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27-30 AUGUST
HONG KONG 2017

Penetration-free acoustic data transmission based active noise control

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ABSTRACT

Active noise control (ANC) problems become more and more evident at low frequencies for underwater applications. Conventional wired techniques are ineffective since feedthroughs can compromise the structural integrity of ships, which would lead to physical isolation between active noise controller and secondary sources as well as error sensors. Wireless electromagnetic telecommunication method is unavailable due to the presence of Faraday shielding effect. In this paper, an acoustic alternative of controlling radiation noise of ships directly under the condition that the secondary sources locate outside the shell is determined. Penetration-free communication techniques are utilized for data transmission between active noise controller and sensors. Modulated signals are transmitted through metallic shell in the form of ultrasonic waves. Equalization algorithm is also added to eliminate channel distortion. All the complicated signal processing procedures can be accomplished in central controller located in the inner side of the ship. Optimized data transmission schemes for ANC are also investigated. Results show that the proposed method is promising for active noise control without physical penetrations.

Keywords: Active noise control, Acoustic data transmission, Penetration-free communication
I-INCE Classification of Subjects Number(s): 74.9

1. INTRODUCTION

Low frequency noise is inevitable for underwater vehicle applications. Active noise control (ANC) is widely used for its prominent advantages in comparison with objected solutions (1, 2). However, active noise controller and secondary sources as well as error sensors usually locate in different sides of the shell. Wireless electromagnetic telecommunication method is unavailable due to the presence of Faraday shielding effect (3). Conventional wired techniques damage the structural integrity of ships, which lead to much serious security problems. Acoustic data transmission provides a promising alternative since sound waves can propagate through metal barrier nondestructively.

To avoid physical penetrations while controlling radiation noise of ships under the condition that the secondary sources locate outside the shell, system reliability plays a significant role. Commination algorithm should be considered carefully with ANC algorithm so as to achieve lower bit error rate (BER). Most penetration-free acoustic data transmission utilize orthogonal frequency division multiplexing (OFDM) techniques (3, 4). OFDM is a kind of multi-carrier solution, which owns the disadvantage of higher peak-to-average power ratio (PAPR). This method is also sensitive to carrier frequency offset (CFO). Additional signal processing method can alleviate these problems, while it also brings in new problems such as wider linear ranges and higher transmission power consumptions (5). Single-carrier frequency domain equalization (SC-FDE) provide new aspects to these difficulties (6-8). It is less sensitive to CFO without PAPR problems, and needs less strict condition to the selection of power amplifier. Moreover, the implementation of SC-FDE makes it suitable to concentrate the system complexity to the receiver of the system. Sensors and simplified hardware are the only needs in the transmitter. When combining penetration-free acoustic data transmission with active noise control, system delay should also be taken into account. Time delay is inevitable when

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signals transmitted between noise controller and sensors by penetration-free data transmission. However, these additional delays degrade the whole performance of active noise control system, and the adaptive signal processing method should also be adjusted.

This paper presents an acoustic data transmission structure for active noise control. Central controller locates inside the ship for convenience of signal tracing and updating. Combining digital communication algorithms with adaptive signal processing methods, effective active noise control can be achieved. SC-FDE algorithm is utilized to reduce inter-symbol interferences (ISI) when transmitting acoustic waves through metal barrier. The remainder of this paper is organized as follows. Section 2 gives a general description of the system design including system features and main algorithms of the penetration-free acoustic data transmission based active noise control system. Section 3 presents the effects of various diagrams associated with the transmitted signals, received signals as well as equalized signals. Section 4 discusses the system influence by different setting of time delay, and the conclusion is drawn in Section 5.

2. ACTIVE NOISE CONTROL SYSTEM DESIGN

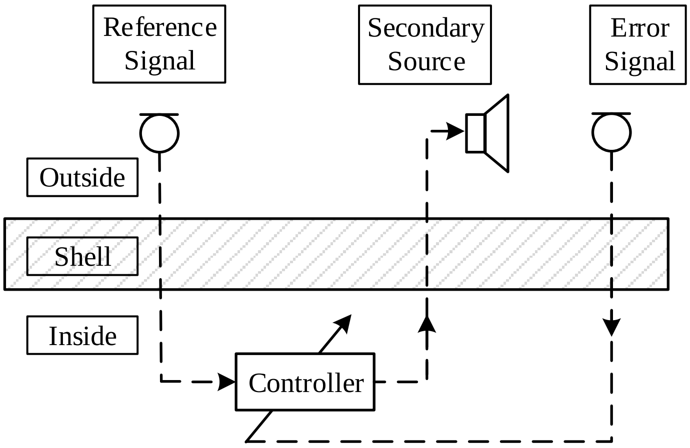


Figure 1 – Diagram of controlling radiation noise

Figure 1 shows the diagram of controlling radiation noise of ships directly under condition that the central controller with complicated signal processing locates inside the ship. The reference microphone, secondary source as well as the error microphone are all located outside the shell. Traditionally, every dotted line in this figure stands for a wired damage. By using the proposed penetration-free acoustic method, the signals penetrate the shell in the form of acoustic waves. In this way, data transmission can be accomplished without any physical destructions.

