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Detection and acoustical visualization of internal defects in shotcrete structures by spatial spectral entropy for noncontact acoustic inspection method

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Abstract— **Deterioration of concrete structures is a serious problem in social infrastructures such as tunnels and viaducts. In order to solve this problem, we have examined the method to inspect the internal defects of concrete structure in a noncontact and non-destructive manner. In our noncontact acoustic inspection method, the concrete surface is vibrated by strong airborne sound waves, 2-dimensional distribution of vibration velocity is measured by a scanning laser Doppler vibrometer (SLDV). And the internal defects (up to a depth of about 10 cm from the surface) is detected from a long distance (about 5-30m). It was made possible to detect internal defects of concrete with smooth surface in a released space such as a viaduct or a tunnel. However, in a closed space surrounded by concrete, such as an underground cavity, the S/N ratio was lowered due to reverberation from the surroundings. In shotcrete with uneven surface, the reflectance of laser light on the surface varies. And it is more difficult to detect internal defects. To detect internal defects of concrete, we have proposed the defect detection algorithm combining acoustic features (vibrational energy ratio and spectral entropy). At a measured point of internal defect, vibrational energy tends to be high and spectral entropy tends to be low. Since acoustic excitation is used, in a closed space, more intense resonance occurs in a head of SLDV due to reverberation from the surroundings. Since resonance frequency of a laser head and its frequency range can be detected by spatial spectral entropy (SSE) proposed previously, the resonance frequency peaks can be removed in data analysis. In addition, the influence of shotcrete surface was reduced by detecting resonance frequencies of internal defects on the measured surface by SSE, selecting frequency bands to analyze, and statistically evaluating healthy part by two acoustical features.**

Keywords— Noncontact acoustic inspection, Spatial spectral entropy, NDT, laser Doppler vibrometer, LRAD

I. INTRODUCTION

While measuring the vibration velocity of a target, the high-sensitivity laser Doppler vibrometer measures slight vibration from the surroundings as a background noise. In our noncontact acoustic inspection, by acoustic waves from a strong sound source, the concrete surface is acoustically excited from a long distance (5-30m) and internal defects in the shallow layer of concrete are detected by the two-dimensional vibration velocity distribution. In a closed space surrounded by concrete (for example, in a large cavity) or a semi-closed space, reverberation from the surrounding concrete attack the head of a scanning laser Doppler vibrometer (SLDV). Then, the resonance due to a galvanometer mirror etc. occur. As a result, the resonance peak due to the SLDV head is observed in a vibration velocity spectrum. In the closed space, the main lobe of resonance peak of an SLDV head becomes higher and the side lobe is widened. In addition to the first and second resonance peaks, a smaller resonance peak due to SLDV head may be seen. In order to evaluate the vibration state of measurement surface from vibration velocity spectrums, we need to remove the resonance peak of an SLDV head in order to calculate the vibration energy in the measurement frequency range. Otherwise, the imaging of internal defects will be adversely affected. Using SSE, the resonance frequencies of both the SLDV head and the internal defects can be detected. Therefore, visualization of internal defects can be achieved. Last time, spatial spectral entropy was proposed and its effectiveness was verified using a concrete wall specimen with cavity defects. In this study, we investigated how to visualize internal defects by applying SSE to shotcrete measured in underground cavities. Unlike ordinary concrete, shotcrete has an uneven surface and is more difficult to detect internal defects from a long distance.

II. EXPERIMENTAL METHOD

Fig.1 shows the experimental setup. In order to detect Internal defects, such as a crack or a peeling, in shallow layer of concrete in noncontact non-destructive manner, strong plane waves were irradiated from a long-range acoustic device

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(LRAD; LRAD corp., LRAD-300X) installed at a distance of about 5 m from the measurement plane, and the concrete measurement surface was acoustically excited. A scanning laser Doppler vibrometer (SLDV; Polytec, RSV-500Xtra scanning vibrometer) was installed at a distance of 5-7 m from the measurement surface, and the two-dimensional vibration velocity distribution on the measurement plane was measured.

