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Research Article

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Research on ultrasonic measurement technology for concrete structures by based on digital compensation filtering

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ABSTRACT

In ultrasonic pulse-echo NDT of structures, the transducers usually operate in its harmonic frequencies in order to maximize the amplitude response. However, there exist some unwanted effects in such mode. For instance, the generated/detected signals will have long ringing, which means the spatiotemporal resolution will be reduced. Presented here is a digital filtering method to compensate the unwanted frequency response characteristics of transducers. The first step is to establish a discrete transfer function model of transducer system based on time-domain system identification algorithms. Then the established model can be realized by a digital compensation filter to reduce the ringing effects of the measured signals. Experimental verification of the proposed method is carried out. After calibrating and modeling for transducers by water-immersion test, a compensation model is established and used to the thickness measurement of a concrete specimen. The compensation results show that the ring of transducer can be greatly reduced and the reflection from bottom of the specimen can be extracted from the original overlapped signals. To further validate the effect of the proposed method, its application in B-scan imaging of a concrete element with embedded anomaly is also given.

Key words: concrete structures, ultrasonic measurement, spatiotemporal resolution, signal-to-noise ratio, digital compensation filter

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INTRODUCTION

Ultrasonic pulse-echo method provides a powerful tool in detecting the inner structure of concrete elements. Usually, the harmonic frequency of the transducers is selected to give maximum response amplitude and to increase signal-to-noise ratio (SNR) [1-3]. However, ultrasonic transducers working in its harmonic frequencies usually have obvious ringing effects and the ringing will submerge the reflected wave. As a result, the spatiotemporal resolution will be reduced [4].

In order to solve the above problem, the ringing needs to be eliminated by digital signal processing techniques. In the related NDT fields, system identification method has been used to compensate the non-ideal features of measurement systems. Lin has used a blind system identification approach to estimate and compensate the ultrasonic wavefront distortion. Experimental results indicate the method can improve both the transmit and the receive focus [5].Chen conducted a linear analysis for single-element transducers and designed an eighth-order linear ARMA model to describe the transfer characteristics of such system. In his research, the echo signals containing tissue information can be collected and analyzed more clearly [6]. In addition, Kim presented a nonlinear system modeling/identification method to find a mathematical model of the nonlinear dynamic transformation between the excitation and the received signals by using Laguerre-Volterra networks [7]. Gehrke also provided a way to accurately determine the impulse response of a transducer by system identification based on experimental data [8].

The discrete transfer function model of an ultrasonic transducer system is also established here in this paper. For the special case of transmitting and receiving transducer pairs, a calibration process using water-immersion test is proposed. A digital compensation filter is designed based on the time-domain calibration data. It is cascaded as an inverse system behind the transducer system to reduce the effect of ringing.

In the next section the principle and experimental setup to establish the digital compensation filter are first illustrated. Then the proposed method is applied to the measurement of the ultrasonic velocity and thickness of a specimen. Finally, 2-D ultrasonic imaging test of the concrete specimen is further used to verify the effects of the proposed method.

THEORY OF DIGITAL FILTERING

The concept of compensation based on digital filtering is shown in Figure 1. On the assumption that $H(z)$ is a measurement system with non-ideal response characteristics, the digital compensation filter can be seen as an inverse system to recover the real shape of the input $x(n)$. The first step is to establish a model of the discrete transfer function $H(z)$ according to a pair of known input $x(n)$ and output $y(n)$ of the system, and then the inverse system with transfer function $G(z)$ can be established and cascade with the test system.

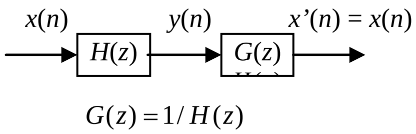

Figure 1. The concept of digital compensation

Dynamic characteristics of any linear time-invariant (LTI) system can be described by a difference equation [9,10]:

$$y(n)+\sum_{k=1}^{N}a_k y(n-k)=\sum_{r=0}^{M}b_r x(n-r) \tag{1}$$

Here a_k (k = 1,2,3…N) and b_r (r = 1,2,3…M) are constant coefficients. And then taking Z-transform of Equation 1:

$$Y(z)[1+\sum_{k=1}^{N}a_k z^{-k}]=X(z)[b_0+\sum_{r=1}^{M}b_r z^{-r}] \tag{2}$$

The discrete transfer function of a measurement system can be derived:

$$H(z)=\frac{Y(z)}{X(z)}=\frac{\sum_{r=0}^{M}b_r z^{-r}}{1+\sum_{k=1}^{N}a_k z^{-k}}=\frac{B(z)}{A(z)} \tag{3}$$

The parameters of $H(z)$ can be estimated according to the relation shown in Equation 2 by algorithm of system identification [11,12]. Then the inverse system $G(z) = A(z)/B(z)$ can be established:

$$H(z)G(z)=1 \text{ or } G(z)=1/H(z) \tag{4}$$

Because any LTI system can be expressed as a minimum-phase system in series with an all-pass system, and the inverse system of the minimum-phase system is stable. $G(z)$ would be affirmed to be a stable and causal system as long as $H(z)$ is a minimum phase system [13,14]. After passing the output of the first system $H(z)$, $x'(n)$ equal to $x(n)$ will be derived in the output of $G(z)$.