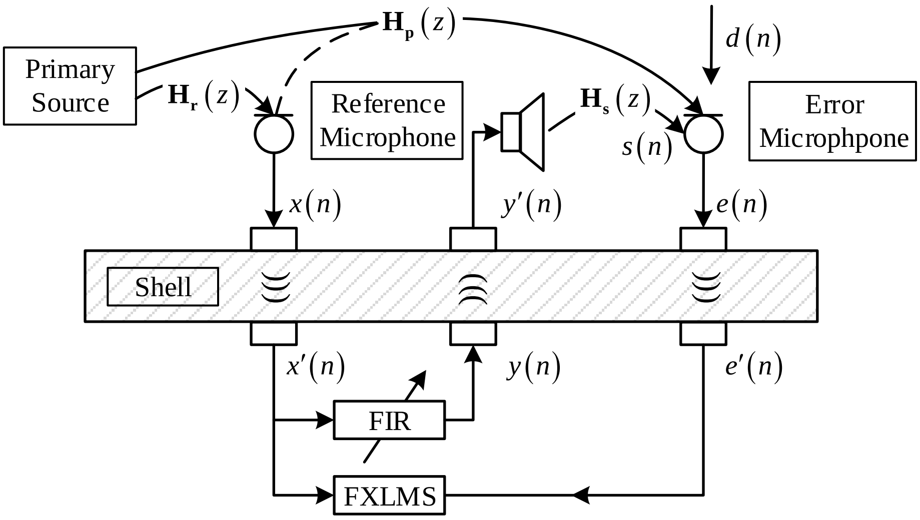


Figure 2 – Framework of the penetration-free ANC system

The system framework of forward penetration-free ANC system is shown as Figure 2. $\mathbf{H}_\mathbf{r}(z)$ represents the path from primary source to the reference microphone, and $\mathbf{H}_\mathbf{p}(z)$ is the path from primary source to error microphone. For simplicity, we assume that $\mathbf{H}_\mathbf{r}(z)=1$, then $\mathbf{H}_\mathbf{p}(z)$ turns out to be the path from reference microphone to error microphone. Signal of reference microphone $x(n)$ penetrates the shell and changes to $x'(n)$. $\mathbf{H}_\mathbf{s}(z)$ represents the secondary path from secondary source to error microphone, and $d(n)$ is the desired signal.

Assume that $\mathbf{H}_\mathbf{s}(z)=z^{-\Delta t}$ and $\mathbf{H}_\mathbf{p}(z)=z^{-\Delta T}$. The reference signal $x(n)$ is set as white noise, then

$$d(n)=x(n-\Delta T) \tag{1}$$

Due to the existence of secondary path $\mathbf{H}_\mathbf{s}(z)$, conventional least mean square (LMS) algorithm is modified as the filtered-X LMS (FXLMS) filter shown in equation (2).

$$\mathbf{w}(n+1)=\mathbf{w}(n)+\mu\mathbf{x}_1(n)e(n) \tag{2}$$

Where $\mathbf{w}(n)$ is the coefficient vector of $\mathbf{W}(z)$ at time n, μ is the step size and $\mathbf{x}_1(n)$ is the input signal vector $\mathbf{x}(n)$ filtered by $\hat{\mathbf{H}}_\mathbf{s}(z)=\mathbf{H}_\mathbf{s}(z)$ (1). The objective of the adaptive filter $\mathbf{W}(z)$ in the central controller is to minimize the residual error signal $e(n)=d(n)-y(n)$ where $y(n)$ is linear convolution result caused by impulse response of secondary path.

