Recognition of abnormal vibrational responses of concrete structures
A new pattern matching software using multi-CPU

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1 Introduction

The prolonged effects of wind, rain and temperature variations can initiate and expand cavities in exposed concrete structures. Cavities compromise the integrity of concrete structure and can lead to catastrophic failure. Technicians can estimate and monitor the presence and extent of cavity compromise in concrete expressway structures by tapping them with a hammer and aurally evaluating the resultant sound. Skilled workers must be used to interpret the generated tap sounds. As an improvement, we have developed software to detect abnormal vibrational responses so that non-skilled workers can routinely and reliably inspect the same concrete structures [1].

Procedurally the recognition software: (1) detects and segments waveforms of the vibrational response from a concrete structure, (2) extracts spectrograms from the segmented waveforms using the LPC (Linear Predictive Coefficient) spectrum analysis, and (3) matches the detected spectrum patterns in the segmented waveforms with the exemplar signal using a similarity scale. To expedite the process, the software executes parallel processing using multiple CPUs.

In this paper, we establish a vibrational model to simulate the acoustic characteristics of a concrete structure with and without voids. Using test specimens, we demonstrate a new pattern matching method for impact sounds recorded by a microphone. This method provides increased recognition accuracy where the acoustic parameters of the tap response vary with respect to the physical parameters and depth of the cavity, and/or the density and composition of the concrete.

2 The LPC spectrogram of impact sounds

The upper diagram of Fig. 1 shows a two-dimensional (time-frequency-power) spectrogram extracted from the sound generated by tapping a concrete test specimen with a hammer. Steps 1-4 of Fig. 2 show the processing procedure to calculate the 2-d spectrogram shown in Fig. 1.

- In Step 1 of Fig. 2, a high pass filter with the range of 500 Hz to 24000 Hz is used to remove the noise of wind. The high pass filter software executes parallel processing using multi-CPU.
- In Step 2, the software detects and segments impact sound waveforms automatically from a continuous recording using multi-CPU [2].
- In Step 3, as shown at the bottom of Fig. 1, the waveform is segmented with 1.062 msec frame width and 0.021 msec frame period, and a one-dimensional (frequency-power) LPC spectrum is calculated in each frame. The right side of Fig. 1

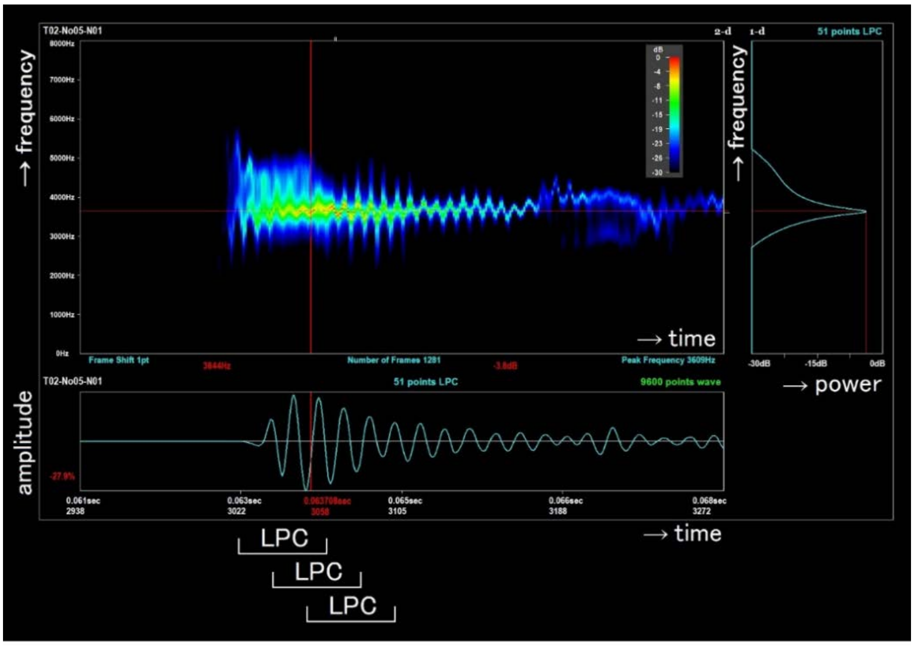

Fig. 1 Spectrogram of abnormal vibrational response of concrete test specimen

shows the 1-d LPC spectrum corresponding to the vertical red line transect of the spectrogram to the left.