EXPERIMENTAL VERIFICATION

Test system

To validate the proposed method, a test system shown in Figure 2 is established. An arbitrary function generator is used to generate pulse waveform in the experiment. Under the Matlab environment, several kinds of excitation pulse could be designed for the excitation of the ultrasonic transducer. The maximum output voltage of the generator is 10V, so a power amplifier is employed. The power amplifier can output stably up to 200V within bandwidth of DC~20MHz. Two ultrasonic transducers are used as transmitter and receiver. Low frequency transducers with low damping are employed to offer high-energy pulses [1]. The receiving unit consists of a signal amplifier and a data acquisition card. The signals can be amplified by the amplifier to about 20 times within bandwidth of 100Hz~1MHz. The maximum sampling frequency of the data acquisition card can reach up to 10MHz. The sampled data is then uploaded to computer and imaged.

Establishing model of transducers
A pair of market available ultrasonic transducers working at 50kHz is selected. Excitation pulse of 50kHz frequency is a considerable low frequency, and it is used to increase the measurable depth in detection.
In order to measure the dynamic response characteristic of the transducers, water-immersion test is designed. A water tank similar to the configuration in Figure 2 is used, and the depth of the tank is 30cm in order to avoid overlapping of reflected signals. Because water is a homogeneous medium, the longitudinal wave propagating in it can be thought to have just attenuation in amplitude. The effect of medium can be eliminated by rectifying the amplitude of input waveform. Thus unwanted effect of the signal will be due to the transducer system only.

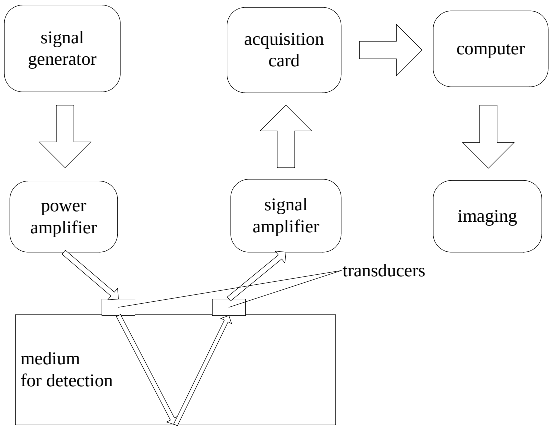

Figure 2. Configuration of the test system

In the experiment, excitation pulse below is adopted:

$$\psi(t) = \cos(2\pi ft) \cdot e^{(-((t-t_i)\cdot w)^2)} \quad (5)$$

It is a cosine function modulated by Gaussian pulse, where, f is the main frequency, w is a pulse-width coefficient of Gaussian pulse and t_i is positional parameter of wave-packet in the transmitting cycle. Actual waveform and its spectrum are shown in Figure 3. Figure 4 is the measured input of the transmitting transducer and the output of the receiving transducer. The first wave-packet of sampling signal is the reflected wave-packet from bottom of the tank, which has apparent change comparing to the excitation waveform.

In order to eliminate ringing in the detected signal, the measured input and output is used to establish a compensation filter. As the first step, the amplitude of the two waveforms needs to be rectified according to their maximum values, as shown in Figure 5. By this way the effect of attenuation caused by water may be removed. Then a model of the transducer system can be established by algorithm of system identification, and transfer function $H(z) = B(z)/A(z)$ can be obtained. Its corresponding $H(j\omega)$ is shown in Figure 6. It clearly shows the inherent peak near 50kHz, which is the main reason why the long ringing arose. Therefore the inverse system $G(z) = A(z)/B(z)$ can be calculated and cascaded to the test system to compensate frequency response of the transducer. The process can be achieved through tool box of system identification in Matlab environment.. A fifth-order model is finally designed. As shown in Figure 7, the compensated signal $x'(n)$ is very close to the original signal $x(n)$. The proposed method works well in this test example.

