Detection of internal defects of concrete for noncontact acoustic inspection method using healthy part extraction

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Abstract

In recent years, degradation of concrete structures built in the period of high economic growth has become a social problem in Japan. A noncontact acoustic inspection method has been studied to detect internal defects of surface layer (~ 10 cm) of concrete such as bridge and tunnel from a long distance (5-33 m away) at our laboratory. The surface layer of concrete is acoustically vibrated with strong aerial sound waves, and the vibration velocity is measured at a two-dimensional lattice point with a laser Doppler vibrometer. If there are internal defects such as a peeling and a crack in the concrete surface layer, flexural vibration, which is the same physical phenomenon as a hammering test, occurs. Obtained data is signal processed by time-frequency gate, noise is reduced, and a change in vibration state due to flexural vibration is obtained. Two acoustic feature quantities, vibrational energy ratio and spectral entropy, is introduced and the defect detection algorithm is proposed. Then internal defects of concrete were visualized by vibrational energy ratio. Generally, it can be said that a healthy part of concrete is acoustically homogeneous and isotropic. From measured results, it has been found that the distributions of two acoustic feature quantities follow a normal distribution, against a healthy part of concrete with a smooth surface. By drawing a scatter diagram using two acoustic feature quantities in case of a simple shaped specimen such as cavity defect, a healthy part of concrete and a defective part can be separated clearly. However, in case of actual concrete structure, measured points, which are difficult to distinguish whether it is healthy or defective, exist. Therefore, we propose a method to statistically extract and evaluate a healthy part of concrete. By statistically evaluating a healthy part of concrete, it is possible to detect internal defects of concrete even for an actual concrete structure.

1. Introduction

In Japan, social needs for the maintenance and management of concrete structures during the high growth period are increasing. As a non-destructive inspection of concrete, a hammering test has been mainly used. However, there are problems that it relies on the experience and intuition of inspection worker and needs a foothold in case of high place. There exist other various methods. Since many methods must be inspected in contact with or close to measuring plane, they have the problem of requiring a scaffold and high place workers. As a non-destructive inspection method, recently in Japan, there are three non-destructive testing methods, "Infrared thermography", "Laser remote sensing method" and "Noncontact non-destructive acoustic inspection method". The first measures change and distribution of temperature, therefore it is influenced by environmental conditions. The second is utilized shock excitation by a powerful pulsed laser. High power laser requires
careful handling. Considering a melting point of concrete, there is a limit to raise power in proportion to the depth of defects. The third is "Non-contact acoustic inspection method (NCAI)", in order to inspect internal defects of concrete from a long distance in a noncontact and non-destructive manner, has been studied in our laboratory using sound wave irradiation excitation and a laser Doppler vibrometer.

2. Non-contact acoustic inspection method

2.1 principle and experimental setup
As shown in Fig.1, the measuring surface is excited by plane acoustic waves emitted from a long range acoustic device (LRAD Corp., LRAD-300X) and its vibration velocity is measured using a scanning laser Doppler vibrometer (Polytec Corp, PSV-500Xtra, etc.). If a defect such as a crack, a peeling or a void are present inside the surface layer of concrete to be measured, a flexural rigidity of defective part is lower than that of the healthy part of concrete, so that flexural vibration is likely to occur. By effectively utilizing the resonance phenomenon, that is, by continuous excitation, it is possible to generate effective vibration with a weak force. Therefore, despite a weak force of sound wave irradiation excitation, an internal defect existing near the surface layer of concrete can be detected by generating a flexural vibration of the same mechanism of a hammering test. Normally, the resonance frequency of a defective part is unknown. Accordingly, single-tone burst waves or multi-tone burst wave, which can cover the necessary frequency band by changing the transmission frequency step by step, was used as a transmission waveform (1).

2.2 Numerical analysis (2,3)
Two acoustic feature quantities, vibrational energy ratio and spectral entropy, and two algorithm ‘Defect detection algorithm’ and ‘Healthy part extraction algorithm’ were used to detect internal defects of concrete.

2.2.1 Vibrational energy ratio
In the case of a circular cavity defect buried in a concrete specimen, the flexural resonance frequency is determined depending on the defect diameter and the depth to the defect, so defect detection can be performed by displaying the peak resonance frequency on an image. However, in the case of a defect existing in a real concrete structure, the causes of defects are also various, so its shape and depth are not simple. For this reason, when actually looking at vibration velocity spectrum, it often has multiple peaks, so it is not
sufficient to detect and display defects by only a single frequency peak in an actual concrete structure. In this method, if sum of power spectrum of vibration velocity is calculated as a value of vibrational energy in the frequency range assumed to have frequency peaks of defect part, a clear difference can be considered to occur between defect part and healthy part. Define the vibrational energy ratio (VER: Vibration Energy Ratio) as in Eq. (1).

\[
[\text{VER}]_{dB} = 10 \log_{10} \frac{\int_{f_1}^{f_2} (\text{PSD}_{\text{defect}})^2 df}{\int_{f_1}^{f_2} (\text{PSD}_{\text{health}})^2 df}
\]

Here, \(\text{PSD}_{\text{defect}}\) and \(\text{PSD}_{\text{health}}\) are power spectral densities of a defective part and a healthy part, and \(f_1\) and \(f_2\) are the lower limit and the upper limit frequency. Vibrational energy in a healthy part may have small variations in case of actual concrete structure. VER is calculated using the lowest value of vibrational energy as a reference value of healthy part of concrete.

