A wavelet time entropy algorithm for ultrasonic signal detection

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Abstract

Ultrasonic signal detection is an important method of the non-destructive test. The ultrasonic signal detection can diagnosis the internal defects of materials or mechanical components non-destructively. There are some difficulties of ultrasonic signal detection to check the echo signal within the ultrasonic signal. With the wavelet transform and Shannon entropy theory, an improved wavelet-time entropy algorithm is put forward in this paper. The high-frequency coefficients of wavelet transform are replaced by the low-frequency coefficients, and the optimal width of window is worked out for actual ultrasonic signal. The numerical simulations are carried out to prove the feasibility of this algorithm in abnormal signal detection. The results show that the improved wavelet-time entropy algorithm can detect the echo signal in ultrasonic signal effectively.

Keywords: ultrasonic signal detection, wavelet transforms, wavelet-time entropy, non-destructive test

1 Introduction

Ultrasonic signal detection is one type of the non-destructive testing methods [1-4]. The ultrasonic signal detection can diagnosis the internal defects of materials or mechanical components non-destructively. It has broad applicability, detection sensitivity, and ease of use. It is the most extensive and most frequently used non-destructive testing technologies and one kind of fast developing technology among five conventional non-destructive testing methods.

As a regular means, ultrasonic testing technology can be non-destructive inspection of the internal defects of materials or mechanical components, and its application is almost penetrated into the various industrial fields [1-4]. At present, in the conventional ultrasonic testing, the quantitative detection of material defects is gained by the detection of defects echo wave location and the measurement of amplitude. One of the difficulties of ultrasonic signal detection is the detection of the echo signal in the ultrasonic signal, because much interference included in the echo signal, such as reflected wave, refracted wave, outside noise and so on. The interference makes the echo signal detection more difficult. Traditional detection methods rely on the observation of the original ultrasonic signal to determine the time of the echo signal appearance based on experience. This approach often obtains the error results and low detection efficiency.

The wavelet transform is a new technique to analyze the signal. The main advantage gained by using wavelet transform is the ability to perform analysis of a signal in localized time and frequency domain [11-13]. In paper [13], with the wavelet transform and the Shannon entropy theorem, the wavelet-time entropy is defined. It can be used to characterize the degree of confusion of the signal at different moments. First of all, the signal is decomposed into multi-scale wavelet coefficients. And then towards high-frequency coefficients, the degree of confusion can be calculated for different moments. Ultimately the entropy of the signal can be obtained in each time window. The theory of wavelet-time entropy is applied to the mutation detection of the signal and the fault diagnosis of vibration signal in paper [13], and the application effect is excellent.

This paper firstly introduces the wavelet-time entropy algorithm. Then, the feasibility of the algorithm is confirmed through the numerical simulation experiments. On this basis, in accordance with the characteristics of ultrasonic echo detection, an improved arithmetic is proposed for ultrasonic signal detection. Mainly, the operation object of the wavelet-time entropy is changed from the high-frequency coefficients into low-frequency coefficient, and the scheme of wavelet coefficient selection and window width selection is given for actual ultrasonic signals .The actual signal processing shows that the time entropy technique can remove extraneous information and remain the specific echo information, thereby enhancing the accuracy and stability of the ultrasonic signal detection. The time entropy technique also makes ultrasonic echo signal detection automatically probable.

2 Wavelet-time entropy theory and algorithm simulation

2.1 WAVELET-TIME ENTROPY THEORY

For any signal $S(t)$, discrete wavelet transform is defined as:

$$(W_\psi S)(j,k) = \int_{-\infty}^{+\infty} S(t)\psi_{j,k}(t)dt \,, \tag{1}$$

where $\psi_{j,k}(t)$ represents the discrete mother wavelet function, and it constitutes an orthogonal basis of the Hilbert space $L^2(R)$ consisting of finite-energy signal with $j,k \in Z$.

