Developments in Ultrasonic Inspection I

Ultrasonic Propagation Behaviour in Composite Material for Velocity Measurements of Concrete Structure
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ABSTRACT

Guarantee of the strength for an aging structure, especially for a concrete structure, has been required. Possibility of the evaluation of a concrete structure using ultrasonic velocity has been investigated in civil engineering field in Japan. However, because the concrete is the complicate composite material which contains aggregates in mortar, and the ultrasonic propagation becomes complicate with high attenuation. In this paper, the accurate three-dimensional FEM code was applied to investigate the ultrasonic propagation behaviour using the single aggregate ball model and the concrete model.

Keywords: ultrasound, low frequency, concrete, FEM, sound field analysis

INTRODUCTION

Maintenance of the aging structures becomes a serious social problem, and the nondestructive strength evaluation has been applied for the steel structures and also for the concrete structures. Since the rust of the reinforcing bar in concrete causes the exfoliation and the fracture of the concrete structures, the most efficient maintenance technique for the usual concrete structures at this stage is a visual inspection [5, 6]. However in the electric power plant, the early stage damage must be detected and then other nondestructive methods are also required. These techniques also considered to use for the quality control in construction process. Though ultrasonic techniques are widely used in the steel structures for this propose, the serious problems have been reported in ultrasonic measurement in a concrete structure due to the large attenuation. Since the large attenuation is caused by the complicate structures in concrete where aggregates and reinforcing bars are distributed in mortar, the low frequency ultrasound have been applied for the measurement of concrete structures. For example, an acoustic velocity measurement using low frequency ultrasonic transmission is plan to applied the bridge structures in Japan [1]. Even in these measurements, only the first received transmitted echo planes to measure the velocity of the concrete and the velocity expect to use the material damage evaluation because other echoes are difficult to determine even the traveling path by complicate overlapping each other. Moreover, even these simple velocity measurements by the first received echo in concrete structures are not so easy due to low S/N ratio and low repeatability [2]. As a velocity is the most basic property for ultrasonic measurement, an accurate measurement and estimation cannot be realized without knowing accurate velocity in the concrete structure.

In this study, we analyzed the accurate ultrasonic propagation in concrete structures using the highly precise three-dimensional FEM code [3,4] that specialized to analyze ultrasonic propagation. As the results, the FEM could analyze an accurate ultrasonic propagation in concrete structures and this code was an effective tool for the optimization of the evaluation technique for the concrete structure.
ULTRASONIC PROPAGATION AND RECEIVED WAVEFORM IN CONCRETE STRUCTURE

Time dispersion in waveform by simple model

The basic model of the concrete structure is an aggregate of fast velocity material distributes in mortar of slow velocity materials. In industrial concrete, air bubbles mixed in manufacturing process and reinforcing bar of a supporting structure will still add to this model, but in this paper, we simply considered an analytical concrete structure as an aggregate distributes in mortar. Fig.1 showed the first demonstration considering the multiple ultrasonic transmitted lines before FEM analysis. Received waveform of this model was obtained by superposing with each delayed echoes of 77 numbers of linear traveling path due to the travelling ratio of the aggregate and the mortal. Longitudinal wave through the center of an aggregate reached the receiving position first because wave velocity of the aggregate was faster than that of the mortal. Thus, received RF echo show the large dispersion because other echoes along the other path arose varied lager delay. Although this was a simple prediction of one aggregate model with no refraction, no reflection and no attenuation, we considered it could roughly estimate the ultrasonic propagation in the concrete.

Ultrasonic propagation analysis of single aggregate model by high precision FEM

Industrial concrete has the complicated structures, and a received waveform has the low reproducibility and the extraction of a common ultrasonic parameter from an individual ultrasonic measurement is not easy. In order to obtain the prospect of the ultrasonic parameter for the nondestructive evaluation of a concrete structure, Finite Element Method (FEM) analysis was applied. The precise FEM codes of "Com WAVE™" which had been developed only for ultrasonic propagation analysis were used. The first FEM analysis model was shown in Fig. 2. A spherical aggregate of 30 mm in diameter was placed in the center of the mortar of 90x100x100 mm, and the longitudinal wave incident from the upper piezoelectric element of 3.3 mm in thickness and 76 mm in diameter.
Figure 2 - Mortar-aggregate FEM model

