Figure-1 Schematic illustration of the wave propagation in the elastic plate

The wave propagation signal of P_1 shown in Figure-1 is described as Eq.1 where $x(t)$ is the impact signal and $h_{P1}(\tau)$, $h_{S1}(\tau)$ are impulse response functions of P and surface waves between the impact point and P_1 respectively.

$$y_1(t) = \int_0^{\infty} \{h_{P1}(\tau) + h_{S1}(\tau)\} x(t-\tau) d\tau$$
$$y_2(t) = \int_0^{\infty} \{h_{P2}(\tau) + h_{S2}(\tau)\} x(t-\tau) d\tau \qquad (1)$$

If the surface waves propagate from the impact point to the measuring points P_1, P_2 at only one time, $h_{S1}(\tau)$ and $h_{S2}(\tau)$ are given as:

$$h_{S1}(\tau) = \begin{cases} a_1 & ,t = l_1 / V_s \\ 0 & ,t \neq l_1 / V_s \end{cases} \qquad (2)$$

$$h_{S2}(\tau) = \begin{cases} a_2 & ,t = l_2 / V_s \\ 0 & ,t \neq l_2 / V_s \end{cases} \qquad (2)'$$

where V_s is the velocity of the surface wave, a_1 and a_2 are amplitude transfer rates of the surface waves between the impact point and P_1, P_2. On the other hand, P waves propagate into the concrete plate along the spherical wave fronts and are reflected by internal flaws and the boundaries of the plate. The impulse response functions of P waves are given as:

$$h_{P1}(\tau) = \begin{cases} \dfrac{b}{2\pi L_1(i)^2} \exp \dfrac{2\pi L_1(i) c}{V_P} & ,t = \dfrac{L_1(i)}{V_P} \\ 0 & ,t \neq \dfrac{L_1(i)}{V_P} \end{cases} \qquad (3)$$

$$h_{P2}(\tau) = \begin{cases} \dfrac{b}{2\pi L_2(i)^2} \exp \dfrac{2\pi L_2(i) c}{V_P} & ,t = \dfrac{L_2(i)}{V_P} \\ 0 & ,t \neq \dfrac{L_2(i)}{V_P} \end{cases} \qquad (3)'$$

where i represents the times of the round trip of P waves between the boundaries and c is the damping coefficient of the P wave in the concrete plate. The length of the propagation path L_1 and L_2 are shown as:

$$L_1 = \sqrt{l_1^2 + 4i^2 D^2} \qquad L_2 = \sqrt{l_2^2 + 4i^2 D^2} \qquad (4)$$

where D is the depth of the plate. If the distance between the impact point and measuring points are shorter enough to compare with the depth, then Eq.4 becomes Eq.5.

$$L_1 \approx L_2 \approx 2iD \qquad (5)$$

Considering the relationship between Eq.3, Eq.4 and Eq.5, the following conclusions are made.

(a) Depth of D is only determined by the frequency response functions of P waves.
(b) It is possible to separate P waves from surface waves by using time windows onto the measured waves.

The item (a) is given by the fact that only the impulse response functions of P waves have parameter D and periodicity of which cycle is $T = 2D / V_P$. If the cycle time T is determined, the depth of D is given as Eq.6:

$$D = \frac{V_P}{2 f_0} \qquad (6)$$

where $f_0 = 1/T$ is the resonant frequency of the plate having depth D. The time window cross correlation function is defined as Eq.7. Here, P_1, P_2 are measured wave signals at point P_1 and P_2 and T_D, T_W, τ are delay time, time width of the window and lag time of the correlation function, respectively.

$$C_R(T_D, \tau) = \int_{T_D}^{T_D+T_w} P_1(t) P_2(t+\tau) dt \qquad (7)$$

If adequate time windows are chosen, it is possible to separate the time when no surface waves are measured from the time when the surface waves are dominant by using time window cross correlation functions between waves of P_1 and P_2. This is deduced from the consideration as follows: Examining the Eq.3, there are time differences of $t_\Delta = (l_2 - l_1)/V_S$ between the impulse response functions of P_1 and P_2 for the surface waves. That is, if the cross correlation function of the surface waves between P_1 and P_2 are given, the lag time when the peak of the plus side appears is not 0 lag time. On the other hand, there are no time differences between the impulse response functions of the P waves of P_1 and P_2, therefore the peak of plus side appears at lag time 0. Thus it is possible to separate the time duration when the P waves are dominant and the surface wave is dominant.

