Study on applicability of noncontact acoustic inspection method to shotcrete with rough surface

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Abstract

By using acoustic irradiation induced vibration and laser Doppler vibrometer (LDV), noncontact acoustic inspection method for concrete non-destructive measurement has been studied. By using a long range acoustic device (LRAD) as a sound source and a scanning vibrometer (SLDV; Scanning Laser Doppler Vibrometer) as a LDV, it has already been demonstrated that non-destructive exploration can be performed even if it is separated from concrete specimens or actual structures by 30 m or more.

On the other hand, in shotcrete inside huge cavities of underground power plants, cracking and small surface peeling due to drilling and secular change have been confirmed. For safety, there are cases where periodic hammering inspections using ceiling cranes are performed for ceiling cracks, but because it is difficult to hit directly without a scaffolding etc., development of an inspection method that can be carried out over a long distance without contact is required. However, the surface condition of shotcrete in the underground huge cavities differs greatly from general concrete specimens and actual concrete structures which have been used conventionally, and the surface unevenness is considerably large. In order to investigate the applicability of noncontact acoustic inspection method for defect detection of shotcrete, a verification experiment was conducted on the wall of the huge cavity inside the existing underground power station.

The defect judgment result by the noncontact acoustic inspection method was almost consistent with the defect judgment result by the existing hammering inspections at any place. Therefore, we have confirmed the applicability of this method to shotcrete, which has the feature that noncontact measurement from a long distance is possible.

1. Introduction

Various methods have already been developed as a method for investigating the degree of peeling or deterioration existing in the vicinity of the surface of a concrete structure. However, many research methods have the problem of requiring scaffolding and aerial work vehicles because they must be used in close contact with or close to the inspection object. Therefore, it is expected to develop an inspection method which enables noncontact and long-term inspection equivalent to conventional hammering method. As a non-destructive inspection method which can actually perform noncontact measurement from a distance of 5 m or more actually, an infrared method using an infrared camera, a laser remote sensing method using a pulsed laser as a vibration source, a sound irradiation excitation, and non-contact acoustic inspection method using acoustic irradiation induced vibration and laser Doppler vibrometer.
The first infrared method basically measures the change and distribution of temperature. When used outdoors, in addition to depending on environmental conditions such as sunshine, when used in a tunnel or the like with little temperature change, it is necessary to heat it actively using a heater or the like. In addition, there is a problem that it is difficult to use it on a high ceiling. The second laser remote sensing method is a method using shock excitation by a powerful pulsed laser and is basically a method suitable for inspecting a metal surface. However, when the object to be measured is concrete, since the melting point of the object to be measured is low and the resonance frequency of the defect to be detected is also low, it is difficult to perform efficient vibration excitation. Furthermore, the existence of danger of handling due to the use of multiple high-power lasers affecting the human body is also a problem.

The last non-contact acoustic inspection method by the authors is a method that utilizes deflection resonance of the defect part like the conventional hammering method, and is a very energy efficient and safe method. Even with commercially available laser Doppler vibrometer (LDV) with low power (1 to 10 mW), it was shown that defects can be detected at almost the same level as the conventional hammer method from a long distance of 5 m or more using concrete test pieces and real concrete structures (tunnel lining and bridges of railroads and roads)1-3).

On the other hand, in shotcrete inside large cavities of underground power plants, cracking and small surface peeling due to drilling and secular change have been confirmed. However, the surface condition of shotcrete in the underground large cavities differs greatly from general concrete specimens and actual concrete structures which have been used conventionally, and the surface unevenness is considerably large. In other words, the possibility that the measurement might not be stabilized due to the influence such as the excitation force and the laser return light being unstable was considered. Therefore, in order to investigate the applicability of non-contact acoustic inspection method for defect detection of shotcrete, a verification experiment was conducted on the side wall inside the existing underground power plant cavity.

2. The non-contact acoustic inspection method

2.1 Fundamental setup
The fundamental setup of non-contact acoustic inspection method is shown in Fig.1.

![Figure 1. Fundamental setup for non-contact acoustic inspection method. Vibration energy is applied to the target surface by irradiating the sound wave from the directional sound source. The vibration velocity distribution at that time is measured by LDV. By utilizing the flexural resonance of the defective part, it is possible to perform noncontact search from a long distance.](image-url)
As a sound source, use LRAD or a strong ultrasonic sound source having a sharp directivity and excite the wall surface to be measured with the generated sound wave. Two-dimensional vibration velocity distribution is measured using high sensitivity scanning laser Doppler vibrometer (SLDV) or LDV. If defects such as cracks in the horizontal direction are present inside the wall surface, the flexural rigidity of the defective portion is lower than that of the sound portion, so that it is easy to generate flexural resonance even with a weak force such as a sound wave. Therefore, in this method, by generating a flexural resonance phenomenon using sound wave irradiation excitation, it is possible to generate the same flexural vibration as the hammering sound method and to detect a defect existing near the surface of the measurement target.