Since wavelet coefficients are given by $C_j(k) = \langle S, \psi_{j,k} \rangle$, that is the value of discrete wavelet transform. The energy of a signal at each scale $j = 1,2,...,N$ will be

$$E_j = \sum_k \left| C_j(k) \right|^2 \,. \tag{2}$$

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In consequence, the total energy can be interpreted as

$$E_{tol} = \|S\|^2 = \sum_j \sum_k |C_j(k)|^2 = \sum_j E_j \ . \tag{3}$$

For the decomposition scale, the relative wavelet energy is considered as

$$p_j = \frac{E_j}{E_{tol}} \ . \tag{4}$$

According to the Shannon entropy theory and the relative wavelet energy defined above, wavelet entropy [13-16] can be defined as

$$S_{wt} = S_{WT}(p) = -\sum_j p_j \ln[p_j] \ . \tag{5}$$

In a sense, wavelet entropy is a kind of average information and can represent the extent of the wavelet coefficients confusion. If the wavelet coefficients of each scale are well-distributed, and namely the energy is distributed evenly in each scale, the value of wavelet entropy will be relatively greater. If the distribution of wavelet coefficients is quite confused, such as the value of wavelet coefficients is concentrated in one scale, that is to say the energy of a signal mainly concentrated in one scale, the wavelet entropy will be very small, even equal to zero.

In order to research a temporal evolution, the analyzed signal is divided by no-overlapping temporal windows of the width L in paper [13]. For each interval i ($i = 1, 2, ..., N_L$), the time evolution of wavelet energy and wavelet entropy can be evaluated. The widow width L represents the number of wavelet coefficient in each interval i. The value of wavelet-time entropy obtained is assigned to the central point of the temporal window. In case of discrete wavelet decomposition, the number of wavelet coefficients at the resolution level j is two times smaller than the number at the previous one, that is to say the window width L at the resolution level j is two times larger than at the previous one. Therefore, in each scale, the minimum width of the window will include at least one wavelet coefficient.

By considering mean wavelet energy instead of total wavelet energy, the mean wavelet energy at a resolution level j for the time window i is defined as

$$E_j^{(i)} = \frac{1}{N_j} \sum_{k=(i-1)L+1}^{i+L} |C_j(k)|^2 \ , \tag{6}$$

where N_j can represent the number of wavelet coefficients at a resolution level j included in the time interval i.

Therefore, the total mean energy at this same time interval can be interpreted as:

$$E_{tol}^{(i)} = \sum_{j=1}^{N} E_j^{(i)} \ . \tag{7}$$

Then the time evolution of relative wavelet energy is given by:

$$p_j^{(i)} = \frac{E_j^{(i)}}{E_{tol}^{(i)}} \ . \tag{8}$$

The time evolution of wavelet entropy (wavelet-time entropy) is defined as:

$$S_{WT}^{(i)}(p) = -\sum_{j=1}^{N} p_j^{(i)} \ln[p_j^{(i)}] \ . \tag{9}$$

According to the above definition of wavelet-time entropy, the steps of the algorithm are written as follows.

The signal $S(t)$ is assumed to be given by the sampled values $S = \{s_0(n), n = 1, 2, ..., M\}$. Low-frequency wavelet coefficients series $Ca_j(k)$ and high-frequency wavelet coefficients series $Cd_j(k)$ can be obtained by being carried out the discrete wavelet transform with $j = 1, 2, ..., N$ and $k = 1, ..., N_j$.

Assumed that N_L denotes the number of the time window, j denotes the scale of wavelet decomposition and i denotes the window-number. The algorithm is described as follows:

1) For j circulation, $j = 1, 2, \ldots, N$.

1.1) Take coefficient arrays $Cd_j(k)$, calculate the window width $L_j = \left\lceil \frac{N_j}{N_L} \right\rceil$.

1.2) For i circulation, calculate mean wavelet energy $E_j^{(i)}$ for each window i according to Equation (6) $i = 1, 2, \ldots, N_L$.