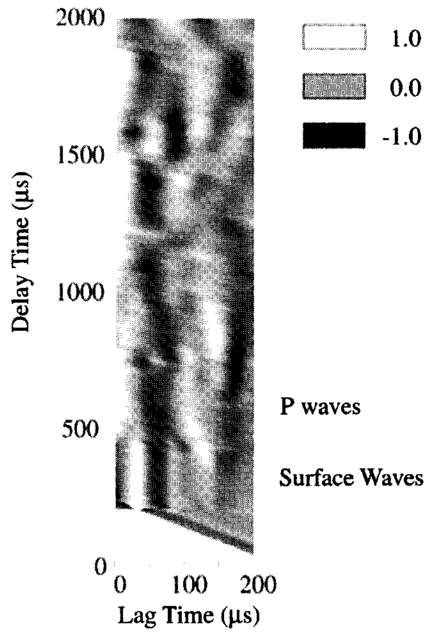


Figure-2 Time Window Cross Correlation Function between P_1 and P_2

Figure-2 shows the time window cross correlation function between the waves measured at P_1 and P_2 points as shown in Figure-1 for a 200mm thickness concrete plate using a 10mm diameter steel ball as the impactor. The width of time window is 1mili second. The bright zone in Figure-2 indicates high correlation values. The time between 200μs and 500μs is the time when the surface waves are dominant, because there are high correlations in the lag time of about 25μs.

The distance between P_1 and P_2 is 50mm, and then the velocity of the surface waves are determined almost 2,000m/s from this lag time. And this value coincides with the actual velocity of the surface waves in the testing concrete plate. After a delay time of 500μs, peak values of the cross correlation functions are mainly observed at the lag time of 0μs. This fact shows that the surface wave pass through the measuring points by 500μs, then the P waves become dominant. The cross correlation functions at the delay time 230μs and 650μs are shown in Figure-3.

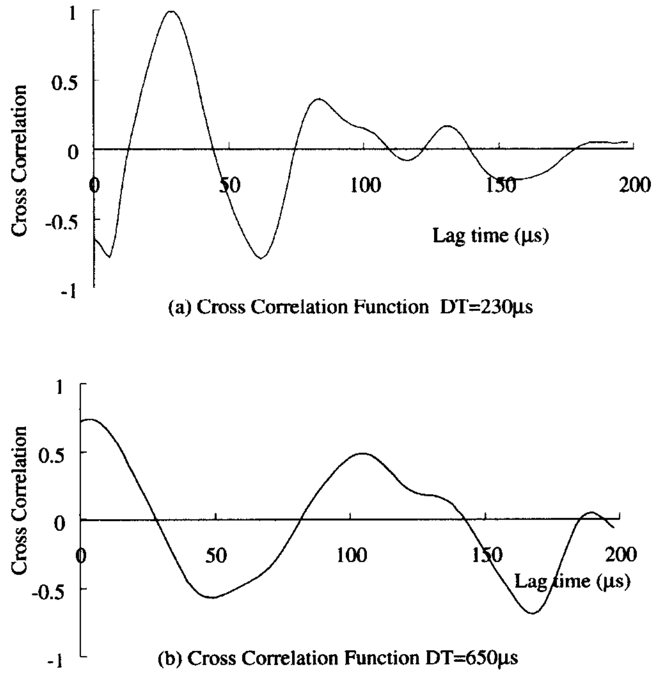


Figure-3 Cross correlation function at delay time 230μs and 650μs

The power spectrums shown in Figure-4 were obtained by using MEM (Maximum Entropy Method) spectrum analysis method. And horizontal axis in Figure-4 shows the frequency converted into the distance using the relationship shown in Eq.6. The reason why we use MEM for the spectrum analysis is as follows: As shown in Eq.1, the impulse response function of P waves should be obtained to detect the period of the multiple reflection or resonant frequency of the concrete plate. That is, deconvolution of Eq.1 should be given when no surface waves exist. The MEM spectrum generally gives the deconvolution of measured waves. And the fact that the MEM technique is better than FFT is verified in the later section of this paper.

