

# Vehicle Dynamic Testing Data Processing Using Wavelet Analysis

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**Abstract**— The vehicle dynamic test data usually have some noise which would bring serious negative effects. In order to accurately obtain vehicle dynamic response. The test data must be denoised using suitable signal denoising method. For this purpose, the basic principle of wavelet analysis is presented and the method of wavelet threshold denoising is used in automotive handling and stability test data processing. The denoising result shows that the wavelet denoising method is effective. And it provided a theoretical basis and practical engineering experience for vehicle handling and stability test data de-noising processing.

**Keywords**—vehicle; testing; wavelet analysis; denoising

## I. INTRODUCTION

The handling and stability performance is an important part of vehicle dynamic performance evaluation system. The accuracy of test data is very important to the dynamic performance evaluation. But in the process of vehicle handling and stability test, there are many interferential factors such as environmental factor, instrumental factor and artificial factor, these would bring much noise signals, so the test data has noise components. Dye noise signals bring negative effect to the performance evaluation, because the dye noise signals will bring error. When the dye noise condition is serious, the test must be renewed. So the scientific signal processing method can improve the reliability of test and reduce test cost.

Wavelet transform has many fine properties such as low entropy, multiresolution, decorrelation. It provide a new method for signal process field. In recent years, wavelet transform has been widely used in vibration and noise signal processing, mechanical signal detection, machinery fault diagnosis and other fields[1]. Hai Wang[2] used wavelet analysis to de-noise the vehicle wheel speed signals. Yifan Li[3] used wavelet denoising method to deal with the vehicle transmission vibration signals. Hou Tieshuang[4] used wavelet analysis in the ship-radiated noise signal processing. Many Researchers analyzed the wavelet denoising method with different threshold functions, noise estimation and the wavelet decomposition levels and so on[5,6].

## II. BASIC THEORY OF WAVELET DENOISING

Assuming  $\psi(t) \in L^2(R)$ , its fourier transform is  $\hat{\psi}(\omega)$ , when the  $\hat{\psi}(\omega)$  fit the admissible condition[7]:

$$C_\psi = \int_R \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \quad (1)$$

The  $\psi(t)$  is called wavelet base or mother wavelet. And the  $C_\psi$  is wavelet transform coefficient. The wavelet array as followed:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{t-b}{a}\right), a, b \in R; a \neq 0 \quad (2)$$

It could be deduced through stretch and translation transform, where  $a$  is stretch factor,  $b$  is translation factor. For the any function  $f(t) \in L^2(R)$ , its CWT (continuous wavelet transform) is followed:

$$W_f(a,b) = \langle f, \psi_{a,b} \rangle = |a|^{-\frac{1}{2}} \int_R f(t) \overline{\psi\left(\frac{t-b}{a}\right)} dt \quad (3)$$

And its reconstruction transform is given by:

$$f(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{a^2} W_f(a,b) \psi\left(\frac{t-b}{a}\right) da db \quad (4)$$

Because the realization of digital signals processing should depend on the computer, the CWT must be discretization. In the process of discretization,  $a$  is limited to positive value. Then the admissible condition is transformed as follows:

$$C_\psi = \int_0^{\infty} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \quad (5)$$

In discretization process, stretch factor  $a$  and translation factor  $b$  usually be given by  $a = a_0^j$ ,  $b = ka_0^j b_0$ , where  $j \in Z$ ,  $a_0 \neq 1$ , and  $a_0$  is a fixed value. So the corresponding DWT(discrete wavelet transform)  $\psi_{j,k}(t)$  can be writing:

$$\psi_{j,k}(t) = a_0^{-\frac{j}{2}} \psi\left(\frac{t - ka_0^j b_0}{a_0^j}\right) = a_0^{-\frac{j}{2}} \psi(a_0^{-j} t - kb_0) \quad (6)$$

Discretization wavelet coefficient is given by:

$$C_{j,k} = \int_{-\infty}^{\infty} f(t) \psi_{j,k}^*(t) dt = \langle f, \psi_{j,k} \rangle \quad (7)$$

So the reconstruction formula of the DWT is followed:

$$f(t) = C \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} C_{j,k} \psi_{j,k}(t) \quad (8)$$

Where C is a constant which is irrelevant with the signals.

#### A. Wavelet Decomposition And Reconstruction

The wavelet decomposition fast algorithm is presented by Mallat. It decompose the original signal to low frequency components which describe the approximate shape of original signal and high frequency components which describe the detail informations of original signal[8].

