Study on Noise Reduction Using a Wavelet Packet for Ultrasonic Flaw Detection Signal of a Small Diameter Steel Pipe with a Thick Wall

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Ultrasonic detection technology is an important tool that is used to ensure the safe operation of equipment. However, when carrying out ultrasonic testing, especially in the ultrasonic detection of small-diameter steel pipes with thick walls, a mass of structural noise causes the useful information to get lost. This is problematic because the quality of ultrasonic echo signals is the foundation for the pipeline flaw-identification and feature extraction. At present, the wavelet packet thresholding method is the most widely used in signal de-noising processes. In this paper, a de-noising method of a wavelet packet based on the threshold is proposed for the limitation of both soft and hard thresholds. The ultrasonic wave pipeline detection signal that is often contaminated by noise is de-noised by this method. Moreover, the contrastive analysis is performed among the wavelet packet transform based on an adjusted threshold, the original ultrasonic echo signal, and the default threshold. Experiment results show that the noise reduction effect of the wavelet packet based on the adjusted threshold is the most reasonable one, and the signal-to-noise ratio (SNR) of the signals is also improved.

1. INTRODUCTION

With the wide application of small-diameter steel pipes with thick walls that transport high-temperature or high-pressure fluid, it is critical to ensure that small-diameter steel pipes with thick walls have high intensity and high quality.1 When detecting the small-diameter steel pipes with thick walls using the ultrasonic contact technique, their small diameter and high curvature leads to a small contact surface of the probe and tubing, large wear, poor coupling, serious proliferation of wave beams, and low examination-sensitivity.2 Seamless steel pipes, working under the situation of high temperature and high pressure, have the diameter of approximately 10 mm–3000 mm and a wall thickness of approximately 2 mm–60 mm.3 Because of these rather harsh working conditions and high quality requirements, it is necessary to do non-destructive testing.

The detection of small-diameter steel pipes with a thick wall usually requires ultrasonic-testing technology, which is extensively applied in the field of non-destructive testing technology.2,4 Ultrasonic testing, a non-destructive type of testing for metals as well as non-metallic and composite materials, has strong penetration, high sensitivity, low cost, high efficiency, and non-contact detection. It is also an important direction for pipeline flaw detection.4,5

However, due to the multi-modal characteristics and dispersion phenomena of the ultrasonic wave, the received flaw-echo signal is relatively weak. When the ultrasonic wave is used for the actual flaw detection, the signal is inevitably disturbed by noise, and the difficulty of extraction and recognition for the flaw-echo wave signal is increased. Therefore, it is necessary for the ultrasonic echo signals that have been detected to receive de-noise pre-treatment.6

Enhancement of the signal-to-noise ratio (SNR) by using various signal processing techniques has become surprisingly well developed.3–8 Signal time averaging, sparse de-convolution method, matched band-pass filtering, frequency spectrum analysis, autocorrelation analysis, high-order spectrum analysis, split spectrum processing technique (SSP), and autoregressive analysis have all been used to de-noise ultrasonic signals.7

At present, wavelet analysis is extensively applied in the field of ultrasonic signal de-noising. Threshold de-noising is a wavelet de-noising method that is simple and more effective, but the traditional soft and hard threshold de-noising methods still have some limitations.6–8 The discontinuity of the hard threshold function can make the de-noised signal generate oscillatory phenomena. Although the soft threshold function can overcome the discontinuity, the method always has a constant deviation; the de-noised signal has obvious distortion when the wavelet coefficient with the larger absolute value is reduced. In the wavelet analysis method, the signal is decomposed into different levels and different location wavelet components, and the senior and most senior mean square wavelet amplitude values are made the necessary extracted eigenvalues.9 However, the wavelet decomposition only decomposes the low-frequency signal and cannot decompose the high-frequency signal; so, the high-frequency signal cannot be used, and the extracted signal is not comprehensive enough. The wavelet packet that is equivalent to both a low-pass filter and a high-pass filter can decompose the low-frequency signal and the...
The ultrasonic signals obtained in the ultrasonic pulse non-destructive testing (NDT) are usually broadband pulse signals modulated at the central frequency of the transducer. Therefore, the properties of the ultrasonic signals are usually revealed by transforms that decompose signals over elementary functions that are well concentrated in time and frequency. For this reason, the utilization of time-frequency analysis may be more appropriate.