For reference, the Fourier Power spectrums at the delay time 230 and 650 μs are shown in Figure-5. Though the peak value around 200mm is shown in Figure-5, there are many peaks and in the case of delay time 650μs, the amplitude of the peak at 90mm is almost the same to the peaks around 200mm. From the comparison between Figure-4 and Figure-5, it can be seen that the MEM technique is better than the FFT if we need to detect the thickness of the concrete plate.

The reason why the MEM is better than the FFT method for determining the thickness of the concrete plate is as follows: Even though it is important to be given the correct auto or cross correlation function before calculating the power spectrum function, the auto correlation function for the transient waves is not given by the FFT method, because the FFT method is premise on the steady state. On the other hand, the auto correlation function is estimated as the calculation parameters of the auto regression function of the steady state when the MEM is used for the transient signal analysis. And in addition, as mentioned above, though the frequency response function should be obtained for determining the thickness of the concrete plate, the only power spectrum function is given by the FFT method where the frequency response function of the P wave is estimated as the deconvolution of measured wave by the MEM.

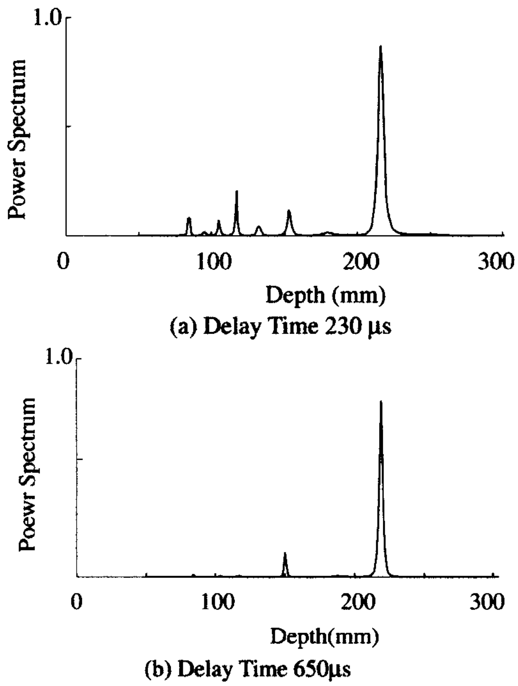


Figure-4 MEM Power Spectrum at 230 and 650μs in delay times for 200mm concrete plate

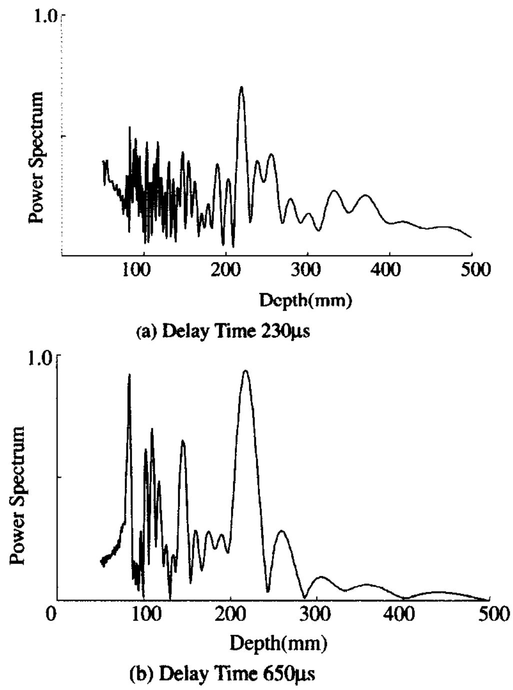


Figure-5 FFT Power Spectrum at 230 and 650μs in delay times for 200mm concrete plate

3. Time windows spectrum method

Though two of the measuring points were illustrated in Figure-1, P_1 signal was used for this method of analysis. This method premises a single channel data acquisition system. In this experiment, different masses of 9 steel balls from 5mm to 32mm diameter were employed as impactors.