○ Note that in Step 3, each of the CPUs executes parallel processing. The software detects the number of CPUs automatically.

● In Step 4, a single CPU merges the individual LPC spectral slices (frequency-power) calculated in Step 3 into a two-dimensional spectrogram (time-frequency-power). Next, the spectrogram is coloured according to logarithmic power of the LPC spectrum.

We have set the analysis conditions of the impact sound with a 48 kHz sampling frequency, 16 bit quantization, 11 order LPC, 0 Hz to 8000 Hz frequency range, 11.5 Hz frequency resolution, and 0 dB to -30 dB logarithmic power spectrum. If we analyze transient signals such as impact sounds, we then need to set the short frame width as shown at the bottom of Fig. 1. LPC spectrum analysis is suitable for such transient signals.

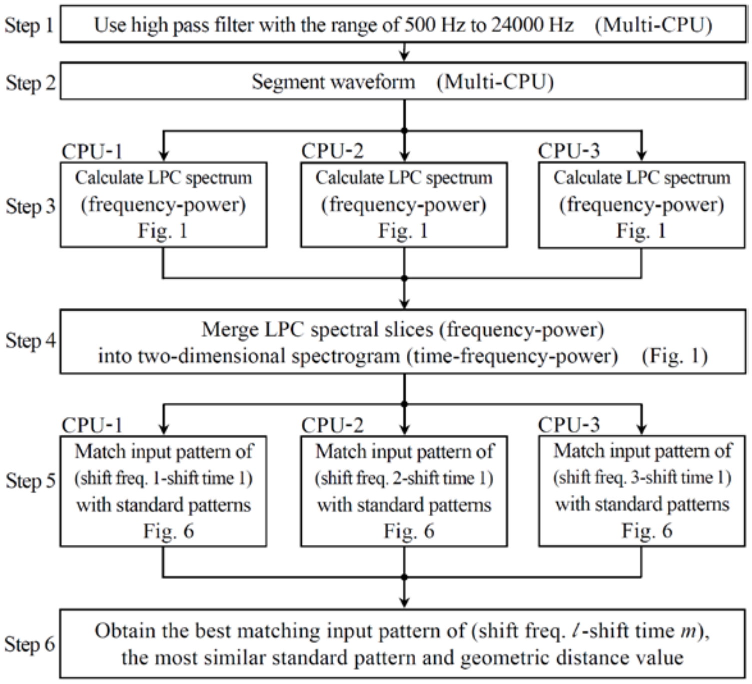

Fig. 2 Flowchart for pattern matching

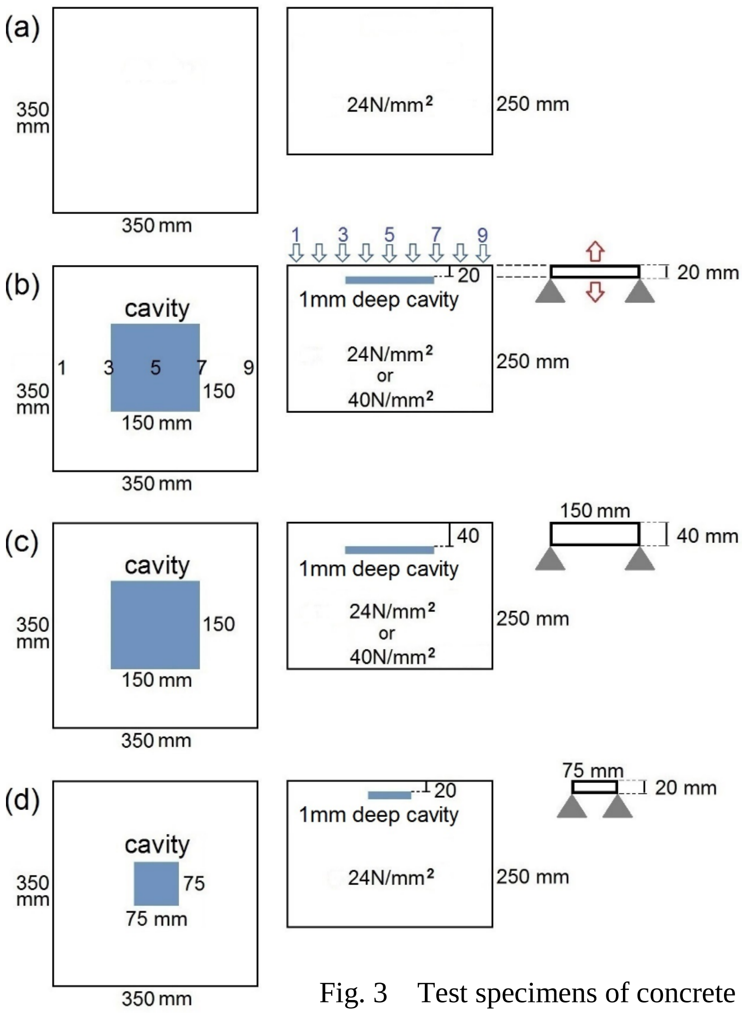

Fig. 3 Test specimens of concrete

3 Vibrational model of concrete

Figs. 3(a)-(d) show the plan (left), and end elevation (centre), of the concrete test specimens. Each specimen is 250mm deep (top to bottom) and 350mm×350mm in horizontal cross section. There is no cavity in test specimen (a)(control). In each test specimen design (b), (c) and (d), a 1mm deep cavity is located 20, 40 and 20mm