

# Research of Penetration Overload Signals Processing Method Based on EEMD and WT

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**Abstract.** Hard Target Penetration is a very complex dynamic problem, and penetration signals contain axial de-acceleration signals, vibration signals and other weakly noise signals. It is difficult to obtain penetration feature signals through some methods filtering unwanted vibration signals and noise signals. As such, we propose a joint filtering method based on EEMD (Ensemble Empirical Mode Decomposition) and WT (Wavelet Transform) to solve this problem. This method consists of four main steps: (a) penetration signals decomposing via EEMD method, this gets the IMF (Intrinsic Mode Function) components, (b) then we calculate the Whole BURG power spectrum of the original signals and each component, after that compare the power spectrum of each component with the original signals, this draws the original signals EEMD decomposition scale, (c) the high-frequency components of IMF filtering based on the WT threshold, (d) signals reconstruct by using low-frequency IMF components which reflect signals characteristic and high-frequency IMF components through wavelet filtered. Experiment show that proposed method can effectively determine the penetration signals decomposition scale, eliminate vibration and noise signals of penetration process, avoid the losing of the high-frequency components when using a single wavelet filtering method. The result of the proposed method can get better SNR than WT, the velocity and depth are in good agreement with the results of experiment.

## 1. INTRODUCTION

Recently, hard target penetration overload signals processing has become increasingly important in national defense research. Projectile important parameters (such as the penetration depth, time, layers of medium, etc.) in the process of penetration could be obtained through analysis of measured overload signals. And projectile parameters provide an important basis for the design of projectile structural strength, explosive stability and fuse reliability [1]. When penetration occurring, the overload signals generally contain two major components: one is the de-acceleration signal that has been formed by encountered resistance in the process of penetrate the target medium, this signal spreads in the manner of tress wave; Another is vibration signal in the process of penetration, which included projectile horizontal and vertical vibration[2]. The key of penetration signal processing is find that the right filtering cut-off frequency, then remove the vibration signal during penetration process (including projectile horizontal and vertical vibration signal), weakly interference signal, finally reserve de-acceleration signal that reacts projectile penetrating resistance.

At present, domestic and foreign scholars have carried out many studies about penetration signals processing technology. For example, American Sandia Laboratories had finished 3KHZ frequency filtering wave of the measured data in the 1990s[3]. Domestic Nanjing University of Science and Technology measured acceleration curve and made an analysis comparison of 3KHZ and 10KHZ filtering wave in the early 2000[4].

Beijing Institute of Space Long aircraft applied the first-order cut off frequency filtered wave. These all three methods are hardware threshold filtering. Those characteristics are given based on specific conditions of a fixed frequency threshold. When the frequency-domain transform is greater than the threshold value, the original value has been retained, otherwise has been set to zero. This filtering method is a single threshold function processing, and has a general de-noising effect. With the development of signal theory, Donoho et al. proposed wavelet threshold de-noising method [5]. Many people started this extensive research [6]. This method decomposes of the signals by selecting the appropriate wavelet, and filters noise from high-frequency component after wavelet decomposition by using reasonable threshold function, then gets the de-noising signals by wavelet reconstruction. Wavelet can better analyze the details and characteristics of the signals than traditional methods, and can remove Gaussian noise, get good SNR. Currently, wavelet decomposition de-noising method based on different thresholds also been applied to the field of penetration acceleration signal processing. However, the choice of wavelet and threshold function needs further analysis in actual signals processing. EEMD is a signal decomposition method which pluses auxiliary noise on the basis of the Empirical Mode Decomposition. And it solves the model mixing problem when signals adopt EMD decomposition method in the complex and abnormal noise environment. This method has certain advantages for the complex noise signal's separation and processing.

We propose a joint filtering method based on EEMD and WT for the non-stationary random vibration

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acceleration signals in the hard target penetration processing.

## 2. EEMD and penetration acceleration signals analysis

### 2.1 EEMD Principle

Empirical Mode Decomposition has been proposed as an adaptive time-frequency data analysis method by Huang et al. of National Aeronautics and Space Administration (NASA) in 1998 . It has been proved quite versatile in extracting useful signal from these non-stationary and non-linear signals .