Figure-6 shows power spectrums of each impactor and also shows the averaged power spectrum. The strokes of the steel balls are almost 50 to 100mm for any case of trial. There are no influence of the stroke of the steel ball to the frequency contain of measured signals, therefore the strokes of the steel balls were not described in Figure-6. The MEM (Maximum Entropy Method) was used for the frequency analysis.

The power spectrums shown in Figure-6 are weighted means of time window MEM spectrums in the condition of 1ms width of window time, 100μs time interval and 4ms of measuring time. To obtain the mean values of frequency spectrum, each time window MEM spectrums were normalized, as the total power becomes 1. Therefore, the power of multiple reflecting P waves was emphasized if the amplitude of P waves was weaker than surface waves.

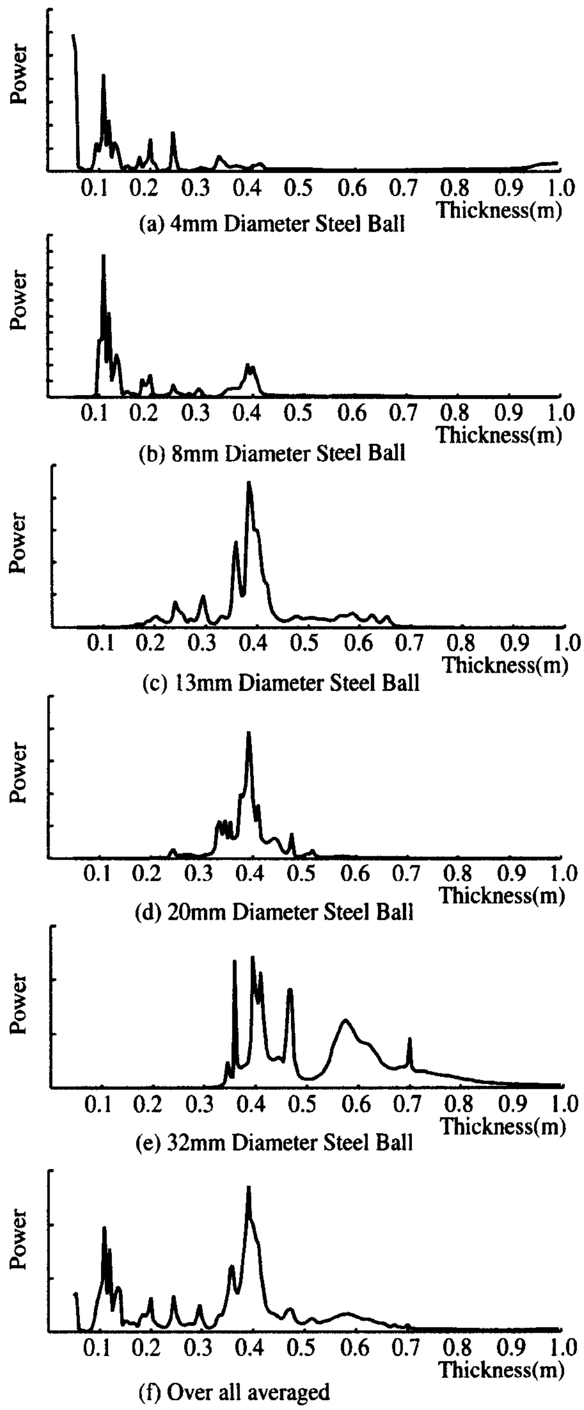


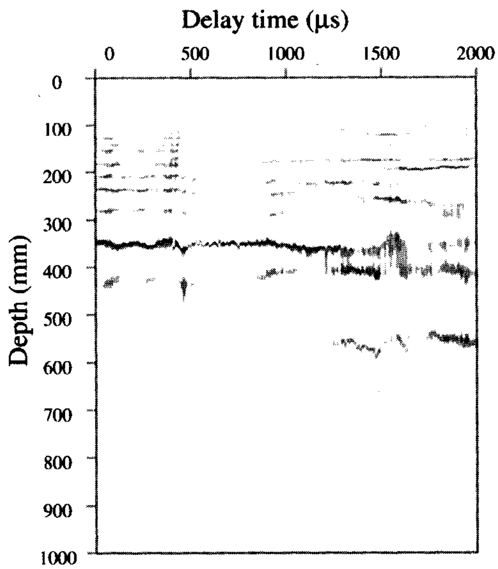
Figure-6 Power spectrums for different masses of impactors

Nine of steel balls were used but the results of 5 cases were shown in Figure-6 herein.

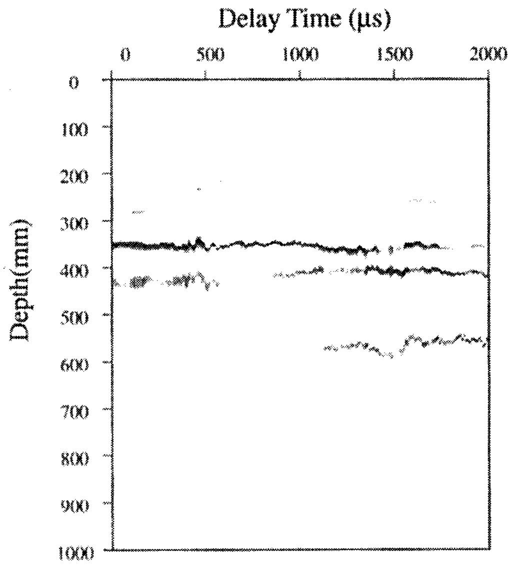
Frequency contain of power spectrums are different each other. For example, in the cases of the 4mm and 8mm diameter steel ball, there are no high amplitude spectrums in 400mm of the actual thickness of the tested concrete plate. However in the cases of the 13mm and 20mm, the thickness of the concrete plate is obtained as the high amplitude peak frequency. And if the 32mm steel ball is chosen, the thickness of the testing concrete plate is difficult to determine, because there are many peaks and a deepest peak appears around 700mm.