respectively below the upper surface of the test specimen. The cavities are 150mm ×150mm in horizontal cross section in design (b) and (c) and 75mm×75mm in (d). Test specimens of design (b) and (c) were produced at two compressive strengths, 24N/mm^2 (b1 and c1) and 40N/mm^2 (b2 and c2).

The right side of Figs. 3(b)-(d) shows the respective vibrational model for each concrete test specimen. Each test specimen vibrates at its respective natural frequency when the bridging layer above the cavity is tapped at location 5 (see Fig. 3(b)). The vibrational frequency depends on the area, thickness, density and elastic modulus of the respective bridging layers.

The test specimen represented in Fig. 3(a) and the struck sound arising from striking this test specimen at location 5 (Fig. 3(b)) simulate a normal concrete structure uncompromised by voids. Test specimens represented in Figs. 3(b)-(d) and the struck sounds arising from striking these test specimens at location 5, represent abnormal concrete structures, compromised by internal voids.

The upper and lower images in Fig. 1 show the spectrogram and waveform respectively, of a sound generated by tapping the test specimen shown in Fig. 3 (c1, 24N/mm^2) at location 5 with a hammer.

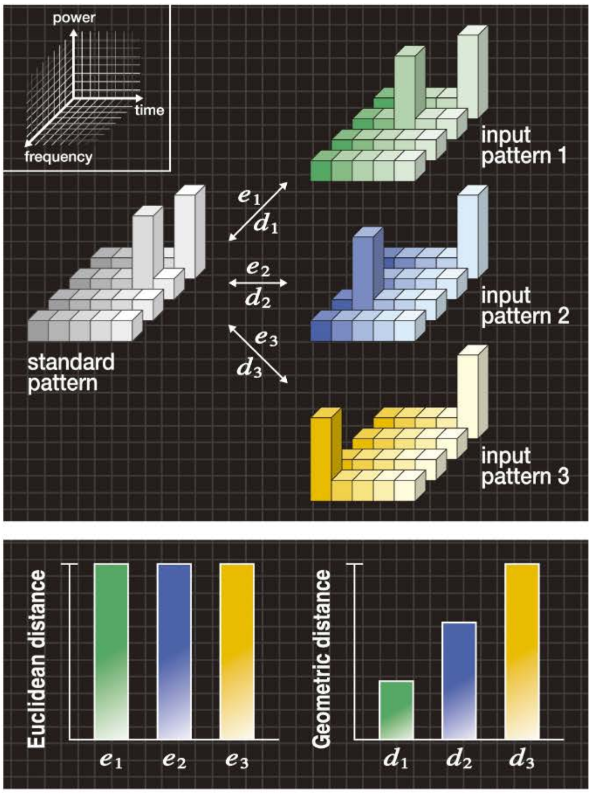

Fig. 4 Typical example of “difference”

