Non-Contact Acoustic Inspection Method using Air-borne sound for Concrete Structures

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Abstract
We study a non-contact inspection method using air-borne sound for concrete structures. In this method, the concrete surface is excited by air-borne sound wave emitted with a high-powered sound source, and then the vibration velocity on the concrete surface is optically detected by a scanning laser Doppler vibrometer (SLDV). From the experimental result, we confirmed that the bending resonance frequency detected was proportional to the depth of the circular defect, and was in inverse proportion to the plane size (area) coincident to the analytical result for a circular plate. Moreover, we confirmed that the very small crack using a pillar test object could also be detected. We also found that the vibration energy of the defect shows a strong dependency on its depth. Finally the defect of the real concrete structure could also be detected and practicality of this technique was clarified.

Keywords: Non destructive test, non-contact inspection, long range acoustic device, scanning laser Doppler vibrometer, non-contact acoustic imaging

1. Introduction

Hammering test is widely used to inspect the peeling defects in concrete structures. However, this method has a major difficulty in inspecting a high-place, such as a tunnel roof or a bridge girder. Moreover, its detection accuracy is dependent on a tester’s experience. Various kinds of NDT technologies have been developed for inspection, and these methods are used as the situation demands. Common problems among these methods are that a tester must approach to a concrete surface. Infrared method is the well-known method as non-contact inspection method. Although this method can be conducted an inspection at a long range (within 30 m), it has difficulty in inspecting a place out of the sun, for example, a tunnel roof and a bridge girder. Therefore, several non-contact and quantitative inspection methods have been developed. One of the proposed methods, there is non-contact acoustic inspection method, which based on a sound excitation and optical vibration measurement. The method has been proposed with a purpose of land-mine detection [1], non-destructive inspection of concrete structures [2]. A potential disadvantage of the method is that a sound wave has a heavy attenuation in the air. Using a loud speaker, a sufficient energy of an excitation for a concrete surface is unavailable at a practical distance of 5 m or more. Thus we proposed a non-contact acoustic imaging method which consists of a high-powered sound source and an SLDV (Scanning Laser Doppler Vibrometer). Our proposed method is a combination of an area excitation by using a sound wave and an efficient measurement by using the SLDV. A long range acoustic device (LRAD) is used as a high-powered sound source. The LRAD is a powerful speaker which can maintain a sound pressure of 100 dB or more at a distance of 10 m. In order to investigate the defective detection performance of our proposed method, the experiment which used various concrete test objects (circular defect, peeling defect) was conducted [3]. Moreover, in order to investigate practicality, investigation with real concrete was also performed.
2. Principle of non-contact acoustic inspection method

The fundamental concept of conventional non-contact acoustic inspection method is shown in Fig. 1. If a defect such as a cavity or a crack exists in a shallow part under concrete surface, the upper part on the defect behaves like vibrating plate. When the damaged part is excited, a flexural vibration is caused on the damaged part. Therefore, the defective part has a resonance frequency of flexural vibration. The flexural vibration is excited by an airborne sound wave, which contains the resonance frequency component. The vibration speed of the concrete surface is optically detected by the SLDV. After frequency analysis, this vibration speed signal from the defective part shows characteristics due to the natural resonance of the defect structure. The defective part can be detected by the spatial distribution of the vibration speed signal, because the abnormal vibration signal is observed only on the damaged part.

Assuming that an existing defect is a circular shape, the damaged part can be approximated as a simply supported circular plate. Hence, first resonance frequency of the circular plate is indicated[4] by

\[
f = \frac{4.98}{2\pi a^2} \sqrt{\frac{Eh^2}{12\rho(1-\nu^2)}}
\]

(1)

Here, \(a\) is the radius, \(h\) is the thickness of the plate, \(E\) is Young’s modulus, \(\rho\) is the density, and \(\nu\) is Poisson’s ratio. From equation (1), it can be expected that the resonance frequency is proportional to the depth and inverse proportion to the square of a diameter.
3. Experiment I: Circular defect models

In order to examine the detectable size and depth of a defect, the experiment which used the circular defect model was carried out.

