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Experimental Study of Ultrasonic SAFT Imaging for Concrete Structures

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Abstract: Being a promising approach in ultrasonic nondestructive testing (NDT) methods, synthetic aperture focusing technique (SAFT) subsequently focuses the data measured on an aperture to every point of the reconstructed imaging area through superposition of the time records. For validate the potential of this method, an experimental system is established to perform cross-surface scan of the test specimen, an SAFT processing program is used to give a 2D display of the inner structure of the specimen based on the measured backscattered ultrasonic signals. Two different concrete specimens were cast with embedded objects. Design of the inspection pulse, for example the pulse shape and central frequency is discussed. According to SAFT imaging algorithm, images of these concrete structure are pictured. Compared to original B-scan method, SAFT gives better imaging quality.

Key words: Concrete structures, ultrasonic imaging, SAFT

INTRODUCTION

Concrete is one of the main structural materials, which has been widely used for buildings, pavements, bridges and the infrastructures. It can be cast in to a great variability of shapes and is adaptable to many tasks. Being such a popular engineering material, concrete structures needs to be tested and inspected both in its construction process and in its whole life-cycle.

The thickness of pavements, detection of object embedded and localization of defects in concrete elements are all significant and valuable. In the past decades, some kinds of semi-destructive and NDT techniques have been employed to investigate concrete elements and structures (Jean *et al.*, 2003; Fan and Fukuo, 2006; Li *et al.*, 2010). Among these methods, the ultrasonic pulse-echo technique has become an important tool because of their sensitivity to the abnormity in the continuous medium. As well known, however, hardened concrete consists of sand, cement and aggregate and is a strongly scattering medium with porosity and inhomogenous (Schickert, 2002; Pier and Sigrun, 2004:Phanidhar *et al.*, 2001), therefore the received signal includes complex components, such as structural and scattering noise, reflection from back wall and embedded object, which lower signal-to-noise ratio (SNR) and increase the difficulty to inspect concrete elements. Ultrasonic method will be promising through improved equipment, testing methods and signal processing methods (Schickert, 2006; Schickert and Krause, 2010). Traditional method in ultrasonic imaging of concrete elements is B-scan, which is the two-dimension presentation of several A-scans, forming a cross section through the specimen depth. The imaging method use few signal processing to diminish disturbing signals such as structural noise and mode-converted waves, so its quality is considerably rough and unclear and extensive works need to be carried out in order to extract clear display of the inhomogeneous and porous concrete. At present, SAFT has been introduced to imaging for testing concrete elements and better imaging quality has been obtained compared to other methods. SAFT is based on subsequent focusing of the data measured on an aperture to every point of the reconstructed area through superposition of the time records (Schickert and Krause, 2010: Mustafa *et al.*, 1995; Schickert, 1995). A synthetic aperture imitates a large transducer by sampling its area at many points. The algorithm focuses the received signals to any point of reconstructed image by coherent superposition and a large virtual transducer with variable focus is synthesized (Schickert, 1995: Paris and Roy, 2003).

CONFIGURATION OF THE TEST SYSTEM

For the inspection of concrete elements by ultrasonic method, a test system shown in Fig. 1 is established. The

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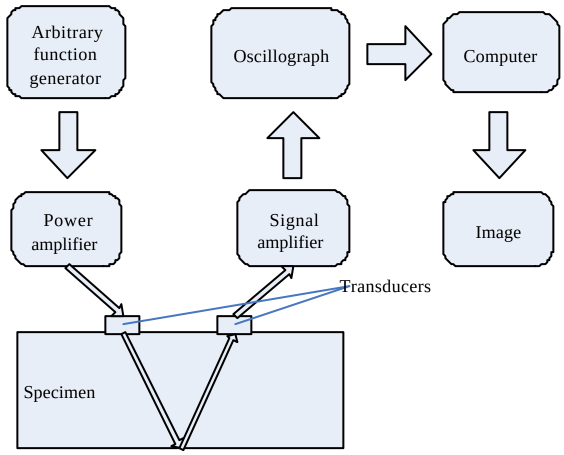

Fig. 1: Configuration of the test system

system can be divided into four sections: pulse generator, ultrasonic transducers, data acquisition system and imaging software. An arbitrary function generator, Tektronix AFG3021, is used to generate pulse waveform for the experiment. Under the Matlab environment, several kinds of excitation pulse were designed for the excitation of the transducer. A power amplifier, Model 7602 M, is employed to ensure output signal up to 200 V within bandwidth of DC~20 MHz. Two 50 kHz ultrasonic transducers are used as transmitter and receiver. Usually, low frequency transducers with low damping are employed to offer high-energy pulses (Krause *et al*., 1997; Chaix *et al*., 2006). During the experiment, however, it is found the echoes from the detected objects will be overlapped by the rings of the generated pulse if the input frequency is selected as 50 kHz. To avoid the transducer's resonance the signal frequency far from 50 kHz, for examples, 25 and 100 kHz are selected for inspection. The receiving unit consists of a signal amplifier and a digital oscillograph. The signals can be amplified by the amplifier to about 20 times within bandwidth of 100 Hz-1MHz. An oscillograph, Model TDS3032 by Tektronix, is used to receive the amplified signals. The sampled data is then uploaded to an imaging computer through GPIB interface. An SAFT algorithm is programmed in Matlab to give the image display of the detection result.