The essence of EMD is obtained intrinsic mode functions (IMF) by using time scale characteristic of signals. The procedure of extracting an IMF is called sifting. The sifting process is as follows:

- 1) Identify all the local extrema in the original data  $S(t)$ .
- 2) Connect all the local maxima by a cubic spline line as the upper envelope.
- 3) Repeat the procedure for the local minima to produce the lower envelope.

The upper and lower envelopes should cover all the data between them. Their mean is  $M_1$ . The difference between the data and  $M_1$  is the first component  $H_1$ :

$$S(t) - M_1 = H_1 \quad (1-1)$$

Ideally,  $H_1$  should satisfy the definition of an IMF, for the construction of  $H_1$  described above should have made it symmetric and having all maxima positive and all minima negative. After the first round of sifting, a crest may become a local maximum. New extreme point generated in this way actually reveals the proper modes lost in the initial examination. In the subsequent sifting process,  $H_1$  can only be treated as a proto-IMF. In the next step, it is treated as the data, then

$$H_1 - M_{1l} = H_{1l} \quad (1-2)$$

After repeated sifting up to  $k$  times,  $H_1$  becomes an IMF, that is

$$H_{1(k-1)} - M_{1k} = H_{1k} \quad (1-3)$$

Then, it is designated as the first IMF component from the data:

$$C_1 = H_{1k} \quad (1-4)$$

Overall,  $C_1$  should contain the finest scale or the shortest period component of the signal. We can, then, separate  $C_1$  from the rest of the data by

$$R_1 = X(t) - C_1 \quad (1-5)$$

Since the residue,  $R_1$ , still contains longer period variations in the data, it is treated as the new data and subjected to the same sifting process as described above. This procedure can be repeated to all the subsequent and

several indecomposable IMF  $C_i$  can be obtained until  $C_n$ .

From the above equations, we can induce that the original signal sequence as:

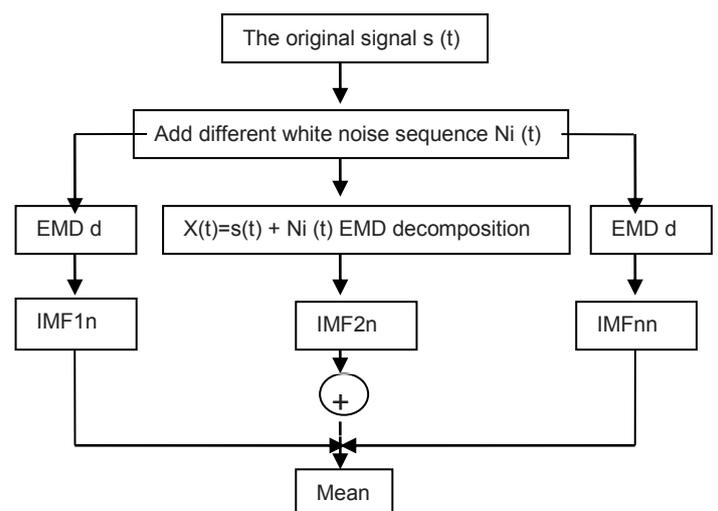
$$S(t) = C_1 + C_2 + \dots + C_i + \dots + C_n + R_n \quad (1-6)$$

$C_i$  represents the first  $i$  intrinsic mode function;  $R_n$  becomes a monotonic function from which no more IMF can be extracted.

In the above method, obtaining reasonable IMF component depends on the distribution of signal extreme points. If the signal extreme points are uneven in distribution, the case of mode mixing will appear. Huang proposed EEMD method through adding white Gaussian noise on the basis of EMD. The decomposition process is similar. The only difference is that  $N$  different sets Gaussian white noise is added to the original signal before EMD decomposition , and form a new whole signal sequence  $S_1(t), S_2(t), \dots, S_n(t)$ . Then different scales intrinsic mode functions  $IMF_{i1}, IMF_{i2}, \dots, IMF_{in}$  has been got by decomposing the new signal sequence  $S_1(t), S_2(t), \dots, S_n(t)$ . Finally, the whole signal's  $IMF_1, IMF_2, \dots, IMF_n$  has been obtained after meaning of results of decomposition. Noise will be inter-neutralization because of added noise has zero mean characteristics [14].