$$y(n)=h_s(n)*\left[\mathbf{w}^\mathrm{T}(n)\mathbf{x}(n)\right] \tag{3}$$

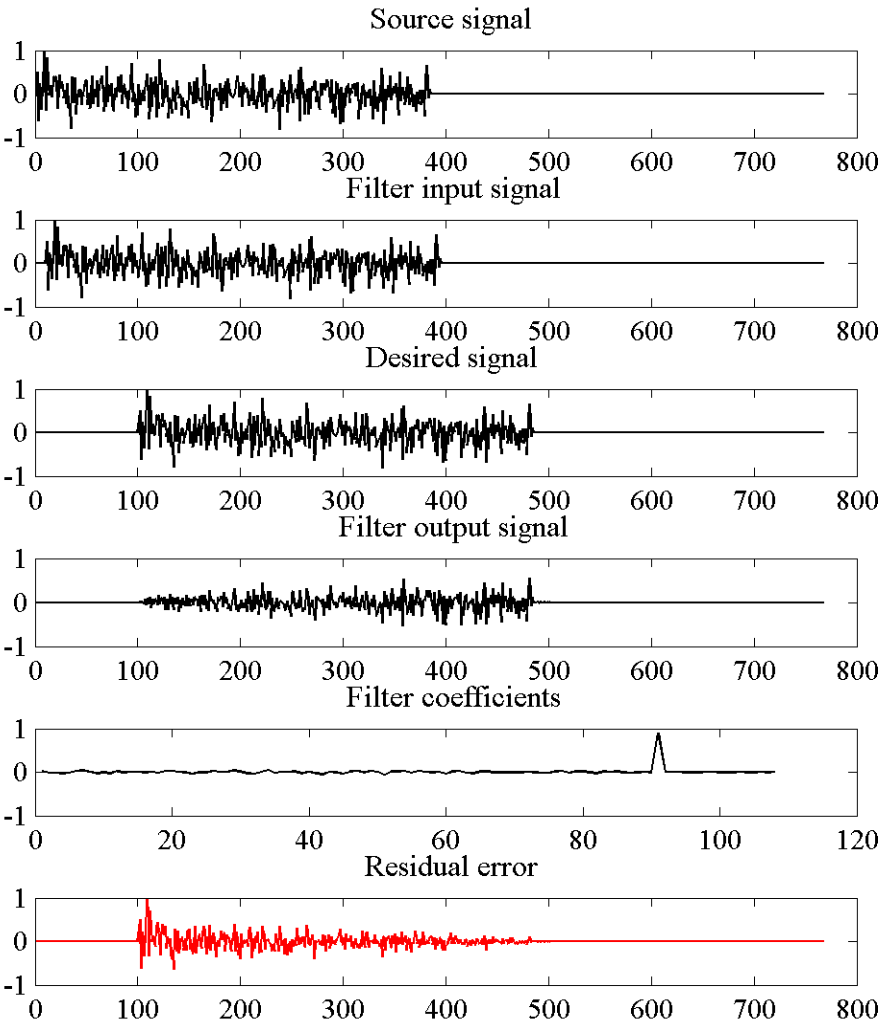


Figure 3 – Time domain waveforms of ANC system

Practically, output of the central controller $y(n)$ and signal of the error microphone $e(n)$ should also pass penetration-free acoustic channel, respectively. For simplicity, we only take into account the acoustic path of the reference signal under the hypothesis that $y(n)$ and $e(n)$ goes directly through the barrier for interaction with the central controller.

Time domain waves are illustrated as Figure 3. Desired signal delays from the source signal $x(n)$ for the existence of $\mathbf{H}_{\mathrm{p}}(z)$. $\mathbf{H}_{\mathrm{s}}(z)$ is also considered. Input signal of the adaptive filter is the one penetrates acoustic data transmission channel, detailed procedures of which will be illustrated in the following section. System identification is acquired by the path from the input signal to the desired signal, and then output signal is calculated by the convolution of input signal and filter coefficients. Residual error shows the tracing trend of the FXLMS filter.

3. PENETRATION-FREE DATA TRANSMISSION

3.1 Algorithm Diagram

Signal of reference microphone is encoded as input binary source code word by acoustic source encoder. Convolutional codes with memory are added as channel encoder before the quadrature amplitude modulation (QAM) digital modulator to overcome the effects of noise and interference (9). Unique word (UW) sequence is added for each small fast Fourier transform (FFT) block in SC-FDE algorithm for both synchronization and channel estimation. A root raised cosine (RRC) filter with a matched one in the transmitter is implemented in the transmitter. Therefore, a raised cosine roll-off Nyquist filter for pulse shaping (10) can be formed. Subsequently, the transmitted signal is amplified and output by the transmitted piezoelectric transducer in the form of ultrasonic waves.

