An Application of Burst Elastic Wave to Nondestructive Testing for Concrete Structure

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Abstract
We propose a method of applying burst elastic waves to test concrete structures in a nondestructive way. Elastic waves are produced by an actuator which generates bursts of intermitted waves. By measuring the vibration of an object between bursts the affect of the actuator can be reduced. We apply the present method to two types of defects in concrete specimens; a circular void defect with a diameter of 20 cm at a depth of 10 cm and a void defect in a tendon duct. We show the imaging of the circular void defect and the detection of the presence or absence of grout in the tendon duct.

Keywords: Burst Elastic Wave, Nondestructive Testing, Concrete, Tendon Duct, Defect

1. Introduction

There are several methods of detecting defects in concrete structures such as the X-ray method, the radar method, and the elastic wave method. The elastic wave method can be broken into the ultrasonic method, the impact echo method [1] and the acoustic method. All of these methods are effective in detecting shallow delimitations or defects. However, a useful and reliable inspection technique for detecting the presence of grout in a tendon duct has not yet been developed. The detecting the presence of grout in a tendon duct and the defect detection is essentially the same problem. The difference is that the grout is found in a steel duct and in comparatively deep parts of the concrete structure. Therefore, we believe if we can make the detection of defect more accurate that it will improve the detection of the presence of grout.

In this paper, we propose the burst elastic wave method which combines the good features of the ultrasonic method and the impact echo method. We apply the present method to two types of defects in concrete specimens; a circular void defect with a diameter of 20 cm at a depth of 10 cm buried in a concrete specimen and a void defect in a tendon duct.

2. Principal of the burst elastic wave method

2.1 Features and problems of ultrasonic method and impact-echo method

The features of the ultrasonic method, the impact echo method, and the burst elastic wave method are shown in table 1. In the ultrasonic method, defects are detected by ultrasonic waves generated by a probe. Information of a defect is obtained based on the arrival time or/amplitude of the ultrasonic wave reflected from the defect. The frequency of the ultrasonic waves is from 100 kHz to 100 MHz. Small defects can be detected by using high frequency and short wave lengths. However, it is difficult to obtain the information in deep parts of concrete structures due to the diffusion of the ultrasonic waves. Moreover, the vibration energy generated by a probe is weak for large concrete structures.

In the impact echo method [1], elastic waves are generated by tapping a steel ball or a hammer. The vibration is measured with an accelerometer. The frequency of the standing waves is measured. The frequency used in this method is up to 50 kHz because high
frequency elastic waves cannot be generated by the tapping. The low frequency is advantageous for the inspection of concrete structure. One problem is that the distribution of the frequency of the vibration generated by the tapping of a steel ball occasionally fluctuates. It is likely the key frequency content is missing. This causes an accuracy deterioration of dimension measurements or even overlooking defects.

**Table 1** Comparison among the ultrasonic method, the impact echo method and the burst elastic wave method

<table>
<thead>
<tr>
<th>Method</th>
<th>Excitation method</th>
<th>Measuring method</th>
<th>Frequency</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic method</td>
<td>Probe</td>
<td>Probe</td>
<td>100 kHz - 100 MHz</td>
<td>Reflection time Reflection amplitude</td>
</tr>
<tr>
<td>Impact-echo method</td>
<td>Steel ball</td>
<td>Accelerometer</td>
<td>100 Hz - 50 kHz</td>
<td>Frequency and amplitude of standing wave</td>
</tr>
<tr>
<td>Burst elastic wave method</td>
<td>Piezoelectric actuator</td>
<td>Accelerometer</td>
<td>100 Hz - 50 kHz</td>
<td>Frequency and amplitude of standing wave</td>
</tr>
</tbody>
</table>

**2.2 Burst elastic waves**

The authors propose the method of using burst elastic waves for nondestructive evaluation as shown in figure 1. The vibration is measured between the burst excitations. Elastic waves are generated by a laminated piezoelectric actuator and the vibrations are measured by an accelerometer as shown in figure 2.
The advantage of the burst elastic wave is that the elastic waves with an accurate frequency and steady strength can be generated. Excitation up to about 100K hertz is possible in case of using an accumulating piezoelectric actuator. The vibration energy has theoretically no limitation by increasing the burst-number of the elastic waves. Moreover, the synchronization of the signal is easy, and the average in the time-domain of the detection signal and the correlation can be calculated.

Another good point is that the excitation time and the measurement time can be separated. The influence of the direct vibration due to the actuator can be reduced by making measurement between burst excitations.

2.3 Frequency modulation of burst elastic waves

The frequency of the burst elastic waves should be modulated because the standing wave is the target in the burst elastic wave method. The frequencies of the standing waves for various defects are unknown. The frequency range of the burst elastic waves should contain the frequency of the standing wave.

