Influence of the input frequency for soundness evaluation of concrete structure based on waveform analysis

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Abstract. In the soundness evaluation method based on waveform analysis in time domain, the response waveforms that are measured while the target is in sound condition is indispensable. Therefore, it is expected that this method is for the evaluation of precast concrete products because the state of the products is almost identical and it is able to measure the response waveforms before using the products. On the other hand, although there are difficulties to apply this method for the evaluation of the existing structures because the response waveform is not measured before using, it is expected that this method can be applied to the evaluation of the existing structures by making the response waveform on the basis of the numerical simulation. The computational conditions should be set properly based on the actual measurement conditions for the numerical simulation. Among the computational conditions, the input frequency is determined based on the diameter of the steel ball and contact time if the excitation is given by making an impact with the steel ball by using the theory proposed by Sansalone et al. However, Kubo et al. reported that the measured contact time is different from the theoretical value and the difference reaches maximum twice. The influence of the difference would not be negligible for the soundness evaluation and should be considered carefully to perform the soundness evaluation accurately. Therefore, in this study, the response waveforms are computed on a numerical model with excitations of various input frequencies, and the influence of the input frequency to the response waveform is discussed by comparing the computed response waveforms.

1. Introduction
In Japan, the quality and performance of structures are managed based on the results of testing that are performed during the construction and the service period of the structures to make the structures safe and longer life. In this background, non-destructive testing is frequency used because it gives information of a structure without any damage.

The impact elastic wave method is one of the non-destructive testing, for detecting the defects in the concrete structures. This method uses elastic waves that are excited by using a hammer or a steel ball as an input device. The frequency range of the elastic wave is relatively low, and it is suitable for the investigation of concrete structures due to the low attenuation of the input wave and long wavelength. However, it is known the conventional soundness evaluation method cannot be applied if the target is not a plate.

Therefore, in order to evaluate the position and size of internal defects regardless of the shape of the target structures, the authors propose a new soundness evaluation method that detects internal defects on the basis of change of the response waveform in time domain. On the other hand, there are difficulties
to apply this method for the evaluation of the existing structures. Because the response waveform is not measured generally at the initial state, it is impossible to compute the difference value for the structures. However, it is expected that this method can be applied to existing structures if the response waveforms can be obtained by numerical simulations. In the generation of response waveforms by the numerical simulation, the parameters for the simulation should be set properly to simulate the measurement conditions.

The input frequency in the impact elastic method is determined by calculating the contact time from the diameter of the steel ball using the theoretical formula proposed by Sansalone et al. [1]. However, Kubo et al. reported that the measured contact time is different from the theoretical value, and the difference reaches twice at a maximum [2]. The influence of this difference would not be negligible, and it is influence should be revealed.

Therefore, in this study, the response waveforms are computed on a numerical model with excitations of various input frequencies, and the influence of the input frequency to the response waveform is discussed.

2. Soundness evaluation method

2.1. Elastic Wave Method
Impact elastic wave method is an inspection method to evaluate a target by applying input wave to the target and observing the acoustic waves that is reflected at a defect or a boundary. This method uses the elastic waves that have relatively low frequency component that is emitted by using a hammer or a steel ball as an excitation. The use of the lower frequency component is suitable for the investigation of concrete structures, since the concrete structures are the composite materials and low frequency component is less, affected by the internal structure. Furthermore, the attenuation of lower frequency component is relatively small and propagates in longer distance as consequence.

Figure 1 shows a schematic diagram of the impact elastic wave method. Elastic waves are emitted by striking the concrete surface with an iron ball, and the emitted elastic waves are received near the excitation point. Focusing on the dominant frequency of the frequency spectrum obtained by frequency analysis of the response waveforms of multiple reflections in the depth direction, the method is widely used mainly to detect the thickness and internal defects of plate structures [1]. Figure 2 shows an example of a frequency spectrum diagram obtained using the FFT (Fast Fourier Transform). The vertical axis is the spectral intensity and the horizontal axis is the frequency. From the dominant frequency $F_{\text{max}}$ at this time, the thickness $D_p$ can be obtained from the relationship with the elastic wave velocity $V_p$, as shown in the following equation:

$$D_p = \frac{V_p}{2F_{\text{max}}}$$

However, it should be noted that the length and the width of the plate are sufficiently large in comparison with the thickness of the plate according to the Japanese Society Non-Destructive Inspection standard "NDIS2426-2: Non-destructive examining of concrete-elastic wave method-Part 2: Impact elastic wave method" [3]. This is because, the reflection path of the waves is complicated if the shape of the plate is not like a plate, the assumption is not fulfilled and the dominant frequency corresponding to the depth direction cannot be observed.