3.1 Experimental setup

An experiment setup is shown in Fig.2. The distance of a concrete test object and LRAD (LRAD 300X, LRAD Corp.) as 5 m, and have arranged SLDV (PSV400-H4, Polytec Co. Ltd.) a little behind LRAD. The sound pressure was about 100 dB near the object surface. The short pulse wave changed from 500 Hz to about 8 kHz in frequency as a emitted wave was used.

3.2 Circular defect model

The concrete test object (2x1.5x0.3 m$^3$) in which the circular defect model (styrene foam, 25 mm thickness) changed in the burial depth and a diameter was buried and was manufactured. An arrangement plan and a photograph are shown in Fig.5 (a) and (b). As for the diameter and the depth of circular styrene foam, 50 mm in diameters are buried under the depth 10, 20, 40, and 60 mm, 100 mm in diameters are buried under the depth 20, 40, 60, and 80 mm and 150, 200, and 300 mm diameters are buried under the depth 40, 60, 80, and 100 mm.

Fig.5. Circular defect of a concrete test object, (a) defect arrangement, (b) photograph.
3.3 Experimental results

The experimental result using a circular defect model is shown in Table 1. The upper row show the detection result of the hammer method using a rock test hammer (883g). This blind test is done by three persons (O: All three persons detected, △: One or two persons detected, x: No person detected). The lower row shows the detection result of our proposed method (O: Bending resonance peak is clearly detected, △: Bending resonance peak can be detected, x: Bending resonance peak is undetectable). Shaded regions show the range of proposed method which can be investigated. From this table, though high frequency cannot be generated when a hammer is used, the detection range is limited, our proposed method and hammer method show the almost comparable detection performance. Moreover, it turns out that bending resonance frequency is proportional to the depth (example: 300 mm in diameter), and it is in inverse proportion to the diameter (example: a depth of 40 mm).

<table>
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<th>(mm)</th>
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<th>Depth 80</th>
<th>Depth 60</th>
<th>Depth 40</th>
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<td>φ 50</td>
<td>—</td>
<td>—</td>
<td>△</td>
<td>△</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>φ 100</td>
<td>—</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>△</td>
<td>—</td>
</tr>
<tr>
<td>φ 150</td>
<td>x</td>
<td>x</td>
<td>△</td>
<td>△4958Hz</td>
<td>△4449Hz</td>
<td>—</td>
</tr>
<tr>
<td>φ 200</td>
<td>x</td>
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<td>△4389Hz</td>
<td>O</td>
<td>O</td>
<td>—</td>
</tr>
<tr>
<td>φ 300</td>
<td>△3155Hz</td>
<td>△2734Hz</td>
<td>△2106Hz</td>
<td>△1449Hz</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 1. Experimental result of a circular defect model.

4. Experiment II: Crack models

Although the circular defect used 25 mm styrofoam board, actual crack is assumed to be a very thin air layer. Then, the crack models which tore the pillar test piece to two and adjusted using small spacers were created. The experimental setup is same as the former section.

4.1 Circular defect model

The procedure to fabricate the crack models is as follows and the schematic of the procedure is shown in Fig. 6.

1. Cylindrical concrete test pieces (100 x 200 mm²) are divided into two pieces by a procedure for the modulus of tensile strength estimation.
2. To flatten out the measurement surface, each of the two divided pieces is flatly cut in half.
3. The gap widths within the two pieces are adjusted using small spacers.
(4) These cylindrical concrete test pieces, which have cracks, are embedded in the formwork of the concrete wall test piece. Concrete is poured in the formwork of the concrete wall test piece. To prevent infiltration of concrete, the crack surrounding is covered with epoxy bond. At this time, the air gaps on the x–y plane are kept.

Then, the crack models which tore the pillar test piece to two and adjusted using small spacers were created. The gap width adjusted at this time is 1.0 mm, 0.5 mm, and 0 mm. Here, 0 mm means unites again, without inserting a spacer, after dividing into two. For comparison, one model used a 25 mm thick styrofoam as a substitute of a crack was also created. The depth and the defective size of the crack of each models after burying under the concrete wall are 25 mm and 100 x 200 mm², respectively.

