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Applying sub-band energy extraction to noise cancellation of ultrasonic NDT signal*

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Abstract: In ultrasonic non-destructive tests, the echo signal at the flaw is highly complex due to the interference of multiple echoes with random amplitudes and phases, and is disturbed by all kinds of noises, such as thermal noise, digitalization noise, and structure noise. In this paper, the ultrasonic signal was decomposed by empirical mode decomposition (EMD) to obtain the intrinsic mode function (IMF) components according to ultrasonic defect echo signals occuring at the corresponding time, and the energy of the ultrasonic signal was concentrated. The IMF component selection criterion based on sub-band energy extraction was proposed to extract the ultrasonic signal component accurately and automatically from IMF components. When the selected IMF components were filtered by a band pass filter, the signal-to-noise ratio (SNR) was enhanced greatly.

Key words: Empirical mode decomposition (EMD), Signal-to-noise ratio (SNR), De-noising, Non-destructive testing (NDT), Intrinsic mode function (IMF)

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INTRODUCTION

Ultrasonic non-destructive testing (NDT) technique is one of the NDT techniques. The ultrasonic sensor transmits the ultrasonic pulse and receives the echo reflected from the specimen. The echo signal at the flaw is highly complex due to the interference of multiple echoes with random amplitudes and phases. One of the most difficult tasks faced by the data interpreter is the recognition of the ultrasonic signals from flaw regions.

In ultrasonic NDT, the echo signal of pulse reflection, as a basic testing datum, is disturbed by electronic noise (such as thermal noise, digitalization noise) and structure noise. Because of these noises, it is difficult to identify the ultrasonic defect signal. The processing of the ultrasonic signal is important before it is analyzed. So far, several signal processing techniques, such as split spectrum algorithms (Gustafsson and Stepinski, 1993), synchronous averaging (Bilgutay *et al*., 1990), adaptive noise cancellation (Kim *et al*., 2001), and discrete wavelet transform (Lazaro *et al*., 2002), have been used to improve the detection of ultrasonic non-destructive evaluation (NDE) signals.

Hilbert-Huang Transform (HHT) proposed by Huang *et al*.(1998) is a promising signal processing technique coping with nonlinear and non-stationary time-series signals. The HHT has two components: one is empirical mode decomposition (EMD) for obtaining the intrinsic mode functions (IMFs), and the other applies Hilbert transform to IMFs for obtaining the spectrum. The numerical experiment based on fractional Gaussian noise has turned out that EMD acts essentially as a dyadic filter bank resembling those involved in wavelet decompositions (Flandrin *et al*., 2004). EMD has already received considerable attention and has been used to process many kinds of signals, such as biological signals, physiological signals (Balocchi *et al*., 2004; Andrade *et al*., 2006), voiced speech signals (Bouzid and Ellouze, 2004; Huang and Pan, 2006), ultrasonic flaw detection

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signals (Mao and Que, 2006), and fault diagnosis signals (Liu *et al*., 2006). Furthermore, it is more efficient than the wavelet transform for it is not defined through an integral transform, but defined by an algorithm and is fully data driven. Therefore, there is no need for selecting a basis function and decomposition level. In contrast, using wavelet transform only when the basis function and decomposition level are determined, can the signal be de-noised automatically.

Because the EMD can decompose the original signal into different frequency bands by time scale to obtain a small number of IMFs, which contain information of different frequency bands of the signal, EMD can be adopted as an adaptive filter. In the noise cancellation with EMD, IMF component selection is important. If IMF components are not properly selected, the noise cannot be cancelled, and the performance of the signal will be destroyed. In this paper, the selection of IMF components based on sub-band energy extraction was proposed, and the selected IMF components were filtered by a band pass filter for enhancing the signal-to-noise ratio (SNR) of the ultrasonic signal. By the proposed method, the SNR was enhanced and the ultrasonic flaw signal was easily identified.

DE-NOISING ALGORITHM FOR ULTRASONIC SIGNALS

Fig.1 shows the framework of the proposed ultrasonic signal processing algorithm. The details of the processing are depicted as follows.

Empirical mode decomposition

The EMD technique can decompose the original signal into a small number of IMFs, which are of the same length as the original signal, and preserve the frequency variations over time. The obtained IMF must satisfy two conditions: (1) In the whole dataset, the number of extrema and the number of zero crossings must either be equal or differ at most by one; (2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

The decomposition method is as follows.