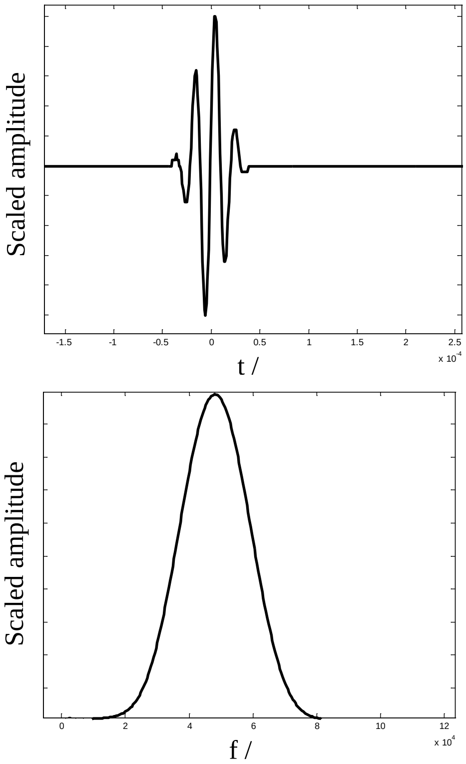

Figure 3. Waveform and spectrum of excitation pulse

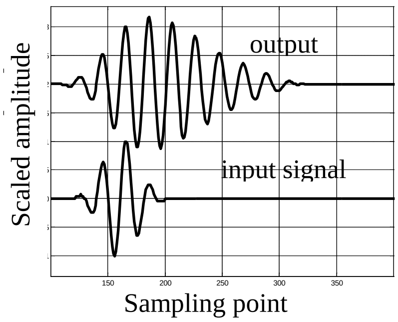

Figure 4. Comparison of input signal and output signal

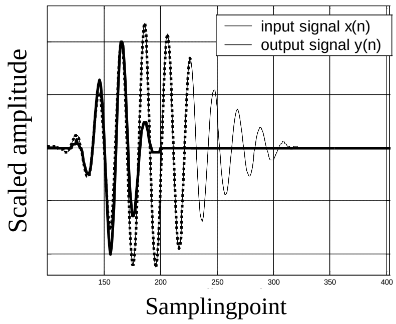

Figure5.Sketch of rectifying input signal.

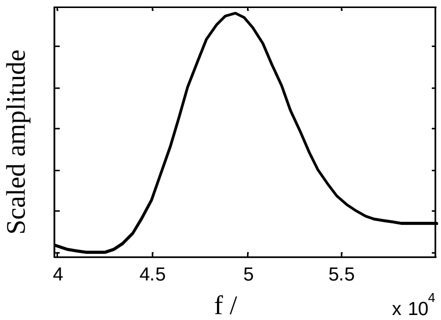

Figure6.Frequency response of *H*(*j* ω) .

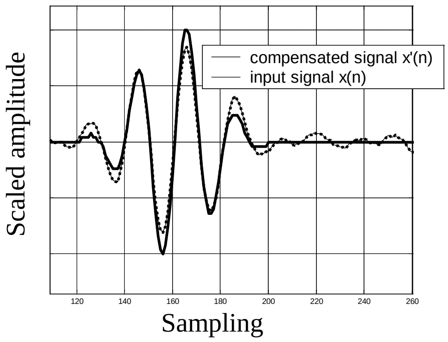

Figure7. Comparison of input signal and compensated signal

APPLICATION RESULTS

Measurement of velocity and thickness

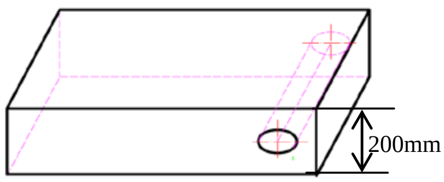

Figure 8. Structure of specimen

The proposed method is applied to measure the thickness of a concrete element. A specimen of concrete are designed and cast with the same compounding ratio as the normal architectural concrete. Its dimensions are of $(500\times300\times200)mm^3$, and a PVC pipe with diameter of 50mm is embedded in as shown in Figure 8. Pitch-catch method is used to measure the ultrasonic velocity and thickness of specimen. First of all, the transmitter is coupled with glycerin and positioned on the one side of surface of specimen away from the PVC pip. And then the receiver is placed on the same surface with distance of 50mm to transmitter (the distance is the length between centers of two transducers, which is determined by outside diameter of the transducers). As shown in Figure 9, by moving the receiver at the step of 20mm, bottom reflected waveforms are collected on six positions, respectively. The received signals are passed to the compensation filter to eliminate the ringing and enhance the spatiotemporal resolution. Figure 10 gives an example of the compensation results.