According to the Mallat algorithm, assuming  $f(n), (n = 1, 2, \dots, N)$  is the discrete sampling sequence of the signal  $f(t) \in L^2(R)$ , if regard  $f(n)$  as an approximate value when stretch factor  $j = 0$  The fast orthogonal wavelet transform as follows:

$$\begin{cases} a_{j+1}(n) = \sum_{k \in \mathbb{Z}} h(k - 2n) a_j(k) \\ d_{j+1}(n) = \sum_{k \in \mathbb{Z}} g(k - 2n) d_j(k) \end{cases} \quad (9)$$

Where  $\{h_k\}_{k \in \mathbb{Z}} \in L^2(\mathbb{Z})$  and  $\{g_k\}_{k \in \mathbb{Z}} \in L^2(\mathbb{Z})$  are coefficients of orthogonal conjugate filter determined by wavelet function  $\psi(t)$ ;  $g(k) = (-1)^{1-k} h(1-k)$ .  $a_j$  is the approximate coefficient; and  $d_j$  is the detail coefficient at the level j. So the wavelet decomposition principle as figure 1 shows, signal  $f(t)$  can be decomposed as followed:

$$f(t) = A_J + \sum_{j \leq J} D_j \quad (10)$$

In which  $A_J$  is approximate coefficient at level J, and  $D_j$  is detail coefficient at level J.

#### B. Basic Denosing Model

Assuming  $f(n)$  is original signal and  $s(n)$  is dye noise signal, so the basic noise model can be expressed as :

$$s(n) = f(n) + e(n) \quad (11)$$

Where  $e(n)$  is noise. The aim of wavelet transform is to decompose signal  $s(n)$  to different frequency range, then the main frequency range which is contaminated by noise is processed with threshold processing. It means that noise  $e(n)$  is restrained and eliminated by threshold process. So we can get the  $\hat{f}(n)$  which is the best approximation of  $f(n)$

### III. THRESHOLD SELECTION

In the process of wavelet threshold denoising method, threshold selection is a critical part which is direct affect the quality of signal denoising. We used the visushrink principle. And the visushrink threshold principle is also called general threshold presented by Donoho and Johostone. And it is concluded in the condition that aim at multidimensional independent normal variable joint distribution when dimension tending to infinite

$$t = \sigma \sqrt{2 \ln N} \quad (12)$$

Where  $\sigma$  is the variance of noise signal. N is the length of signal. We can see from formula (11). Threshold value and logarithm square root of singal length are in direct proportion. When the length of signal is longer, the threshold value is bigger, so the threshold value tend to put all wavelet coefficient to be zero.

In the process of wavelet threshold denoising, threshold function express the different process strategies and estimation method to the wavelet coefficients.

Hard threshold function:

$$\hat{W}(j,n) = \begin{cases} 0 & |W(j,n)| < T \\ W(j,n) & \text{otherwise} \end{cases} \quad (13)$$

Soft threshold function:

$$\hat{W}(j,n) = \begin{cases} 0 & |W(j,n)| < T \\ W(j,n) - T \cdot \text{sgn}(W(j,n)) & \text{otherwise} \end{cases} \quad (14)$$

Where  $w(j,n)$  is wavelet coefficient of original signal,  $\hat{w}(j,n)$  is estimation value of wavelet coefficient, T is threshold,  $\text{sgn}(\cdot)$  is sign function.

#### A. Denoising Effect Assess Criterion

Usually, SNR is used for assess criterion in the process of signal denoising. SNR is higher, then the effect of denoising is better. The formula of SNR as follow:

$$SNR = 20 \ln \frac{\sum_{n=1}^N f^2(n)}{\sum_{n=1}^N e^2(n)} \quad (15)$$

Where n is the number of each sample point, N is the total of signal sample points,  $f(n)$  is original signal,  $e(n)$  is noise signal.

### IV. VEHICLE HANDLING AND STABILITY TEST

We proceeded vehicle handling and stability tests according to the national standard of handling and stability test, taking slalom test as a example explains the procedure of test and data processing.

The test object is a commercial vehicle. The suspension, steering system, tires and loading were adjusted correspond with the standard before road tests. The test ground is proving ground which is strictly correspond with all requirements in the national test standard.



Figure 1. GYROSCOPE AND INSTALL LOCATION

Test condition: the vehicle moves with the speed of 65km/h along the path of the slalom drawn on the ground, when the vehicle in the test area, the steering wheel angle, steering wheel torque, lateral acceleration and yaw rate are going to be recorded. The vehicle moving one circle of slalom route means one time test. In the process of the test data record, driver should keep the vehicle speed stable, rotating steering wheel steady in the test process, and do not allow the vehicle to knock down any stake.

