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Application of Empirical Mode Decomposition for Ultrasonic Testing of Coarse-grained Materials

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Abstract

In ultrasonic testing of coarse-grained materials, signal to noise ratio (SNR) of testing signals is reduced seriously for the structure noise, and echoes from defects are difficult to be identified. In order to improve the SNR and the reliability of ultrasonic testing of coarse-grained materials, empirical mode decomposition (EMD) is introduced to process the testing signal here. Signal envelope can be formed by using cubic spline interpolation, and nonlinear and non-stationary signal can be decomposed self-adaptive into the sum of several intrinsic mode functions (IMF) by using characteristic time scale of the signals, and then higher order and tendency of the original signals can be obtained. The denoising experiment with low SNR simulated signal are achieved according to the feature of EMD, and SNR is enhanced more by comparison with the wavelet analysis method. And testing signal collected from coarse-grained materials is used to finish denoising experiment, and it is shown from the experiment result that the EMD has better adaptive ability in decomposing noise-polluted signals and less empirical information is required in the denoising process.

Keywords: *ultrasonic testing, coarse-grained materials, signal denoising*

1. Introduction

Coarse-grained materials have some advantages, such as anti-corrosion, high temperature creep ability, good low-temperature toughness. In recent years, this kind of materials was used more widely in modern industry, for example the chemical reaction vessels and piping, liquid and gas storage and transportation, nuclear power and others industrial departments [1, 2]. Therefore, it is essential for this kind of materials to non-destructive testing (NDT) both in the production process and in the daily maintenance.

Ultrasonic detection technology has many characteristics, such as great detecting depth, high sensitivity, great penetrating power, positioning accuracy, lower cost, high speed, harmless to human body and easy to field use [3, 4], and so ultrasonic testing technology is the most widely used than others NDT methods. During the Ultrasonic testing of coarse-grained materials, strongly ultrasonic scattering is produced on interface between those irregular and big grains, which gives rise to serious structural noise and ultrasonic energy attenuation, and besides random noise from acoustic-electric strings mixed between the transmitting and receiving transducer and test system various, which lead to decrease detecting sensitivity and defects detection rate of [5-6]. The research focal point is how to restrain strong noise of signals and improve the signal-to-noise ratio (SNR) and defects detection rate.

From the perspective of digital signal processing, there are many common approaches for enhancing the SNR of the coarse-grained materials detecting signal at present, such as split spectrum analysis technology, average filter technology and correlation analysis, frequency spectrum analysis and wavelet analysis technology, by which technologies desirable results had be obtained in some respects and some weak points were assignable [7-10]. The empirical mode decomposition (EMD) was first proposed in 1998 by Huang, which was suitable for processing non-linear and non-stationary signals [11]. EMD is similar to the wavelet analysis, but the basis function is not needed to be defined, and the time scale can be automatically adjusted with the local features of the detecting data by cubic spline interpolation, and signal

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details are gotten layer by layer, and the original signal can be represented by a series of narrow-band stationary intrinsic mode functions (IMF) and a residual, and therefore high frequency resolution can be gotten. By comparison with others methods, EMD is adaptive time-frequency analysis method without any prior knowledge [12-14]. In this contribution, because structural noise of ultrasonic testing signal of the coarse-grained materials is non-linear, non-stationary, EMD method is applied to decompose the detecting signal and IMF components forming the detecting signal are obtained at first, and then structural noise and environmental noise can be removed by sifting IMF components, and the SNR and defects detection rate can be improved.

2.EMD Basic Principles

EMD is formed ideologically according to the thought which any signals are composed by the different intrinsic vibration modes. And EMD is a process of smoothing the signal *x(t)* in essence: The delay between the adjacent peak point of the decomposed signal is defined as the time scale at first, and then a series of stationary signals with different time scales $c_i(t)$ (i=1…n) and residual *R(t)* can be calculated as following equation after the signals are sifted and decomposed.

$$x(t) = \sum_{i=1}^{n} c_i(t) + r(t) \tag{1}$$

Here $c_i(t)$ denotes different order IMF component respectively which must meet two conditions: Firstly, whether the number of the extrema point and the zero crossing point in *h(t)* are equal or differ by at most one. And secondly, average value of two envelopes composed by any point, the local maxima point and local minima point must be zero. The whole sifting flowchart is shown in Figure 1, these steady IMF components reflect vibration modes from high frequency to low frequency in accordance with the decomposition sequence respectively, and the remaining residual reflects the overall trend of the original signal.

