

Denoising of Vibration Signal of CNC Machine Tool Spindle based on Improved Wavelet Threshold

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Abstract

Aiming at the problem that the vibration signal of CNC machine tool spindle is often accompanied by noise, this paper proposes an improved wavelet threshold. This method introduces adjustment parameters and exponential functions. The new threshold function optimizes the defects of discontinuity of hard threshold function and constant deviation of soft threshold function, and realizes the filtering of noise and the retention of original signal information. Experimental results show that compared with the hard threshold method, the signal-to-noise ratio of vibration signals in three directions is improved by 4.7082dB, 6.0584dB and 8.1177dB respectively, and the root mean square error is reduced by 0.6684, 1.094 and 1.3093 respectively, which verifies the accuracy and reliability of this method in vibration signal processing.

Keywords

CNC Machine Tools; Vibration Signal; Wavelet Denoising; Threshold Function; Signal-to-Noise Ratio.

1. Introduction

In the collection of spindle vibration signals of CNC machine tools, due to the combined influence of the harsh external environment and multiple internal factors, the spindle vibration signals are often contaminated by interference noise, which seriously affects the accuracy of the detection signals. Therefore, in order to extract effective information from the spindle vibration signal, denoising is an indispensable step[1]. Considering the non-stationary characteristics of the main shaft vibration signal, the traditional short-time Fourier transform has certain limitations in processing such signals, because its resolution is fixed and it is difficult to adapt to the non-stationary changes of the signal. As a time-frequency analysis method, wavelet transform has the ability of multi-resolution analysis, which not only reduces errors but also better retains useful information. Therefore, it has been widely used in non-stationary signal processing[2]. Especially in the field of wavelet denoising, it has the advantages of multi-resolution properties, flexibility in selecting basis and retaining useful signals. These advantages make wavelet denoising an efficient and reliable method in signal processing and widely used in various fields such as image processing, speech processing, biomedical signal processing, etc. The limitation of traditional wavelet threshold denoising in signal processing lies mainly in the problem of threshold selection. The hard threshold function may cause signal oscillation due to its discontinuity; while the soft threshold function, although continuous, may cause a constant deviation from the original signal. In order to overcome these problems, many scholars have conducted in-depth research and proposed a series of improvement methods. Lu et al. proposed an improved

wavelet threshold function and a fixed threshold formula, introduced the logarithmic function of the wavelet decomposition layer number, and designed a new fixed threshold formula. This method can improve the problems of constant deviation and discontinuity in speech signal denoising[3]. Il K K et al. proposed a wavelet threshold function between the Garrote and hyperbolic threshold functions. The new threshold function solves the problems of constant error and discontinuity of the traditional threshold function. The new threshold method is more suitable for removing environmental noise than previous methods[4]. Du et al. proposed a denoising method based on an improved threshold function and used this method to denoise the gas content signal measured by a fiber optic probe. Experimental results showed that the improved threshold wavelet denoising method has better denoising effect than the traditional soft and hard threshold functions[5]. Ouyang et al. proposed a wavelet threshold denoising method that adjusts two independent factors, and used this method to denoise surface electromyographic signals. Experimental results show that this method can select noise from a large number of function models. Reduce the most significant filtered signal to obtain an optimal threshold function that effectively suppresses noise[6]. Hao et al. proposed a new wavelet threshold denoising algorithm that combines dual parameters and three-segment threshold functions, and used this method to denoise the simulation signals, vibration and acoustic signals collected by the belt conveyor experimental platform. The experimental results show that the denoising effect of this method is better than the traditional threshold function denoising algorithm, and it effectively solves the denoising preprocessing problem of idler roller fault signals under strong noise background[7]. Based on an in-depth analysis of previous research experience, this paper proposes an improved threshold function and applies the wavelet of this improved threshold function to the denoising of the spindle vibration signal of CNC machine tools. This method aims to more effectively filter out the noise in the signal and more accurately extract valuable signal information, thereby optimizing the effect of signal processing.

2. Soft and Hard Threshold Function

In the CNC machining process, the spindle vibration signal collected by the three-axis vibration sensor not only truly reflects the spindle vibration state signal, but is also inevitably mixed with noise signals. Therefore, the collected vibration signal is usually expressed as:

$$f_i = s_i + \varphi c_i \quad (1)$$

Where: f_i is the noisy signal; s_i is the actual data signal; φ is the noise correlation coefficient; c_i is the noise.