For this reason, conventional evaluation principles are not applicable to structures of rectangular cross sections such as columns and beams. In addition, in the evaluation of internal defects focusing on the dominant frequency, the change of the dominant frequency with the size and the position of the defect has not been concretely clarified. Although it is possible to evaluate the planar position and size of the defect, it is not possible to evaluate the position and size of the defect in the thickness direction.
2.2. **Response Waveform Analysis in Time Domain**

Figure 3 shows a schematic diagram of the measurements in the impact elastic wave method using response waveform in time domain. The index value of the soundness evaluation is the difference value that is computed by using response waveforms in time domain. This difference value shows the amount of change in the response waveform in time domain. Figure 3 (a) and (b) illustrate approximated wave paths in a model without void and with a void respectively. The difference of the model is only the existence of the void, and the change of the response wave form caused by the void is shown in figure 3 (c) as an example. The difference value \( D \) is proposed as equation (2), and the position and size of internal defects are evaluated on the basis of the difference value.

\[
D = \frac{1}{N} \sum_{i=1}^{N} (f_i - f'_i)^2
\]  

where \( f_i \) is the amplitude value of the response waveform in the time domain without void, \( f'_i \) is the amplitude value of the response waveform in the time domain with void, and \( N \) is the number of data measured in the sampling interval values.
2.3. Advantage of Response Waveform Analysis in Time Domain
This soundness evaluation method based on the waveform analysis in time domain can be applied to the structures of any shape, and it is expected that the method is applied for soundness evaluation of the existing structures. In particular, this method is advantage if the structure is constructed by using products since the response waveform before using can be measured and it can be used for the other structurers that are consecrated by using the same products. In addition, it has been confirmed from previous studies that it is possible to evaluate the size and position of internal defects by providing multiple measurement points [5-7].

On the other hand, although there are difficulties to apply this method for the evaluation of the existing structures if the response waveform is not measured before using, However, it is expected that this method can be applied to the evaluation of the existing structures if the response waveform in the soundness condition can be obtained in numerical simulation. Furthermore, the generation of intact response waveforms by the simulation eliminates the need to measure them in advance, and the effect of internal defects on the response waveforms can be understood in advance by the numerical simulation.

3. Problem in generating soundness response waveforms by numerical simulation

3.1. Setting condition of input frequency in numerical simulation
For the generation of response waveforms by numerical simulation, it is important to set the appropriate initial condition of the structure and determine the measurement conditions. Among these parameters, the related the analysis model and the measurement point are easily determined. On the other hand, are should be care full determined if the not observable directly. The input frequency in this measurement method is calculated from the contact time between the steel balls used for input and the concrete, and the theoretical expression for this contact time is proposed by Sansalone et al. [1].

3.2. Input frequency by steel ball contact time
Assuming that the collision phenomenon between steel ball and concrete is theoretically developed based on Hertz contact theory, the contact time $T_c$ can be obtained by equation (3) [4].

$$T_c = 4.53 \left\{ \frac{(\delta_s + \delta_c)m_s}{\sqrt{R_s} v_0} \right\}^{\frac{2}{5}}$$

where $m_s$ is the mass of the steel ball, $R_s$ is the radius of the steel ball, $v_0$ is the impact velocity of the steel ball, $\nu_s$ is the Poisson's ratio of the steel ball, $E_s$ is the modulus of elasticity of the steel ball, $\nu_c$ is the Poisson's ratio of the concrete, and $E_c$ is the modulus of elasticity of the concrete. In equation (3)

$$m_s = \rho_s V_s$$

$$v_0 = \sqrt{2gh}$$

if we organize the equation as:

$$T_c = 5.97R_s \frac{\{(\delta_s + \delta_c) \rho_s\}^{\frac{2}{5}}}{h^{0.1}}$$
it is organized as in equation (8). \( \rho \) is the density of the steel ball, \( V \) is the volume of the steel ball, \( g \) is the gravitational acceleration, and \( h \) is the falling height of the steel ball. In equation (8), if we substitute general physical properties for each material constant, convert the steel ball radius \( R_s \) to steel ball diameter \( d_s (=2R_s) \), and assume that the effect of drop height can be neglected, we can obtain equation (9), which is the relationship between contact time and steel ball diameter proposed by Sansalone et al. [1].

\[
T_c = 0.0043d_s
\]  

(9)

And the maximum frequency (\( F_{max} \)) of the input elastic wave is given as the inverse of the contact time as shown in the following equation.

\[
F_{max} = \frac{1}{T_c}
\]  

(10)

3.3. The authenticity of the theoretical value of contact time

However, since concrete is not perfectly elastic, the theoretical and actual contact times generally do not coincide. For this reason, Kubo et al. conducted a verification experiment on the difference from the theoretical value. In this experiment, a sheet sensor was attached to the impact surface of several concrete specimens with different material strengths, and the contact time of steel balls of various diameters was verified experimentally.

