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De-noising Algorithm of Ultrasonic Echo Signal Based on Wavelet Transform and Independent Component Analysis

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Abstract

In ultrasonic nondestructive testing, the presence of noise makes great trouble for defect recognition, so it is very necessary to reduce noise in collected ultrasonic signal. In this paper a de-noising algorithm of ultrasonic echo signal based on wavelet transform and Independent Component Analysis (ICA) was presented. First, wavelet transform was used to decompose original noisy signal, and then ICA was applied to decomposed detail coefficients, separated independent components were evaluated by threshold, noise was filtered, and finally, de-noised ultrasonic signal was obtained by wavelet reconstruction. Simulation and experimental results showed that the proposed algorithm can improve signal-to-noise ratio, meanwhile, overcome some other de-noising algorithms' shortcoming of losing useful information in de-noising, the performance is superior to wavelet threshold de-noising algorithm.

***Keywords**: nondestructive testing; ultrasonic; wavelet transform; independent component analysis; de-noising*

1. Introduction

The existing defects of workpiece are serious security risks, so it is necessary to detect the quality before using workpiece. The pulse-echo ultrasonic testing is one of the commonly used nondestructive testing (NDT) methods. The actual collected ultrasonic echo signal contains a lot of information about defect properties, but also mixed with different degrees of random noise (structural noise and white noise). The presence of noise often bury some useful signals, make great trouble for defect recognition, so de-noising is necessary in order to obtain the essential defect features.

Although there are many de-noising algorithms, such as split spectrum technology [1], self-adapting filtering [2] and Hilbert-Huang transform [3], most of them process signals only use either frequency domain or time domain information, due to defect echo signals and noise signals are mixed in time domain and frequency domain, so it's very hard to separate signal from noise only in time or frequency domain.

Wavelet Transform (WT) can provide time domain and frequency domain information of a signal, and has very good localization characteristics in both time domain and frequency domain, very suitable for extracting local signal characteristics, so WT is an ideal tool for dealing with time-varying, non-stationary signals. WT is a research hotspot in signal noise reduction and good results have been achieved in many application fields [4, 5]. The important feature of WT contributed to de-noising performance is that it can concentrate a signal's energy on limited coefficients [6], but WT can't give good results when the signal spectrum content is not compactly supported. To solve the problem, Azzerboni [7] proposed a method called WICA based on WT and ICA to eliminate noise

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in electromyography. In WICA all ICs related to noise were completely eliminated which might lead to some useful signals loss.

Independent Component Analysis (ICA) is an analysis method developed in recent years based on high order statistical analysis. ICA uses optimization algorithm to decompose multi-channel signals into independent components each other, can separate signal from strong background noise and meanwhile minimally decrease the loss of useful information without additional reference information. In practical application, useful signal and noise signal contained in noisy signal is generally independent of each other, so the noise in signal can be reduced by ICA. At present, ICA method has been widely used in de-noising and showed good performance [8, 9].

The paper made full use of the characteristics of WT and ICA, combined both approaches to reduce noise of ultrasonic echo signal in nondestructive testing. First, Discrete Wavelet Transform (DWT) and ICA were introduced, and then a de-noising algorithm of ultrasonic echo signal called WICAW based on them was proposed, finally, the performance of proposed algorithm was evaluated by testing on simulated and measured ultrasonic echo signals.

2. Theory Background

2.1. DWT Method

The DWT expansion of a signal $f(t) \in L^2(R)$ can be defined as follows [10, 11]:

$$f(t) = \sum_{k} c_{j_0 k} \varphi_{j_0 k}(t) + \sum_{j=j_0}^{\infty} \sum_{k} d_{jk} \psi_{jk}(t) \tag{1}$$

The formula (1) contains two parts: the first part is low frequency signal and the second part is high frequency signal. For the low frequency signal, the approximation coefficient $c_{j_0 k}$ is defined as:

$$c_{j_0 k} = \int f(t) \varphi_{j_0 k}^{*}(t) dt \tag{2}$$

Where

$$\varphi_{j_0 k} = \frac{1}{\sqrt{2^{j_0}}} \varphi\left(\frac{t - k2^{j_0}}{2^{j_0}}\right) \tag{3}$$

is called scaling function, the symbol * represents complex conjugate. For the high frequency signal, the detail coefficient d_{jk} is defined as:

$$d_{jk} = \int f(t) \psi_{jk}^{*}(t) dt \tag{4}$$

Where

$$\psi_{jk} = \frac{1}{\sqrt{2^{j}}} \psi\left(\frac{t - k2^{j}}{2^{j}}\right) \tag{5}$$

is called wavelet function. The detail and approximation part is defined as follows respectively:

$$D_j(t) = \sum_{k=-\infty}^{\infty} d_{jk} \psi_{jk}(t) \tag{6}$$

$$\mathrm{A_j(t)} = \sum_{\mathrm{k}=-\infty}^{\infty} \mathrm{c_{jk}} \varphi_{\mathrm{jk}}(\mathrm{t}) \tag{7}$$