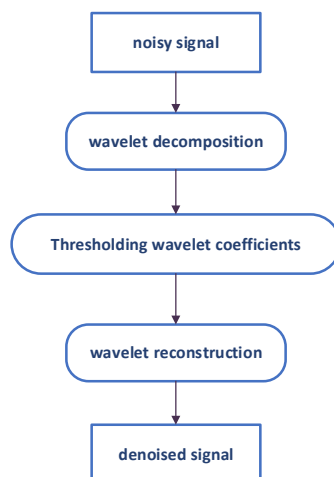


Fig. 1 The process of wavelet threshold denoising

As an effective signal processing technology, wavelet threshold denoising method has a process as shown in Fig. 1. First, by performing wavelet decomposition on the noisy signal, the corresponding wavelet coefficients can be obtained. These coefficients carry different frequency components of the signal. Then, the processing of the threshold function becomes the key. By reasonably setting the threshold and applying the appropriate threshold function, the influence of noise on the wavelet coefficients can be reduced, thereby highlighting the main features of the signal. Finally, the inverse wavelet transform can be used to reconstruct the denoised signal.

The two typical threshold functions are hard threshold and soft threshold. The hard threshold function is expressed as:

$$\hat{w}_{j,k} = \begin{cases} w_{j,k} & |w_{j,k}| \geq \lambda \\ 0 & |w_{j,k}| < \lambda \end{cases} \quad (2)$$

The soft threshold function expression is:

$$\hat{w}_{j,k} = \begin{cases} \text{sign}(w_{j,k}) (|w_{j,k}| - \lambda) & |w_{j,k}| \geq \lambda \\ 0 & |w_{j,k}| < \lambda \end{cases} \quad (3)$$

Where: $w_{j,k}$ represents the original wavelet coefficients; $\hat{w}_{j,k}$ represents the wavelet coefficients after threshold processing; $\text{sign}(\)$ represents the step function; λ represents the threshold.

It can be seen from the formula that the discontinuity of the hard threshold processing function and the constant deviation of the soft threshold processing function both affect the reconstruction accuracy of the wavelet coefficients, which in turn has an adverse effect on the final effect of wavelet denoising.

3. Improved Wavelet Threshold Function

In view of the limitations of soft and hard threshold functions in signal denoising, this paper introduces the adjustment parameter L and exponential function to give the new threshold function adaptability and continuity respectively, thereby improving the denoising effect. The expression of the improved threshold function is as follows:

$$\hat{w}_{j,k} = \begin{cases} \text{sign}(w_{j,k}) \left\{ |w_{j,k}| - \lambda \exp \left[L(\lambda - |w_{j,k}|) \right] \right\} & |w_{j,k}| \geq \lambda \\ 0 & |w_{j,k}| < \lambda \end{cases} \quad (4)$$

In the formula, L is used as an adjustment parameter, and the value of L determines the characteristics of the threshold function. When $L = 0$, the function is equivalent to the soft threshold function; when $L \rightarrow +\infty$, the function is a hard threshold function; when L takes a moderate value, it can effectively make up for the shortcomings of the soft and hard threshold functions and optimize the denoising effect.

In the following, we select the improved threshold function for an in-depth analysis in the specific case of $L = 1$, focusing on its continuity and gradual characteristics.

(1) Continuity

$$\begin{aligned} \lim_{w_{j,k} \rightarrow \lambda^+} \hat{w}_{j,k} &= \lim_{w_{j,k} \rightarrow \lambda^+} w_{j,k} - \lambda \exp \left[L(\lambda - w_{j,k}) \right] = \\ &= 0 = \lim_{w_{j,k} \rightarrow \lambda^-} \hat{w}_{j,k} \end{aligned} \quad (5)$$

According to the calculation results of formula (5), it is found that at the threshold λ , the left limit and the right limit of the improved threshold function are equal, which ensures the continuity of the function at this point. Since the function has the property of an odd function, it can maintain continuity at the threshold $-\lambda$, thereby avoiding the oscillation or mutation that may occur in the signal during the processing process, which helps to improve the denoising effect and quality.