2) For i circulation, compute total mean wavelet energy for the time interval i according to Equation (8).

$$E_{tol}^{(i)} = \sum_{j=1}^{N} E_j^{(i)} \ , \ i = 1, 2, \ldots, N_L \ .$$

3) For j circulation, $j = 1, 2, \ldots, N$, and i circulation, $i = 1, 2, \ldots, N_L$, calculate the relative wavelet energy according to the results from the step (1) and (2).

$$p_j^{(i)} = \frac{E_j^{(i)}}{E_{tol}^{(i)}} \ .$$

4) For i circulation again, calculate the wavelet-time entropy according to Equation (9)

$$S_{WT}^{(i)}(p) = -\sum_{j=1}^{N} p_j^{(i)} \ln\left(p_j^{(i)}\right), \ i = 1, 2, \ldots, N_L \ .$$

2.2 SIMULATION TESTS AND ANALYSIS

According to the above arithmetic, numerical simulation tests are carries out for two different signals in order to testify the feasibility of the method by using wavelet entropy. MATLAB is used to apply the discrete wavelet transform.

The first simulation signal $f_1(t)$ is three-component harmonic function.

$$f_1(t) = \begin{cases} \sin(2\pi t) + \sin(5\pi t) + \sin(12\pi t), (0 \le t \le 10s) \\ \sin(1.996\pi t) + \sin(5\pi t) + \sin(12\pi t), (10 < t \le 20s) \end{cases} . \tag{10}$$

This harmonic function basically contains three frequencies, 1.0, 2.5, and 6.0 Hz up to 10 s. After 10s, 1.0 Hz frequency is suddenly reduced to 0.998 Hz and other frequencies remain unchanged. As shown in. Figure 1, the small mutation of the 1.0 Hz frequency cannot be visible from time history. However, this small abrupt change in the frequency and the moment of its occurrence can be easily detected by wavelet-time entropy. Firstly, the discrete wavelet transform is carried out for the three-component harmonic function. The wavelet function used is db4 wavelet. To set up a slip window on wavelet transform coefficient series with a window width of 256 and the step value is 5. Wavelet-time entropy is then calculated according to Equations (6)-(9). Figure 1 shows the curve of wavelet-time entropy. A spike at 10 s can be clearly seen, which demonstrates that the abrupt shift in frequency is generated at 10 s.

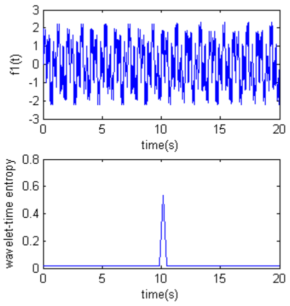


FIGURE 1 Three-component harmonic function $f_1(t)$ and its wavelet-time entropy

The second simulation signal $f_2(t)$ is a vibration signal with echo

$$f_2(t)=\begin{cases}2e^{-0.4t}\cos(4\pi t+0.1), & (0\le t\le 10s)\\ 2e^{-0.4t}\cos(4\pi t+0.1)+0.15e^{-0.35t}\cos(3.5\pi(t-10)+0.2), & (10<t\le 20s)\end{cases}. \quad (11)$$

This function contains only one vibration signal up to 10s. After 10 seconds, the vibration signal with echo can be detected by using wavelet-time entropy. The wavelet function used is dB4 wavelet and the discrete wavelet transform is carried out. Similarly, a slip window is set on the obtained wavelet transform coefficient series with a window width of 256 and the step value is 5. Then, the wavelet-time entropy of this vibration signal can be calculated. In Figure 2, a peak at 10 s can be clearly observed, which demonstrates that the abrupt break is generated at 10 s.

As shown in Figure 1 and Figure 2, the small shift of the signal occurred at any time can be detected by using wavelet-time entropy, which confirms that the arithmetic of wavelet-time entropy is feasible and effective for abnormal signal detection.