2. THEORETICAL ANALYSIS

2.1. The Basic Principle of Wavelet Packet

Wavelet packet transform is a further development of the wavelet transform. Wavelet packet analysis can provide a more detailed analysis for the signal. Wavelet packet transform not only decomposes the low-frequency signal, but also further decomposes the high-frequency signal, which is not subdivided. Based on the character of the analysed signal, wavelet packet transform can adaptively select the relevant frequency band and make the frequency band match the signal spectrum. Thus, these advantages not only enhance the time-frequency resolution of signal, but they also make the wavelet packet transform have a wider application value.

The wavelet packet is roughly considered a family of functions that can construct the orthonormal basis of $L_2(R)$. Wavelet function is one function in this family of functions. The wavelet packet is the popularization of the wavelet function.

The $\{h_n\}_{n \in Z}$ is assumed as the orthogonal low-pass real coefficients filter, which corresponds to the orthogonal function $\phi(t)$. The $\{g_n\}_{n \in Z}$ is assumed as the orthogonal high-pass real coefficients filter, which corresponds to the orthogonal wavelet function $\mu(t)$, where the orthogonal scaling functions $\nu_0(t)$ and $\nu_1(t)$ are given. The $g(k) = (-1)^k h(1 - k)$ is given. The dual scaling relation is as follows:

$$
\begin{align*}
\nu_0(t) &= \sqrt{2} \sum_{k \in Z} h_k \phi(2t - k) \\
\nu_1(t) &= \sqrt{2} \sum_{k \in Z} g_k \phi(2t - k).
\end{align*}
$$

With further popularization we can obtain:

$$
\begin{align*}
\nu_{2n}(t) &= \sqrt{2} \sum_{k \in Z} h_k \nu_{n}(2t - k) \\
\nu_{2n+1}(t) &= \sqrt{2} \sum_{k \in Z} g_k \nu_{n}(2t - k).
\end{align*}
$$

The $\{\nu_n(t)\}_{n \in Z}$, which is determined by the scaling function $\nu_0 = \phi(t)$, is called the wavelet packet function. The wavelet packet function is the further popularization of the wavelet function.

Assume that the scale space $V_j$ and the wavelet space $W_j$ are expressed by the new space $U_j$, where

$$
\begin{align*}
U_0^0 &= V_j \\
U_1^0 &= W_j, \quad j \in \mathbb{Z}.
\end{align*}
$$

So, the orthogonal decomposition of Hilbert space, which is the $U_{n+1}^j = U_n^j + U_{n+1}^j$, can be unified by the $U_{n+1}^0$. These are further extended to wavelet packet, and we can obtain the $U_{n+1}^j = U_{2n}^j + U_{2n+1}^j$, $j \in \mathbb{Z}$, $n \in \mathbb{Z}_+$. The three-layered wavelet packet analysis tree is given as Fig. 1.

The $d_{2n}^j$ and $d_{2n+1}^j$ are made the wavelet packet coefficients, which are in the subspace $U_{2n}^j$ and $U_{2n+1}^j$ of function $f(t) \in V_L = U_L$. The wavelet packet can be decomposed as follows:

$$
\begin{align*}
d_{2n}^j[k] &= \sum_{l \in Z} h_{l-2k} d_{n+1}^{j+1}[l] \\
d_{2n+1}^j[k] &= \sum_{l \in Z} h_{l-2k} d_{n+1}^{j+1}[l],
\end{align*}
$$

Wavelet reconstruction is given as:

$$
d_{2n}^j[k] = \sum_{k \in Z} h_{k-2} d_{2n}^j[l] + \sum_{k \in Z} g_{k-2} d_{2n+1}^j[l].
$$

2.2. Wavelet Packet De-noising Steps

The wavelet packet de-noising process is a basic function of wavelet packet analysis. The steps of the wavelet packet de-noising process are given as follows in Fig. 2:

The step entitled “Calculation of the Best Tree” is meant to determine the basis of the best wavelet packet. The threshold quantization of wavelet packet decomposition coefficients is used to select an appropriate threshold and make the threshold quantization for the wavelet packet decomposition coefficients.