(2) Gradualness

When $\hat{w}_{j,k} \rightarrow +\infty$:

$$\lim_{w_{j,k} \rightarrow +\infty} \hat{w}_{j,k} / w_{j,k} = \lim_{w_{j,k} \rightarrow +\infty} \{w_{j,k} - \lambda \exp[L(\lambda - w_{j,k})]\} / w_{j,k} = 1 - \lim_{w_{j,k} \rightarrow +\infty} \lambda \exp[L(\lambda - w_{j,k})] / w_{j,k} = 1 \quad (6)$$

When $\hat{w}_{j,k} \rightarrow -\infty$:

$$\lim_{w_{j,k} \rightarrow -\infty} \hat{w}_{j,k} / w_{j,k} = \lim_{w_{j,k} \rightarrow -\infty} -\{-w_{j,k} - \lambda \exp[L(\lambda + w_{j,k})]\} / w_{j,k} = 1 + \lim_{w_{j,k} \rightarrow -\infty} \lambda \exp[L(\lambda + w_{j,k})] / w_{j,k} = 1 \quad (7)$$

Therefore:

$$\lim_{w_{j,k} \rightarrow +\infty} \hat{w}_{j,k} / w_{j,k} = \lim_{w_{j,k} \rightarrow -\infty} \hat{w}_{j,k} / w_{j,k} = 1 \quad (8)$$

According to the calculation results of equations (5)-(8), it is found that the improved function has a specific asymptote $\hat{w}_{j,k} = w_{j,k}$, which effectively solves the problem of constant deviation between the wavelet coefficient $\hat{w}_{j,k}$ and the true wavelet coefficient $w_{j,k}$ caused by the soft threshold function in the processing process. The asymptote characteristics of the improved function ensure that the signal can more accurately approximate the original signal during the reconstruction process, thereby improving the denoising effect and signal quality.

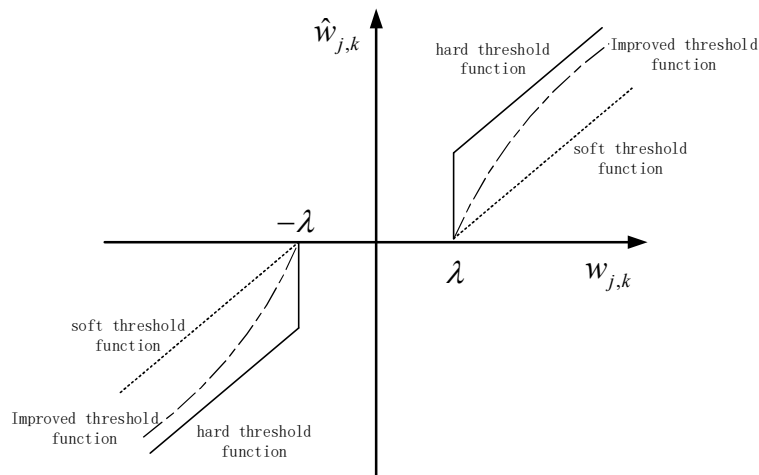


Fig. 2 Comparison of three threshold functions

As shown in Fig. 2, by introducing the adjustment parameter L , the improved threshold function successfully achieves continuity and effectively avoids the signal oscillation problem caused by discontinuity. At the same time, this function also alleviates the constant deviation between the wavelet coefficients and the true value, further improving the accuracy of signal reconstruction.

4. Vibration Signal Acquisition and Simulation Verification of CNC Machine Tools

Signal acquisition is the primary link of signal noise reduction. In this paper, the XK-7132 CNC machine tool is used to carry out experiments. The spindle vibration signal during the operation of the machine tool is monitored by a three-axis vibration sensor. The structure of the experimental system is shown in Fig. 3.

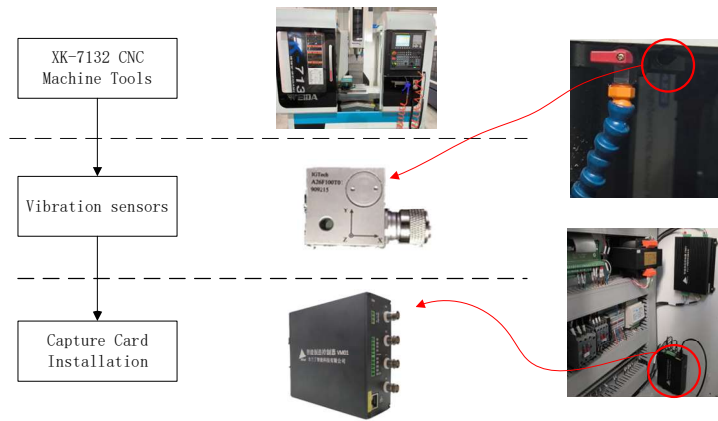


Fig. 3 Experimental system structure diagram

In order to further verify the effectiveness of the proposed method in the denoising method of the spindle vibration signal of CNC machine tools, the two evaluation indicators of signal-to-noise ratio (SNR) and root mean square error (RMSE) were analyzed. The signal-to-noise ratio value is in dB. The larger the signal-to-noise ratio value, the better the noise reduction effect, and the smaller the root mean square error, the better the noise reduction effect. The calculation formulas for SNR and RMSE are as follows:

$$SNR = 10 \log \frac{\sum_n d^2(n)}{\sum_n [d(n) - d'(n)]^2} \quad (9)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_n [d(n) - d'(n)]^2} \quad (10)$$