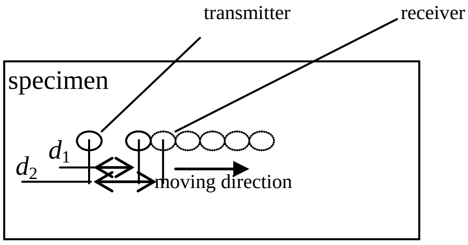

Figure 9. Method of single-site measurement

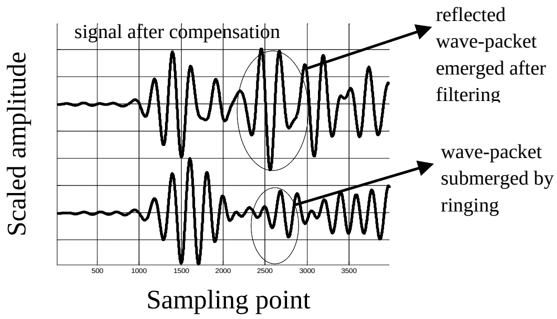

Figure 10. Comparison between original waveform and waveform after filtering

By time of arrival measurement of the bottom reflected pulse, velocity of ultrasonic waves in concrete can be derived. According to Equation 6, velocity on each point and average velocity of ultrasound can be calculated as listed in Table 1:

$$v = \sqrt{(d_2^{\ 2} - d_1^{\ 2})/(t_2^{\ 2} - t_1^{\ 2})} \qquad (6)$$

Here *d*1 and *d*2 are the distance of two transducers as shown in Figure 9, *t*1 and *t*2 are the time of propagation.

Based on the derived velocity, thickness of the specimen on each measurement point can be calculated using Equation 7 and the results are listed in Table 2.

It is obvious that the measurement result is very accurate after using the compensation filter.

Table 1. Velocity calculated from adjacent measurement points.

Distance of center (mm)	Velocity (m/s)
50	/
70	4170.7
90	4012.1
110	4072.3
130	4259.6
150	4254.0
Average	4166.7

$$h = \sqrt{(vt_2/2)^2 - (d_2/2)^2} \qquad (7)$$

B-scan imaging

A B-scan along the length direction of specimen is also carried out. The collected data is compensated by passing through the filter and then shown by image. A comparison is carried out between the imaging results before and after filtering. The result is shown in Figure 11.

In the figures, the dashed straight lines represent the position of surface and bottom and dashed circles show the position of PVC pipe in the specimen. After using the compensation filter, the shape of PVC pipe is revealed and the bottom of the specimen is clearly shown.

Table 2. Thickness measured on each measurement point

Distance of center (mm)	Thichness (mm)	Error (%)
50	203.05	1.53
70	203.19	1.59
90	203.32	1.66
110	203.20	1.60
130	203.05	1.53
150	203.05	1.53
Average	203.14	1.57

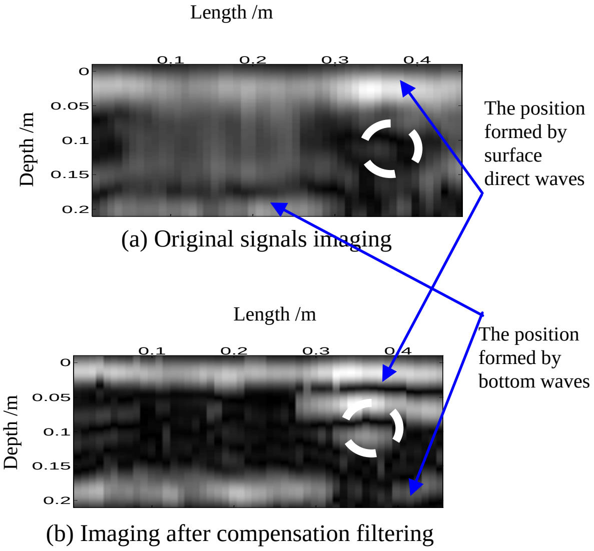

Figure 11. Comparison of imaging results: (a) image of original waveform; (b) image after filtering

CONCLUSION

A compensation method for low-frequency ultrasonic transducers based on digital filtering is presented. The ringing effect caused by transducer system can be effectively suppressed by compensation and the spatiotemporal resolution is enhanced. The method is applied to measurement of the thickness of concrete specimen. After compensation, the reflected signals are intensified and the thickness measurement error is within 2%. The compensation method is also used in B-scan imaging of concrete structure. The effect of compensation filtering is also obvious. This kind of digital compensation filter provides an effective signal processing method for pulse-echo NDT to improve its spatiotemporal resolution.

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