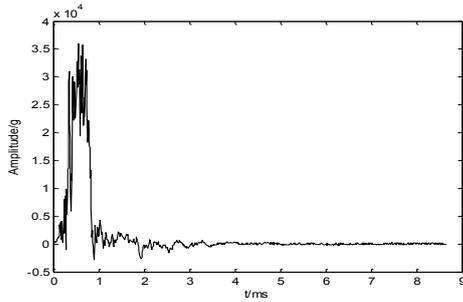
### 2.2 EEMD decomposition of Penetration acceleration signal

EEMD can resolve the mode mixing problem which happening in using EMD method to decompose signals. EEMD can clearly decompose the natural frequency of the penetration signals. The decomposition process show in Figure 1:



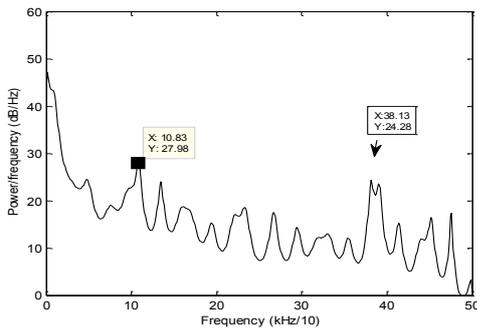
**Fig1.** EEMD decomposition process of penetration signals

Penetration acceleration signals curve has been obtained when 100mm diameter projectile penetrates unlimited concrete target, which is shown in Figure 2.

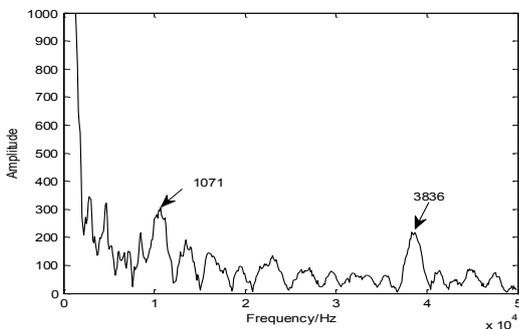


**Fig2.** Penetration acceleration signals curve

The Whole BURG Power Spectrum has been calculated before signal decomposition by using EEMD. The result is shown in Figure 3. We know the whole signal energy concentrated in the vicinity of the frequency 1083Hz and 3813Hz from Figure. Then projectile energy gradually decline with increasing of penetrate target's depth, and finally drop to zero. And this result are very similar with the signal frequency domain analysis in Figure 4, the main frequency is 1071Hz and 3836Hz, 1071Hz is the first-order natural frequency of projectile that reflects corresponding intrinsic vibration frequency of penetration process, 3836Hz may be the two or multiple harmonic frequency of projectile.

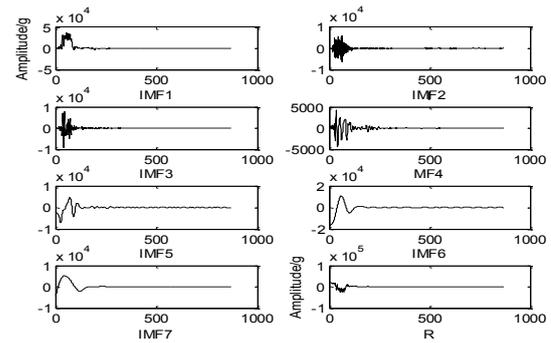


**Fig3.** The Whole BURG Power Spectral of Penetration acceleration signals



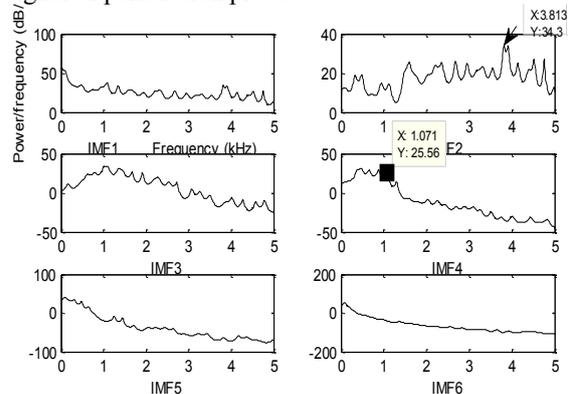
**Fig4.** Frequency analysis of Penetration acceleration signals

In order to remove the noise signal from acceleration curve of penetration process, we decompose penetration signals according to the above EEMD decomposition process after calculating of whole projectile energy. The  $IMF_i$  components and the rest of the data R have been got after EEMD decomposition, and it is show in Figure 5.