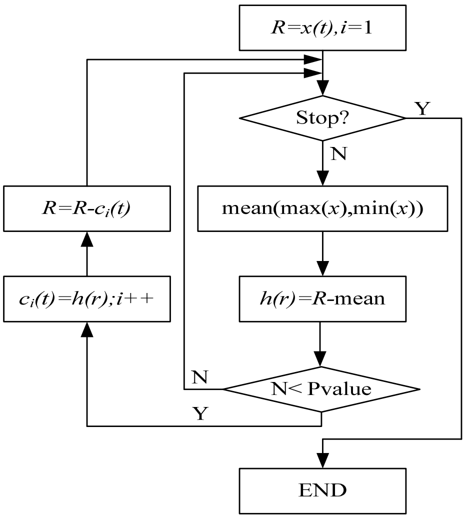


Figure 1. Flowchart of EMD

Termination conditions of whole sifting process will affect the decomposition effect, and so judgment conditions for termination commonly are that EMD decomposition is finished when the remainder $R_n(t)$ is a monotonic function or energy of the last decomposed $c_n(t)$ or $R_n(t)$ is lower pre-set value (Pvalue) according to project needs [11]. It can be judged as following equation whether the latter condition is met.

$$N = \frac{\sum_{t=0}^{T} \left| h_{k-1}(t) - h_k(t) \right|^2}{\sum_{t=0}^{T} \left| h_{k-1}(t) \right|^2} < \text{Pvalue} \tag{2}$$

Here $h_k(t)$ and $h_{k-1}(t)$ are the residual signals after the kth and $(k-1)$th sifting, and Pvalue express the pre-set value.

EMD also has well spatio-temporal filtering ability, and rebuilding signal can be obtained by selecting different IMF components according to requirement and low-pass filtering, high-pass filter and band-pass filtering are able to be achieved respectively.

3. Simulation Research

A simulated signal is designed as Figure 2(a) according to the actually detected conditions, which includes, the defect wave and the bottom wave, and the detecting frequency of the signal is 2.5MHz. And then the original signal $x(t)$ with 2dB SNR is obtained as shown in Fig. 2(b) after random noise is added into. From the figure, the reflected wave from defect is submerged into the noise, and merely the starting wave and the bottom wave can be seen.

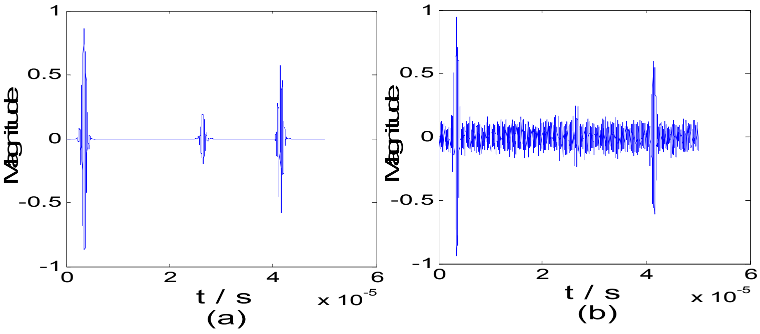
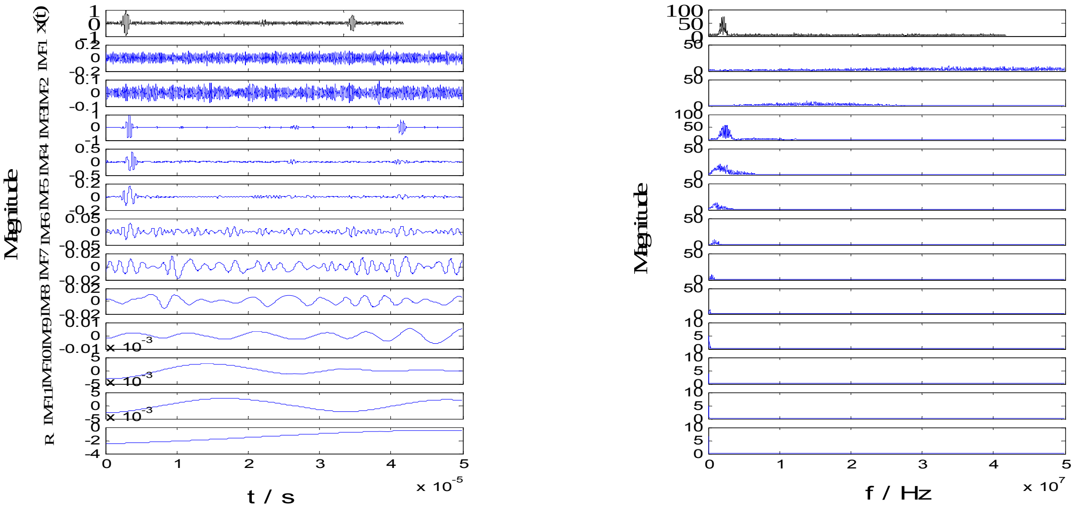