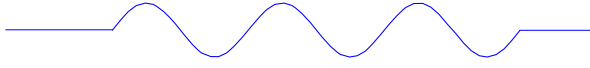


Figure 2. SLALOM TEST PATH

#### V. VEHICLE TEST DATA DENOISING PROCESSING

Usually, the measurement signal of angle rate and lateral acceleration have strong noise component (as blue curve shown in figure4), so it need to remove the noise component before vehicle performance evaluation. According to practical engineering experience, the best level of wavelet decomposition for signal denoising is five. So we selected level five. And we dealt with the test data using wavelet base db3, which is used in wavelet threshold denoising commonly. The result as shown in figure 5 and figure 7.

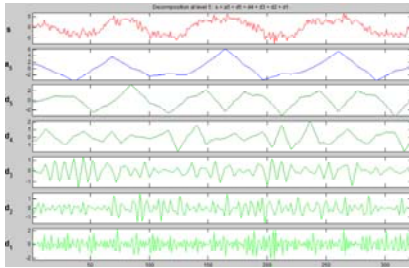


Figure 3. YAW ANGLE RATE SIGNAL DENOISING USING LEVEL 5, DB3 BASE WAVELET DECOMPOSITION AND DENOISING

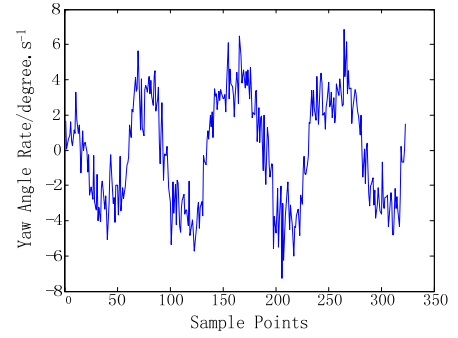


Figure 4. YAW ANGLE RATE DATAS MEASURED BY GYROSCOPE

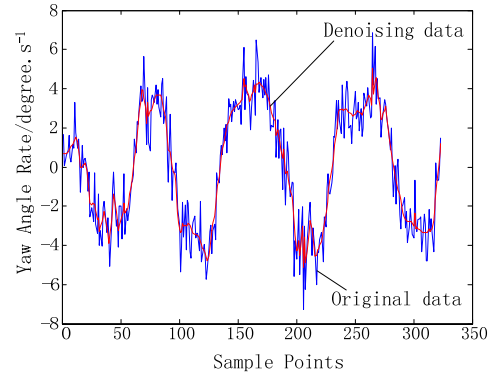


Figure 5. ORIGINAL YAW ANGLE RATE DATA AND DENOISING DATA

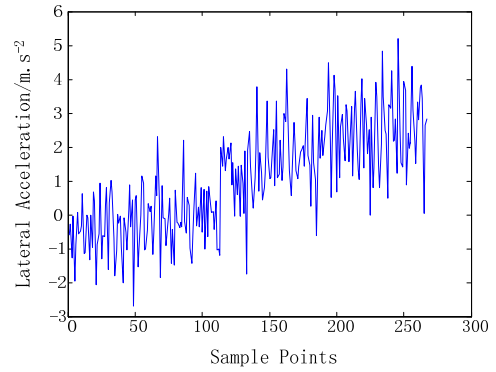


Figure 6. LATERAL ACCELERATION DATAS MEASURED BY GYROSCOPE

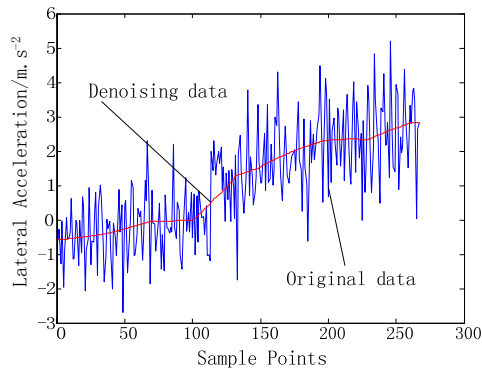


Figure 7. ORIGINAL LATERAL ACCELERATION DATA AND DENOISING DATA

According to function (15), we calculated the SNR of the denoising signals. The results show that SNR of yaw angle rate is 12.5247 and SNR of lateral acceleration is 11.9562.

## VI. CONCLUSION

Using wavelet denoising method can remove the noisy component of vehicle dynamic test data. And the SNR through wavelet denoising processing is higher, so the value of vehicle response is more credible.

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