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Nondestructive Diagnosis for Existing Structures Using Amplitude Attenuation of High Frequency Wave†

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Abstract:

Urgent inspection and maintenance works are required for structures and facilities which were built during high economic-growth period since they started aging. In this study the authors developed a new nondestructive diagnosis method by using amplitude attenuation of high frequency pseudo random wave. The experimental results show cracks and voids in the precast concrete block are detectable by attenuation image and cracks in the crane runway girder are detectable in a short time without using a scaffold even under crane operation.

1. Introduction

More than 50 years have passed since Japan's high economic growth era began in 1955, and reduced safety due to aging of the structures constructed during that period has now become a problem. For example, of approximately 150 000 bridges with lengths of 15 m or more, around 20% will be more than 50 years old in 2016, and will exceed the guideline for useful service life[1]. The situation in Japan's steel works is similar, as the number of 40–50 years old equipment is increasing. Thus, reliable inspection has become an urgent issue. However, for the following reasons, very little progress has been achieved in inspection work related to structures: (1) It is difficult to proceed with work in inspections of bridges and facilities which are in use, due to the presence of traffic and on-going operation must not be disturbed. (2) Due to the large number of facilities and number of points to be inspected, too long time and much cost are required in inspections by the conventional techniques of ultrasonic inspection and magnetic powder testing. (3) Visual and tap-tone inspections require skill and experience, and lack objectivity and accuracy.

In order to solve these problems, "objective primary screening techniques, with which a wide range can be inspected in a short time" are considered necessary. For example, examination techniques which should be positioned between "ultrasonic inspection, which is detailed but covers a narrow range" and "seismic exploration, which covers a wide range but has rough resolution" are considered necessary (**Fig. 1**). As existing research, Sakakibara et al.[2] showed the possibility of a diagnosis technology which is positioned this intermediate position controlling of the frequency of oscillation waves. This is a technology in which the wave generation and receiving technology "High resolution geological survey by high frequency seismic wave"[3] is applied to structural diagnosis. In this technique, a pseudo random binary sequence wave[4] having an arbitrary frequency and amplitude is output as the oscillation wave, and its travel time and amplitude loss are measured with the necessary accuracy. The present paper discusses

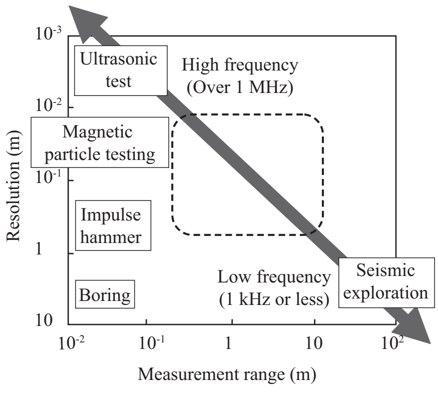

Fig. 1 Comparison of diagnosis method from the viewpoint of resolution and measurement range

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application of this approach to nondestructive diagnosis of concrete structures and steel structures by focusing on the amplitude loss of the wave in addition to wave generation of an appropriate frequency, as presented by Sakakibara et al., and also describes verification of the appropriateness of the method and the experimental result of trial testing at actual sites.

2. Diagnosis of Concrete Structure

2.1 Measurement Principle

The purposes of diagnosing concrete structures are to determine whether construction was proper or not and to grasp the progress of internal destruction and the propagation of cracks due to corrosion of the reinforcing steel bars and internal deterioration due to neutralization, etc. However, with the conventional technique, which evaluates only the P wave velocity, it is not possible to determine whether the decrease in the obtained velocity is caused by material quality or by internal deterioration. The effectiveness of simultaneous evaluation of velocity and attenuation in subsurface investigation has been shown[5]. For example, **Fig. 2** shows the geological classification by travel time (velocity) in the ground. Using only velocity, there are cases in which classification is limited to "weathered rock or dense sand" and "loose sand or compacted clay." In contrast to this, **Fig. 3** shows the geological classification using attenuation in addition to velocity. Identifying differences of sand, rock, or clay using the result of attenuation, it can be understood that discrimination of "existence of crack in bedrock or not" and "existing of cobble/gravel or gas in sand or clay" is also possible. Attenuation described in this paper means Q^{-1} shown in Eqs. (1) and (2). However, a wave propagating in a material is also affected by geometric loss, scattering loss L_s, which is caused by scattering/reflection of sound at the boundary of two materials having different densities, and transmission loss L_t, which is caused by conversion of the wave to heat at this boundary[6]. Because waves which propagate in the interior of a concrete structure are considered to be attenuated by scattering loss and transmission loss at voids, cracks, etc., an experiment was carried out focusing on these attenuation and amplitude loss.