By considering the results of the power spectrums shown in Figure-6, we can figure that the thickness of the testing concrete plate may be around 400mm. Figure-6 (f), which shows an averaged MEM spectrum for all trials of each the mass of steel balls, makes this idea sound. That is, it can be seen that the means spectrum of all the steel balls minimizes the influence of individual impactor size. From the fact shown in Figure-6, this method is a powerful technique to detect the thickness of the plate when no information on that is given.

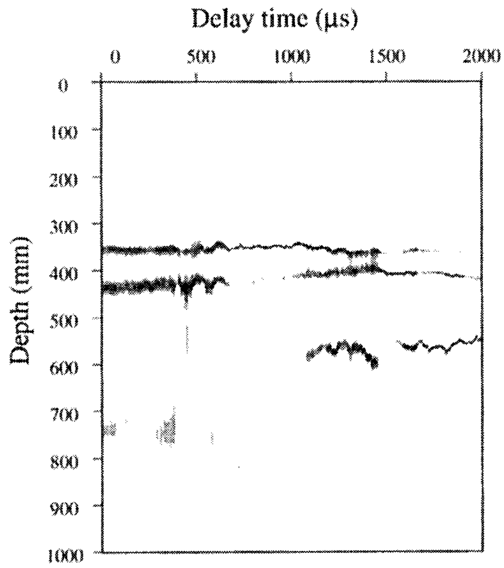
Figure-7 shows time change of the MEM spectrum for a 400mm thickness concrete plate impacted by 8, 20 and 32mm diameter steel ball. Though it is difficult to determine the thickness of the testing concrete plate from the MEM spectrum shown in Figure-6 (b), (e), it is clearly shown that the thickness of this plate is around 400mm, because high amplitude peaks around 400mm can be seen for almost all of the lag times. If the width of the time window used for the MEM analysis is three times wider than the round trip time of multiple reflection of P waves between both ends of the plate, the thickness frequency spectrum must be observed in any time window, because the resonant frequency is the most durable frequency component in the normal vibration systems. And also, patterns of the time window MEM