**Fig5.** IMF components of penetration signal after EEMD decomposition

We can find  $IMF_1$ ,  $IMF_2$ ,  $IMF_3$  has small amplitude and high frequency feature from Figure 5. These characteristics reflect the high-frequency components in the penetration process, which represent horizontal and vertical vibration signals of the projectile and high-frequency vibration signals causing by accelerometers and external factors. If continue to decompose signals, we discover  $IMF_4$  and  $IMF_5$  component is boundary of the high frequency and low frequency, and  $IMF_6$  and  $IMF_7$  component is completely similar, which shows signals don't need to continually decompose after the 6-order decomposition. At this time the measured signals have reached the trend term. But what order is the optimal decomposition order that need to further analysis. Paper presents to calculate the decomposed BURG Power Spectrum of each order IMF method to analysis. From Figure 6, we find  $IMF_4$  Power Spectrum is very similar with the previous obtained Whole Signal Power Spectrum. The energy of  $IMF_4$  Power Spectrum concentrated at the 1083Hz, and the energy of  $IMF_2$  Power Spectrum concentrated at the 3871Hz, then the energy began to decline sharply after  $IMF_4$  component. Furthermore, the second harmonic response or multiple harmonic response frequency—3813Hz high frequency has been decomposed after EEMD the fourth-order decomposition, that is to say the fourth-order decomposition has separated the high-frequency vibration signals which generate in the penetration process. So we can draw a conclusion that  $IMF_4$  is the optimal EEMD decomposition, which reflects the response acceleration signal of penetration process.



**Fig6.** The BURG Power Spectral of each IMF component

### 3 Wavelet Multi-resolution Analysis and Penetration acceleration signal filtering

#### 3.1 Wavelet Analysis

Morel proposed wavelet analysis when he was analyzing the local characteristics of seismic wave in 1984. The wavelet analysis is different with traditional Fourier transform. With the development of the various wavelet basis and proposal of the multi-resolution thinking, the wavelet analysis is widely used for non-stationary signal analysis and filtering processing because of good localization features in the time-frequency domain.

It is defined as: function  $\psi(t) \in L^2(R)$ , its Fourier transform is  $\hat{\psi}(w)$ . Meet the following local conditions:

$$C_{\psi} = \int_{-\infty}^{\infty} \frac{|\hat{\psi}(w)|^2}{|w|} dw < \infty \quad (1-7)$$

That is  $C_{\psi}$  bounded,  $\psi(t)$  has been called a basic wavelet or mother wavelet. Scaling and shifting the mother wavelet function, a as its stretching factor, b as shift factor, translation function  $\psi_{a,b}(t)$  has been got after stretching and shifting:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \quad a, b \in R \quad a \neq 0 \quad (1-8)$$

So  $\psi_{a,b}(t)$  has been called associated wavelet basis function with parameters a and b. Due to continuous transformational values of a and b, it is also called continuous wavelet basis function. These series functions were got through the same mother function after scaling and translating.

When the analytical signal  $f(t) \in L^2(R)$ , Wavelet transform is it's expand on this wavelet function, marked:

$$WT_f(a,b) = \langle f, \psi_{a,b} \rangle = \frac{1}{\sqrt{|a|}} \int_R f(t) \cdot \overline{\psi\left(\frac{t-b}{a}\right)} dt \quad (1-9)$$

As such, a time function can be projected onto 2-Dimensional time-scales plane, and the same time the local characteristics of the signal were obtained in the time-frequency domains.