2.2.2 Spectral entropy (4)

In this method, since laser light is used for vibration measurement, if the laser return light decreases due to decrease in reflectance, for example dirt or unevenness on the concrete surface to be measured, optical noise due to light reception leakage may occur in a case. Since the optical noise due to light reception leakage shows characteristics close to white noise, if defect detection depends only on vibrational energy calculated from power spectrum of vibration velocity, an abnormal measurement point due to the light reception leakage is detected by mistake as a defect part. The frequency characteristic of the signal shows characteristics close to white noise. Therefore, spectral entropy \(H\), which is a feature quantity representing the whiteness of the signal, is introduced. This is an information entropy calculated by considering a signal spectrum as a probability distribution and is defined by the following equation.

\[
H = - \sum_f p_f \log_2 p_f , \quad p_f = \frac{S_f}{\sum_f S_f}
\]

Here, \(S_f\) is the power spectrum of vibration velocity at a measurement point. The spectral entropy \(H\) has a high value in a white signal having a uniform spectrum. An abnormal measured point due to light leakage have high white noise level, then \(H\) shows a high value. In the healthy area, the signal level is low, but since it does not have a characteristic peak, \(H\) shows a high value.

2.2.3 Defect detection algorithm (4)

As shown in Fig.2, the defect detection algorithm was devised. By combining two acoustic feature quantities, vibrational energy ratio and spectral entropy, if the threshold value can be selected appropriately, it is possible to distinguish a defective part, a healthy part and an abnormal measurement point (see Table 1). In case of an actual concrete structure, a region considered as a defect part and a region considered as a healthy part overlap each other, and it is sometimes so difficult that such distinct identification can be made. Therefore, in order to clearly detect an internal defect of actual concrete structures, it is gradually clear that a quantitative evaluation of a healthy part is very important.
2.2.4 Healthy part extraction algorithm

Generally, a healthy part of concrete is considered that it hardly vibrates with the excitation level of sound waves. However, when the surface layer of concrete is excited using our method, distributions of two acoustic feature quantities are seen for a healthy part. Concrete is a composite material and may be influenced by the state of surface and the distribution of internal aggregates and the like. But if it is regarded acoustically isotropic and homogeneous, it is thought that statistically natural variability will be produced around certain acoustic feature quantity. That is, it is expected that the distributions of two acoustic feature quantities in a healthy part of concrete follows a normal distribution. Thus, an algorithm for extracting a healthy part of concrete was newly devised using statistical evaluation as shown in Fig. 3.
From the vibration velocity data of each measurement point, two acoustic feature quantities, vibration energy ratio and spectral entropy, were calculated. Next, conformity to a normal distribution is judged by Q-Q plot with respect to vibration energy ratio, and some outliers from a normal distribution are statistically detected using box plot. Excluding outliers makes it possible to extract a healthy part of concrete. Subsequently, for spectral entropy as well, outliers are removed. In this way, the measurement point considered as a healthy part of the measurement region can be extracted.

3. Result

Figure 4 shows a correlation diagram between vibrational energy ratio and spectral entropy in case of a circular peeling defect, which was embedded to a depth of 60 mm from the concrete surface, with a diameter of 200 mm. After applying ‘healthy part extraction algorithm’, a healthy part and a defect part were separated clearly.

![Figure 4. A correlation diagram between ‘Spectral Entropy’ and ‘Vibrational Energy Ratio’.](image)

Figure 4 shows an example of extraction process of ‘healthy part extraction algorithm’. The green ovals indicate some outliers out of a healthy part of concrete. The points of a peeling defect were included in it.

![Figure 5. A process of ‘Healthy part extraction algorithm’.](image)

Figure 5 shows an example of extraction process of ‘healthy part extraction algorithm’. The green ovals indicate some outliers out of a healthy part of concrete. The points of a peeling defect were included in it.

Some measured points with lower vibrational energy ratio than a healthy part were excluded from candidate of defects and that with higher spectral entropy than a healthy part were excluded as an abnormal measurement point.
In Fig.6, a circular peeling defect was visualized by vibrational energy ratio. Fig 6(a) shows an original defect image. Since vibrational energy of a healthy part and a peeling defect part are about the same level, those cannot be separated by vibrational energy ratio alone. However, by extracting a healthy part of concrete using two acoustic feature quantities, points of a peeling defect were identified and visualized clearly as shown in Fig.6 (b).

Figure 6. Peeling defect image, (a) before, (b) after applying ‘Healthy part extraction algorithm’.

4. Conclusions
A defect detection algorithm for noncontact acoustic inspection method was developed using two acoustic features such as vibrational energy ratio and spectral entropy. Especially, by statistically evaluating and extracting a healthy part of concrete, on the assumption that each distribution of two acoustic feature quantities is a normal distribution, it became possible to visualize a peeling defect clearly.

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References