Step 1: Given a signal $x(n)$, finding the local maxima of the signal, all the maxima are connected by a cubic spline line as the upper envelope. Then finding the local minima of the signal, all the minima are connected by a cubic spline line as the lower envelope. The mean of the upper envelope and the lower envelope is designated as $m_1(n)$,

$$h_1(n) = x(n) - m_1(n). \quad (1)$$

If $h_1(n)$ satisfies all the requirements of the IMF, it is the first IMF.

Step 2: If $h_1(n)$ does not satisfy the conditions of the IMF, it is treated as the datum, and Step 1 is repeated. $m_{11}(n)$ is the mean of the upper and the lower envelopes of $h_1(n)$, then

$$h_{11}(n)=h_1(n)-m_{11}(n). \quad (2)$$

If $h_{11}(n)$ satisfies all the requirements of the IMF, it is the first IMF. If $h_{11}(n)$ does not satisfy all the requirements of the IMF, Step 1 is repeated continually up to k times until $h_{1k}(n)$ is an IMF, that is,

$$h_{1k}(n)=h_{1(k-1)}(n)-m_{1(k-1)}(n). \quad (3)$$

It is designated as the first IMF component $c_1(n)$ from $x(n)$, that is, $c_1(n)=h_{1k}(n)$.

Then $c_1(n)$ is removed from $x(n)$ to obtain the residue $r_1(n)$, that is,

$$r_1(n)=x(n)-c_1(n). \quad (4)$$

The residue $r_1(n)$ is treated as the new datum. Then Steps 1 and 2 are repeated to obtain the second IMF $c_2(n)$. This procedure is repeated to obtain all the IMFs, and the results are

$$r_i(n) = r_{i-1}(n) - c_i(n), \quad i = 2,3,...,l. \quad (5)$$

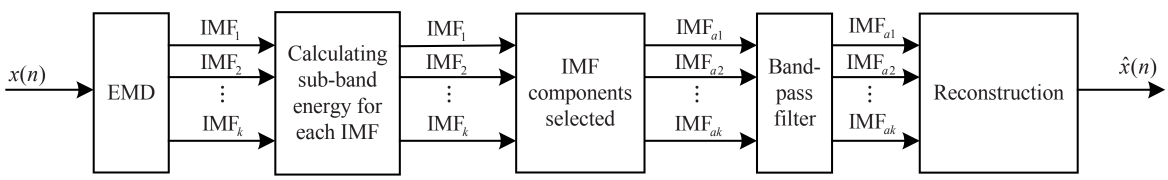

Fig.1 De-nosing algorithm for ultrasonic non-destructive testing signals

The decomposition stops as any of the following predetermined criteria is achieved: (1) Either the component $c_l(n)$ or the residue $r_l(t)$ becomes so small that the residue is less than the predetermined value of the substantial consequence; (2) The residue $r_l(t)$ becomes a monotonic function from which no more IMF can be extracted. Thus, the original data are the residue plus the sum of the IMF components:

$$x(n)=r_l(n)+\sum_{i=1}^{l}c_i(n). \tag{6}$$

To guarantee that the IMF components retain enough physical sense of amplitudes and frequency modulations, a criterion for stopping the EMD process is determined by *SD*,

$$SD=\sum_{n=0}^{T}\frac{|h_{1(k-1)}(n)-h_{1k}(n)|^2}{h_{1(k-1)}^2(n)}. \tag{7}$$

A typical value for *SD* can be set between 0.2 and 0.3 (Huang *et al*., 1998).

Sub-band energy extraction and IMF component selection

EMD decomposes the original signal into different frequency bands by time scale, and the IMF components contain information of different frequency bands of the signal. Simulated ultrasonic signal is a Gaussian echo model and is decomposed adaptively to get IMFs by EMD. Each IMF component reflects a different oscillation mode with different amplitude and frequency content. The first IMF component always has the highest frequency content and the frequency content decreases with increasing IMF numbers.

Because the ultrasonic defect echo signal occured at the corresponding time and the energy of the ultrasonic signal was concentrated, the energy of a certain IMF was maximal and the main signal was distributed at this IMF. If the maximal energy of the IMF component is found, it is easy to reconstruct the ultrasonic signal. But when the SNR is so small that the energy of the noise is higher than the energy of the ultrasonic signal, the energy of the first IMF must be higher than others'. According to the IMF component selection criterion based on the energy of each IMF, the ultrasonic signal cannot be extracted accurately. In order to find the IMF component of the ultrasonic signal, the selection criterion based on sub-band energy of the IMF component was proposed.