#### 3.1 Multi-resolution Analysis

MRA (Multi-resolution Analysis) is an effective analytical method which had been proposed by Mallet and Meyer on the constructing wavelet basis in 1986. The main idea is that use different time resolution to approximate the analyzed signal f (t) after continuous signal are disserted. This approach decomposes the signal step by step on the orthogonal space of  $L^2(R)$ . Each level of the input signal can decompose into two parts: the high frequency detail signals and the low frequency approximation signals. Sample frequency halves step by step. If the frequency space of signal f (t) is  $A_0$  which was decomposed into two sub-spaces in the first stage: low frequency  $A_1$  and high frequency  $D_1$ .  $A_1$  will

continue to break down into low frequency  $A_2$  and high frequency  $D_2$ . This decomposition process continues until no useful information could decompose. Its decomposition process can be noted as:

$$A_0 = A_1 + D_1; A_1 = A_2 + D_2; A_{i-1} = A_i + D_i \quad (1-10)$$

$\oplus$  represents two sub-spaces "orthogonal sum",  $A_i$  represents multi-resolution analysis sub-space corresponding to the resolution  $2^{-j}$ . This result indicates that the signal f (t) could be infinitely approximated by  $2^{-j}$  multi-resolution analysis. Signal f (t) can be expressed as:

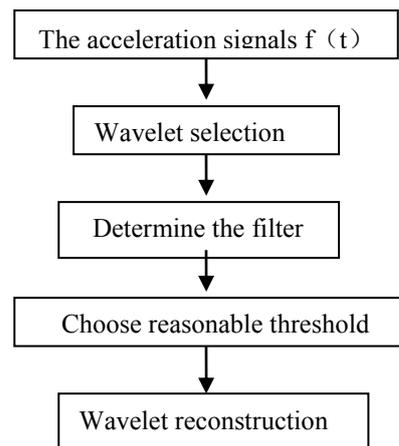
$$F(t) = A_0(f) = A_1(f) + D_1(f) = A_2(f) + D_1(f) + D_2(f) = \dots \quad (1-11)$$

#### 3.2 Penetration acceleration signals Wavelet analysis

Wavelet analysis of signals are also widely used in recent years, We summarized wavelet decomposing of penetration acceleration signals in the following three steps:

- 1) The penetration acceleration signals wavelet decomposition. Select the appropriate wavelet and determine the layers N of filtering, then the signal N layers wavelet decomposition;
- 2) The high-frequency signals of wavelet decomposition filtering noise. Choose reasonable threshold filtering High-frequency coefficients of each layer from 1 to layer N;
- 3) The signal reconstructing. The signals wavelet reconstructs according to the low-frequency coefficients N-layer of wavelet decomposition and high-frequency coefficients from 1 to N after filtering.

The WT process of penetration acceleration signals is following figure 7.



**Fig7.** Wavelet de-noising process

The main factors that determine the filtering effects to penetration acceleration signals wavelet analysis are:

- 1) Wavelet Type. Because different type of wavelet have different result of the decomposition, So paper decomposes signal by selecting the Daubechies II wavelet as mother wavelet due to penetration overload signals characteristics and previous experience.

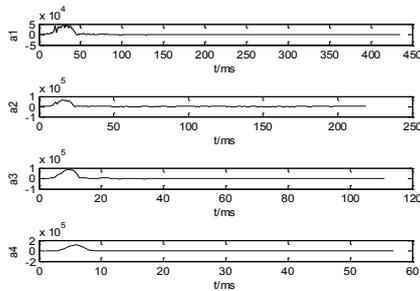
Daubechies II wavelet has the following characteristics: Proximity with penetration measured characteristic curve, compactness, orthogonality etc. The main components of the measured signal can be obtained by Daubechies II wavelet decomposition;

2) Wavelet decomposition layers. How many layers have been decomposed which depends on the low-frequency signal could not appear obvious peak extinction phenomenon after WT decomposition. Paper decomposes the penetration acceleration signals by using Daubechies II wavelet, and finds 3 layers of decomposition is better than others. “Daubechies II wavelet decomposition coefficients” is following diagram 8.