There are several methods of the frequency modulation in the burst elastic wave method as shown Fig. 3. Figure 3(a) shows the burst wave when the frequency is swept in one burst signal. In the burst elastic wave method the measuring vibration just after the excitation is important. In this one signal sweep, some interval occurs between the beginning of the burst signal and the starting of the measurement. This may cause the accuracy deterioration for the frequency at the beginning of the burst signal.

Figure 3(b) is using white noise. White noise can theoretically contain an arbitrary frequency range. However, one burst signal can't contain the required frequency range because the duration of one burst is short and the number of waves contained in one burst is limited.

Figure 3(c) shows a method that the frequency of one burst signal is constant and the frequency in each burst signal is changed. In this method accurate frequency and stable excitation amplitude is possible. Moreover, a specific frequency may not become dominant because each frequency of the excitation is measured just after the excitation. Therefore, we adopt this one frequency in one burst method in this paper.

![Figure 3](image)

Figure 3 Types of burst elastic waves

3. Experimental method

The experimental system is shown in Fig. 4. Burst signals are generated with a personal computer. The signals are amplified and drive an accumulating piezoelectric actuator (NEC/TOKIN AE1010D44H40F). The vibrations of a wall are converted into electric signals
with an acceleration sensor. The signals are acquired by a personal computer. The distance between the piezoelectric actuator and the accelerometer is four centimetres.

One burst signal has ten sinusoidal waves. The interval time between the burst signals is 200 ms. One measurement consists of eleven burst signals. The frequency change between burst signals is ten percent of the frequency. Measurement duration is 100 ms just after the excitation.

4. Application for an inspection of an artificial circular defect

4.1 Specimen

Figure 5 shows a cubic specimen with an artificial circular defect. The mixture proportion of the specimen is shown in Table 1. The dimensions of the specimen are 500 mm square. The diameter and the thickness of the defect are 200 mm and 10 mm, respectively. The depth, \( d \) of the defect is 25 mm, 50 mm and 100 mm. The density, the Young's coefficient and Poisson's ratio is 2580 kg/m\(^3\), 25 GPa and 0.19, respectively.
### Table 2 Mixture proportion

<table>
<thead>
<tr>
<th>Nominal strength (N/mm²)</th>
<th>Slump (cm)</th>
<th>Maximum grain size (mm)</th>
<th>Water to cement ratio (%)</th>
<th>Sand-total aggregate ratio (%)</th>
<th>Quantity per unit volume (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Water</td>
<td>Cement</td>
<td>Fine aggregate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W</td>
<td>C</td>
<td>S</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>20</td>
<td>66</td>
<td>50</td>
<td>183</td>
</tr>
</tbody>
</table>

#### 4.2 Experimental results

The accelerations of the specimen surface were converted into frequency spectrums by the fast Fourier transform (FFT), and the frequency spectrums were averaged. Figure 6 is an example of the frequency spectrums measuring a defect at 100 mm depth. The measurement point was on the axis of the centre of the circular defect. We can see a sharp peak at 3kHz as shown in Fig.6.

![Acceleration vs Frequency](image)

**Figure 6. Frequency spectrum of a specimen with a defect (d = 100mm)**

The sound speed of the specimen obtained from the above-mentioned material properties is $C_p = 3300$ m/s. The natural frequency, $f_l$ of longitudinal wave multiple reflections is obtained by the equation [2] as follows:

$$f_l = \frac{0.96 \cdot C_p}{2d} = \frac{0.96 \cdot 3300}{2 \cdot 0.1} \approx 16 \text{ kHz}$$  \hspace{1cm} (1)

The resonant frequency, $f_i$ of the circular disk plate between the defect and the specimen surface can be estimated by the expression of the natural frequency of a circular disk with the fixed edge [3,4];

$$f_i = \frac{K_n d}{4\pi a^2} \sqrt{\frac{E}{3(1 - v^2)\rho}}$$ \hspace{1cm} (2)

where $a$ and $d$ are the diameter and the thickness of the circular disk, and $K_n$ is a coefficient calculated based on the vibration mode. The coefficient, $K_n$ becomes 4.99 when the vibration mode is the primary vibration.

Substituting the material properties and $K_n = 4.99$ into Eq. (2), we find

$$f_i = 7.3 \text{ kHz}$$ \hspace{1cm} (3)
The frequency of 3 kHz obtained by the experiment can be considered as the resonant frequency. The actual frequency becomes lower for two reasons. One reason is that the edge of the circular disk is not fixed perfectly. Another reason is that the defect is made of polystyrene, and the polystyrene resists the vibration of the circular disk.

Figure 7 shows a vibration amplitude map. Measures are made on grid points with 4 cm intervals. From Fig. 7 we can make a defect map by making the measurement point intervals one fifth of the size of the target defect. Evidence that the frequency of 3 kHz is the resonant frequency can be seen in Fig. 7, where the amplitude of the vibration at the centre is larger than that at the edge.