(a)8mm diameter steel ball



(a) 20mm diameter steel ball



(a) 32mm diameter steel ball

Figure-7 Time window MEM spectrum

Spectrums are almost the same between these cases of 8, 20 and 32mm steel ball impactors.
From these analyses, if the time window MEM spectrum is employed, the thickness of concrete plates are possible to determine even though smaller or larger impactors were chosen

4. Examination in the analysis methods

Fourier transform technique is prescribed for the frequency analysis in ASTM for the Impact-echo method to calculate the thickness of the plate.
As previously discussed, the purpose of the frequency analysis is to obtain the impulse response function of the P waves in the frequency domain. From this point of view, it seems that the Fourier transform technique is not the suitable method. If the measured waveform represented in Eq.1 is simply transformed into the frequency domain,

$$Y(\omega) = \{H_S(\omega) + H_P(\omega)\}X(\omega) \qquad \textbf{(8)}$$

Equation 8 is given where ω is the angle frequency. That is, FFT of the measured waveforms do not represent the impulse response function of the P waves. And unfortunately, the FFT technique cannot avoid the unexpected effect of the surface waves. If $H_S(\omega)$ as the frequency response function of the surface wave and $X(\omega)$ as the applied signal in the frequency domain are given, the frequency response function of the P wave $H_P(\omega)$ is solved as Eq.9.

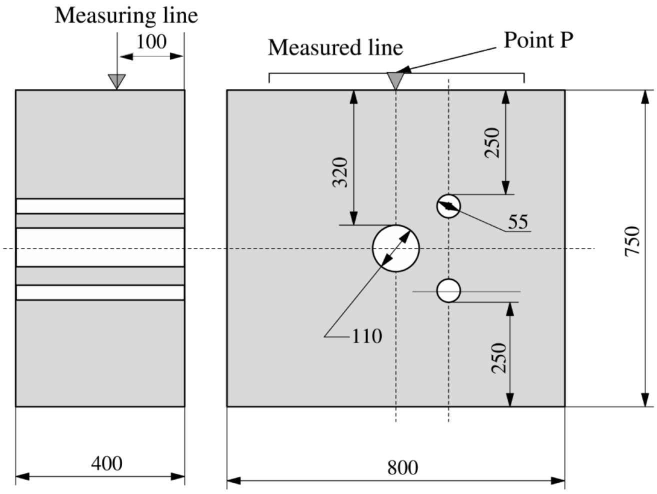
$$H_P(\omega) = \frac{Y(\omega)X^*(\omega)}{X(\omega)X^*(\omega)} - H_S(\omega) \qquad (9)$$

If the damping coefficient for the surface wave represented by Eq.1 is negligible, $H_S(\omega)$ becomes constant. Then Eq.8 becomes Eq.9.

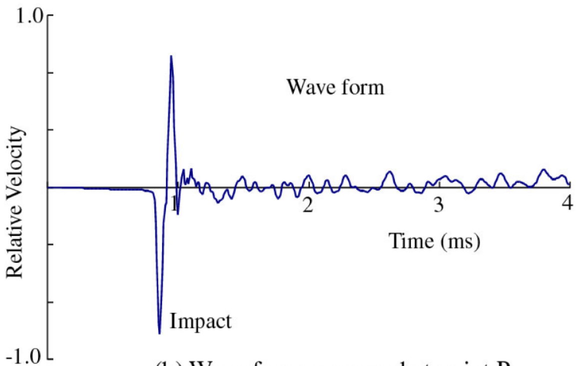
$$H_P(\omega) \approx \frac{Y(\omega)X^*(\omega)}{X(\omega)X^*(\omega)} \qquad (10)$$