Where: $d(n)$ represents the original CNC machine tool spindle vibration signal; $d'(n)$ represents the spindle vibration signal after noise reduction.

In order to carry out the subsequent data denoising, the collected vibration signal is converted into CSV data format, and then the three methods of soft threshold function, hard threshold function and improved threshold are used to carry out denoising simulation experiments. In the simulation process, db4 is selected as the wavelet function, and the number of wavelet decomposition layers is set to 3 to ensure the consistency of experimental conditions. Next, under the premise of ensuring the same

threshold setting, the adjustment parameter L in the improved threshold function is set to 1. The experimental results are shown in Figs 4, 5, and 6.

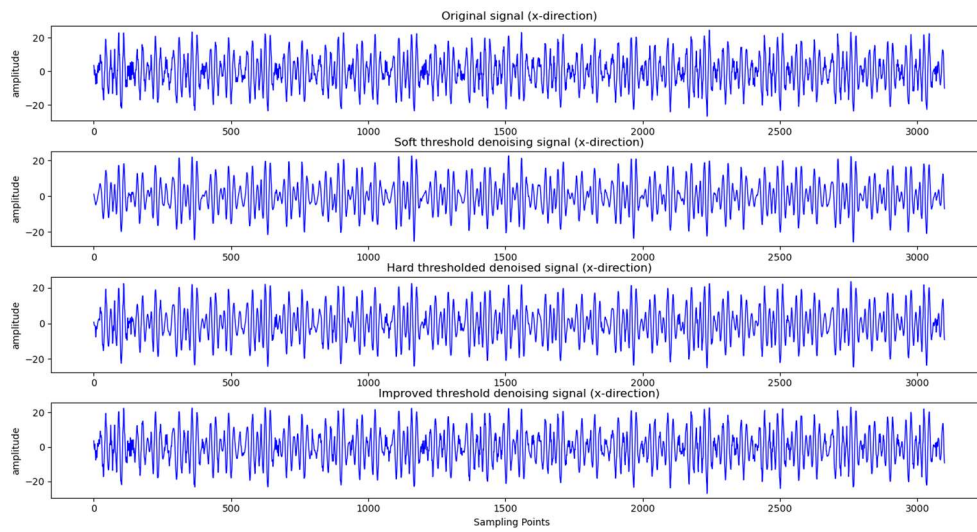


Fig. 4 Denoising of vibration signal in x direction

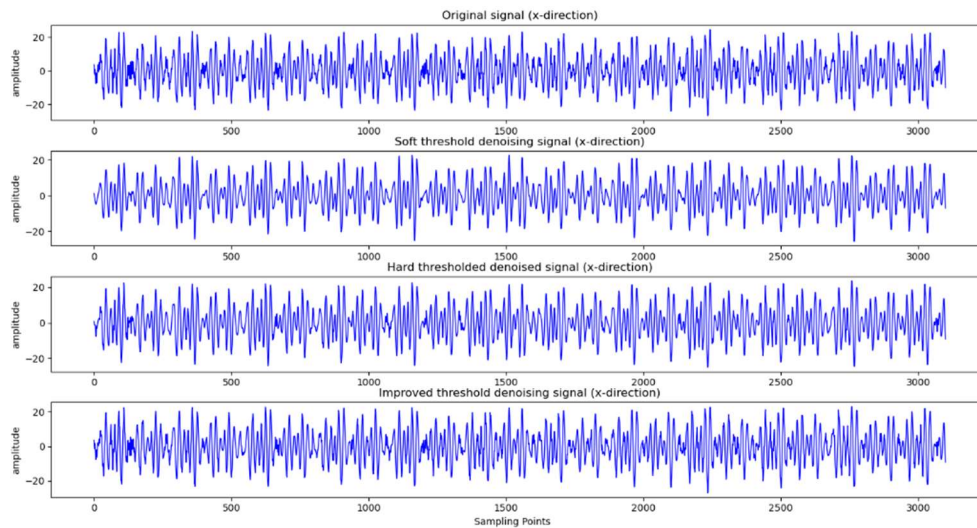


Fig. 5 Denoising of vibration signal in y direction

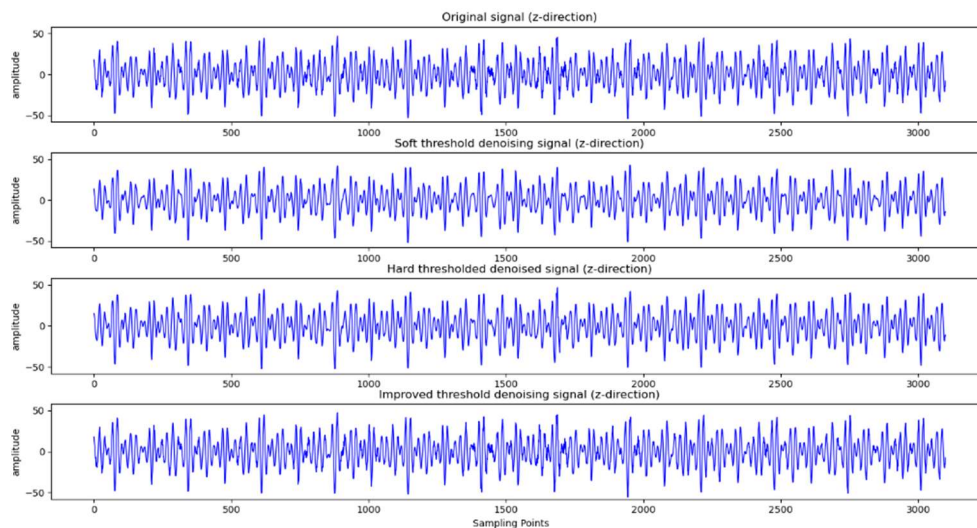


Fig. 6 Denoising of vibration signal in z direction

From the analysis of the experimental results in Figs 4, 5, and 6, it can be seen that there is noise in the original spindle vibration signal. Although the hard threshold and soft threshold denoising methods can filter out most of the noise, this method will inevitably lose some vibration features in the original signal. The improved threshold denoising method retains the vibration features of the original signal while filtering out most of the noise. Therefore, the improved threshold algorithm has better performance in vibration signal processing, can more effectively extract useful information from the signal, and suppress noise interference. Next, the effectiveness of the proposed method is verified by evaluating the denoising effect of each method, as shown in Table 1.

Table 1. Comparison of denoising effects of three methods

Vibration signals	SNR	RMSE
Hard threshold x-direction	15.2819	1.6191
Soft threshold x-direction	11.2961	2.3636