$$A = A_0 - \log_{10} r - \alpha r \log_{10} e - L_s - L_t \quad \cdots\cdots\cdots\cdots (1)$$

$$\alpha = \frac{\pi f}{V} Q^{-1} \quad \cdots\cdots\cdots\cdots (2)$$

A: received sound pressure,
A_0: oscillation sound pressure, r: travel distance,
f: oscillation frequency, V: travel time (velocity),
Q^{-1}: attenuation factor

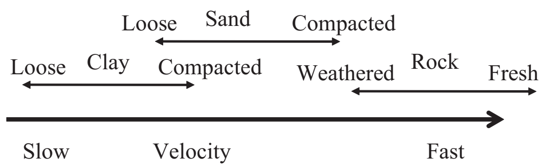

Fig. 2 Geological classification by velocity

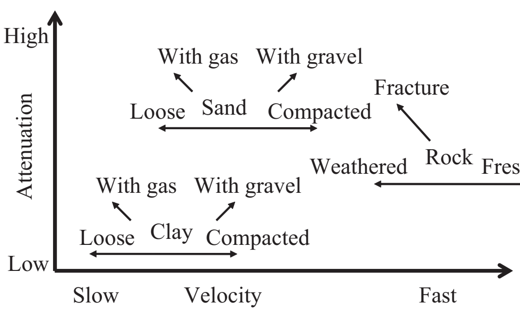

Fig. 3 Geological classification by velocity and attenuation

2.2 Verification Experiment

In order to verify the applicability of this method to diagnosis of concrete structures, an experiment was carried out using a concrete specimen (height 1 m × width 0.9 m × depth 0.9 m; shown in **Fig. 4**) containing

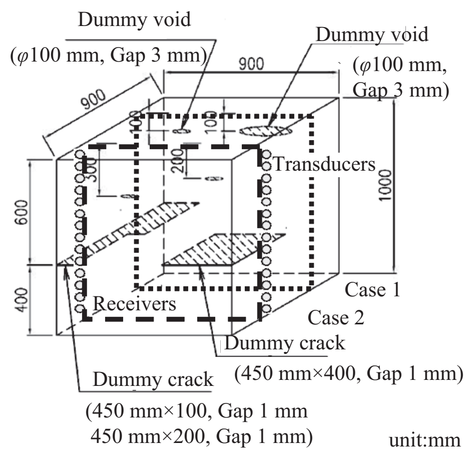

Fig. 4 Layout of dummy voids and cracks of concrete specimen

Table 1 Equipment list for experiment

Equipment	Specifications
Transducer, Receiver	φ10 mm, Thickness 5 mm
Power amplifier	Bandwidth DC-100 kHz Output voltage 100 V_{rms} (30 kHz)
Signal filter	Bandwidth 1–100 kHz Output gain 1–100 times
Signal generator	Bandwidth 1–150 kHz
Data logger	Sampling frequency 1.2 MHz (1 Channel)