The behavior of the transmitted ultrasonic wave could be investigated and especially the transmitted waveform of stress was monitored at the receiver position in this model. Acoustic properties for each structure were as following, the longitudinal and the shear wave velocity and the density of a mortal were 3545 m/s, 2108 m/s and $2.3759 \times 10^3$ kg/m$^3$, and the longitudinal and the shear wave velocity and the density of an aggregate were 4721 m/s, 2866 m/s and $2.605 \times 10^3$ kg/m$^3$, and the longitudinal and the shear wave velocity and the density of a piezoelectric element (PZT) were 4600 m/s, 2900 m/s and $7.5 \times 10^3$ kg/m$^3$, respectively. Three-dimensional analysis of 0.4 mm in pitch and 35 million meshes in number were applied to analyze.

Ultrasonic pulse of 0.5 MHz in frequency was used as a incident wave to analyze the ultrasonic propagation behavior and the transmitted waveform. Fig.3 showed the sample of the FEM analysis of the ultrasonic propagation and the received waveform. Even one aggregate made the propagation behavior complicate and the amplitude of the first transmitted echo made weak.

Thus, the first received echo at the transmission measurement, which planed to use the velocity and the damage estimation in a concrete structure in Japan, mainly relate to aggregate properties because its main traveling path was in aggregate.

Figure 3 - Example of the FEM analysis of the ultrasonic propagation and received waveform
Ultrasonic propagation analysis in concrete by high accurate FEM

The concrete model with many aggregates dispersed in mortar and the pure mortal model for FEM analysis were shown in Fig. 4. Size of these models were 110x110x200 mm and the ellipse aggregate of 20-25 mm in long axes and of 25-30 mm in short axes were randomly dispersed in mortal of 45 in volume percent. The acoustic properties for the FEM analysis of mortar, aggregate and PZT were same as the above mentioned model’s value and the analysis elements were 0.4 mm in pitch and 40 million in number.

Figure 4 - Concrete model for FEM analysis

The sides of the models were set to no reflective boundary condition. Incidence waveform of a sound pressure was a single polar pulse of 0.5 MHz in frequency. Fig. 5 show the example of the ultrasonic transmitting behaviour in mortar and concrete, red show compression and blue was nearly zero in sound pressure expression. Comparing to Fig.3, the ultrasonic propagation in concrete became very complicate and time dispersion of travelling echo was also increased. The RF waveform measured at receiving PZT was shown in Fig. 6.

Figure 5 - The example of the ultrasonic behaviour transmitting in mortar and concrete
The amplitude and the S/N ratio of the "first received echo" were not so high because of the large scattering from aggregate. In addition, since the "first received echo" travels mainly in aggregate, the only aggregate structure could be estimated using the "first received echo". For the nondestructive estimation of the average damage in a concrete structure, thus, we should try to use not only first received echo but also subsequenced complicate echoes.

**EXPERIMENTAL TRANSMITTED WAVEFORM IN CONCRETE SPECIMEN**

Fig. 7 shows the experimental example of the waveform after transmitting through a concrete specimen of 250 mm in thickness. The center frequency and the size of the transducer were 2 MHz and 20 mm in diameter.

The incident monopole ultrasonic wave became bipolar shape according to the propagation in concrete specimen. As predicted with the FEM analysis in Fig. 6, the received RF waveform through concrete structure show large dispersion due to the velocity difference between aggregate and mortal, and its S/N ratio also became worth. Though the acoustic properties and the detail of the concrete structure between the experiment and the FEM analysis were different, both results show similar at least in qualitative meaning.

**CONCLUSION**

We succeed three dimensional FEM analysis for the ultrasonic wave propagation in concrete structure, aggregate distributed in mortal, using "ComWAVE" as shown in Figs. 3 and 5. Single plane wave transmission in mortar model changed to the complicate dispersion wave in the concrete model due to the large scattering of aggregates. This
time dispersion was caused by the velocity difference between aggregate and mortar, and the first received wave propagated through mainly aggregate. For the velocity measurement and the damage evaluation for the concrete structure by ultrasonic method, we should investigate to use not only first received echo in transmission but also other echoes. For the industrial use of other echoes, more investigation of ultrasonic propagation behavior using the accurate simulation technique like the FEM analysis as used in this study will be effective also for the development of the measurement systems.

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REFERENCES