Original signal can be reconstructed as follows:

$$S(t) = A_N(t) + D_1(t) + D_2(t) + \cdots D_N(t) \tag{8}$$

Where $S(t)$ is the reconstructed signal, N is the decomposition level [7].

The one-dimension DWT of a signal can be regarded as a filtering process by a series of band-pass filters, low-pass filters extract the approximation coefficients and high-pass filters extract the detail coefficients, the standard decomposition tree of DWT process is shown in Figure 1, only two decomposition levels are depicted, HP and LP represents high-pass filter and low-pass filter respectively, ↑2 and↓2 represents up-sampling and down-sampling respectively.

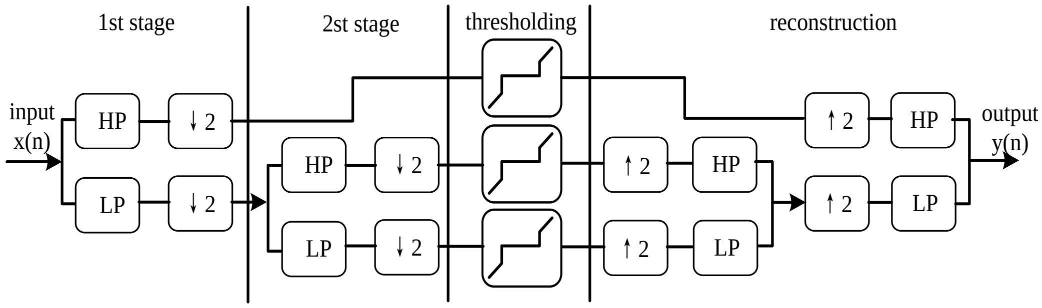


Figure 1. Standard Decomposition Tree of DWT Process

In general, the wavelet de-noising process of one-dimension signal can be divided into three steps.

The first step is wavelet decomposition. Selecting an appropriate wavelet function and determining decomposition layer N, then WT is used to decompose the original signal into N layers, the approximation and detail coefficients can be obtained.

The second step is threshold quantization of detail coefficients. A threshold method is selected and all detail coefficients from layer 1 to layer N are quantified.

The third step is signal reconstruction. The original signal is reconstructed by using decomposed approximation coefficient and quantified detail coefficients, de-noised signal can be obtained.

2.2. ICA Method

ICA is an efficient method to recover independent components from observed (mixed) signals of source signal, also known as Blind Source Separation (BBS) [13]. Let $x(t) = [x_1(t), x_2(t), \cdots x_M(t)]^T$ be M random observation signals of N source signals $s(t) = [s_1(t), s_2(t), \cdots s_N(t)]^T$ .Vector $s(t)$ is statistically independent and vector $x(t)$ is linear mixture of vector $s(t)$, their linear relation is given as follows:

$$x(t) = As(t) = \sum_{j=1}^{N} a_j s_j(t)(i = 1 \sim M) \quad (9)$$

The formula above can be denoted as $x(t) = As(t)$ for convenience, where A is an independent unknown $M \times N$ mixed full rank matrix. It's generally assumed that mixing source is at least as much as independent source ($M \geq N$).The blind signal processing technique does not use any training data and prior knowledge of mixing system parameters, namely don't need knowledge of matrix A. The main objective of ICA is to obtain a de-mixing matrix B so as to obtained signal source Y when it operates on X is the optimal approximation of independent source $s(t)$, the relationship can be expressed as follows:

$$Y = BX = \sum_{j=1}^{N} b_j x_j = BAS, A = inv(B) \quad (10)$$

The description of ICA method is shown in Figure 2.