We were able to obtain similar results for specimens with a defect at 25 mm depth and 50 mm depth.

![Figure 7 Map of surface vibration of a specimen with a defect (d = 100mm)](image)

**5. Application for the detection of the existence of grout in a tendon duct**

**5.1 Specimen**

We tried to detect the existence of grout in a tendon duct. This detection is difficult when using the conventional elastic wave methods. The specimen is shown in Fig. 8. The diameter of the tendon duct is 45 mm and the diameter of the PC steel bar is 36 mm. We examined two types of specimens with grout and un-grouted tendon ducts. The mixture proportion is equal to that of the specimen in Fig. 5, and is shown in Table 2.

![Figure 8. Specimen for grout evaluation](image)
We measured the thickness frequency between the sides having a width of 400 mm to evaluate the speed of the longitudinal elastic wave by the impact echo method. The thickness frequency was 4.3 kHz. Therefore, the longitudinal elastic wave speed, $C_p$ of these specimens can be obtained as follows [3]:

$$C_p = \frac{2d \cdot f_i}{0.96} = \frac{2 \times 0.40 \times 4300}{0.96} \approx 3600 \text{ m/s} \quad (4)$$

5.1 Experiment results

We measured the 500 mm x 600 mm side and the 400 mm x 600 mm side. In the measurement of the 500 mm x 600 mm side, the depth of the centre of the tendon duct is 200 mm. In the measurement of the 400 mm x 600 mm side, the depth of the centre of the tendon duct is 250 mm. The distance between the tendon duct and the specimen surface for these specimens is about 180 mm and 230 mm, respectively.

The frequencies of the longitudinal wave vibration between the tendon duct and the specimen surface is estimated as follows;

In the case of $d = 200$ mm,

$$f_i = \frac{0.96 \cdot C_p}{2d} = \frac{0.96 \cdot 3600}{2 \cdot 0.18} \approx 9.6 \text{ kHz} \quad (5)$$

In the case of $d = 250$ mm,

$$f_i = \frac{0.96 \cdot C_p}{2d} = \frac{0.96 \cdot 3600}{2 \cdot 0.23} \approx 7.5 \text{ kHz} \quad (6)$$

Figures 9 and 10 show the frequency spectrums of the tendon duct at 200 mm centre depth and 250 mm centre depth. These results are the average of the ten measurements. The peak frequencies in Figs. 9 and 10 are close to the frequencies in Eqs. 5 and 6, and are considered as the frequencies of the longitudinal wave vibration between tendon duct and the specimen surface.

Figures 9 (a) and 10 (a) are the case of the grouted tendon duct and Figs. 9 (b) and 10 (b) are the case of the un-grouted tendon duct. The difference in the frequency spectrum due to the existence of grout is the number of peaks and the height of the peaks. In the case of the grouted tendon duct, two peaks exist in the frequency spectrum. However, in the case of the un-grouted tendon duct, only one peak exists.

It is considered that this difference is caused by the difference of the length of the elastic wave path. The elastic wave path is illustrated in Fig. 11. In the case of a grouted tendon duct, the elastic wave is reflected from the tendon duct and the PC steel bar. There are two different lengths of elastic wave path. Therefore, two peaks appear in the frequency spectrum. However, in the case of an un-grouted tendon duct, there is only one elastic wave path. Therefore, only one peak appears in the spectrum.

The height of peak in a frequency spectrum expresses the amplitude of vibration. The peak becomes higher as the amplitude of vibration becomes larger. In the case of an un-grouted tendon duct, elastic waves are reflected perfectly because the inside of the tendon duct is void. Therefore, the energy of the reflected elastic waves become larger, and the peak in the frequency spectrum becomes larger. Accordingly the existence of grout is determined based on the number and the amplitude of peaks in the frequency spectrum of the surface vibration.
Figure 9 Results of tendon ducts of 200 mm centre depth

Figure 10 Results of tendon ducts of 250 mm centre depth

Figure 11 Difference of elastic wave path

6. Conclusion

We proposed a method of applying burst elastic waves to test concrete structures in a nondestructive way. It is called "the burst elastic wave method." We applied the present method to the inspection of two types of defects in concrete specimens; a circular void defect and a void defect in a tendon duct. According to the results we conclude as follows:

(1) We need a burst signal that contains at least ten sine waves to get enough information. We also found that a one percent frequency shift in bursts giving good results.

(2) Using the burst elastic wave method, a circular void defect with a diameter of 20 cm at depth of 10 cm can be detected. Defects can be imaged by making grid measurements of one fifth intervals compared to the target defect size.

(3) Using the burst elastic wave method, it is possible to detect the existence of grout in a tendon duct with a diameter of 45 mm at a depth of 250 mm. The existence of grout is determined based on the number and the amplitude of peaks in the frequency spectrum of the surface vibration.
References

2. Reference 1, pp. 51.