2.2 Tone burst wave
Since the resonance frequency of the defect part is unknown, it is necessary to find the flexural resonance frequency of the defect part in this method. Meanwhile, in order to avoid a decrease in S/N ratio (Signal to Noise Ratio) due to the influence of reflected sound waves from the measurement target, it is desirable to measure with intermittent waveform rather than continuous waveform. For this purpose, we use a waveform called tone burst wave in our method. A schematic diagram of this waveform is shown in Fig.2 (a). It is characterized by using the time (measurable time) until the sound wave reaches the LDV after being reflected from the object. In the experiments, this multi-tone burst wave with multiple short burst waves with different frequencies within the measurable time was used for high speed measurement (see Fig. 2 (b)).

![Figure 2. Tone burst wave. (a) Conceptual diagram of time waveform and spectrum, (b) example of waveform used for experiment (3 frequencies × 16 groups).](image)

2.3 Vibrational energy ratio
Defects in actual concrete structures often have complicated shapes, and it is often impossible to clarify the defect scale in imaging using only the resonance frequency. However, if it is assumed that the sum of the power spectra of the vibration velocities in a certain frequency range is a value corresponding to the vibration energy, it is conceivable that a clear difference occurs between the defect portion and the healthy portion. Therefore, the vibration energy ratio (VER) is defined as in the equation (1).

\[
[\text{VER}]_{\text{dB}} = 10 \log_{10} \frac{\int_{f_1}^{f_f} (\text{PSD}_{\text{defect}}) \text{d}f}{\int_{f_1}^{f_f} (\text{PSD}_{\text{health}}) \text{d}f}
\]  

(1)
Here, \( \text{PSD}_{\text{defect}} \) and \( \text{PSD}_{\text{health}} \) are the power spectral densities of the defective part and the healthy part, and \( f_1 \) and \( f_2 \) are the lower limit and the upper limit frequency. It is conceivable that there are variations in the actual part of the concrete structure, but in this case, the lowest value of the vibration energy in the measured healthy part is calculated as the reference of the healthy part.

3. Verification experiment on shotcrete

3.1 About the experimental site
The investigation site of shotcrete in this study is the underground large cavity inside the pumped storage power plant. This cavity is an egg-shaped cavity with a height of 51.4 m, a width of 33 m and a cross-sectional area of 1,400 m\(^2\) at the largest cross section, and the main rock reinforcement is PS anchor and spray concrete. In this study, in order to confirm the applicability of non-contact acoustic inspection method to shotcrete, experiments were conducted on the side wall part which is easy to compare with the conventional inspection method. The place which was judged as defected by preliminary hammering inspection was selected as the investigation part.

3.2 Experimental setup
Experimental setup of contactless acoustic survey at 5 m apart at the investigation site is shown in Fig.3. LRAD-300X (LRAD Corp.) was used as the sound source, and RSV-150 (semiconductor laser, 1550 nm, 10 mW, Polytec Corp.) was used as the LDV.

![Figure 3. Experiment set-up in the underground cavity.](image)

As an emission wave for measurement, a multi-tone burst wave using a frequency range of 300 to 5,000 Hz, a pulse length of 5 ms, an interval time of 50 ms, and multiple frequencies was used. In addition, the sound pressure on the measurement target surface was set to about 100 dB (2 Pa), and the measurement was performed five times with average / point. The photograph of measurement area is shown in Fig.4. The measurement area was set to 50 × 50 cm\(^2\), and the number of measurement points was set to 81 points of 9 × 9. The white frame indicates the scan area, and the intersection indicates the scan point position.

3.3 Experimental result
An example of the vibration velocity spectrum after the time & frequency gate processing is shown in Fig.5. The red line shows the spectrum of the center part (the
white ○ in Fig. 4 (a)) which is thought to be a defect part, the blue line shows the spectrum of the upper end part considered as a healthy part (white × mark in Fig. 4 (a)) respectively. From this figure, it can be seen that the vibration velocity peak estimated to be the resonance of the shotcrete defect portion is detected around 1 kHz.

Figure 4. Picture of measurement area and experimental setup. (a) Measurement area (0.5 × 0.5m², white ○: defective area, white ×: healthy area), (b) top image of experimental setup.

Figure 5. Example of vibrational velocity spectrum. Red line: Spectrum of the center part (white circle in Fig. 4 (a)) considered to be a recessed part, Blue line: Spectrum of the upper end considered to be a healthy area (white × mark in Fig. 4 (a)).

Fig.6 shows the results of the hammering test and the defect judgment result by the noncontact acoustic inspection method. The vibration energy ratio distribution integrates 950 to 1,050 Hz near the resonance frequency. As with the hammer method, the vibration energy ratio distribution by the noncontact acoustic inspection method shows large value in the region from the central part and the central part to the lower left of the measurement area.
4. Conclusions
In order to confirm applicability of noncontact acoustic inspection method to shotcrete surface, verification experiments were conducted on shotcrete on the side wall inside the existing underground power plant cavity. As a prediction in advance, it was considered that the measurement might not be stabilized due to the influence such as the excitation force and the laser return light being unstable, depending on the degree of unevenness of the shotcrete. However, the defect judgment result by the non-contact acoustic inspection method was almost consistent with the defect judgment result by the existing hammer method. Therefore, applicability of this method to shotcrete was clarified. Further study will be planned for practical application in the future.

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References