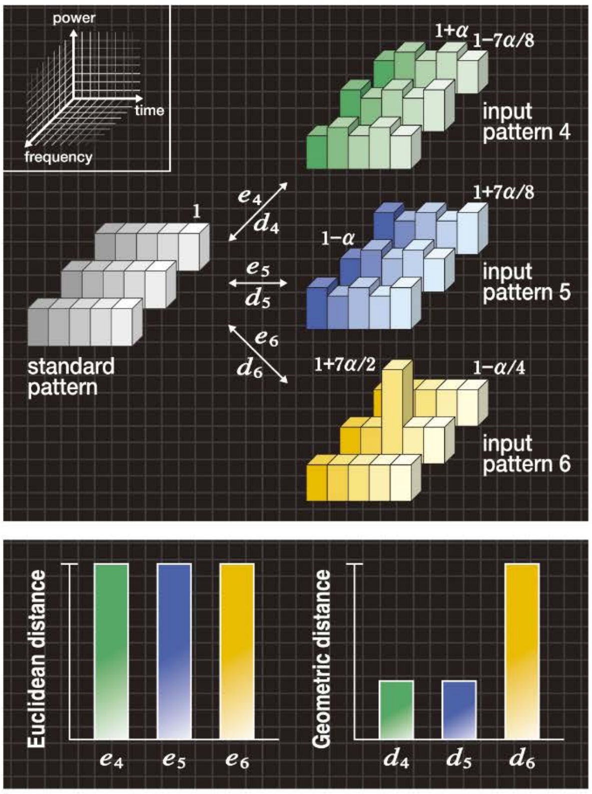

Fig. 5 Typical example of “wobble”

We assume that the concrete bridging layer shown in the right side of Fig. 3(c) vibrates at its natural frequency over the cavity when tapped. The resultant sound is represented in the waveform and spectrogram in Fig. 1.

4 New similarity scale

We use a novel similarity metric (Geometric Distance or ‘GD’ [1]) to compare standardised acoustic patterns of tap sounds arising from both integral concrete specimens and specimens experimentally compromised by voids. A similarity scale is a concept that should intuitively concur with the human concept of similarity in hearing and sight. For a functional similarity scale, we need first to develop a mathematical model for similarity, that can perform numerical processing by computation. In the GD process, a mathematical model incorporating the following two characteristics is used:

< 1 > A distance metric which shows good immunity to noise.

< 2 > A distance metric which increases monotonically when a difference increases between peaks of the standard and input patterns.

The GD has a new algorithm based on one-to-many point mapping to realize the mathematical model. In the GD, when a “difference” occurs between peaks of the standard and input patterns with a “wobble” due to noise, the “wobble” is absorbed and the distance metric increases monotonically according to the increase of the “difference”.

Figs. 4 and 5 graphically demonstrate the underlying computational and algorithmetric processes. The upper diagram of Fig. 4 shows an example of the “difference” where the standard pattern has two peaks in the spectrogram, and input patterns 1, 2, and 3 have a different position on the first peak. Note that both the standard and input patterns have the same volume. Fig. 5 shows an example of the “wobble” where the standard pattern has a flat spectrogram. Input patterns 4 and 5 have the “wobble” on the flat spectrogram, and input pattern 6 has a single peak. However, each pattern is assumed to have variable α in the relationship shown in Fig. 5. Therefore, the standard and input patterns always have the same volume.

Bar graphs at the bottom right of Figs. 4 and 5 express the mathematical model diagrammatically.

5 Shift matching of input pattern

As per section 3, the struck acoustic vibrational frequency of each test specimen varies due to the presence or absence of a void and the area, thickness, density and elastic modulus of the concrete bridge spanning those voids (Figs. 3(b)-(d), right hand column). In application, the naturally weathered voids and the bridges spanning those voids in standing expressways, can have myriad variability, far exceeding the limited parameters of our vibrational model. To assimilate and reconcile this variability, we incorporate a time and frequency shift function to the software. This function allows tap sounds from varying standing structures to be compared using GD, to standards established from test specimens as per the vibrational model.

The diagram at the top left of Fig. 6 shows a typical example of the input pattern that shifts in the directions of the frequency and time axes on the spectrogram of the input sound. We obtain the input pattern by cutting the spectrogram through the window. The software matches the input pattern with the standard pattern accurately, even if the vibrational frequency varies due to the area, thickness, density and elastic modulus of the concrete bridging piece. The bottom diagrams of Fig. 6 graphically represent a good match between the input sound captured by tapping a standing structure with a void and the abnormal sound standard established from our test specimens containing voids. Step 5 of Fig. 2 shows the pattern matching method. Note that each of the CPUs executes parallel processing for the process of Step 5. In Step 6, we obtain the best matching input pattern of (shift freq. *l*-shift time *m*), the most similar standard pattern and a geometric distance value.