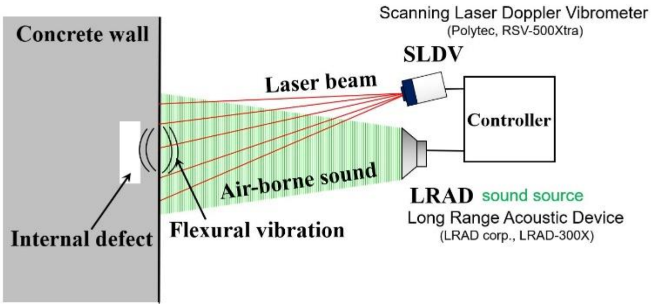

Fig. 1. Normal experimental setup.

III. Principle of Defect Detection

A. Vibrational energy ratio

In order to visualize internal defects, vibrational energy ratio[1] was used as follows:

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

In actual concrete structures, there are defects of various shapes, depths and resonance frequencies. In order to evaluate them with the same standard, vibration energy is calculated in the measured frequency range, and the ratio with the vibration energy of a healthy part of concrete is obtained. Then, the position and scale of defect are evaluated and visualized.

B. Spectral entropy

The spectral entropy is represented as H by the following equation (2),

$$H = -\sum_f P_f \, log_2 \, P_f \qquad (2)$$

$$P_f = \frac{S_f}{\sum_f S_f}$$

where S_f is the power spectrum of the vibration velocity at a measured point. The spectral entropy expresses the white characteristic of the signal. The spectrum of the signal is regarded as a probability distribution and the information entropy is calculated.

C. Previous defect detection

In the initial defect detection algorithm [2,3], in case that surface condition (irregularity or reflectivity) of the measurement surface was poor, an abnormal measurement point due to decrease in the amount of light received was observed in a laser Doppler vibrometer (He-Ne laser). So, to figure out them, the defect detection algorithm was invented. In the algorithm, two acoustic feature quantities (spectral entropy, vibrational energy ratio) were used, the tendency shown in Table 1 was observed, and it could be applied to defect detection. Fig. 2 shows an example of experimental results for a concrete specimen with a circular cavity defect.

TABLE I. Defect detection using two acoustic feature quantities

	Vibrational energy	Spectral entropy
Healthy part	low	high
Defective part	high	low
Abnormal measurement point	high	high

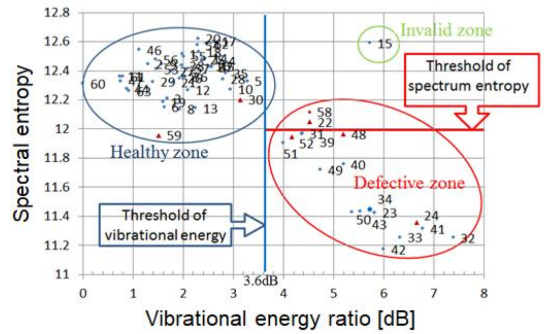

Fig. 2. Defect detection using spectral entropy and vibrational energy ratio.

D. Spatial spectral entropy (SSE)

Fig.3 is an illustration to explain the principle of 'Spatial Spectral Entropy (SSE)'. Some of vibration velocity spectrum at a measured point were displayed perpendicular to the measurement surface. Focusing on a frequency component f [Hz] of power spectrum of vibration velocity. The frequency component f exists at each measured point. Their distribution is regarded as probability distribution whether an frequency component f exists in real space (the measured plane). And information entropy is calculated. Vibration velocity spectrum were calculated using FFT after Time-Frequency gate processing. Using Spatial Spectral Entropy, both the resonance frequency of a laser head of laser Doppler vibrometer and the resonance frequency of internal defect were detected in a planar measurement.