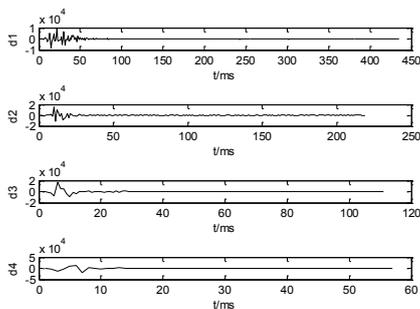
3) The choice of threshold function. Different threshold function determines the different filtering effect of the high-frequency coefficients of wavelet decomposition, and also determines the effect of the reconstruction signal after signal filtering. Paper uses two different threshold methods filtering: One is high-frequency coefficients compulsory de-noising, and this method can obtain relatively smooth curve, but it filters out the useful components of signals; Another method is default threshold de-noising, which retains some of the high-frequency vibration signals and has the better details of the signal and SNR than compulsory de-noising. Different filtering result has been shown in figure8, SNR value is following table 1.

**Table1.** SNR of two filtering methods

filtering methods	Compulsory de-noising	Default threshold de-noising
SNR	29.69	45.28

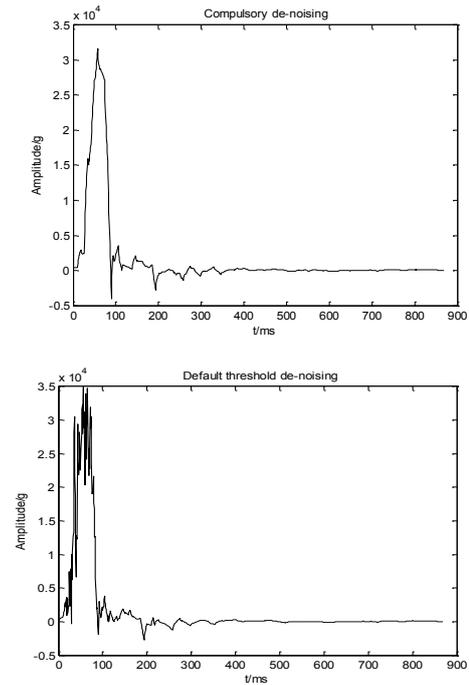


a. Low-frequency coefficients



b. High-frequency coefficients

**Fig8.**Coefficients of the db2 wavelet decomposition



**Fig9.** Different threshold Wavelet de-nosing

Although WT filtering has been widely used in penetration signals process, but there are two difficulties.

1) The choice of Wavelet has not strictly theoretical foundation. Many Wavelets has been choice depending on continuous experiments and previous experience. It brings a lot of work of signals filtering and don't obtains the optimal result.

2) Wavelet decomposition layers depends on the low-frequency signals could not appear obvious peak extinction phenomenon after WT decomposition. This conclusion always been drawn by direct observation, there is no strict criteria, which may bring bias of decomposition levels.

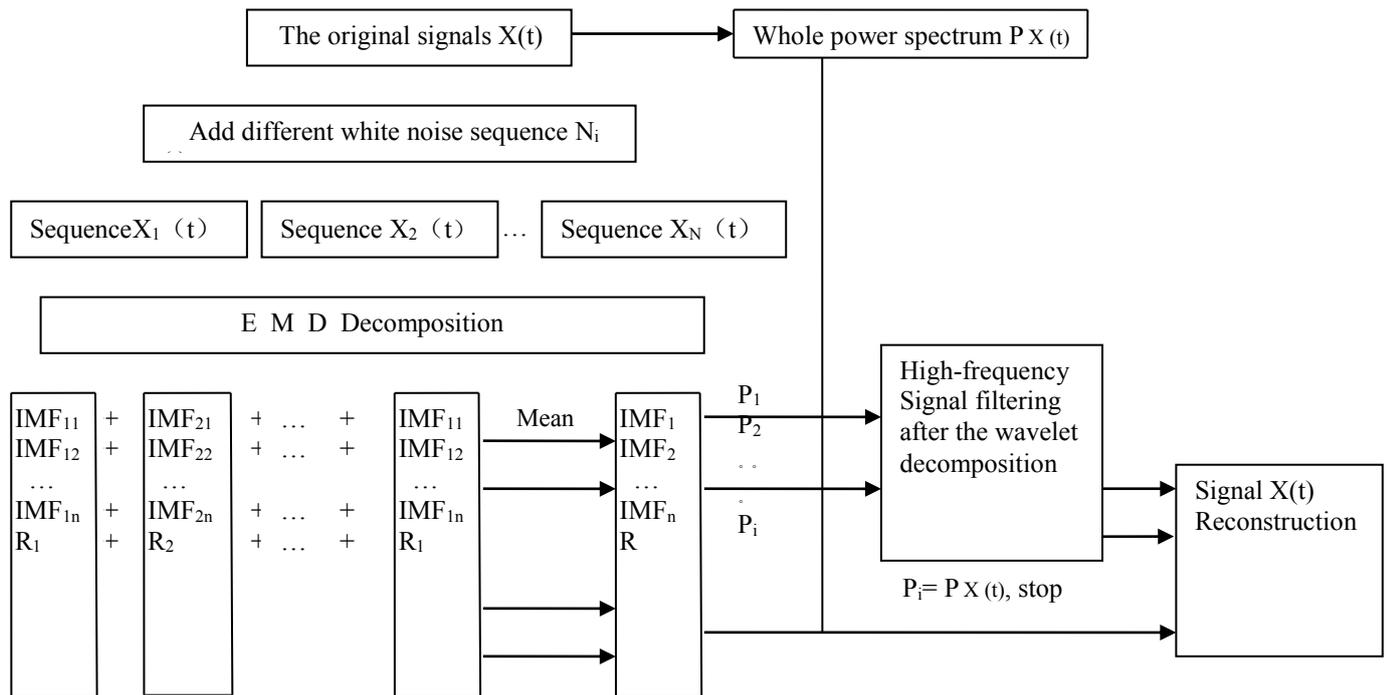
Based on the above advantages and disadvantages of EEMD and WT, we propose a joint filtering method based on EEMD and WT to analysis complex penetration acceleration signals.