6 Evaluation experiments

To check the effectiveness of the pattern matching method described in Sections 4 and 5, we perform evaluation experiments comparing the struck sound of test specimens using the algorithm shown in Figs. 2 and 6. Table 1 shows the types of test specimens used for the standard and input patterns. Spectrograms extracted from the test specimen without cavity (Fig. 3(a)) were used as the standard patterns of the normal sound. Spectrograms extracted from the test specimen types 3(b) and 3(c) were used as the standard patterns for an abnormal sound (cavity compromised). By virtue of the inbuilt spectral shift function, the software is able to recognize input sounds that are extracted from the test specimen shown in Fig. 3(d) by comparing them to standard patterns from specimens 3(b) and 3(c) even though all five (b1, b2, c1, c2 and d) have different cavity characteristics. This is facilitated by the frequency shift function. In Fig. 6, the window has been shifted by a 156 Hz window period (468 Hz total shift) to correctly detect abnormal characteristics despite dissimilar void characteristics. Note that we did not shift the window in the direction of the time axis in the evaluation experiment.

Table 1 Sound spectrograms for evaluation experiments

Sound spectrogram	Test specimen	Tapping location	Number of taps
Standard pattern	Fig. 3(a) 24N/mm^2	1-9 (No cavity)	9×1
	Fig. 3(b) 24N/mm^2	5 (Cavity)	7
	Fig. 3(b) 40N/mm^2	5 (Cavity)	7
	Fig. 3(c) 24N/mm^2	5 (Cavity)	7
	Fig. 3(c) 40N/mm^2	5 (Cavity)	7
Input pattern	Fig. 3(d) 24N/mm^2	1-4 (No cavity)	4×20
		5 (Cavity)	20
		6-9 (No cavity)	4×20

Table 2 Result of evaluation experiments

Test specimen of Fig. 3(d)	Normal	Abnormal
Tapping locations 1-4, 6-9 (No cavity)	160 / 160	0 / 160
Tapping location 5 (Cavity)	3 / 20	17 / 20

Table 2 shows the result of evaluation experiments. From Table 2, it is learned that the input sounds recorded at tapping locations 1-4 and 6-9, each beyond the cavity footprint, are recognized as 'normal' in all cases, and the recognition accuracy at tapping location 5 above cavities is 17/20. Thus we have verified the effectiveness of the proposed method.

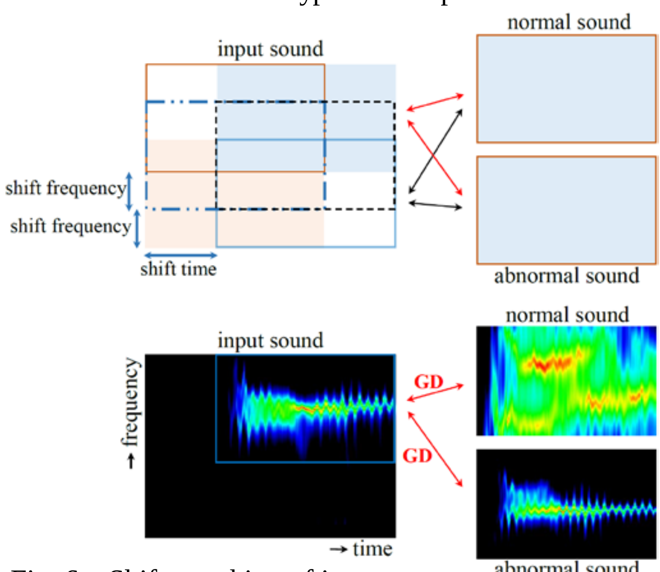

Fig. 6 Shift matching of input pattern

7 Conclusions and future work

We have introduced automatic recognition software that executes parallel processing using multi-CPU and have proposed here a new pattern matching method which may facilitate more cost-effective and reliable integrity testing of standing and pre-delivery concrete structures. In our future work, we will continue to improve the recognition software.

References

[1] M. Jinnai, Y. Akashi, K. Hashimoto and S. Hayashi, "Method for detecting abnormal sound and method for judging abnormality in structure by use of detected value thereof", *Patent No.* US9552831(2017), AU2016200487(2017), CA2918533(2018), JP5956624(2016)

[2] M. Jinnai, "A new segmentation method of bird vocalisations recorded in the distance", *2018 Autumn Meeting, Acoustical Society of Japan*, 3-1-5