Based on the wavelet packet decomposition coefficients of the lowest level, wavelet packet reconstruction of the ultrasonic signal is reconstructed, and the de-noising testing signal in the pipeline is obtained. In each of the above steps, it is critical to select the threshold and to quantize the threshold, which is directly related to the quality of the de-noised signal to some extent.

2.3. Wavelet Packet Threshold De-noising

Wavelet packet transform can make the signal energy concentrate on some of the large wavelet packet coefficients, but it makes the noise energy uniformly distributed on the entire wavelet packet coefficients axis. Therefore, the amplitude of the wavelet packet coefficient for the signal that is decomposed...
by the wavelet packet is greater than the amplitude of the noise factor. It is believed that the wavelet packet coefficient of larger amplitude is generally the signal, and the smaller amplitude coefficient is, to a large extent, the noise. Therefore, the threshold method keeps the signal coefficient reserved and reduces the highest noise factor to zero. In view of this phenomenon, the selected appropriate threshold makes the quantized processing for the wavelet packet decomposition coefficients useful in engineering. The wavelet packet coefficients that are less than or equal to the threshold are set as zero, and only the data that is greater than the threshold is used for rebuilding the signal. So, most of the noise is removed, and the singular points and characteristics of the original signal are retained. Therefore, regardless of whether or not the threshold is properly selected, the effectiveness of the de-noising algorithm is directly affected. If the selected threshold is too large, the wavelet packet decomposition coefficient that is too great is set as zero, and the signal detail that is too great is destroyed. If the selected threshold is too small, the desired de-noising effect is achieved. Because the wavelet packet decomposition coefficient of a different frequency band reflects the different characteristics of the signal, it is difficult to find a particularly effective uniform threshold to process the wavelet packet coefficient of each band. Based on the different manifestations of the wavelet packet decomposition coefficients for noise and signal in each frequency band, a multiple-threshold de-noising is used in this article.

In this paper, the single measurement vector (SMV) method is used for the de-noising process. The original signal, \( x(n) \), is decomposed by the wavelet packet, and the wavelet packet decomposition coefficient \( w_{j,k} \) is obtained. Finally, the \( \hat{w}_{j,k} \) is obtained by the soft threshold; namely,

\[
\hat{w}_{j,k} = \begin{cases} 
\text{sgn}(w_{j,k}) (|w_{j,k}| - \lambda(\alpha)) & , |w_{j,k}| \geq \lambda(\alpha) \\
0 & , |w_{j,k}| < \lambda(\alpha).
\end{cases} 
\]  

(5)

The estimated wavelet packet coefficient \( \hat{w}_{j,k} \) is obtained after processing, and the de-noising signal, \( x(n) \), is obtained by wavelet packet reconstruction.

3. EXPERIMENTAL SYSTEM

This typical PC-based ultrasonic flaw detection system is set up as shown in Fig. 3. Our experiment used a line-focused probe (SIR5-03), produced in the USA by the Pan-Pacific Automation Instrument Corporation. The carrier frequency and bandwidth of the transducers are 5 MHz and 1.5 MHz respectively. A regular small-diameter steel pipe with a thick wall is used as the specimen. The wall thickness of the specimen has a diameter of 50 mm and 12 mm, and the depths of the outside surface cracks and inside surface cracks measure 1 mm. An EVOC EIC-2406 industrial computer and three ultrasonic plate cards, including the data acquisition card PR401, the 8 bit 100M A/D converter card, and the integrated timing control and filter card TCF640, also produced in the USA by the Pan-Pacific Automation Instrument Corporation, were used in the automated testing system. The experimental ultrasonic signals for crack detection were obtained by an A-scan with a sampling frequency of 100 MHz.