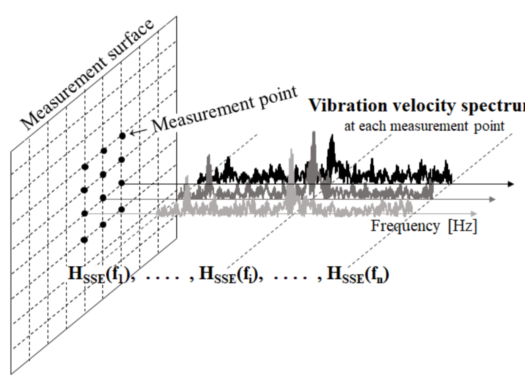

Fig. 3. Explanation of the principle of 'Spatial Spectral Entropy'.

The SE expanded to such a planar measuring surface is called 'Spatial Spectral Entropy (SSE)'[4]. SSE was defined by equation (1).

$$H_{SSE}(f) = -\sum_{i=1}^{m}\sum_{j=1}^{n} P_{i,j}(f) \, log_2 \, P_{i,j}(f) \qquad (1)$$

$$P_{i,j}(f) = \frac{S_{i,j}(f)}{\sum_{i=1}^{m}\sum_{j=1}^{n} S_{i,j}(f)}$$

Where $H_{SSE}(f)$ is spectral entropy (a function of frequency f) extended to the real space. $S_{i,j}(f)$ is the frequency component f [Hz] of power spectrum obtained by performing discrete Fourier transform on a signal measured at a measurement point. $P_{i,j}(f)$ is a probability that a frequency component f [Hz] of power spectrum at a measurement point exists within the measurement plane.

IV. Results applied to real concrete structures

The noncontact acoustic inspection was conducted on the shotcrete surface of the underground cavities, and data analysis was performed.

A. About the Experiment Place

The experiment was conducted in a large underground cavity in the Kannagawa power plant of TEPCO Holdings. This cavity is an egg-shaped cavity with a maximum cross section of 51.4 m in height, 33 m in width, and a cross-sectional area of 1,500 m^2, and the main rock reinforcement works are PS anchors and shotcrete (thickness 32 cm: 8 cm x 4 layers). Since the excavation work for the cavity was completed in October 2000, the experimental shotcrete has been about 20 years old. This time, the place that was the subject of the experiment is the hollow ceiling. A photograph at the experimental site is shown in Fig.4.

B. Sound-proof and Vibration-proof measures

Fig.5 shows the sound and vibration control measures used during the experiment. There are three types of countermeasures: a sound-proof case and a sound-proof unit, and an insulator for vibration isolation (packing sponge). The sound-proof case and sound-proof unit reduced the reflected waves from the surroundings, and the insulator was used to prevent vibration from the floor.

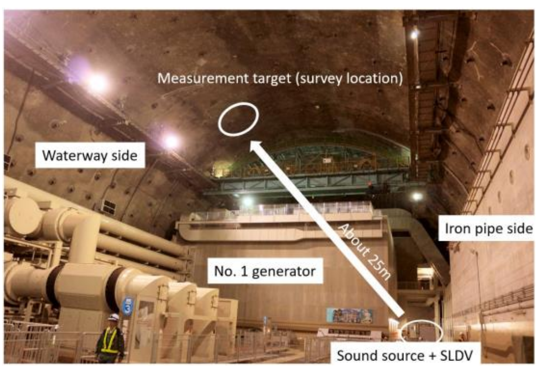

Fig.4. A photograph of the experiment site in the underground cavity.

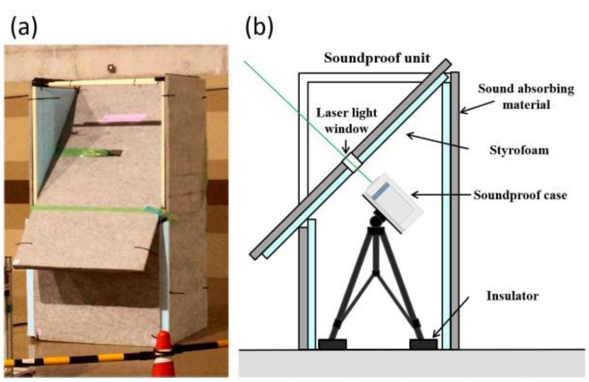

Fig.5. Sound and vibration isolation measures for SLDV, (a) photograph, (b) internal configuration.

