Analysis of loading imaging based on time reversal theory

Hao Feng, Fengjiao Shi and Lei Qin*

School of Civil Engineering and Architectural Engineering, University of Jinan, Jinan, China

*Corresponding author e-mail: cea_qinl@ujn.edu.cn

Abstract. Based on the simulation results of the finite element software, setting up an experimental platform, and the echo signals reflected from the hole interface are collected on the concrete test block, and the positioning imaging is realized through the time inversion model. According to the simulation imaging research, in this paper, the peak-time contrast imaging method will be used to analyze and compare the displacement field, stress field, and energy field respectively. Finally, damage imaging will be performed through the energy field.

1. Research Status
Ultrasound imaging technology based on time inversion is a damage focus imaging technology developed in recent years. That is, the received ultrasonic damage echo signal is time-reversed in the time domain, and then, the time-inverted signal is re-transmitted back at the corresponding position to achieve the focusing effect of the damage points in the structure in time and space.

The application of time-reversed focusing theory in acoustics began in the 1960s. The earliest French scientist Fink introduced the time-reversed focusing theory from the field of optics to the field of ultrasound and conducted a lot of experimental research [1-4]. In 2004, Wang et al. Used Lamb waves to detect preset damage in plate-like structures based on the theory of time-reversed focusing, and combined with the idea of distributed sensor network layout, proposed an innovative time-reversed imaging method. It overcomes the limitations of the excitation and reception modes in actual operation, locates the damage in the plate structure, and can roughly determine the shape of the damage [5]. In 2011, Professor Wang Qiang and others from Nanjing University of Aeronautics and Astronautics studied Lamb's time-reversed focus, and realized the positioning and imaging of preset damages in a plate-like structure. Optimization [6]. In 2014, Samir Mustapha et al. Based on the time inversion focus theory and used wavelet transform to process the signal to improve the signal-to-noise ratio. At the same time, they also compared the correlation coefficients between the excitation and response signals to analyze the concrete structure. Degree and condition of steel corrosion [7].

Ultrasound time-reversal imaging technology is mainly divided into two main steps: forward detection and reverse-time loading imaging, forward detection is to complete the transmission of detection signals and the reception of response signals on the surface of the test block. In this experiment, a single transducer array is used. Element excitation, multiple array elements receive the response signal inside the concrete structure, and then collect the acoustic signal through the post-processing function of the finite element software; inverse time imaging is to receive the scattered wave signal including the damaged interface in the time domain. Rotation, and reload at the corresponding position of the equivalent elastic parameter model of the same size. According to the wavefront interference theory, the
reverse signal will focus at the damage interface when reloading, to realize the location and imaging of the damage location.

2. Set up an experimental platform
Pouring concrete test block, the size of the concrete test block is: 400mm × 400mm × 500mm, and hole defects are set at the same time. In order to analyze the defects of different sizes, two sets of defect sizes are set: d = 10mm, d = 5mm. This article uses C40 concrete, the mix ratio of concrete is: cement: sand: stone = 0.45: 1: 1.152: 2.449, and the preset coordinates of the damage center of the through hole are (225mm, 295mm).

During the establishment of the experimental platform, in order to make the piezoelectric transducer fully contact the surface of the test block and ensure that the ultrasonic signal can effectively enter the concrete test block, it is necessary to apply an appropriate amount of Vaseline as coupling agent between the piezoelectric transducer and the surface of the test block. The overall experimental platform is shown in Figure 1.

![Test system layout](image)

Figure 1. Test system layout

3. Acquisition of experimental damage signals
According to the time-reversed focusing theory, the first step of the experiment is to obtain the echo reflection signal of the hole interface in the concrete test block. Because the diameter of the piezoelectric transducer will have certain limitations in the experiment, the position of the array element transmitting the excitation signal is fixed, and the receiving array element sequentially changes the position according to the experimental design path to collect the scattering signal of the hole interface.

In the experiment, the transmitting array element and the receiving array element are both cylinders, and the coordinate positions of the transducer array elements are based on the center position of the receiving surface of the transducer. The center position coordinates of the transmitting array element are (225mm, 400mm). The transmitting direction of the signal is the -y direction. The center position coordinates of the receiving array element are moved to the two sides at equal distances with the center position coordinates of the transmitting array element as the center to receive the signal. Signal at the hole interface. Among the 23 groups of structural response signals received, three groups of typical waveform signals are selected for listing. As shown in Figure 2, the coordinates of the received positions of the selected three groups of signals are: (a) (105mm, 400mm), (b) (285mm, 400mm), (c) (325mm, 400mm).
Perform multiple tests on the concrete test block to obtain the ultrasonic response signal of the concrete test block, and combine the relevant parameters of the test block size and the excitation signal, select a reasonable time reversal window to intercept the received original waveform signal, and only keep direct The reflected echo at the wave and hole interface is shown in Figure 3 (a). Then the time-reversed processing is performed on the intercepted reflected echo signal to obtain a time-reversed loading signal, as shown in Figure 3 (b). Finally, the time-reversed loading letter is loaded at the corresponding position in the equivalent elastic parameter model, and the time-reversed wave field is obtained to realize the maximum field magnitude imaging.
4. Signal time reversal loading imaging