The experiments were done in LAB and the manufactory. The ultrasonic probe with 5 MHz central frequency and a 10 mm diameter wafer was used, and water was used as couplant. The ultrasonic automatic testing system of the small-diameter steel pipe with thick wall and water immersion is made up of a multi-channel ultrasonic flaw detector and mechanical transmission system. The physical diagram of the ultrasonic automatic testing system for the thick-walled, seamless, steel tube is shown in Fig. 4.

4. RESULTS AND DISCUSSIONS

In order to evaluate the performance of the proposed technique in the practical ultrasonic flaw detection, many practical detected signals of different types were collected. The obtained practical detected signals contained flaw echoes detected by longitudinal waves and transverse waves, and they reflected from the inside wall and the outside wall of the small-diameter steel pipe with thick walls. In accordance with the above wavelet packet transform algorithm in the ultrasonic
signal de-noising, the experiment was first done by wavelet packet de-noising with a default threshold, and then it was done by wavelet packet de-noising with the different wavelet packet quantitative threshold, which was selected on the basis of the actual signal. Consequently, we obtained the different de-noising results. Meanwhile, in order to compare the de-noising results of the different wavelets, the ultrasonic signals were de-noised by the wavelet packets with the db2, db4, db6, sym2, sym4, and sym6. The results are shown in Fig. 5.

The processed ultrasonic signals present a clear waveform, which can be used for flaw detecting. It thus can be concluded that signal processing of the ultrasonic signals using wavelet packet transform can be extremely useful in reducing the noise and improving the detection of small flaws in small-diameter steel pipes with thick walls.

From Fig. 5, the default threshold is not obvious. When the signal is adjusted to the appropriate threshold, the de-noise effect is obvious, and the signal-to-noise ratio is also raised. This lays the foundation for the subsequent signal analysis. The signal processed by the wavelet packet contains richer details. This is mainly because the wavelet analysis only decomposes the low-frequency signal, but the high-frequency signal is not further processed; thus, the de-noised signal is not smooth. Wavelet packets can decompose low-frequency and high-frequency signals, which makes the details of the de-noised signal richer than the wavelet de-noising in the uniform conditions, and the experimental results show that the proposed method is efficient in improving the signal strength and reducing the noise.

5. CONCLUSIONS

The noise interference in ultrasonic testing is an important factor that affects the defect detection and analysis evaluation of small-diameter steel pipes with thick walls. The wavelet packet was applied to de-noising for ultrasonic signals, collected from the small-diameter steel pipes with a thick wall, and contaminated with a lot of noise. Decomposition level dependent thresholds were applied in all cases. The good results, in terms of SNR enhancement, for the experimental traces, were obtained with the soft threshold. There is an ever-present need in industry to detect damage in products, particularly in small-diameter steel pipes with thick walls, which have to meet quality and safety regulations in order to be used. Automated ultrasonic testing is extensively used in the quality detection field, and the automation of the signal analysis has become a necessity. The purpose is to find out the improved automated procedure.

In this paper, the wavelet packet de-noising method is applied to the ultrasonic wave detection signal of small-diameter steel pipes with thick walls. Because the wavelet packet can decompose both the low-frequency and high-frequency signal, it makes the details of the de-noised signal richer than the wavelet de-noising in uniform conditions. The experimental results show that the proposed method is efficient in improving the signal strength and reducing the noise. The results also show that the method can obtain the de-noising effect, effectively filter out noise, improve the signal-to-noise ratio, and also lay the foundation for the feature extraction of subsequent signals. Meanwhile, the results assure the reliability and the efficiency of the method for detecting and measuring cracks in small-diameter steel pipes with thick walls, and they also provide application value for engineering practice.

REFERENCES

Figure 5. The wavelet packet de-noising waveforms of different wavelets and different thresholds.