reinforcing steel bars. Plastic plates were installed as two kinds of dummy defects, surface crack and internal void. The measured cross-sections comprised two cases, Case 1 contains a dummy crack containing a dummy crack 200 mm in depth from the top of the specimen and dummy voids of 300 mm in diameter and 100 mm in diameter and Case 2 contains, a cross-section containing dummy cracks with depths of 100 mm and 400 mm and a dummy void of 100 mm in diameter. The equipment used in this experiment is listed in **Table 1**. The transducers and receivers were arrayed at 31 locations with 30 mm intervals shown by the open circles (○) in the figure. The oscillation frequency was 50 kHz, and the applied voltage on the transducers was 100 V_{rms}. The experimental results are shown in **Fig. 5**. In this figure, tick marks at the *y*-axis are the position of the sensor along the vertical direction and the *x*-axis is the horizontal distance between the transducer and receiver; the dotted lines show the horizontal dummy cracks and horizontal dummy voids which cross the cross section. From Fig. 5, it can be understood that parts where attenuation is 0.11 or higher agree with the positions of voids and cracks with lengths of 20 mm or greater. This is because scattering or transmission loss occurred at crack and void parts. It is also understood that no agreement between high attenuation parts and the defeat with a length of 10 mm is observed. On the other hand, the velocity image is not affected by the defeat. This is considered that the wave passed through these defeats even while attenuating. Neither velocity nor attenuation was affected by the reinforcing steel bars in the block, this is considered that the outer diameter of the reinforcing bars was sufficiently small (approximately 20 mm) in comparison with the wavelength (approximately 70 mm). As stated the above, it was concluded that "the position and size of cracks and voids can be grasped 2-dimensionally using amplitude attenuation."

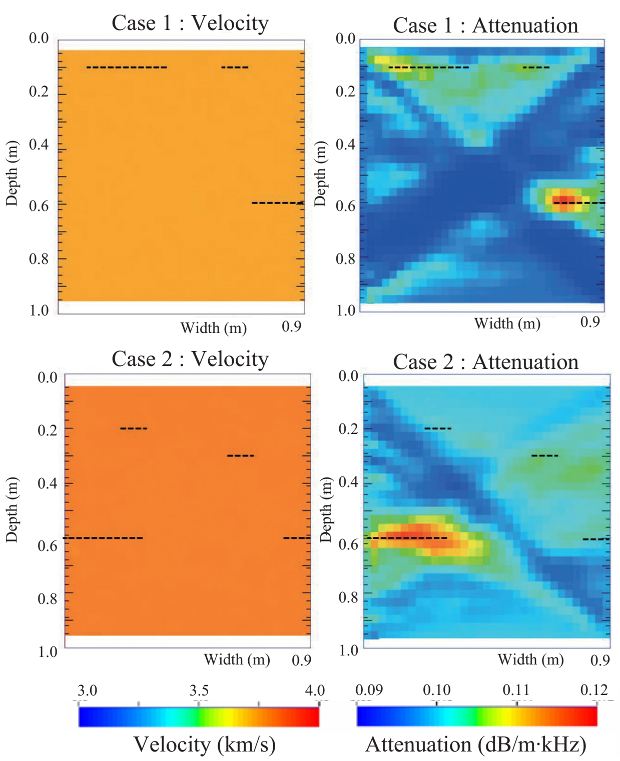

Fig. 5 Experimental result

3. Application to Diagnosis of Steel Structure (Crane Girder)

3.1 Measurement Principle and Results of Fundamental Experiment

Because the crane runway girder (hereinafter, CRG) is one of the most important facility in the steel works, reliable inspection is indispensable as failure of the CRG will result in a serious accident. However, inspecting of CRG is difficult because the operating ratio is high, the number of units is large and the CRG is located at a high position. Therefore, a new inspection method which enables inspection in a short time without interrupting operation had been demanded. In this research, a new diagnosis method using a guided wave[7] was developed for the following purposes: (1) To detect cracks occurring in the bottom flange edge, which causes the most dangerous condition, (2) to enable inspection without using scaffolds and stopping operation, and (3) to perform diagnosis of the entire span (approximately 20 m) in a short time. The guided wave is defined as "the apparent wave which is generated by a share wave (S wave) and a compressional wave (P wave), which are bulk waves, propagate in a material as to satisfy the boundary condition." Because the guided wave propagates at the boundary surface of a material as shown in **Fig. 6**, it is estimated that a guided wave propagating in a flange edge (edge plane) will be affected by a crack that exists in the edge part. Therefore, the fundamental experiment shown in **Fig. 7** was carried out to assess the effects of the existence (or nonexistence) of a crack and its length and the effect of a gusset plate installed on the CRG. The dimensions of the specimen were length: 9 000 mm, thickness: 20 mm, and plate width: 400 mm. The crack lengths were 0 mm to 100 mm, and the lengths of the dummy gusset plate were 0 mm to