C. Experimental Setup

Fig. 6 show the arrangement of measurement equipment at the experimental site. As shown in the figure, the distance from the measurement target surface to the excitation sound source (LRAD-300X) was approximately 25 m, and the distance from the SLDV (PSV-500 Xtra) was approximately 26 m. Two identical sound sources are used to increase the excitation force. The measurement range diagram is shown in Fig. 8 (the white line indicates the defect detected by prior tapping inspection). The number of measurement points is 21 x 21 for a total of 441 points. The size of the measurement area is approximately 0.94 x 0.94 m^2. The multitone burst wave [5] with a frequency range of 300 to 4400 Hz was used as the waveform for excitation

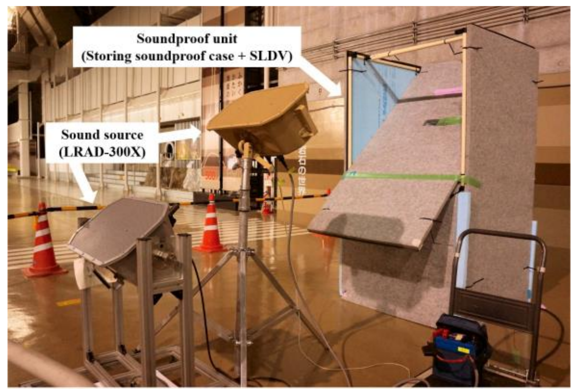

Fig.6. Actual measurement equipment layout.

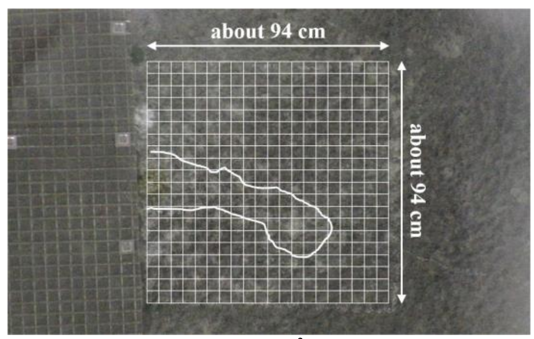

Fig.7. Scan area (441 points, 0.94x0.94m^2).

(pulse length 5 ms, interval 150 ms, overall waveform length 450 ms). The number of averages was 5, and the measurement time was about 25 minutes. The sound pressure was about 100 dB (2 Pa) on the surface to be measured about 25 m away. The sound pressure at a distance of about 1 m from the sound source was about 129.5 dB (the maximum value of Z characteristics when using one sound source).

D. Experimental Result

After time-frequency gate processing using experimental data, SSE analysis was performed. Fig. 8 shows the result of SSE analysis. The vertical axis is the SSE value, and the horizontal axis is the frequency. At resonance frequency due to a laser head of SLDV, SSE value is increasing. At resonance frequency due to internal defects, SSE value is decreasing. We can distinguish two resonance peaks. In a frequency that does not have a resonance frequency, it tends to fluctuate around the median value of SSE distribution. Statistics of SSE distribution is displayed in the figure. The median of the distribution of SSE values is displayed as "Median" or "M", and the standard deviation as "σ". The black dotted line is the median of the SSE distribution, and the blue dotted line is M + σ or M-σ, respectively.

As in Fig. 9, when looking at the envelope of fluctuation waveform, that is, macro fluctuation instead of fine fluctuation, the red frame was extracted so as to exclude the frequency range of resonance frequency due to SLDV.