Received by another coupled piezoelectric transducer acting as the receiver, sound waves after passing the metal barrier are converted back into electrical signals. The attenuated and distorted signals originating from the reflections from boundaries usually lead to severe inter-symbol interferences (ISI). It can be alleviated by combined digital communication algorithms. Signals after the RRC filter are separated back as UW sequence and data sequence, the former of which is used for channel estimation. Equalization weight coefficients can be acquired after FFT. Compared with time domain approaches, SC-FDE offers a better ISI mitigation performance and has lower complexity with efficient FFT data block and simple frequency-domain equalizer (11). The equalized data after SC-FDE are combined and reorganized as time-domain equalization received signal and sent to the digital demodulator. Output signal of the penetration-free data transmission channel is acquired after source encoder as $x'(n)$. Ideally $x'(n)$ should be equivalent to $x(n)$.

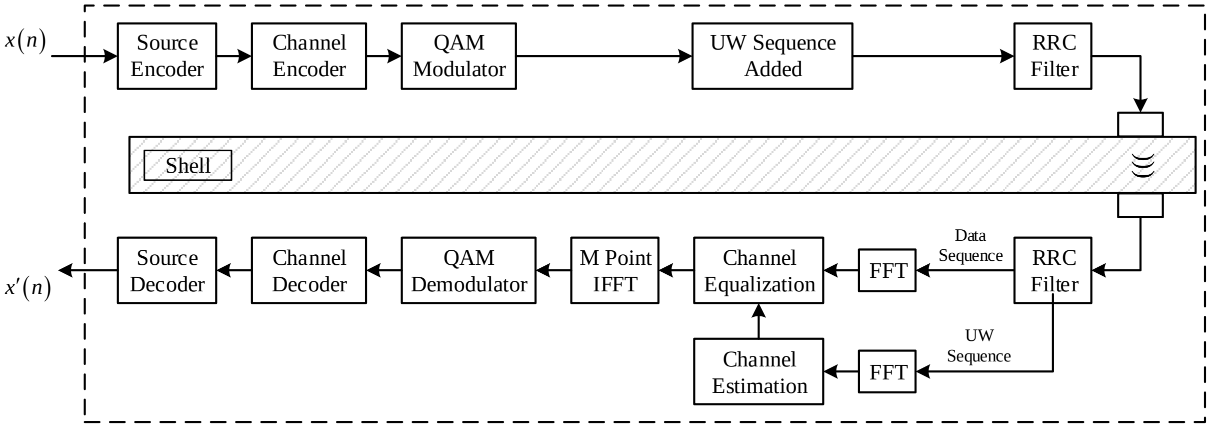


Figure 4 – Diagram of the penetration-free acoustic data transmission channel

3.2 Performance Indices

Primary transmission signal is formed after the channel encoding and digital modulating represented as Figure 4. Ultrasonic waves pass through the metal channel and received by another piezoelectric transducer. To simulate this scenario, the impulse response of a four-cm-thick stainless steel barrier was measured as shown in Figure 5. Received signal is simulated by the convolution of transmitted signal with the real measured channel impulse response. For every single dot input in the source encoder, 24 encoded output bits are shifted out. 64-QAM modulator is adopted for its high modulation efficiency.