#### 4 EEMD and WT joint filtering analysis

##### 4.1 Filtering method and process

Firstly, the penetration acceleration signals have been decomposed by using EEMD method. This gets the series IMF components, and calculates the power spectrum of each component. Secondly, then we compares the BURG Power Spectrum between original signals and IMF components, obtains decomposition scale of original signals, and distinguish the high and low frequency boundaries of signals decomposition. At same time the natural frequency of the projectile overload bodies can be precisely drawn in this process. And next we filter projectile vibration and environmental noises from high-frequency components of IMF by using the different Wavelet (WT) threshold. Finally, we reconstruct the signal by using low-frequency IMF components which reflect signal characteristic and high-frequency IMF components which have been filtered by

wavelet. The process of EEMD and WT joint filtering analysis has been shown in figure 10.



**Fig10.** EEMD and WT joint filtering process

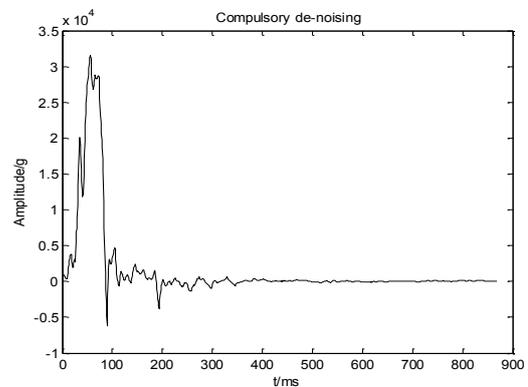
### 4.2. Experiment

We can draw a conclusion that the optimal decomposition scale is 4 levels by comparing the BURG Power Spectrum between original signals and decomposed IMF components, because IMF<sub>4</sub> Power Spectrum is similar with original signal whole power spectrum. Peak value of power spectrum reflects the first order nature frequency of projectile in the penetration process. Then we filters high-frequency component from IMF<sub>1</sub>, IMF<sub>2</sub> and IMF<sub>3</sub> by using Daubechies II wavelet. Finally, signal has been reconstructed by using low-frequency IMF<sub>4</sub> component which reflects the signal characteristic and high-frequency IMF<sub>1</sub>, IMF<sub>2</sub> and IMF<sub>3</sub> components after wavelet filtering. And we get the desired signal through EEMD and WT joint filtering. The result is show in figure11.