Firstly, the ultrasonic signal was decomposed by EMD. Then FFT is applied to each IMF component to obtain the frequency information. Because the center frequency of the ultrasonic signal was known, the window frequency can be defined as $[w_0-\Delta w, w_0+\Delta w]$, where w_0 is the center frequency of the ultrasonic signal, and Δw is shown in Fig.2b. Because the energy of the ultrasonic signal must be concentrated on the window frequency and the energy of the ultrasonic signal at w_0 is maximal, the IMF component of the ultrasonic signal to be reconstructed can be easily obtained. The energy formula is

$$E[k]=\sum_{f=w_a}^{w_b}IMF_k^{\,2}[f], \tag{8}$$

where k is the serial number of each IMF, f is the sub-band frequency, w_a and w_b are window frequencies. Because the sub-band energy of the ultrasonic pulse signal is centralized by computing the EMD of the ultrasonic echo signal with noise, the IMF with the maximal sub-band energy must be the ultrasonic signal component. Obviously, the IMF component with the maximal energy of the ultrasonic signal can be easily found.

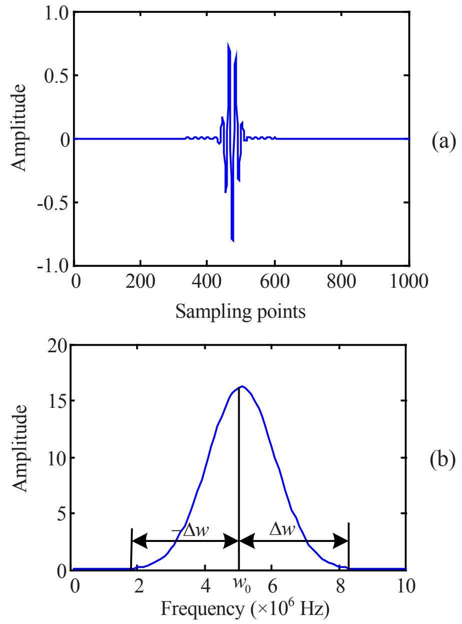

Fig.2 (a) Simulated ultrasonic signal; (b) Frequency band of the simulated ultrasonic signal

Band pass filter design and signal reconstruction

Although the ultrasonic signal can be identified automatically by calculating the sub-band energy of each IMF, these IMF components contain information of different frequency bands of the signal by EMD, that is to say, the frequency band of the IMF with ultrasonic signal components includes not only the center frequency of the ultrasonic signal but also some other frequencies. A band pass filter is designed to filter other frequency components.

A band pass filter works to screen out the frequencies that are either too low or too high, giving easy passage only to frequencies within a certain range. Because the energy of the ultrasonic signal must be concentrated on the window frequency, and the center frequency of the ultrasonic signal was known, the band pass filter can be designed. The passed frequency is between $w_0-\Delta w$ and $w_0+\Delta w$. Although the energy of the other IMF components is low, in order to maintain the integrity of the ultrasonic signal and not to destroy the performance of the ultrasonic signal, the IMF components with low energy are all selected to reconstruct the ultrasonic signal.

After the selected IMF components were filtered by the designed band pass filter, the reconstructed signal can be obtained as follows:

$$y(n)=\sum_{k=m}^{D} c_k(n), \qquad (9)$$

where m is the maximal sub-band energy of the IMF index, D is the last index of the IMF, $y(n)$ is the reconstruction signal, and $c_k(n)$ is the IMF component.

Process of the algorithm

In summary, the algorithm can be implemented by going through the following steps:

Step 1: Decompose the ultrasonic signal by EMD to obtain the finite IMF components;

Step 2: Apply FFT to each IMF component;

Step 3: Calculate the sub-band energy of the each IMF near the center frequency of the ultrasonic signal;

Step 4: Find the maximal sub-band energy of the IMF component;

Step 5: Apply a band pass filter to the selected IMF components;

Step 6: Reconstruct the ultrasonic signal automatically.