Figure 2. Simulated Test Signal



(a) (b)

Figure 3. Waveform and Spectrum of Test Signal and Its IMF

After the signal with noise is decomposed based on EMD method, 11 IMF components and a residual component R are obtained. The time-domain waveforms and corresponding spectrums of *x(t)* and the IMF components are listed in Figure 3. It can be found from the whole decomposition process that bigger the IMF order and smaller the central frequency of the corresponding IMF component, which is similar to the condition of wavelet decomposing the signal, and however the frequency band of different IMF component decomposed by EMD is not fixed and but changed with adaptive variation of EMD based on the stationary of the signal. From Figure 3, the first two IMF components have largest frequency spectrum range and smaller amplitude which are characteristics of the noise, and can be judged that the major components of two components are noise. And however wave packet is obvious in the remaining IMF components starting from 3th order IMF which are useful components. And so the first two order IMF components directly removed and the original signal is rebuilt with the remaining IMF components and the residual. This method of rebuilding signal is simpler and more intuitive unlike wavelet decomposition which is complex and needed to calculate the rebuilding coefficient.

The comparison of EMD denoising result and wavelet denoising result is shown in Figure 4, and the waveform 1 is the original signal, the waveform 2 is the signal with noise, the waveform 3 is rebuilt signal after EMD denoising and the waveform 4 is the result with wavelet denoising which is achieved with db4 wavelet and the threshold automatically selected. From the figure, defects wave can be effectively found by both results, and but in the result of wavelet denoising, wave packet is not smooth and many useful components are removed. And however EMD method is applied to denoise, basis function need not to be selected and can adaptive obtain data envelope and the effective ingredients are remained well, and the filtering result can be better tallied with the original signal. The comparison with both filtering results details is achieved as shown in Figure 5, and the results of EMD denoising method is more consistent with the original signal from the figure. The SNR of both results can be calculated by the Equation 3 [15, 16].

$$\mathrm{SNR} = 10\lg\frac{P_1}{P_2} \qquad (3)$$

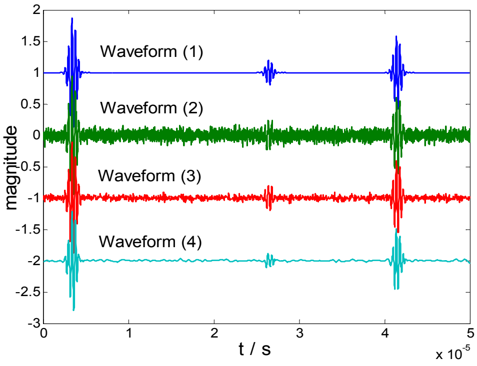


Figure 4. Comparison of Denoising Result by EMD and Wavelet

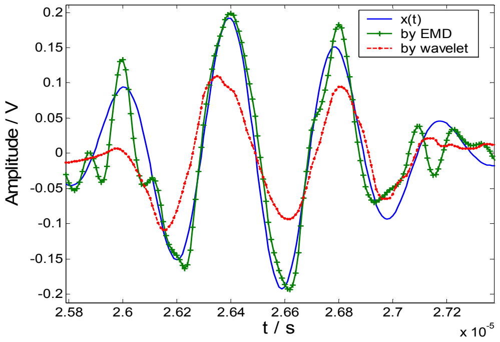


Figure 5. Comparison of Denoising Detail by EMD and Wavelet

Here P_1 is the energy of the original signal, and P_2 expresses the energy of signal after denoising. After calculating, the SNR after Wavelet denoising is 4.62dB and the SNR after EMD denoising is 11.01dB.

4. Experimental Test

Experimental specimen is shown in Fig. 6, it is a cast iron with 2-level grain degree. Thickness of the specimen is 60mm, and a flat bottom hole which aperture is Φ2mm is located inside 45mm deep. The experiment is completed with ultrasonic pulse-echo method. Experimental detection system is composed of the Olympus 5077 ultrasonic signal transmitting and receiving instrument, 2C20N ultrasonic transducer which is produced by Shantou Institute of Ultrasonic Instruments Co., Ltd., 9812 data acquisition card and computer. Experimental test signal is shown in Figure 7, because the test signal is interfered by serious noise and reflected energy from the flat bottom hole is weak, the reflected wave from the flat bottom hole is almost submerged by noise and but merely the beginning wave and the bottom wave can be seen.