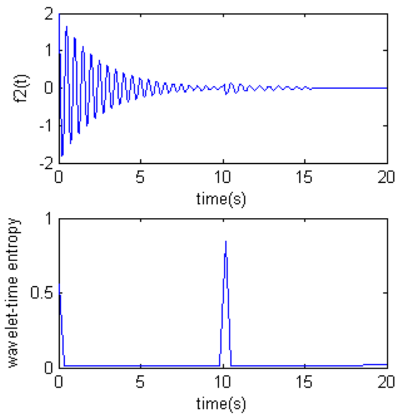


FIGURE 2 Vibration signal with echo $f_2(t)$ and its wavelet-time entropy

3 The improved algorithm of actual ultrasonic signal

Based on the above wavelet-time entropy theory, an improved wavelet-time entropy algorithm is put forward in this section so that it can be applied to the ultrasonic signals detection. The ultrasonic signals in this paper are acquired from vertical detected of light anchor screw by ultrasonic signal acquisition card. The sampling frequency of the acquisition card is 10MHz. Figure 3 is the curve of an actual ultrasonic signal.

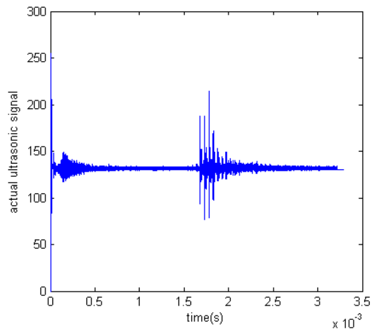


FIGURE 3 The curve of an actual ultrasonic signal

3.1 THE SELECTION OF WAVELET COEFFICIENTS

The high-frequency wavelet coefficients are used in the above simulation tests. High-frequency coefficients usually represent high-frequency part of a signal and contain the detail information of the signal. For ultrasonic signals, echo signals are very susceptible by the interference of outside noise. That is to say the detail information of the signal can be easily polluted by the noise. Consequently, if the high-frequency coefficients are used for calculating the wavelet-time entropy, the results are often unsatisfactory.

Figure 4 shows the wavelet-time entropy curve of ultrasonic signal when exerting the high-frequency coefficients. Figure 5 shows the wavelet-time entropy curve of ultrasonic signal when exerting the low-frequency coefficients. As shown in Figure 5, a relatively large peak can be observed in the vicinity of 1.75ms. The time which the peak is located is considered to be the start time of echo signals, corresponding to the start point of echo signal in Figure 3, so that the echo signal can be detected. However, there is no useful information from Figure 4. Therefore, the wavelet-time entropy of ultrasonic signals is calculated by using low-frequency coefficients. In Figures 4 and 5, the wavelet function used is db4 wavelet and a slip window is set on the obtained discrete wavelet transform coefficient series of ultrasonic signal with a window width of 256 and the step value is 3.

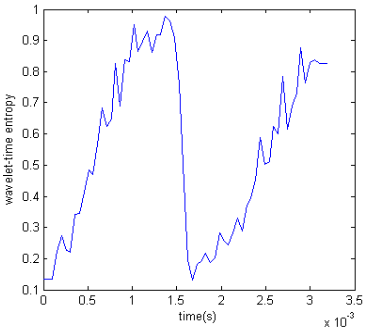


FIGURE 4 The wavelet-time entropy curve when exerting the high-frequency coefficients

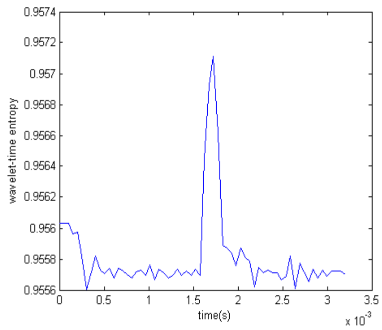
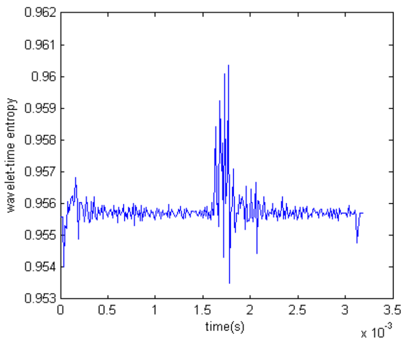