PRINCIPLE OF SAFT ALGORITHM

SAFT derives from synthetic aperture radar, which has a great potential to image concrete elements and to detect embedded objects. In theory, high resolution can be obtained by application of small aperture transducers and using low-frequency, breaking through the limitation of classical theory.

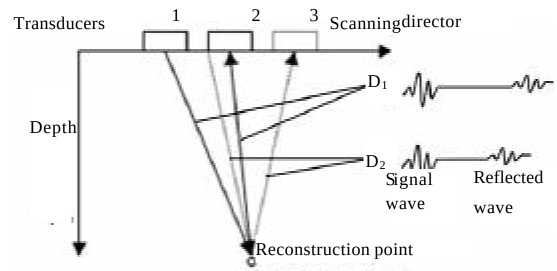

Fig. 2: Sketch map of principle of SAFT

B-scan on concrete with two transducers can be carried out effectively because of divergence angle. The defect or embedded object under detection can reflect echoes to the receiver within the transducers divergence angle. An object will cause reflections in several channels of the pulse-echo detection. As shown in Fig. 2, defects under transducer position 2 can also causes echoes in the measured waveform of transducer in position 1. The difference is that the time-of-flight (TOF) of the echo to 1 is a little longer than that to 2. Thus in traditional B-scan methods, the defect point can not be focused to its real position. To solve this problem, either a transducer with small divergence angle or some signal processing approaches to focus the original image points need to be used.

Hypothesizing signal reflected from different position is $S(i, t_{ij})$, where i represents position of the receiver, j represents one of the reconstruction points and t_{ij} may be depicted reflection position of the j^{th} reconstruction point in the received signal of position i. When the transmitter is placed on position 1 and the receiver is placed on position 2, for example, to the j^{th} reconstruction point ultrasound wave propagates in concrete as solid line in Fig. 2 and propagation distance is D_1, then the time of flight of the j^{th} reconstruction point on the position, t_{1j}, can be given by:

$$t_{1j} = \frac{D_1}{c} \qquad (1)$$

Here c is pulse velocity in concrete. On the other positions of receiver, TOF of the same reconstruction point can be calculated by the same way. So the average intensity of this reconstruction point, S_1, can be expressed by a equation as below:

$$S_1 = \frac{1}{N}\sum_{i=1}^{N} S(i, t_{i1}) \qquad (2)$$

Here, N is the amount of selected relevant positions for calculation. And then the average intensity of all reconstruction points can be calculated. The interval of each reconstruction points should be selected in the light of the maximum resolution in the lateral and axial directions which is about λ or $\lambda/2$ in theory. After the intensity of these points are obtained, the reconstruction image can be mapped.

Indications in SAFT images are reconstructions of object boundaries which are imaged localized at their geometric position and can therefore be interpreted more easily. Another advantage of SAFT is suppressing of incoherent signals such as most mode-converted waves and structural noise. A large divergence angle of the transducer is desired since illuminating an object from many aperture positions increases the signal-to-noise ratio (SNR). As a general result, positional diversification leads to partial suppression of disturbing signals. The main disadvantages of SAFT imaging algorithm are incomplete reconstruction and the possible introduction of artifacts as consequences of finite aperture size and other approximations made to ideal reconstruction conditions. Variations in pulse velocity due to the different sound paths under which an object is viewed from the aperture may blur indications (Schickert and Krause, 2003).