According to the results, the difference between the theoretical and experimental values is reported to be at most twice as large. This difference is not negligible for the generation of response waveforms by numerical simulations and should be carefully examined.

In this study, the influence of the input frequency on the response waveforms is investigated by calculating the response waveforms in are numerical models with various input frequencies and comparing the calculated response waveforms.

4. Overview of numerical simulations

4.1. Experimental model and parameters of numerical simulation

The FDTD (Finite-Difference Time-Domain) method, which is the numerical simulation method used in this paper, is one of the finite difference methods. This method was proposed as a numerical simulation method to formulate Maxwell's equations by the difference method and analyze them in the time domain. Similarly, the wave equation for propagation of elastic waves in a solid material is also formulated by the FDTD method [8].

Figure 4 shows the simulation model used in this study, and table 1 shows the model size and measurement position. This model is an off-the-shelf concrete plate that is standardized in Japan. In this study, measurements were also made under the same conditions as in the numerical simulation in order to compare the calculated and experimental waveforms. The parameters of the numerical simulation were set as shown in table 2 from the results of the experimental values.

![Simulation model](image-url)
Table 1. Model size and measurement conditions.

| Length (mm) | L=X | 910 | Coordinates | X | Y | Z |
|-------------|-----|-----|-------------|---|---|---|
| Height (mm) | b=Y | 300 | Input point (mm) | 455 | 0 | 30 |
| Width (mm)  | d=Z | 60  | Output point (mm) | 400 | 0 | 30 |
| Steel round bar (mm) | A and B | 6 | Grid size (mm) | 10 | 10 | 10 |

Table 2. Parameters of numerical simulation.

|                         |                   |
|-------------------------|-------------------|
| Primary wave velocity: $V_p$ | 4300 m/s |
| Density: $\rho$         | 2000 kg/m$^3$    |
| Lamé’s constants: $\lambda$ | 9.24 Gpa |
| Lamé’s constants: $\mu$  | 13.9 Gpa         |
| Attenuation coefficient | 0.03              |
| Sampling frequency      | 2.00 MHz          |
| Grid size               | 10.0 mm           |
| Calculation data: $n$   | 1000              |

4.2. Calculation conditions of numerical simulations

The input signal in the numerical simulation is a sinusoidal signal of one wavelength of the set input frequency. The calculated response waveform is subjected to LPF for smoothing. In this study, the Cut-off frequency was set to 80 kHz and LPF processing was performed. In addition, elastic wave method uses the artificial excitation, variation in input energy occurs. Therefore, in the experimental measurement waveform, the amplitude of the response waveform is normalized by the absolute value of the maximum amplitude. For this reason, it is normalized in the same way in this numerical simulation.

The simulation was performed under two conditions. In Case 01, the influence of changing the input frequency on the generation of the response waveform was studied. In Case 02, the experimental values measured with a steel ball diameter of 16 mm were used as a reference, and the generated of response waveforms that approximate the experimental result are compared with the reference wave. The input frequency $F$ shown in table 4 is the theoretical input frequency by equation (3).

Table 3. Calculation condition of Case 01.

| Input frequency (kHz) |
|-----------------------|
| 5.0                   |
| 10.0                  |
| 20.0                  |
| 40.0                  |
| 60.0                  |
| 80.0                  |

Table 4. Calculation condition of Case 02.

| Input frequency of steel ball |
|-------------------------------|
| $ds$: 16.0 mm, $F$: 14.5 kHz  |

| Variations of input frequency in numerical simulation (kHz) |
|------------------------------------------------------------|
| 5.0 | 7.8 | 10.0 | 12.5 | 14.5 | 16.5 | 20.0 |