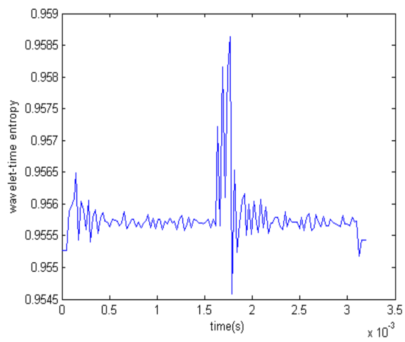
FIGURE 5 The wavelet-time entropy curve when exerting the low-frequency coefficients

3.2 SELECTION OF WINDOW WIDTH

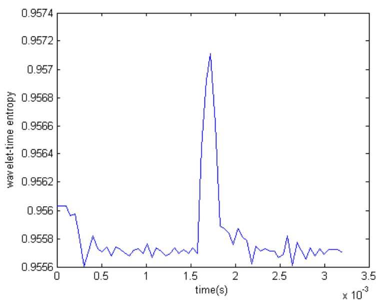
Within the wavelet-time entropy algorithm, the window width L is a really important parameter, and the value L will directly affect the test results. Figure 6 shows the curve of wavelet-time entropy of ultrasonic signal under different window width. When taken a smaller L, the single window will include relatively small number of wavelet coefficients. As shown in Figures 6a and 6b, several peaks and troughs will appear at periods of 1.5-2ms. It is difficult to select the peak or trough corresponding to really start time of echo signals. If taken a relatively larger L, as shown in Figure 6d, the wavelet-time entropy curve will seriously degenerate and the detection conclusion will be unstable for different ultrasonic signals. From above comparison, we can see that Figure 6c acquires the best effect, so in this text the window width is set to 256.



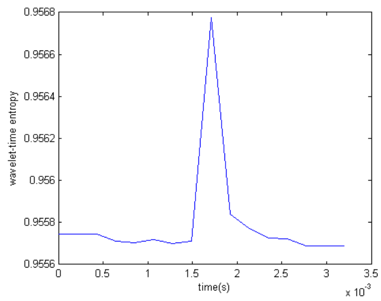
a) The wavelet-time entropy curve with $L = 64$



b) The wavelet-time entropy curve with $L = 128$



c) The wavelet-time entropy curve with $L = 256$



d) The wavelet-time entropy curve with $L = 1024$

FIGURE 6 The wavelet-time entropy curve with different window width L

3.3 DISCUSSION

To summarize the above the actual signal processing tests, the discrete wavelet transform by using db4 wavelet is carried out for the actual ultrasonic signal. The wavelet-time entropy of ultrasonic signal is calculated according to Equations (6)-(9) by exerting low-frequency coefficients. The window width L is set to 256. As shown in Figure 7, the start time of the ultrasonic echo signal can be clearly detected. Therefore, the feasibility and effectiveness of ultrasonic signal detection is confirmed for the improved wavelet-time entropy arithmetic.

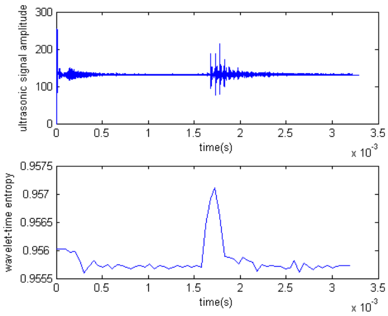


FIGURE 7 An ultrasonic signal and its wavelet-time entropy curve

4 Conclusions

As one of the five conventional detection methods, ultrasonic signal detection technology is developing toward digitized and intelligent. The range of its applications in engineering has become an increasingly widespread, and its importance has become increasingly prominent. At present, the level of the domestic auto-detection is still very low, mainly based on hand detection and the test results are vulnerable to be influenced by subjective factors.

The principium of the wavelet-time entropy is illuminated and demonstrated by simulation tests in this paper. According to the characteristic of ultrasonic signal, the improved algorithm is used to detect ultrasonic signals and brings about good effect of the actual signal processing. To conduct further follow-up treatment with the results obtained by the approach of this paper, the start time of echo signals can be accurately located, thereby achieving automatic detection of ultrasonic signals.

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