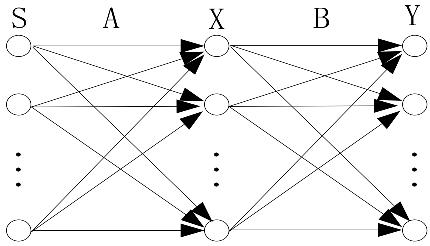


Figure 2. Description of ICA method

In order to perform ICA method many algorithms have been put forward, in practical application, different algorithms can be selected as needed. FastICA uses fixed-point iteration algorithm, it has many merits such as fast convergent rate, good stability, low consumption, high separation efficiency and so on. In this paper, FastICA algorithm was used, the specific procedure of this algorithm was described in literature [14].

3. WICAW De-noising Method

Wavelet transform has good time-frequency localization features, independent component analysis can separate multi-channel signals into independent components with each other, in this paper, combing their merits an ultrasonic signal de-noising algorithm (WICAW) based on wavelet transform (WT) and independent component analysis (ICA) was proposed, the structure diagram was shown in Figure 3. In WICAW algorithm, first, wavelet transform was used to decompose noisy original signal, approximated and detail coefficients were obtained, and then ICA algorithm was applied to decomposed coefficients, independent components (ICs) were obtained, next, isolated ICs were assessed by threshold value to filter out noise, finally, de-noised ultrasonic signal was obtained by reconstructing wavelet coefficients.

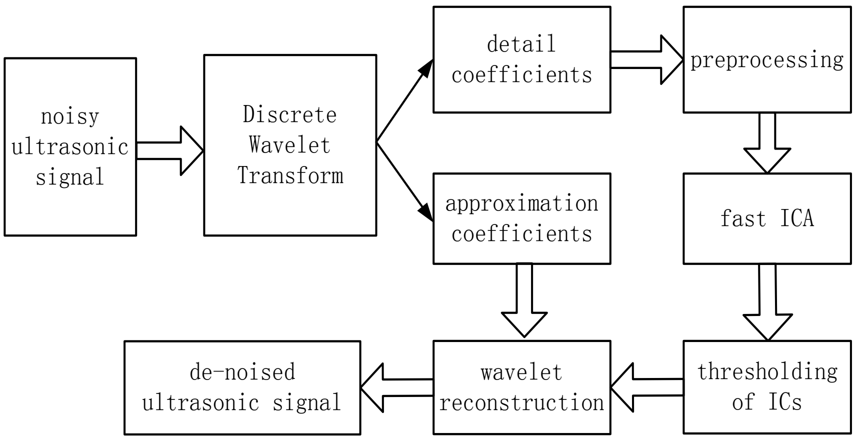


Figure 3. Structure Diagram of WICAW Algorithm

The crux of WICA algorithm is using wavelet transform to transform original single channel mixed signal to multi-channel signal suitable for ICA method. Using Mallat algorithm the observed signal $x(t)$ can be decomposed into N layers, one approximation signal $x_0(t)$ and N detail signals $x_j(t)$, where $t = 1,2,\cdots,n$ is the discrete time serial number and $j = 1,2,\cdots,N$ is the decomposition layer. Let $x(t)$, $x_0(t)$ and $x_j(t)$ are all column vectors, then $(N+1)*n$ dimension matrix $X(t) = [x_0(t), x_1(t), \cdots, x_N(t)]^T$ can be regarded as new multi-channel observation signals, so one dimension ultrasonic signal is transformed into multi-channel ultrasonic signals suitable for ICA. The multi-channel ultrasonic signals are input to ICA hidden source signals can be identified.

In WICA algorithm, noisy ICs were directly set to zero which can cause some useful signal components to be removed, whereas WICAW algorithm evaluates all ICs by threshold, ICs of signal can be preserved perfectly.

4. Research of De-Noising Experiment

In this section, WICAW algorithm and wavelet software threshold algorithm were respectively used to reduce noise in simulated and measured defect echo signals of different power noise, and their de-noising results were compared in order to test the performance of algorithms. According to traditional signal-to-noise ratio (SNR) definition, SNR can be quite large when noise is very small, in this paper, so normalized SNR [15] was used to describe the noise level of signal, the calculation formula is described as follows:

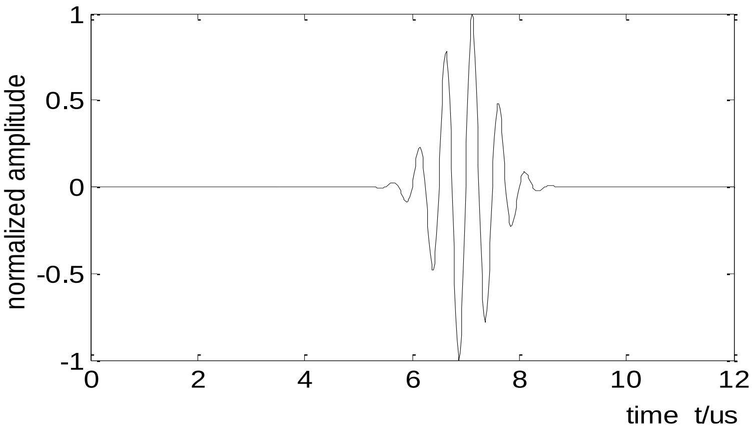
$$R_{NS} = \frac{\sum_{i=T_M-W/2}^{T_M+W/2} x_i^2}{\sum_{i=1}^{N} x_i^2} \tag{11}$$

Where T_M is the center of signal waveform on the time baseline, and W is the width of signal waveform, x_i is signal sequence, N is the length of signal sequence.

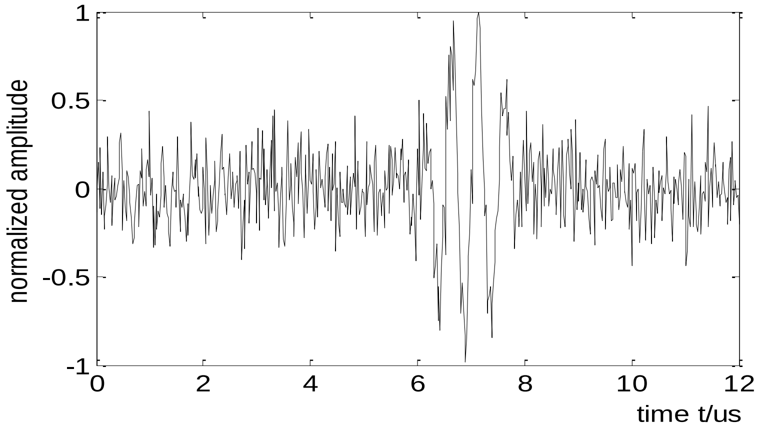
4.1. De-noising of Simulated Ultrasonic Signal

The ultrasonic echo signal was simulated by the model described in formula (12) with sampling frequency of 60MHz, Where$\alpha = 2 \times 10^{12}$,$\omega = 4\pi \times 1MHz$, $\phi = 0$ and A=5, 1024 data points including peak were used as analysis sample, then whiten Gaussian noise was added to the simulated signal, SNR=0.32, the simulated ultrasonic echo was shown in Figure 4.

$$x(t) = exp(-\alpha t^2)\, sin(\omega t + \phi) \tag{12}$$



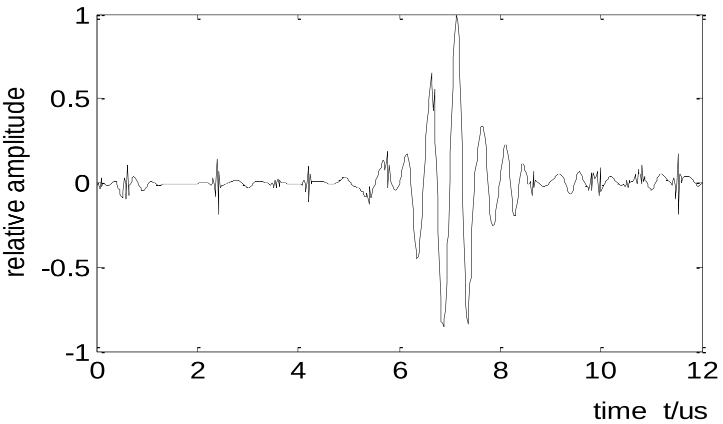
(a) Simulated ultrasonic echo signal



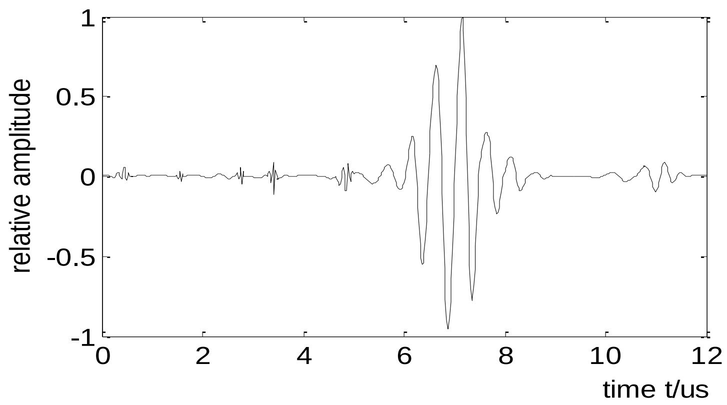
(b) Noisy simulated ultrasonic echo signal