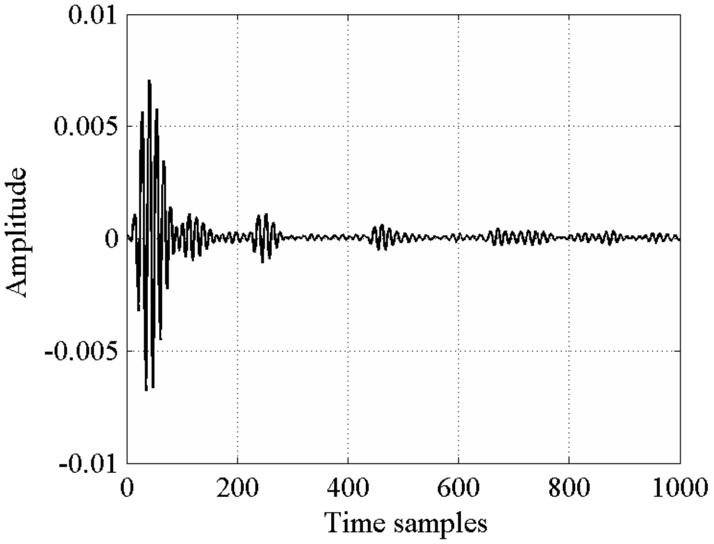
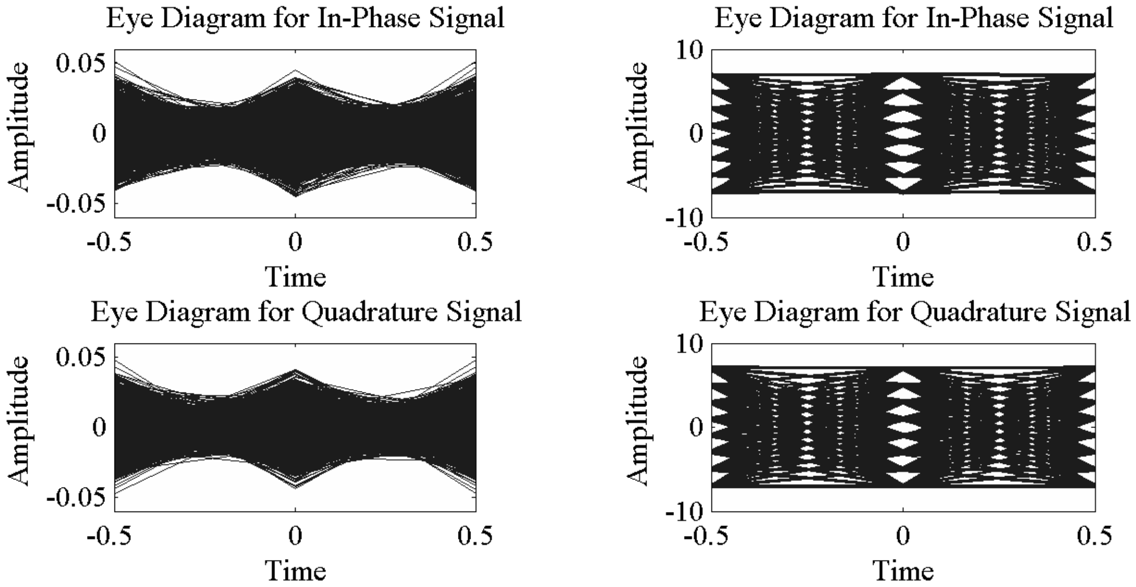


Figure 5 – Impulse response of a four-cm-thick stainless steel barrier

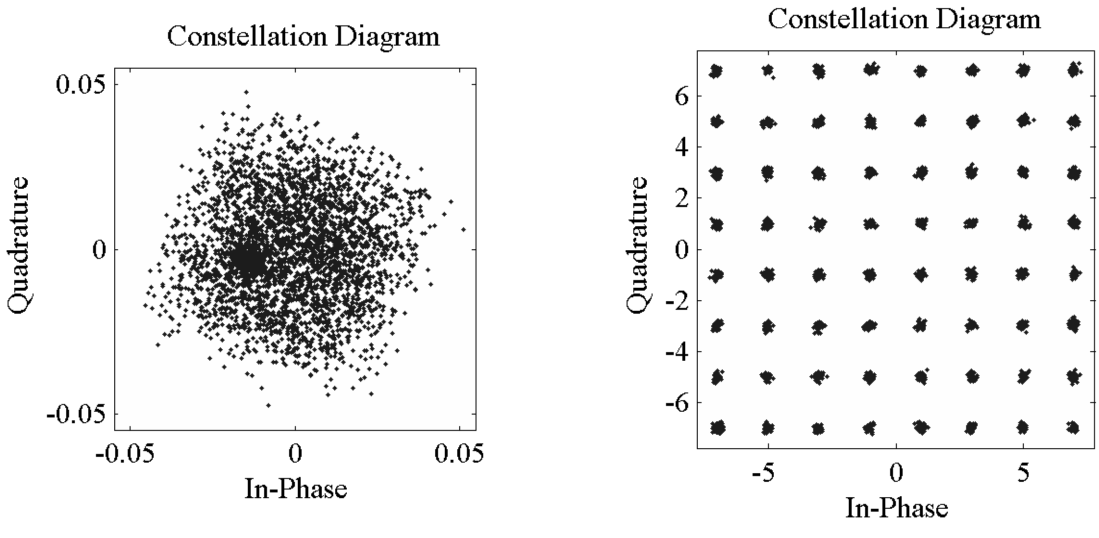
Due to the presence of channel response signals, the eye diagram appears closed and indistinct as illustrated in Figure 6(a). The signal constellation diagram also becomes to be more scattered in the receiver as shown in Figure 7(a). After channel equalization, constellation points reassembled around the original 64 plots and the eye pattern open again. The maximum error of this penetration-free acoustic data transmission channel in this simulation example is 1.18×10^{-7}. It is caused by the fixed-point processing since the error of fixed signals between the transmitted and equalized under the same circumstance equals zero. The more bits we use for fixed-point processing, the higher precision would be acquired and thus results in smaller error.