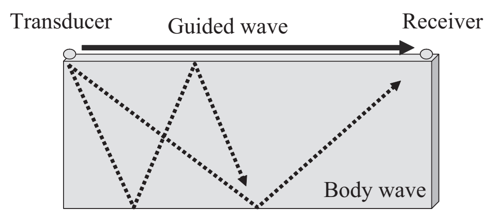

Fig. 6 Schematic image of guided wave and body wave

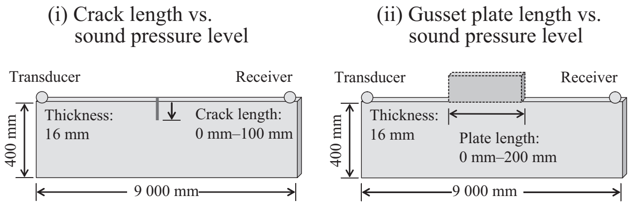

Fig. 7 Schematic images of fundamental experiment

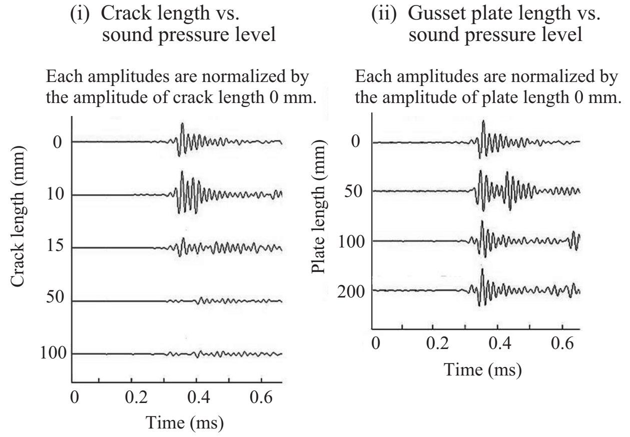

Fig. 8 Results of fundamental experiment

100 mm. The results are shown in **Fig. 8**. The amplitudes shown in the figure have been normalized by a crack length of 0 mm and plate length of 0 mm. From these results, it was found that the received sound pressure decreases with longer crack lengths, and the results are not affected when the gusset plate length is on the order of 200 mm.

Figure 9 shows the results of an experiment which was conducted while changing the crack length from 0 mm to 100 mm using 3 test specimens with different plate lengths from 2 000 mm to 15 000 mm and plate thicknesses from 10 mm to 20 mm. The *y*-axis shows the decrease of received sound pressure based on the sound pressure when the crack length was 0 mm, and the *x*-axis shows the crack length. From these results, it is understood that received sound pressure decreases

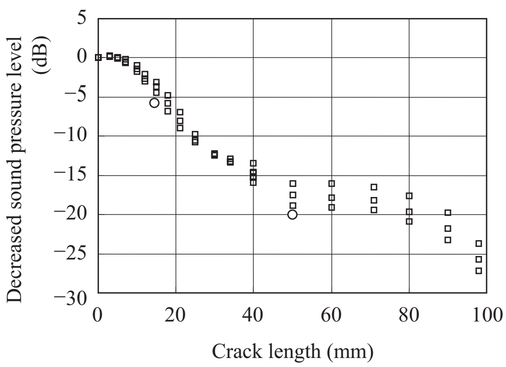

Fig. 9 Relation between crack length and decreased sound pressure level (Solid circles show results of Fig. 8.)

corresponding to crack length, and is independent of plate length and plate thickness. The open circles (○) in the figure plot the results in Fig. 8, which showed good agreement with these results.

3.2 Preparation of Prototype System and Results of Diagnosis at Site

A demonstration experiment was carried out using a prototype system in order to verify applicability of this system on actual production sites. The system outline is summarized in Table 1 and **Fig. 10**. First, the transducer and receiver, which were installed to the end of a telescopic pole, were attached on the edge of the bottom flange by extending telescopic pole from the floor. Next, a pseudo random binary sequence wave of an suitable frequency, which had been generated by a personal computer, was output from the transducer and received by the receiver. These devices were battery-driven. Threshold values for caution (decrease of 12 dB) for a crack length of 20 mm or more and warning (decrease of 20 dB) for a crack length of 60 mm or more from the reference value were prepared based on the results stated the above in the previous section, and these were used in