Figure 4. Simulated Ultrasonic Echo Signal

Simulated ultrasonic echo signal was de-noised by wavelet soft threshold and WICAW algorithm respectively, the de-noised echo signal was shown in Figure 5, where the ordinate was denoted with relative amplitude which was result divided by the maximum of echo signal. It was clear from Figure 5 that the SNR of signal de-noised by wavelet soft threshold improved larger,ΔR_{NS}=0.36, but now the signal energy was relatively much lower , in addition to, de-noising introduced burrs, so the smoothness of signal got worse. Whereas the energy of signal de-noised by WICAW was almost no attenuation, the SNR improved larger than wavelet soft threshold, ΔR_{NS}=0.49, and the smoothness of signal was better.



(a) Signal de-noised by wavelet soft threshold (SNR: 0.74)



(b) Signal de-noised by WICAW (SNR: 0.83)

Figure 5. De-Noising of Simulated Ultrasonic Echo Signal

In order to test the de-noising performance of WICAW algorithm under various noise conditions, simulated signals with different SNR were de-noised by WICAW algorithm and the de-noised results were compared to wavelet soft threshold, the experiment results were shown in Figure 6. The Figure revealed that the whole de-noising performance of WICAW algorithm was better than wavelet soft threshold.

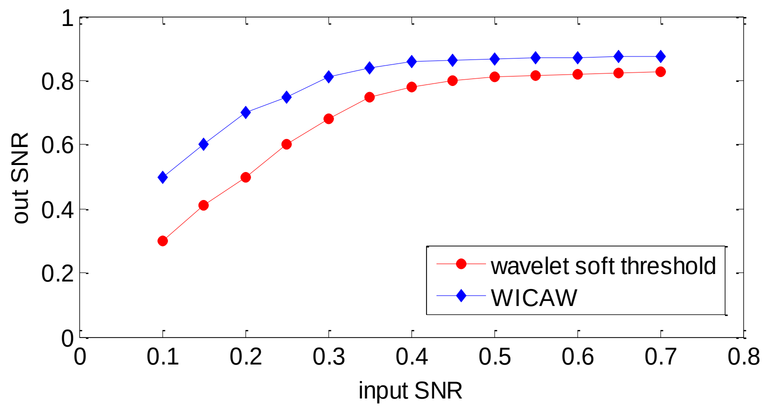
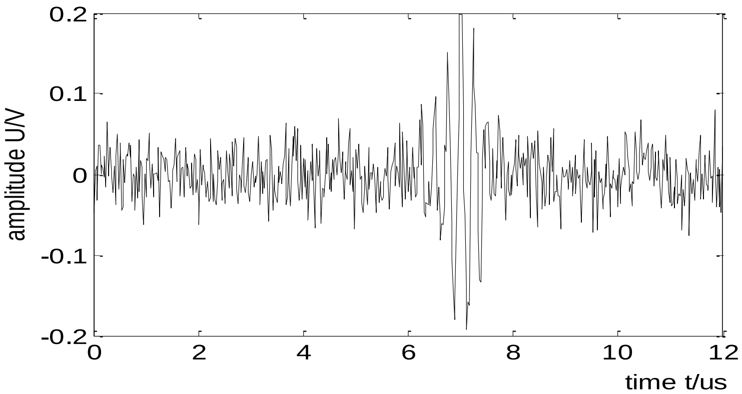


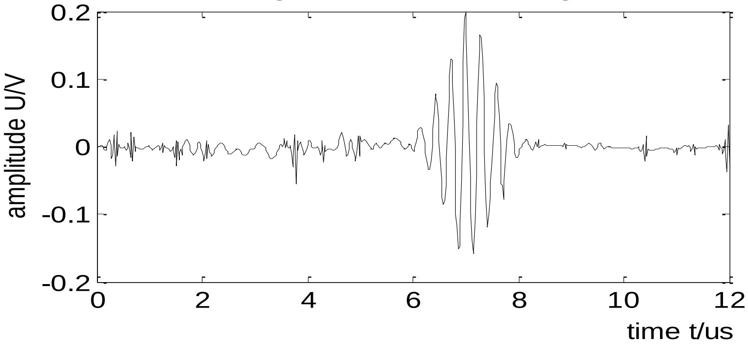
Figure 6. De-Noising of Simulated Ultrasonic Echo Signal with Different SNR