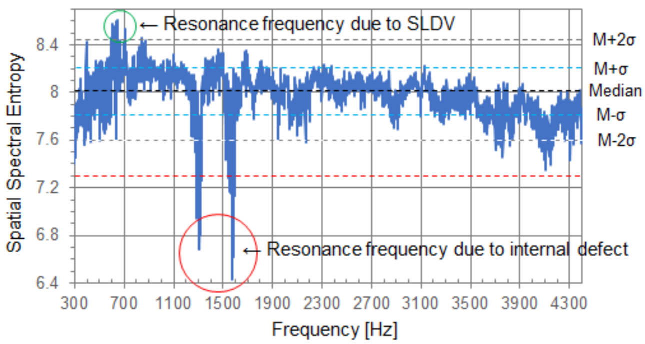

Fig.8. Result of SSE analysis.

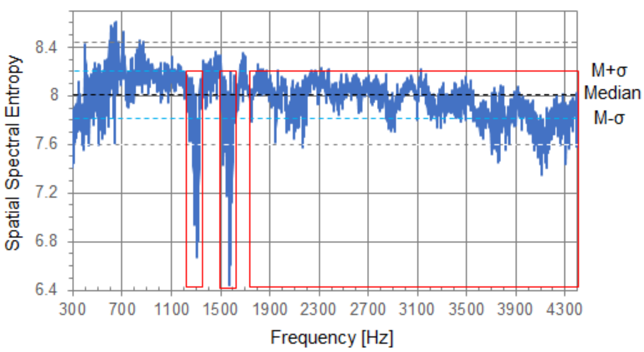

Fig.9. Result of SSE (extraction of resonance frequency band of defect).

As can be seen in Fig. 10, comparing (a) an acoustic image applied SSE analysis by noncontact acoustic inspection method is applied, and (b) an result of hammering test by Kenkon diagnostic portable, it can be said that the position and scale of the defects were detected well.

V. Conclusions

As an actual concrete structure, an attempt was made to remotely detect internal defects in shotcrete in an underground cavity. By SSE analysis of spatial spectral entropy, the resonance frequencies of internal defects and the resonance frequency of a laser head of SLDV can be detected. Therefore, when calculating the vibrational energy ratio for imaging, the analysis frequency range is selected effectively and the acoustical image of internal defects was well created.

(a)

(b)

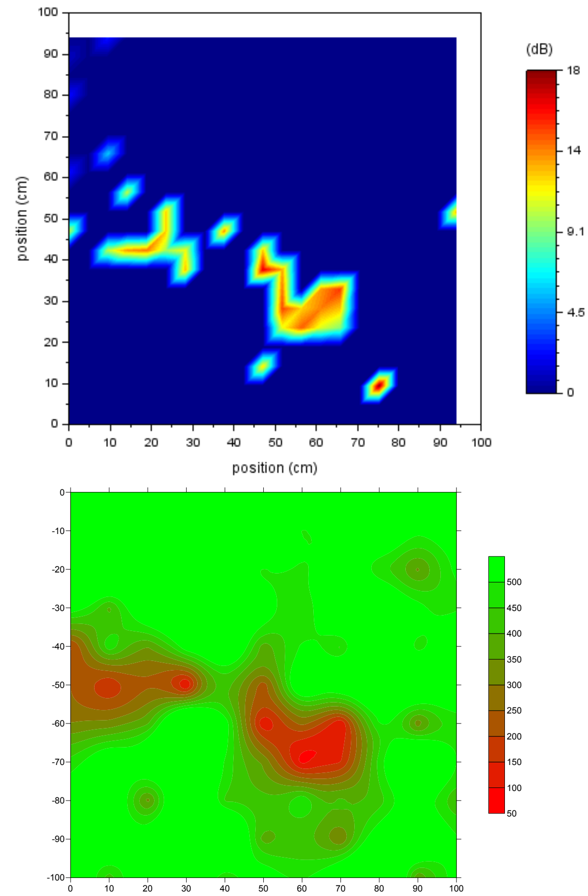

Fig.10. Visualization of internal defects (a) acoustic image applied SSE analysis, (b) Kenkon diagnostic portable (SatoKogyo Co., Ltd.) for health assessment of concrete.

Acknowledgment

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