Improvement of threshold x-direction	19.9901	0.9507
Hard threshold y-direction	1.9818	2.6783
Soft threshold y-direction	1.7502	2.7173
Improvement of threshold y-direction	8.0402	1.5843
Hard threshold z-direction	17.2724	2.3494
Soft threshold z-direction	13.0012	3.5923
Improvement of threshold z-direction	25.3901	0.9301

From Table 1, we can find that the increase in SNR value and the decrease in RMSE value both point to a result: the denoised signal is closer to its original form, thus highlighting a better denoising effect. When the improved threshold is compared with the soft and hard thresholds in the denoising of the spindle vibration signal of the CNC machine tool, the denoising effect of the soft threshold is not as good as that of the hard threshold. However, compared with the hard threshold, the signal-to-noise ratio of the vibration signal in the three directions of the improved threshold is improved by 4.7082dB, 6.0584dB, and 8.1177dB, respectively, and the root mean square error is reduced by 0.6684, 1.094, and 1.3093, respectively. Therefore, the method of wavelet threshold denoising by improving the threshold function shows obvious superiority in noise reduction effect.

This paper combines the advantages and disadvantages of two typical wavelet threshold functions and some improved threshold functions to improve them in a targeted manner. The improved threshold function overcomes the problems of discontinuity and constant deviation of traditional thresholds. The vibration signal of the CNC machine tool spindle is denoised through simulation experiments. The simulation experiments and objective evaluation indicators show that under the same conditions, the improved threshold function is better than the traditional threshold function in denoising the vibration signal of the CNC machine tool spindle, thus providing a good foundation for the subsequent analysis of the vibration signal of the CNC machine tool spindle.

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