SIMULATION OF ULTRASONIC SIGNAL PROCESSING WITH THE PROPOSED METHOD

The ultrasonic pulse-echo can be modeled as (Demirli and Saniie, 2001)

$$f(\boldsymbol{\theta};t)=\beta \mathrm{e}^{-\alpha(t-\tau)^2}\cos[2\pi f_\mathrm{c}(t-\tau)+\phi], \qquad (10)$$

where $\boldsymbol{\theta}=[\beta\ \alpha\ \tau\ f_\mathrm{c}\ \phi]$ represents the parameter vector including the parameters of amplitude β, bandwidth factor α, time of arrival τ, center frequency f_c, and phase ϕ.

A typical simulation of the ultrasonic signal can be represented by

$$x(t)=f(\boldsymbol{\theta};t)+n(t), \qquad (11)$$

where $f(\boldsymbol{\theta};t)$ is the ultrasonic signal, and $n(t)$ is the noise. The signal $x(t)$ is distorted by the noise $n(t)$.

The SNR is calculated by (Kim *et al*., 2001)

$$SNR=10\log_{10}\left(\frac{\dfrac{1}{t_2-t_1+1}\sum_{t=t_1}^{t_2}x^2(t)}{\dfrac{1}{t_1}\sum_{t=1}^{t_1}x^2(t)+\dfrac{1}{T-t_2}\sum_{t=t_2+1}^{T}x^2(t)}\right), \qquad (12)$$

The target signal occurs between t_1 and t_2. T is the number of the total sampling points of the signal, and the sampling length is 1024. The parameters are: β=0.818, ϕ=8.89, α=50, f_c=5 MHz, τ=4.73 μs, and the sampling frequency is 100 MHz. Fig.3a shows the ultrasonic signal with SNR=1.7434, and Fig.3b shows the simulated ultrasonic signal without noise.

In order to extract the ultrasonic flaw signal from the noise, we decomposed the noisy signal by EMD. Fig.4a shows the decomposition results of the signals shown in Fig.3a from IMF_1 to IMF_8. Correspondingly, the Fourier transform of each IMF was plotted in Fig.4b. It is shown that EMD acts as a set of filters and decomposes the original signal from high frequency to low frequency in their turn. It can be seen from Fig.4a that the ultrasonic signal is centralized in the third IMF. In order to select the ultrasonic signal component automatically, we calculated the sub-band energy of each IMF.

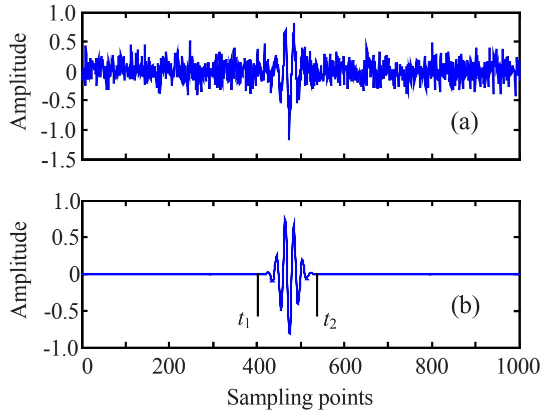

Fig.3 Simulated ultrasonic echo signal with noise (a) and without noise (b)

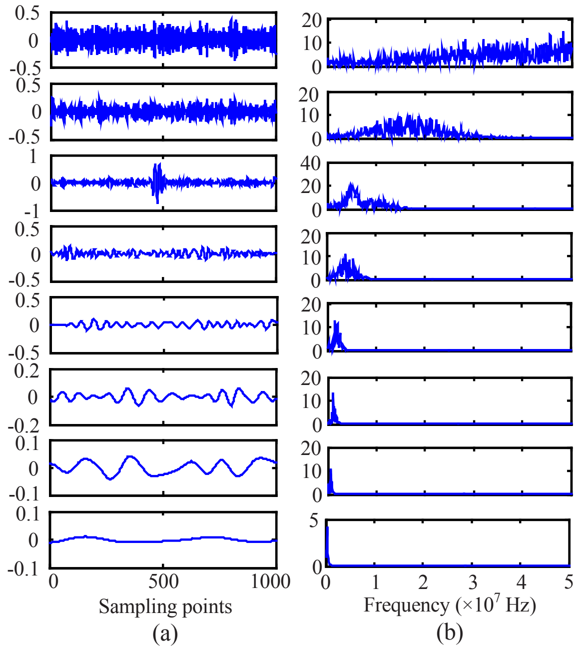

Fig.4 Each IMF component by EMD (a) and its spectrum (b). The sub-figures from top down correspond to IMF_1, IMF_2, ..., IMF_8, respectively

The directly calculated energy of each IMF component was shown in Fig.5a. The maximal energy was the first IMF component, because the *SNR* is so low that the ultrasonic signal is embedded into the noise. If the energy of the IMF component is directly calculated, the ultrasonic signal component cannot be selected. In order to select the ultrasonic signal component at the low *SNR*, we calculated the sub-band energy of the each IMF component, as shown in Fig.5b. Fig.5b also reveals that the maximal energy component was the third IMF component and that the ultrasonic signal component can be selected easily.