4.2 Experimental result
The experimental result of having compared the vibration velocity spectrum on the central point of the position of each crack models and on the healthy part of the circumference is shown in Figs.7-8.

Fig.6. Production procedure of the crack model.

Fig.7. Vibration velocity spectrum on the crack models.
From this figure, the styrofoam and gap width 1.0 mm have same resonance frequency is clearly observed around 3.5 kHz. Although resonance peaks can be observed also in 0.5 mm and 0 mm, compared with the styrene foam and gap width 1.0 mm, amplitude is small and resonance frequency have also shifted. Since setting gap width became narrow, this is considered that the increase contact area has influenced. Fig.8 is an example of a measurement result of the vibrating velocity spectrum in the healthy part of the same concrete test object. The peak seen by about 1 kHz is the resonance frequency of the SLDV laser head itself. In a healthy part, when resonance of a head is removed, otherwise, it turns out that the resonance peak does not exist. From this result, we can confirmed that our proposed method is effective, even if the gap width is 0 mm.

![Vibration velocity spectrum on the healthy part.](image)

**5. The defect detection algorithm using vibration energy ratio**

**5.1 Vibration energy ratio**

Here, it is considered that the sum of the power spectrum of the vibration velocity in a certain frequency range is a value corresponding to vibration energy. In that case, in a defective part and a healthy part, it is possible that the clear difference has occurred. Then, a vibration energy ratio (VER) is defined by

\[
VER = \frac{\int_{\omega_1}^{\omega_2} (X_{\text{defective part}}(\omega))^2 \, d\omega}{\int_{\omega_1}^{\omega_2} (X_{\text{healthy part}}(\omega))^2 \, d\omega}
\]  

(2).

**5.2 Calculation result using circular defect models**

The result of having applied this vibration energy ratio in the case of the circular defect model is shown in Fig.9. From this figure, it turns out that a shallow and big defect shows big vibration energy. This fact shows that this vibration energy ratio may be able to perform the judgment of a defect.
6. Experiment III: Real concrete structure

6.1 Box culvert at Hokuriku highway
The photograph of the box culvert for investigation is shown in Fig.10. An investigation place is a sea side wall considered that damage from salt water is progressing.

![Fig.10. Experimental scenery in a box culvert.](image)

Experimental result of hammer method and the image result of the vibration energy ratio by the non-contact sound investigation method are shown in Fig. 11. The distance from a sound source to an object side is about 4 m. Measured area size is 2 m x 2 m. Measurement was divided into four area of 1 m x 1 m. The number of scanning points of one area is 5 x 5 points, and the number of average is 10. Measurement time is depend on the number of measurement point and average, in this case about 10 min. In order to suppress interference by a floor and ceiling side reflection, the height of the sound source was set to 2 m from the floor. In order to also set the laser head position of SLDV as the same distance and height and to obtain good
sensitivity, a right opposite is carried out to each measurement area. The emitted waveform is a broadband tone burst wave (the sound pressure the surface of concrete; 100 dB, duration time; 3ms, start and stop frequency; 1500 to 6500 Hz, frequency interval; 200Hz, pulse interval 50ms, number of average; 10).

(a)                                                                                       (b)

Fig.11. Experimental result in a box culvert.
(a) hammering test, (b) non-contact acoustic inspection method using vibration energy ratio.

The place where the energy ratio was highly judged by the non-contact acoustic inspection method is almost the same as the place judged by the hammer method to be a float. Therefore, we can see clearly that the investigation precision of the non-contact acoustic inspection method has the performance equivalent to the hammer method.

6. Conclusions
Non-contact acoustic inspection method was examined by several concrete test objects and real concrete structure. From the experimental results, it was confirmed that the detection accuracy of our proposed method is comparable to that of the hammering test. In the future, we are going to develop the practical measurement system.

Acknowledgement
This work was supported by the Ministry of Land, Infrastructure, Transport and Tourism of Japan, technology research development project to contribute to the improvement of the quality of road policy (2010-2013).

References