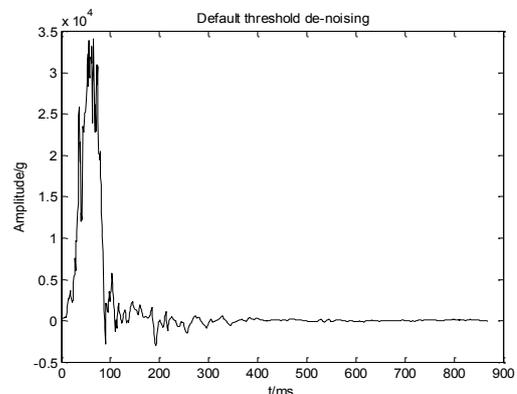
Figure a) shows that the signal has been reconstructed by using wavelet compulsory de-noising method after EEMD decomposed high-frequency. Figure b) shows that the signal has been reconstructed by using wavelet default threshold de-noising after EEMD decomposed high-frequency. SNR values of the two methods are shown in Table 2.

Table2. SNR of two WT filtering methods after EEMD decomposition

filtering methods	Compulsory de-noising	Default threshold de-noising
SNR	31.13	54.79



a. Compulsory de-noising



b. Default threshold de-noising

**Fig11.** EEMD and WT joint filtering signal

Table 2 shows the paper proposed method has better de-noising capability than single wavelet filtering method. Further comparing the signal curves a and b, we find signal curve a is more smooth than curves b. This is because signal curve a filter noise by using compulsory de-noising method, and the method filter out part of the signal which reacts projectile characteristic in penetration process. Signal curve b maintains projectile vibration detail, and has better SNR than signal curve a.

In order to further verify the correctness of the paper propose signal processing method, the Velocity-time curve and Displacement-time curve of projectile penetration process have been got by integrating the acceleration signals b after EEMD and WT joint filtering, and they are shown in Figure12 and Figure13. These indicated that the striking velocity was 424.2m/s and the displacement during the penetration was 1.003 m. Table 3 summarized the results of the paper proposed method and experiment results, and it indicated that the experimental results were in good agreement with results of paper proposed method .

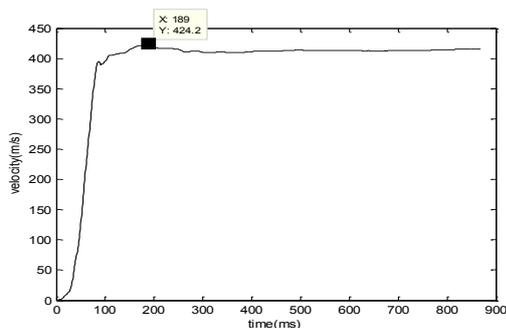


Fig12.Velocity -time curve of projectile penetration process

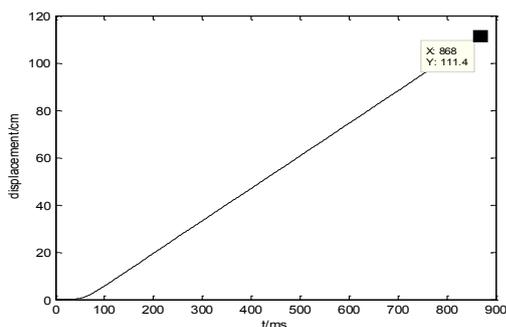


Fig13. Displacement-time curve of projectile penetration process

Table3. The results of the paper proposed method and experiment results

Result	Striking velocity (m/s)	Residual velocity (m/s)	Displacement of penetration (m)
Experiment	478	0	1.005
Proposed method	424.2	0	1.114

## 5 Conclusion

Through comprising the result of different filtering analysis methods that paper proposes that EEMD and WT joint filtering analysis is better than others. The advantages mainly reflect in four aspects:

1) The penetration signals decomposition scale is easy determined through comprising of the BURG power spectrum between the whole signals and IMF components after EEMD decomposition. It solves the problem that wavelet decomposition scale is not easy to determine. And the same time projectile vibration natural frequency could be obtained.

2) This method can eliminate mixed projectile vibration noise and void the loss of itself high-frequency components in the penetration process.

3) High SNR.

4) Penetration velocity and depth are in good agreement with results of experiment.

Overall, paper provides a better filtering method for the research of typical non-stationary random vibration signals filtering processing, and has certain significant guide for high-g penetration signals filtering. However, more detailed analysis of the penetration process and the environments are need to known because some penetration process is relatively complex.

## Acknowledgment

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