In the finite element software COMSOL Multiphysics, a two-dimensional equivalent elastic parameter model with a size of 400mm × 500mm is established. At the same time, the average wave velocity of the ultrasonic wave propagating in the concrete obtained through multiple experiments and calculations is used as the equivalent longitudinal wave velocity. Table 1. Load the time-reversed data in Figure 3 (b) at the corresponding positions in the equivalent elastic parameter mode.

| Equivalent elasticity parameter | \( E/MPa \) | Poisson's ratio \( v \) | Density \(( kg/m^3)\) | Wave velocity \(( m/s)\) |
|---------------------------------|-------------|-----------------|-----------------|-----------------|
| Concrete                        | 32500       | 0.2             | 2600            | 4190.76         |

The meshing of the equivalent elastic parameter model is consistent with the meshing in the simulation experiment, and the propagation time of the wave field is consistent with the time window, \( T = 240 \mu s \). The calculation time step is \( \Delta t = 5.0e-8 \) s.

Contrast imaging of the time peaks of the time-reversed displacement field, stress field, and energy field is performed at the same time. From the focused imaging diagram of the wave field (Figure 4), it can be seen that the peak time comparison of the displacement field, stress field, and energy field in the experiment, the imaging effect is basically the same as that of the simulation experiment. The focused imaging effect of the energy field is the best, and the focused imaging effect of the stress field is the worst.

(a) Displacement field imaging            (b) Stress field imaging                (c) Energy field imaging

Figure 4. Contrast imaging at peak time

| Table 2. Statistics of Damage Location Results |
|-----------------------------------------------|
| Influencing factors | Imaging positioning coordinates | Imaging positioning coordinate error |
|----------------------|---------------------------------|-----------------------------------|
| Displacement field   | (235.6mm, 285.4mm)              | 14.3mm                            |
| Stress field         | (238.3mm, 301.9mm)              | 15.07mm                           |
| Energy field         | (233.5mm, 302.8mm)              | 11.54mm                           |

According to the damage location coordinates and its error data, it can be seen that the time-reversed energy field can achieve higher damage location accuracy, and its focus imaging effect is better, which can more accurately identify the location of the damage.

According to the above experimental results, the energy field is selected for experimental analysis of two sizes of defects. The comparison of the results of recognition imaging is shown in Figure 5.
From the energy field diagram of time-reversed focusing, it can be seen that the time-reversed model is significantly less effective in identifying defects with a size of 5mm than defects with a size of 10mm.

5. Conclusion
In this paper, the ultrasonic response signal inside the concrete test block is collected and processed by the established experimental platform, and used as the loading signal of time-reversal imaging. Damage imaging is completed in the optimized equivalent elastic parameter model. Based on the results of simulation experiments are used to compare and analyze the imaging results of the maximum field magnitude of the time-reversed energy field and the comparative imaging results at the peak time. The experimental results verify that the contrast imaging method at the peak time can locate the damage more accurately.

Acknowledgments
The investigation presented in this paper was supported by National Natural Science Foundation of China (51678277) and Key R & D project of Shangdong Province (2017GGX90107).

References
[1] Roux P, Roman B, Fink M. Time-reversal in an ultrasonic waveguide [J]. Applied Physics Letters, 1997, 70 (14): 1811-1813.
[2] Fink M. Time reversal of ultrasonic fields. I. Basic principles. [J]. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control, 1992, 39 (5): 555-66.
[3] Wang Y M, Judkewitz B, Dimarzio C A, et al. Deep-tissue focal fluorescence imaging with digitally time-reversed ultrasound-encoded light [J]. Nature Communications, 2012, 3 (928): 928.
[4] Fink, M., Prada, C., Wu, F., Cassereau, D.. Self focusing in inhomogeneous media with time reversal acoustic mirrors [P]. Ultrasonics Symposium, 1989. Proceedings., IEEE 1989, 1989.
[5] Wang C H, Rose J T, Chang F K. A synthetic time-reversal imaging method for structural health monitoring [J]. Smart Materials & Structures, 2004, 13 (2): 415-423.
[6] Wang Qiang, Yuan Shenfang, Tian Feng, et al. Research on active Lamb wave damage imaging monitoring based on circular piezoelectric arrays [J]. Sensors and Microsystems, 2011, 30 (10): 75-77.
[7] Mustapha S. Damage detection in rebar-reinforced concrete beams based on time reversal of guided waves [J]. Structural Health Monitoring, 2014, 13 (4): 347–358.