It was experimentally found that the set of optimal parameters of the FIR (finite impulse response) band pass filter ensures the best filter result by running many simulated ultrasonic signals. The parameters of the band pass filter are selected as follows: the order is 96, the window function is Hamming window, the center frequency is 5 MHz, and the bandwidth of interest is 3.06~6.93 MHz. The band was decided by the bandwidth factor of the simulated ultrasonic signal.

When the selected IMF components are filtered by the designed band pass filter, it is easy to reconstruct the signal. In order to maintain the integrity of the ultrasonic signal and not to destroy the performance of the ultrasonic signal, we selected all IMF components from the IMF component with the maximal energy to reconstruct the signal. Fig.6a shows the simulated ultrasonic flaw signal. Fig.6b shows the simulated ultrasonic flaw signal embedded with high noise. Fig.6c shows the simulation results by using the band pass filter directly. Fig.6d shows the simulation results by using the sub-band energy method. Figs.6c and 6d indicate that the proposed method can identify the ultrasonic flaw signal embedded in noise automatically and easily.

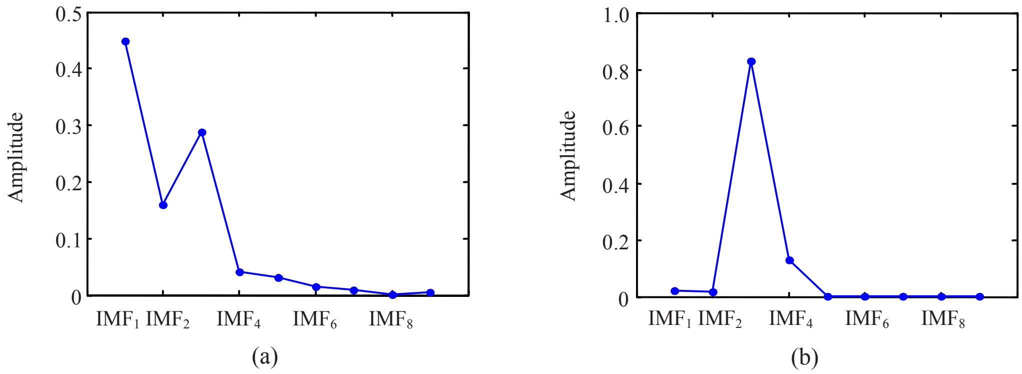

Fig.5 IMFs' energy of direct energy method (a) and sub-band energy method (b)

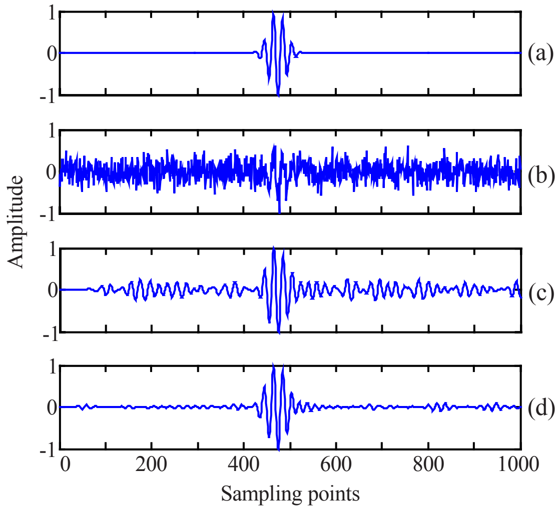

Fig.6 (a) Simulated ultrasonic signal; (b) Signal embedded in noise, *SNR*=−0.554 dB; (c) Processed signal using a band pass filter, *SNR*=8.232 dB; (d) Processed signal using sub-band energy method, *SNR*=11.748 dB

Fig.7 shows the results obtained during the simulation, each of which was averaged by 30 samples. The curve shows the enhancement of *SNR* after processing. Even when the simulation signal was embedded in heavy noise, the signal can be extracted by using the proposed method. Its de-noising effect through the waveforms after processing can be shown. The improvement in output *SNR* of the synthetic signals indicates the validity of the noise cancellation by the proposed method. The proposed method can improve the flaw detection when the ultrasonic signals have lower amplitudes than the noises.