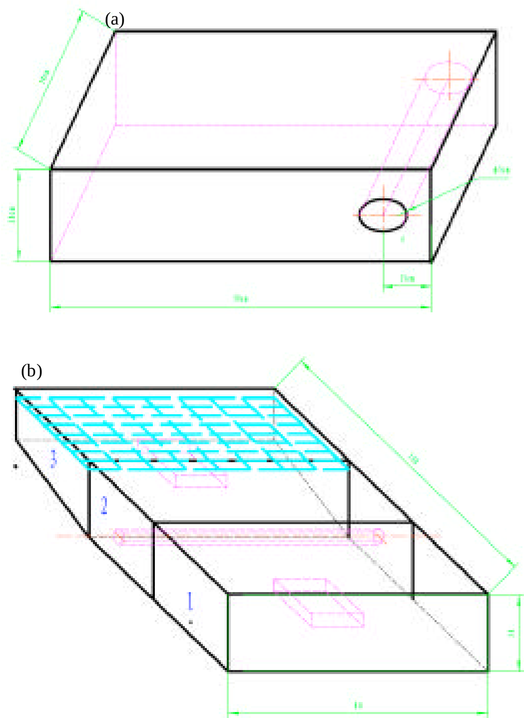

Fig. 3(a-b): Structure of two specimens, (a) Small specimen and (b) Big specimen

EXPERIMENTAL RESULTS

For the experiment, two specimens of concrete are designed and cast with the same mixed material. Dimensions of small specimen are 500×300×200 mm^3 and a PVC pipe with diameter of 50mm is embedded in as shown in Fig. 3a. Dimensions of big specimen are 1000×800×300 mm^3. This block is separated to three sections along the length direction. In the first section of 300 mm a plastic rectangle block with dimensions of 200×100×50 mm^3 is embedded in geometrical center of the section and in the middle section of 300 mm a steel pipe with diameter of 50 mm is embedded in lateral geometrical center of the section and in the last section of 400 mm reinforce bar with interval of 8 mm are placed below surface and the bottom side is made a slope with certain angle and a plastic rectangle block with dimensions of 200×100×50 mm^3 is embedded in as shown in Fig. 3b.

Two 50 kHz transducers were used in the experiment. To avoid long rings caused by resonance of the transducers and then identify the reflections clearly, different waveforms are used and their affects are compared, which includes: (1) 25 kHz cosine function modulated by Gaussian pulse; (2)100 kHz cosine function modulatedby Gaussian pulse; (3) Single cycle sine wave at 25 and 100 kHz and (4) Gaussian pulse with width of 10 μs. Because Gaussian pulse contains 50 kHz frequency content, the resonance appears inevitably with 50 kHz transducers. Considering this effect, excitation signal need to be designed far from 50 kHz. Figure 4 gives the measured result at different excitation waveforms, where the dotted lines represent the excitation pulses and solid lines represent the signals received from the same position on linear aperture. It can be seen that the test results of modulated 100 kHz cosine function is better than others because the wavelength of 25 kHz frequency signals are so long that reflected waves from the object are overlapped by the first input cycle and thus difficult to be identified. Eventually 100 kHz cosine function modulated by Gaussian pulse is selected as excitation waveform. Then according to method of B-scan measurements, two transducers move synchronously along a linear aperture on two specimens, respectively. The detected waveforms are collected and showed on the oscillograph and then sent to a computer, where the data from different specimen are processed with different methods: conventional B-scan and SAFT algorithm. The results are shown in Fig. below.