(a) (b)

Figure 6 – Eye diagrams for both in-phase and quadrature signals

(a) In the receiver (b) After equalization



(a) (b)

Figure 7 – Constellation diagrams for signals of the penetration-free acoustic data transmission channel

(a) In the receiver (b) After equalization

4. TIME DELAY OF THE ACOUSTIC CHANEL

The time delay is inevitable for signal process systems, especially for frequency-domain processing with FFT. To gain more insight the influence of penetration-free acoustic data transmission channel delay, we shall ideally make the assumption that

$$\mathbf{H}_{\mathbf{r}}(z)=1, \text{ and } \quad y(n)=y'(n), s(n)=s'(n) \tag{3}$$

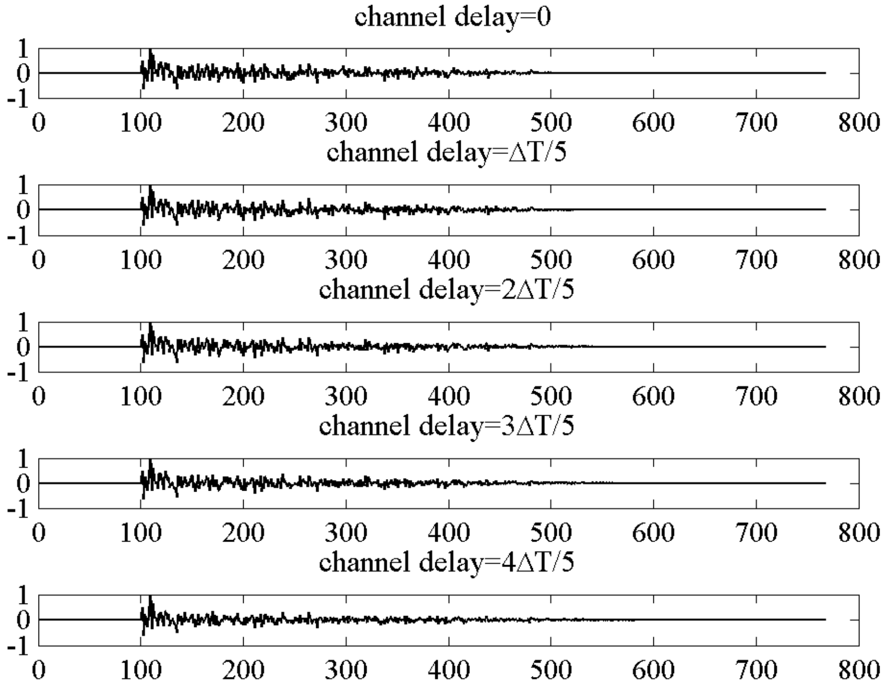


Figure 8 – Residual errors for different time delay

Figure 8 shows residual errors for different time delays. We divided time delay from source signal to the desired signal into several parts. The longer time delay is, the shorter the impulse response estimated from the adaptive filter would be. And the convergence speed of the algorithm also accelerates. However, the real circumstance would be much more complicated. The channel from source microphone to the error microphone is determined by the surrounding environment, which is independent of the delay of the penetration-free acoustic data transmission channel. If the time delay of the acoustic channel is larger than that of the whole channel, causality of the system would be damaged. Moreover, when acoustic channels are added to $y(n)$ and $s(n)$, other adaptive algorithms should also be taken into account. Details of which would be our future work.

5. CONCLUSIONS

An approach to penetration-free acoustic data transmission based active noise control system is demonstrated in this paper. System prototype is simulated by using measured impulse response of a four-cm-thick steel barrier. Combining the adaptive active noise control algorithm with single carrier frequency domain equalization, system performance can be improved. Extra error would be introduced by fixed-point processing, but the precision and accuracy can be increased by longer bits. Using the proposed acoustic channel instead of conventional wires for data transmission, physical penetrations can be avoided. Results show the effectiveness of this scheme while compensating for channel distortion. Influences of time delay brought by the penetration-free acoustic data transmission channel are also discussed. Comparison of the simulation and real-time measurement results will improve our research in the future.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Fund of China under Grants 11674348 and 61501449.

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