Herein the denominator of Eq.10 is the auto power spectrum of the applied signal and the numerator is the cross power spectrum of the applied and measured signals. If the waveform of the applied signal is similar to the waveform of the surface wave, $H_P(\omega)$ can be obtained by the cross power spectrum of the clipped waveform where the surface waves are dominant and the measured waveform (Gokudan 1999).
The waveform for the analyses and a specimen concrete block tested are shown in Figure-8. The 15mm diameter steel ball was chosen as the impactor for this experiment.

Figure-8 Specimen concrete block

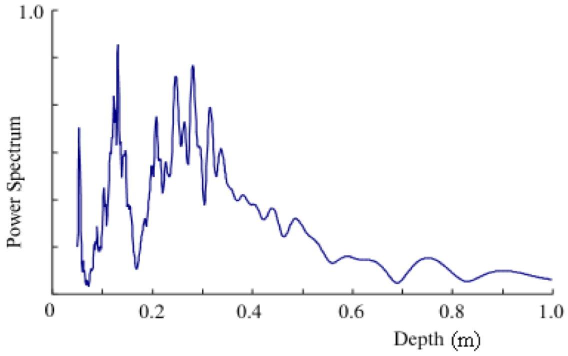


(a) Concrete block with boid hole

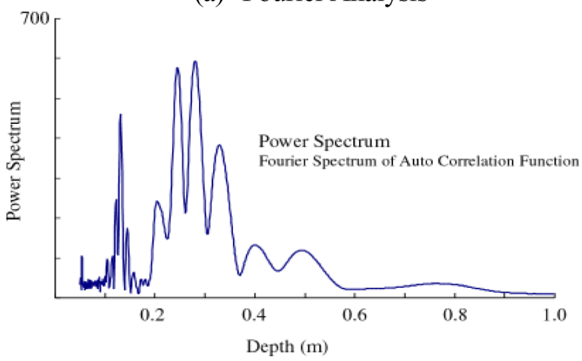


(b) Wave form measured at point P

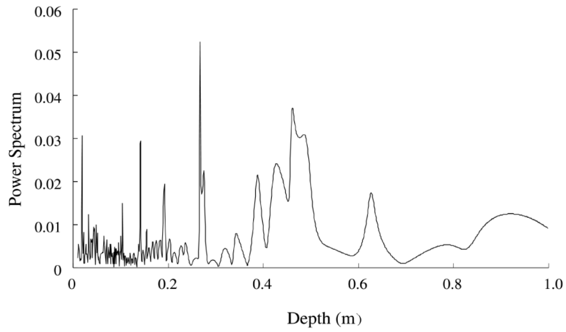
Figure-9 Specimen and waveform



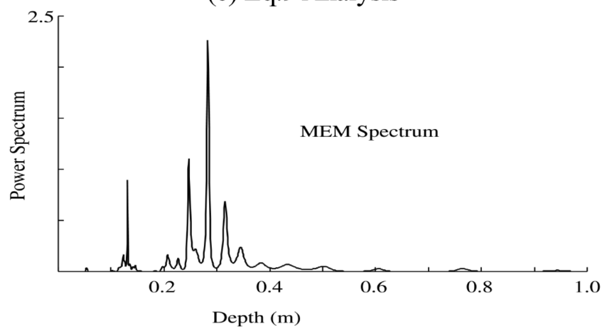
(a) Fourier Analysis



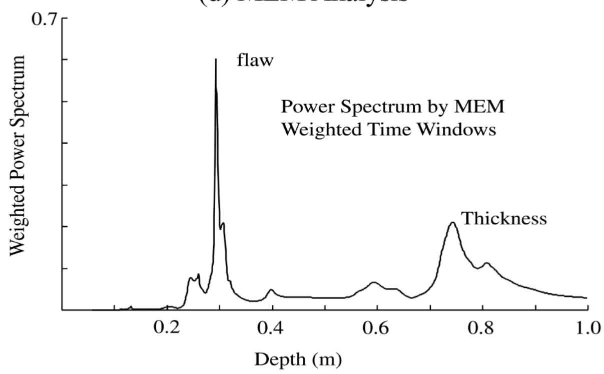
(b) Power Spectrum Analysis



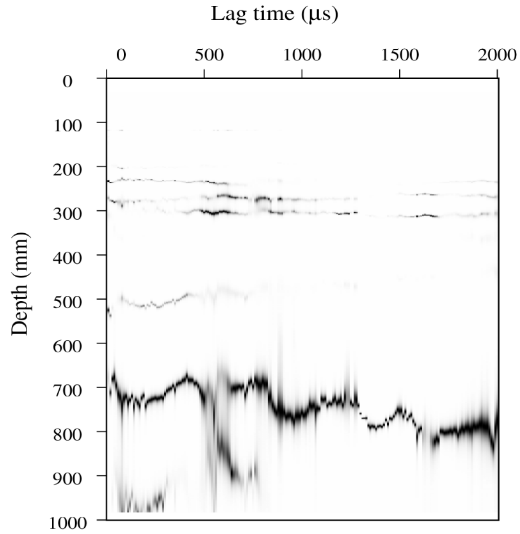
(c) Eq.9 Analysis



(d) MEM Analysis



(e) Time Weighted MEM Analysis



(f) Time Window MEM Analysis

Figure-10 Results of deferent analyses

Figure-10 shows the results of the frequency analyses by various methods. Though the waveform is the same for each analysis method, the results are quite different from each other.
Figure-10(a) is the results of the Fourier transform method used for the Standard Impact echo method. The Actual depth of the concrete block specimen is 750mm and there are void holes at the depth of 250,320 and 445mm. As shown in Figure-10(a), there is the highest peak at the 170mm depth and many peaks are at around the 300mm depth. The depth of the 170mm (11.3kHz) peak is considered as the frequency of the impactor (15mm diameter steel ball). The peaks around 300mm are reflection from the void holes. The frequency component of the thickness (750mm) is too weak to detect. These situations are the same to the power spectrum analysis shown in Figure-10(b). The peaks around 300mm become clearer, but the thickness of 750mm