Evaluation of healthy part of concrete using acoustic characteristics for defect detection
by non-contact acoustic inspection method

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Abstract

Social needs for maintenance and management of concrete structures during the high growth period are increasing in Japan. In our laboratory, we have studied a non-contact nondestructive acoustic inspection method [1-7] combining acoustic irradiation excitation and a laser Doppler vibrometer to inspect internal defects of target. Concrete specimens or actual concrete structures such as tunnel and bridge have been measured remotely apart from 5-7 m from target, and internal defects (such as crack, cavity; up to a depth of 8-10 cm) were detected. We have already clarified internal defects can be visualized clearly. However, in order to detect actual internal defects of concrete, quantitative evaluation of healthy part of concrete is important. We introduce two quantities of acoustic characteristics called ‘Vibrational Energy Ratio (VER)’ and ‘Spectrum Entropy (SE)’. First, vibrational energy (VE) is calculated by integrating measured vibration velocity spectrum in measured frequency range, and the ratio with the minimum value is expressed in decibels. VER make it possible to clarify a place where VE is high within a specific frequency range. SE is a feature quantity representing whiteness of a signal. Using this value, it is possible to identify the optical noise that shows the frequency characteristic similar to white noise generated depending on the surface condition of target. By these acoustic characteristics (VER and SE), it is possible to distinguish a defect part, a healthy part and an abnormal measurement point. That is, in a defective part, flexural vibration tends to occur and VER tends to increase, but since a peak appears at resonance frequency, SE tends to decrease. In a healthy part, VER is low and SE is high. An abnormal measurement point generally tends to show high VER and high SE. For concrete specimens, our defect detection algorithm using VER and SE is effective. However, for an actual concrete structure, it is occasionally difficult to distinguish by conventional algorithm because there is an ambiguous region between healthy part and defective part. So, we devised new method for evaluating and extracting healthy part using statistical method. As a result of applying our invented method to actual concrete structures, it becomes possible to identify healthy part and detect defects clearly. Then, defects can be clearly visualized.

Keywords: non-contact inspection, defect detection algorithm, evaluation of healthy part of concrete, scanning laser Doppler vibrometer, long range acoustic device

1. Introduction

In order to detect concrete internal defects, we have proposed a defect detection algorithm using two acoustic feature quantities, vibrational energy ratio and spectral entropy. Its effect has been verified using a specimen of concrete wall embedded with cavity defects. But in an actual concrete structure, there is an ambiguous boundary area where judgement between a healthy part of concrete and the defect part is difficult. It is not easy, for actual concrete structure, to determine the thresholds of two acoustic feature quantities and it is not good to separate each region with two threshold lines. In general, a healthy
part of concrete can be considered to be acoustically homogeneous and isotropic. In the scatter plot with vibrational energy and spectral entropy on each axis, measured points in a healthy part of concrete gather and the distribution shows the normal distribution. Using this physical phenomenon, in order to identify a healthy part of concrete, a statistical analysis was performed on each distribution of two acoustic feature quantities. And by extracting a healthy part, the rest is found to be a defective part of concrete. Evaluation of healthy part of concrete is important to detect inner defects of concrete.

2. Principle of Defect Detection

In order to detect internal concrete defects, two acoustic features quantities, vibrational energy ratio and spectral entropy, were used.

2.1 Vibrational Energy ratio

Vibrational energy ratio is represented as the following equation:

\[
[\text{VER}]_{\text{dB}} = 10 \log_{10} \frac{\int_{f_1}^{f_2} (PSD_{\text{defect}}) df}{\int_{f_1}^{f_2} (PSD_{\text{healthy}}) df}
\] (1)

With this formula, \( f_1 \) and \( f_2 \) are respectively the lower and the upper limits of analysis frequency within the frequency range of transmission airborne sound waves. PSD is a power spectral density. At previous experiments, concrete specimens simulating cavity defects were used. In the case of a simple shape cavity defect, only one resonance peak is seen. However, in a real concrete structure, it is rare that only one resonance peak appears due to oblique cracks or complicated defect shapes. In many cases, multiple peaks can be seen. Even in such a case, if the vibrational energy is used, the size of the defect can be estimated and the state of the defect can be visualized.