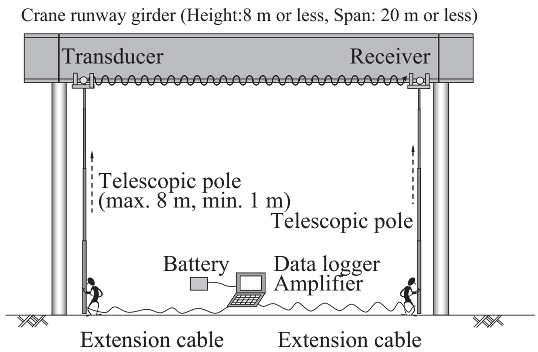

Fig. 10 Schematic image of diagnosis system

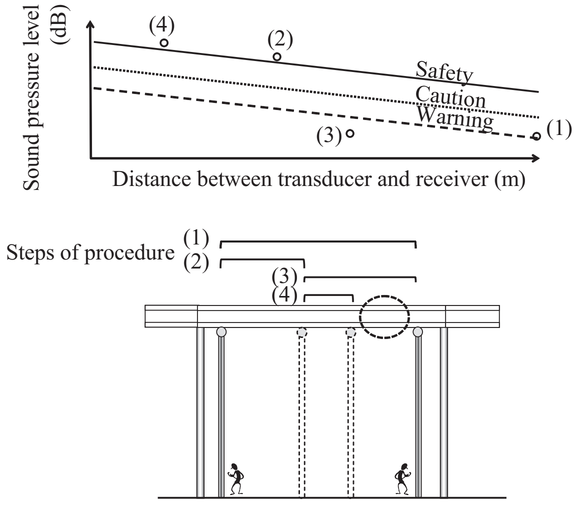

Fig. 11 Example of diagnosis results

judgment of the inspection results.

The CRG which is operating frequently was selected for the experiment. An example of the experimental results is shown in **Fig. 11**, together with the diagnostic procedure. In the upper part of Fig. 11, the *y*-axis shows the measured sound pressure, and the *x*-axis shows the distance between the sensors. The three lines show, from the top, the reference value (safe), caution (monitoring required), and warning (immediate action required), based on the above-mentioned threshold values. The open circles (1) through (4) are actual measured values. The lower part of Fig. 11 shows the diagnostic procedure. First, diagnoses were performed on both edges, resulting in Warning (1). Next, the left half was diagnosed and found to be Safe (2). When the right half was diagnosed, the result was Warning (3). To make doubly sure, the left half of section (3) was diagnosed, and a Safe result was obtained (4). Therefore, a crack was estimated to exist in the part surrounded by the dotted line in the figure. Magnetic powder testing was performed, and a crack was discovered at this position. From the results of this experiment, it was found that the existence (or nonexistence) of a crack, its length, and its approximate position can be determined in a short time without setting scaffolding and without stopping operation.

4. Conclusion

In this research, a new diagnosis method for inspecting the crane runway girder (CRG) by using amplitude attenuation of a pseudo random binary sequence wave was developed. And the results of verification experiments that it is possible to detect internal defects in concrete structures and cracks in the flange edge of a CRG. From this result, this method is considered to fill the blank in the center of Fig. 1, as shown in **Fig. 12**. The CRG diagnosis method discussed here has already been conducted at production sites as a primary screening technique and is getting good results.

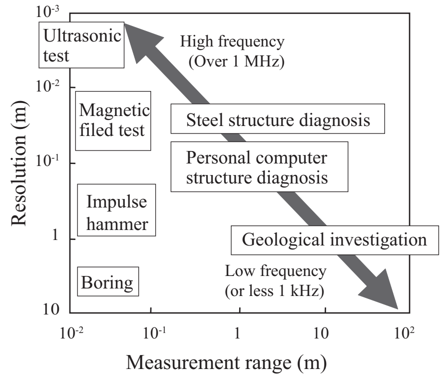

Fig. 12 Comparison of diagnosis method from the viewpoint of resolution and distance

In the future, the authors plan to develop a compact, lightweight system and improve diagnostic accuracy by accumulating actual results. Further, research aimed at developing new fields of application is also planned.

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