is not detected. The keen peak at the 320mm depth is observed in the cross power spectrum shown in Figure-10(c). The peak of the 320mm becomes a high amplitude and clear line spectrum by the simple MEM analysis shown in Figure-10(d), but the thickness of the specimen is still not observed. Figure-10(e) shows the results of the weighted time window MEM spectrum. The highest peak is indicates the location of the flaw, which depth is 320mm and the other peak at 750mm depth seems like the thickness of the specimen.
Figure-10 (f) shows the results of the time window MEM spectrum in a running spectrum form. High intensity spectrums around 750mm are remarkable. And spectrums of 250mm, 320mm and around 500mm are observed. The spectrums around 750mm are fluctuating because the signal is weak and the number of round trip times in the time window is small.
As the results of this analysis, following conclusions are made: (i) the thickness of the specimen seems to be 750mm or so, (ii) something like flaws are located at 270mm, 320mm and approximately 500mm in depth.

5. Conclusions

As the results of these experiments and analyses, the applicability of the impact vibration method for detecting the flaws and thickness of the concrete plate and block is certified. However, the FFT technique does not seem like a good tool to detect the resonant frequencies of the internal reflector in the concrete structures.
The reason way is seems that the FFT method is only a frequency analysis method for steady state signals and not for transient signals, where the MEM gives deconvolution of a response signal when the target system is considered to be driven by a white noise. Therefore, MEM is better than FFT method for estimating the frequency response function of the system. The running spectrum of MEM (Time window MEM spectrum) shows the good performance to detect the both internal flaws and the thickness of the concrete plates. And also this method is effective to avoid the unexpected influence of the impactor size.

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