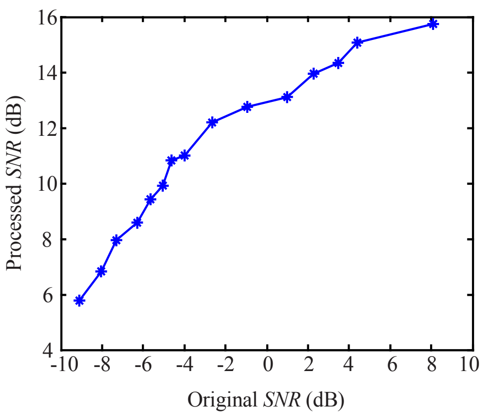

Fig.7 Processed *SNR* at different original *SNR* during the simulation. Each result was averaged by 30 samples

EXPERIMENTAL RESULTS AND ANALYSIS

To verify the effectivity of the proposed method in processing real ultrasonic flaw signals, we applied an offshore pipeline Spacemen, which is frequently used in recent studies, to a series of fabricated cracks. The experimental pulse-echo signals were obtained using a circular ultrasonic probe (6 mm in diameter). The ultrasonic probe produces longitudinal wave with 5 MHz center frequency. The sampling frequency is 100 MHz. The pulser/receiver is Panametrics 5058 PR. After obtaining the real ultrasonic echo signal with 100000 sample length, 1000 sample length with ultrasonic echo signal at flaw is intercepted in 100000 sample length. Before applying the proposed method to the ultrasonic flaw signal, the bandwidth of the ultrasonic flaw signal was estimated.

The proposed method was applied to many experimental ultrasonic signals to evaluate its performance. Fig.8 shows the experimental results of a certain ultrasonic flaw signal. Fig.8a shows the ultrasonic flaw signal embedded in noise whose SNR_{in} is 2.56 dB. Fig.8b is the reconstructed ultrasonic flaw signal using the median filter whose SNR_{out} is 9.68 dB after de-noising. The signal was decomposed into 8 IMFs with the EMD. By calculating the sub-band energy of each IMF, the sub-band energy of the 3rd IMF component is maximal. The IMF components from IMF_3 to IMF_8 were filtered by the designed band pass filter and the signal was reconstructed. Fig.8c shows the reconstructed ultrasonic flaw signal whose SNR_{out} is 12.53 dB after de-noising.

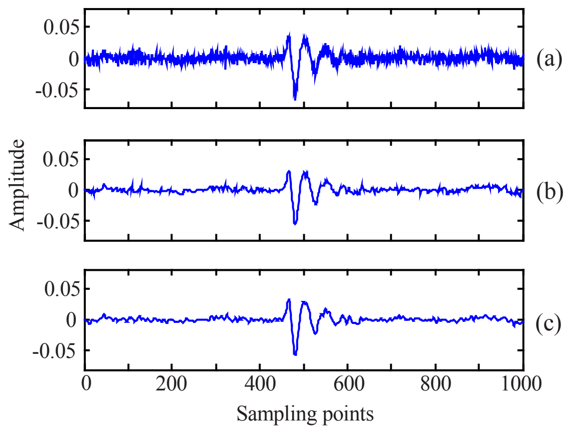

Fig.8 (a) Original signal, *SNR*=2.56 dB; (b) Reconstructed signal using median filter, *SNR*=9.68 dB; (c) Reconstructed signal using our proposed method, *SNR*=12.53 dB

CONCLUSION

The EMD can decompose the original signal into different frequency bands by time scale to obtain a small number of IMFs, which contain information of different frequency bands of the signal. According to the ultrasonic defect echo signal occuring at the corresponding time, the energy of the ultrasonic signal was concentrated. The ultrasonic signal can be extracted accurately and automatically from IMF components based on sub-band energy extraction, and when the selected IMF components were filtered by the band pass filter, the SNR was enhanced greatly. Experimental results show that the proposed technique is effective for removing the white noise from the ultrasonic signals.

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