5. Results and discussions

5.1. Results of Case 01

The response waveforms calculated under the conditions of Case 01 are shown in figure 5. The horizontal axis of the figure is time and the vertical axis is amplitude. It can be visually understood that there is little difference in the shape of the calculated response waveform if the input frequency is
changed from 40 kHz to 80 kHz. However, the input frequency is changed from 5 kHz to 20 kHz, the change of the shape of the calculated response waveform are relatively large. Figure 6 shows the difference values between the response wave from of 80 kHz of input frequency and the other response waveforms. The number of data used for the calculation is 1000. The figure shows that as the input frequency becomes lower, the difference value also increases. This shows that the calculated response waveform changes with the input frequency, and the amount of change is smaller at higher input frequencies and larger at lower frequencies in the numerical simulation. This is due to the fact that the wavelength changes with the input frequency. Since the input frequency used in the measurement of the impact elastic wave method is relatively low, the change of the response waveform calculated by the numerical simulation would be large. These results suggest that the input frequency greatly influences the results of the response waveform.

Figure 5. Case 01: Response waveforms.

Figure 6. Difference value of the response waveform of Case 01 with based on 80 kHz waveform.

5.2. Results of Case 02

The response waveform calculated for Case 02 is shown in figure 7. The red dashed line in the figure is the experimental value measured using a steel ball with a diameter of 16 mm. figure 8 shows the results of the difference values calculated based on the experimental waveforms. The theoretical value of the frequency input from the steel ball used is 14.5 kHz. From the figure, the difference value calculated with respect to the experimental value decreases as the input frequency decreases from 20 kHz to 10 kHz, and then increases, with the value reaching its minimum at 10.0 kHz. This result suggests that a lower frequency than the theoretical value is also input in the results of numerical simulation.

Figure 7. Case 02: Response waveforms.

Figure 8. Difference value of the response waveform of Case 02 with based on experimental waveform.
6. Conclusion

In this paper, the influence of the input frequency on the generation of the response waveform under soundness conditions is investigated by numerical simulation a concrete plate model. The results are summarized as follows:

(a) the shape of the calculated response waveform changes with the change of the input frequency, and the change is large at the lower input frequency;

(b) as a result of comparing the experimental waveform and the numerical simulation waveform, the difference value was minimized when the frequency was calculated at a frequency lower than the theoretical value. As a result, the difference between the theoretical value and the experimental value was seen in this study as well, and it was confirmed that it is necessary to pay attention to the input frequency setting even in the numerical simulation.

From the above results, it can be predicted that the numerical simulation model of this study requires the input frequency to be set lower than the theoretical value in order to calculate the response waveform of the experimental value, and by setting appropriately, it is possible to generate the response waveform during soundness by numerical simulation.

References

[1] Mary J S and William B S 1997 IMPACT-ECHO: Nondestructive Evaluation of Concrete and Masonry New York: Bullbrier Press Ithaca

[2] Kubo G, Uchida S, Iwano S, Yamashita K and Sumitani K 2017 Experimental Study on Frequency of Elastic Wave Input to Concrete by Steel Ball Proceedings of the Concrete Structure Scenarios, JSMS 17 pp 515-520 (in Japanese)

[3] Japanese Society Non-Destructive Inspection Standard 2014 NDIS2426-2: Non-destructive examining of concrete-elastic wave method-Part 2: Impact elastic wave method (Tokyo: Japanese Society Non-Destructive Inspection)

[4] Goldsmith W 1960 Impact: The Theory and Physical Behavior of Colliding Solids (London: Edward Arnold)

[5] Ikebata K, Kobayashi Y, Oda K and Nakamura K 2019 Experimental Study on Detection of Voids in Concrete Slab by Using Responses in Time Domain Inspection Annual Meeting of the Japanese Society for Non-Destructive pp 93-96 (in Japanease)

[6] Ikebata K, Kobayashi Y, Oda K and Nakamura K October 2020 Detection of Defects in Rectangular Cross-Section Structure by Using Responses in Time Domain on the Basis of Numerical Investigations Proceedings of the Concrete Structure Scenarios, JSMS 20 (in Japanese)

[7] Ikebata K, Kobayashi Y, Oda K and Nakamura K 2020 Detection of Defects in Concrete Slab by Using Responses Time Domain on the Basis of Numerical Investigations Inspection Annual Meeting of the Japanese Society for Non-Destructive (in Japanese)

[8] Fujioka T, Nagata Y and Abe M 2017 Experimental and Numerical Analysis for Non-Destructive Inspection of a Void in a PC Sheath by using an Impact Elastic Wave Method Journal of Japanese Society for Non-Destructive Inspection 66 pp 443-450 (in Japanese)