2.2 Spectral Entropy [8]

Spectral entropy is represented as the following equation:

\[
H = - \sum_{f} P_f \log_2 P_f, \quad P_f = \frac{S_f}{\sum S_f}
\] (2)

\( S \) is a power spectrum of vibration velocity at a measured point. Spectral entropy express white characteristics of the signal. Spectrum of the signal is regard to be probability distribution and information entropy is calculated. We used a power spectrum as spectral entropy in this experiment.

2.3 Defect detection algorithm [8]
Using two acoustical feature quantities such as vibrational energy ratio and spectral entropy, it is possible to detect internal defects of concrete. Fig.1 shows a scatter plot of vibrational energy ratio versus spectral entropy as an example of a circular hollow defect (200 φ, depth 80mm). As shown in Fig.1, if scatter plot is drawn by vibrational energy ratio and spectral entropy, internal defect points are found to show the tendency to localize in the lower right of the figure with high vibrational energy and low spectral entropy. In a case of conventionally used concrete, each point of healthy part gathers in the upper left of the figure with low vibrational energy and high spectral entropy. Healthy zone, defective zone and invalid zone were separated by two threshold lines. Where to draw two threshold lines is important.

Figure 1: Scatter plot of vibrational energy ratio vs spectral entropy as an example of circular hollow defect.

2.4 Healthy part extraction algorithm

In order to detect an internal defect of concrete structure, we attempted to extract a healthy part of concrete. Distribution of two acoustic feature quantities were obtained from vibration velocity data at each measurement point. Fig.2 shows healthy part extraction algorithm. First, by the Q-Q plot, we can confirm appropriateness to apply the normal distribution with respect to the distribution of vibrational energy ratio, and detect outliers statistically by the Box plot. Excluding outliers makes it more possible to extract a healthy part. For spectral entropy as well, outliers are detected in the same way. Then, outliers are eliminated. In this way, measured points considered as a healthy part are extracted. After the normal distribution is confirmed, the statistics (average and standard deviation) of the distribution of two acoustic feature quantities are obtained.

Figure 2: Healthy part extraction algorithm.
3. Experiment and the result

Healthy part extraction algorithm was applied to the experimental results of concrete specimen and a huge bridge of real concrete structure.

3.1 Concrete specimen (circular hollow defect)

It was measured in the experiment setup of Fig.3. Circular cavity defects (200mm Φ, depth 60 mm) embedded in the concrete wall were measured. A Scanning Laser Doppler Vibrometer (Polytec Corp, PSV-500Xtra) and a Long Range Acoustic Device (LRAD Corp., LRAD-300X) were used. Multitone burst waveform was used as a transmission waveform. Time-Frequency gate processing was done to reduce noises such as a direct wave and external noise such as reverberation. Taking vibrational energy on the horizontal axis and spectral entropy on the vertical axis, a scatter plot can be drawn as shown in Fig.4.

An image of a circular cavity defect is visualized as shown in Fig.5(b). Fig.5(a) is an image of the concrete surface taken with a CCD camera. The circle with a white dotted line is the estimated position of a circular cavity defect. '+' shows a measured point and a number next to it is the measurement point number. From the experimental experience, defect points are considered to locate at the lower right of Fig.4. And points of healthy part gather around the upper left side. Since it is not easy to draw each threshold line to separate a healthy part from defect points, statistical analysis was performed to identify a healthy part.
Figure 5: Defect visualization (a) CCD camera image of the concrete surface, (b) Image of circular hollow defect by vibrational energy ratio.

One measured point has two acoustic feature quantities calculated from the measured data. In Fig.6, as a result of applying Q-Q plot to the vibrational energy ratio distribution for all measurement data, it is seen that measured points along a red line follow the normal distribution, and outliers are observed on the upper right side. In Fig.6(b), as a result of applying Box plot, outliers from the normal distribution were detected in the green ellipse.