4.2. De-noising of Ultrasonic Signal with Typical Artificial Defects

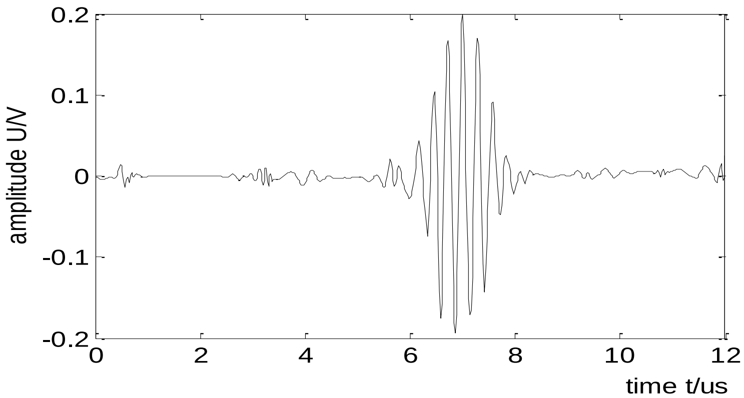
A group of measured ultrasonic echo signals were analyzed respectively by the same method as previous section. The testing object was 25mm thickness steel plate with a 1mm diameter and 2mm depth artificial flat bottom hole. During ultrasonic inspection the center frequency of sensor was 5MHz, sampling frequency was 60MHz. Ten defect signal samples were obtained after measuring the steel plate for 10 times. The original and de-noised ultrasonic echo signal was shown in Figure 7.



(a)Measured original ultrasonic echo signal (SNR: 0.49)



(b) Ultrasonic echo signal de-noised by wavelet soft threshold (SNR: 0.75)



(a) Ultrasonic echo signal de-noised by WICAW (SNR: 0.84)

Figure 7. Original and De-Noised Ultrasonic Echo Signal of a Flat Bottom Hole

Ten measured sample signals were de-noised respectively by the same method as previous section, the SNR comparison was shown in Figure 8, where the sample serial number was ranked in SNR ascending order. As can be seen from Figure 7 and Figure 8, de-noised signal by WICAW had better smoothness, less energy attenuation and higher SNR, so the de-noising performance of WICAW algorithm was better than wavelet soft threshold. Comparing the experiment results of measured signals and simulation signals, effect was basically identical, so once again the effectiveness of de-noising experiments and the superiority of WICAW algorithm were verified.

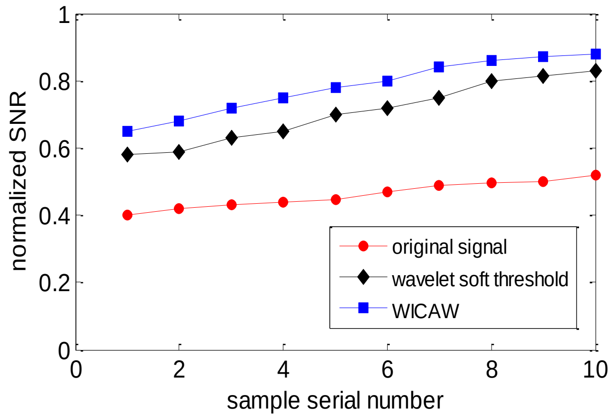


Figure 8. SNR Comparison of Measured Ultrasonic Echo Signal before and After De-Noising

5. Conclusion

The existing problem in the past de-noising algorithms of ultrasonic signal was analyzed. Wavelet transform has good time-frequency localization features and independent component analysis can separate multi-channel signals into independent components with each other, combining their merits an ultrasonic signal de-noising algorithm based on wavelet transform and independent component analysis was proposed. First, noisy original signal was decomposed by wavelet transform, next, ICA algorithm was applied to decomposed coefficients and isolated ICs were assessed by threshold to filter out noise, finally, de-noised ultrasonic signal was obtained by reconstructing wavelet coefficients. Simulated and experimental results showed that the proposed algorithm effectively filtered out noise, improved signal-to-noise ratio, performance excelled wavelet soft threshold de-noising method.

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