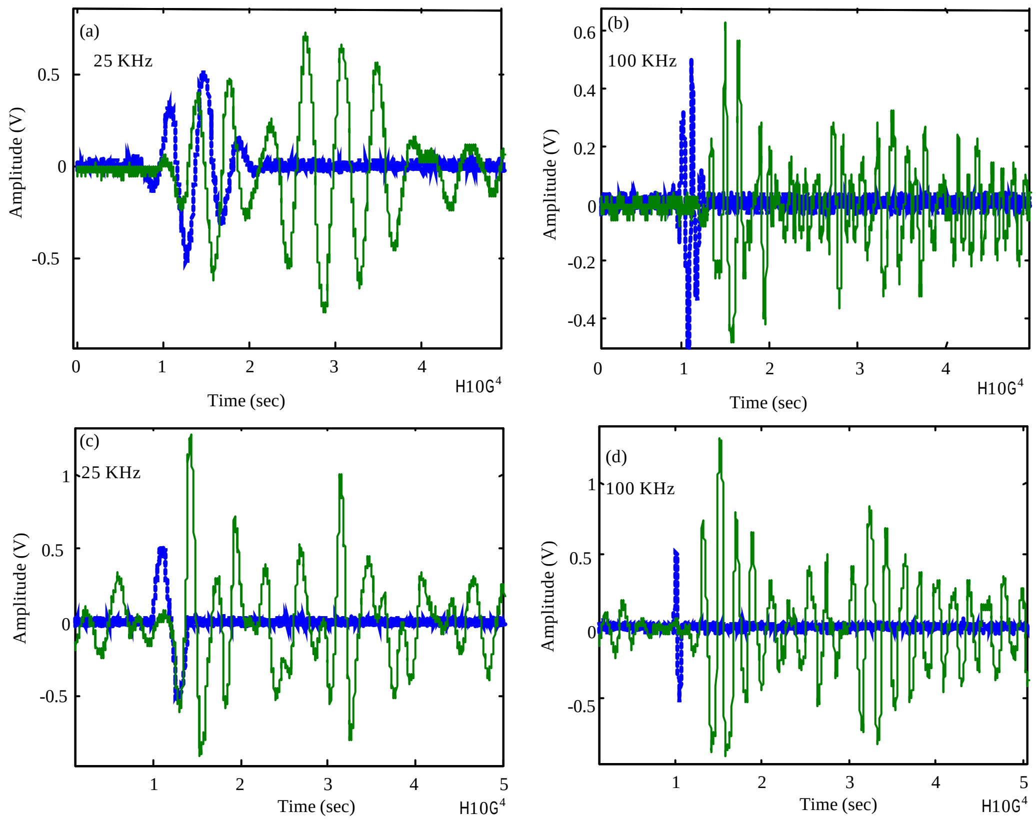

Fig. 4(a-d): Comparison of 25 kHz and 100 kHz signal

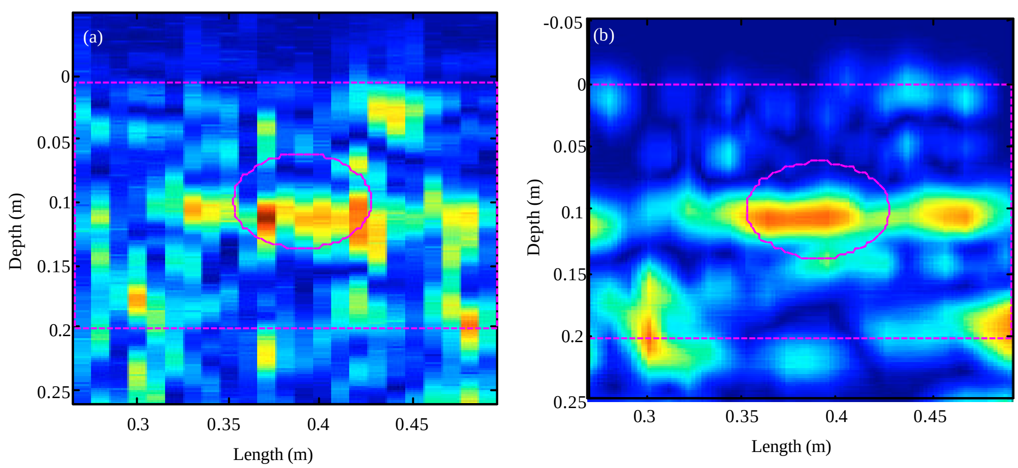

Fig. 5(a-b): Imaging result of small specimen, (a) Image by conventional B-scan method and (b) Image by SAFT algorithm

The imaging results of the small specimen are revealed in Fig. 5 and the images of the big specimen are revealed in Fig. 6 (dashed lines indicate the geometry of two specimens and position of the embedded objects). The pulse velocity in concrete specimens is determined as 4347.8 m sec^{-1} through pitch-catch method.

The original B-scan imaging results are shown in section (a) of both figures. The images by SAFT,

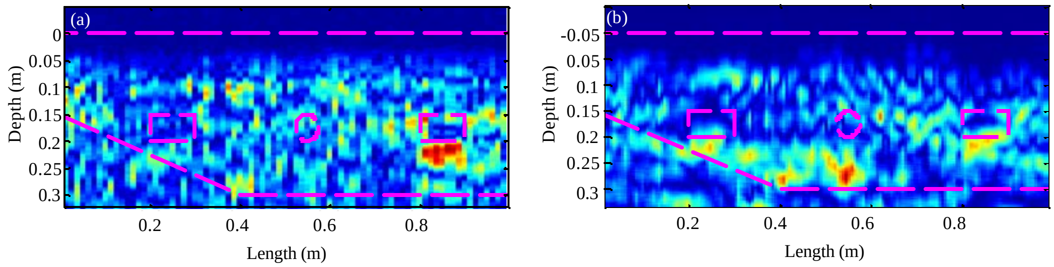

Fig. 6(a-b): Imaging result of big specimen, (a) Image by conventional B-scan method and (b) Image by SAFT algorithm

however, show obvious difference in section (b) of figures and the embedded objects can be distinguished roughly from the images, even the section below the reinforce bar. In Fig. 5b, for example, the most highlight indicates the position of the PVC pipe and the adjacent highlight can be affection of boundary reflection. In Fig. 6, image from section (b) matches with actual specimen more than that from section (a). But there are a few warps in position of objects from the images, the reason may be inaccurate pulse velocity and others errors took from operation in experiment.

CONCLUSION

SAFT algorithm focuses the received signals to any point of the reconstructed image by coherent superposition. An experiment system for ultrasonic test of concrete is established and experiments are carried out to show the validity of the SAFT method in real structures. The imaging effect is better than the original results after introducing SAFT algorithm. This study is only a preliminary stage in detection of concretes by SAFT method. Further work will be done to improve the efficiency of this method by using faster SAFT algorithm and new transducer arrays.

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