Figure 6: Healthy part extraction process on vibrational energy ratio distribution by statistical analysis.

Figure 7: Healthy part extraction process on spectral entropy distribution by statistical analysis.

In Fig.7, as a result of applying Q-Q plot to the spectral entropy distribution for all measurement data, it is seen that measured points along a red line follow the normal distribution. And outliers were
observed on the left side. In Fig.7(b) and (c), as a result of applying Box plot, outliers from the normal distribution were detected in the green ellipse. The process was repeated twice. By statistical analysis, measured points of a healthy part of concrete was identified. By setting healthy part points obtained by statistical analysis to 0 dB, Fig.8 (b) is obtained. A defective part of concrete was visualized clearly.

![Defect image before and after healthy part extraction process.](image)

**Figure 8:** Circular hollow defect: Defect image before and after healthy part extraction process.

### 3.2 Actual concrete structure (huge bridge)

As a real concrete structure, the concrete floor slab was measured at a huge bridge using our method. Fig.9(a) is a photograph of the measured bridge. The red straight line indicates the direction of a transmitted sound waves or a laser light. The distance from the measuring device to the measured surface of concrete floor slab was about 33 m. Experiment setup is seen in Fig.9(b).

![Bridge appearance and experimental setup.](image)

**Figure 9:** Bridge appearance and experimental setup.

Strong plane sound waves are radiated from a sound source of a long range acoustic device (LRAD corp., LRAD-300X) to excite a target surface of concrete. Using a scanning laser Doppler vibrometer (Polytec corp., PSV-500Xtra), the vibration velocity distribution is measured at the two-dimensional lattice point by automatic scanning. In this experiment, measurements were carried out using multi tone burst wave [9] in order to shorten the measurement time. A time-frequency gate process was performed on the obtained data. Then, after the FFT process, the healthy part extraction algorithm was applied to
the vibrational energy ratio distribution for all data. Fig.10 shows an example of healthy part extraction process. Outliers from a healthy part of concrete were detected and surrounded by green oval.

![Figure 10: Healthy part extraction process on vibrational energy ratio distribution by statistical analysis.](image)

Fig.11 is a scatter plot of vibrational energy ratio versus spectral entropy obtained from measured data of the bridge. Healthy points of concrete were gathered on the upper left side of the figure, where vibrational energy is small and spectral entropy is high. Some measured points regarded as an internal defect of concrete are located in the lower right of the figure, where vibrational energy is high and spectral entropy is low.

![Figure 11: Concrete floor slab of bridge: Scatter plot of vibrational energy ratio vs spectral entropy.](image)

Fig.12(a) is a photograph taken with a CCD camera. "Efflorescence" can be seen in the red ellipse in the middle of the photo. When moisture and water vapor, which is intruded into concrete, migrate to

![Figure 12: An inner defect of concrete floor slab of the bridge, (a) CCD camera image of the concrete surface, (b) Inner defect image by vibrational energy ratio.](image)
the surface of concrete, it seeps out to the surface together with soluble components such as lime, then solidifies to be a "Efflorescence". Fig.12(b) shows an inner defect image of concrete floor slab of the bridge by vibrational energy ratio. The defect seen in the center is considered a 'Free lime', where vibrational energy is very higher. ‘Free lime’ is calcium oxide contained in cement, which is one of the materials of concrete. It easily reacts with water to become calcium hydroxide. It is an intumescent substance, and when present in large quantities, it might have caused expansion cracks in concrete.

4. Conclusion

Using a non-contact acoustic inspection method, as actual concrete structure, a concrete floor slab of bridge was measured from distance of about 33 m. We also conducted experiments on a concrete wall specimen with a circular hollow defect. As a result, the distribution state of a healthy part of concrete was be able to identified by vibrational energy ratio and spectral entropy obtained by our method. To evaluate a healthy part of concrete made it possible to detect an inner defect of concrete. As a result of measuring from a distance of about 33 m, it was possible to detect and visualize an internal defect of concrete. It became possible to statistically extract and evaluate a healthy part of concrete.

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References