Figure 6. Outside View of Testing Specimen

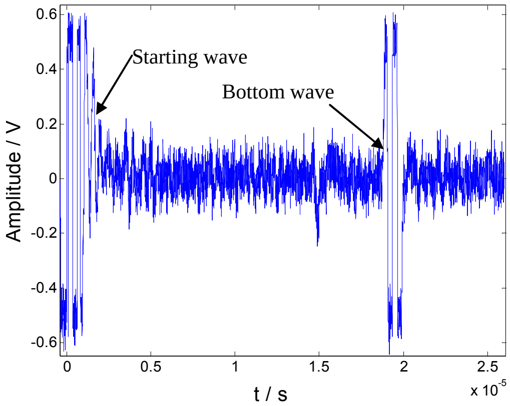


Figure 7. Experimental Testing Signal

After the detecting signal is decomposed with EMD, 14 IMF components and a residual can be obtained. The waveform and frequency spectrum of the IMF components are shown in Figure 8. From the figure, the first 4 IMF components have largest frequency spectrum range and smaller amplitude and so should be removed as noise, and however the others IMF components starting from the 5th order IMF have high spectrum energy and small bands which are useful components of signals. And so the signal can be rebuilt by the IMF components after the 5th order, and the comparison of the rebuilding signal and the original signal is shown in Figure 9. It can be found that the reflected signal from the flat bottom hole has stood out from strong noise and the reflection position is so obvious from the figure.

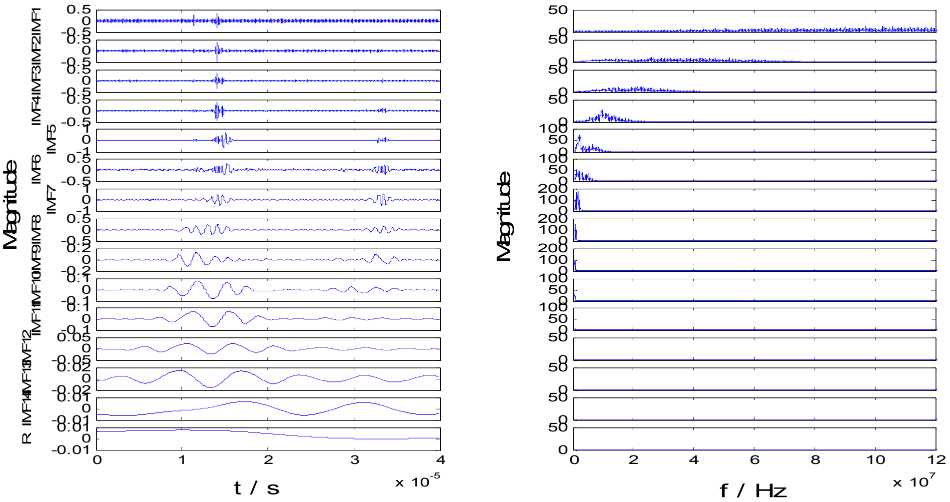


Figure 8. Waveform and Spectrum of Test Signal and Its IMF

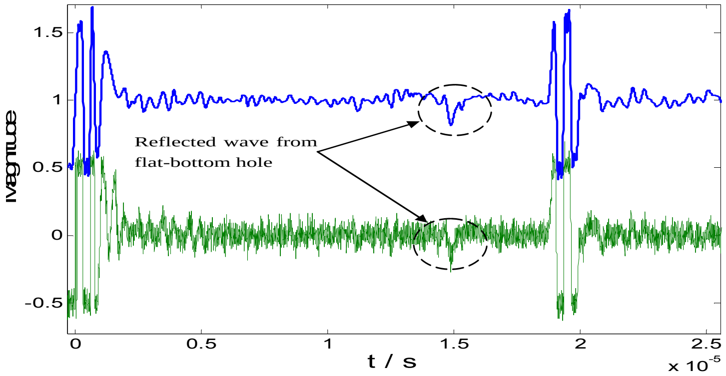


Figure 9. Comparison of Waveforms before and after EMD Processing

5. Conclusion

In the contribution, EMD method which was applied to process the detecting signal for strong structural noise was produced in ultrasonic test of coarse-grain materials. And time domain and frequency spectrum of IMF components were gotten by EMD, and then the noise signal was separated from the test signal and effective sections were picked out. The comparison with denoising effect both by EMD and wavelet was achieved though numerical simulation, and it could be shown from the comparison results that the EMD method focuses more on the intrinsic mode components and could be adaptive signal decomposition without any priori information of the original signal, and better filtering effect could be obtained after the first order IMF components which have the noise characteristics were removed. Finally, decomposition and signal rebuilding for the experiment signal were achieved, and it could be shown from the experiment results that the result processed by EMD was more effective to filter out the strong noise signal, and the reflected signal could be seen obviously.

Acknowledgments

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