Overpressure test and analysis of muzzle blast wave

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Abstract. One of the main evaluation methods of damage effectiveness for weapon system is gathering muzzle shock wave signals through an overpressure test system of shock waves at first, then processing and analyzing acquired data. The evaluation performance depends on the appropriateness of signal processing. This paper proposes a method based on the multi-resolution characteristics of wavelet analysis to denoise the muzzle shock wave signal aimed at the characteristics of wide frequency band, sudden change and short duration of the shock wave signal, which not only filters the impurity signal effectively, but also reduces time delay. Then, according to the different locations of the sensors, overpressure peaks of every de-noising signal are obtained. The shock wave field is modeled by the interpolation methods with those overpressure peaks data. Finally, errors analysis of shock wave field model has been accomplished.

1. Introduction

When the gun launches a projectile and the projectile flies out, muzzle blast wave is formed when the propellant gas of high temperature and high pressure swells up at the muzzle. The muzzle blast wave is likely a serious hazard to the facilities, equipment and personnel around. Thus, the militaries in the world have developed appropriate standards of safety and protection. And the overpressure peak of muzzle shock wave is an important basic parameter which is one of the most important index of weapons damage assessment. The signal of muzzle shock wave results that the classical Fourier transformation cannot determine the change from the signal of frequency spectrum when the muzzle shock wave's signal in the time domain has a sudden change in some moments. That is unable to reflect the time of signal characteristics[1]. And wavelet transform has good local features in both time domain and frequency domain. It provides convenience for transient signal of follow-up analysis[2]. So in this paper,a signal processing method is selected based on wavelet transformation and analyzing the data collected by overpressure testing system. According to the processing data, each sensor's overpressure peak is gotten, and according to sensor's location, using interpolation method to describe the shock wave field. Then show the rule of changes of shock wave and the propagation rule of the signal of shock wave[3]. Finally, through the analysis of error, the effect of interpolation error of different position sensors has been studied.

2. The Composition of Shock Testing System

The test system consists of two parts. The hardware system consists of sensors, data acquisition and signal conditioning. The function of the software part is mainly composed of LabVIEW software of the NI Company and Matlab software. Through acquiring the external shock wave pressure, sensors change the pressure signal into voltage signal. Filtered and amplified by the signal conditioning circuit, the voltage signal is stored in the Data Acquisition Card, and then the voltage signal has been converted into a digital signal by A/D converter. The host computer reads in the data from the data acquisition card through the program. Fig. 1 is the tested system diagram[4].

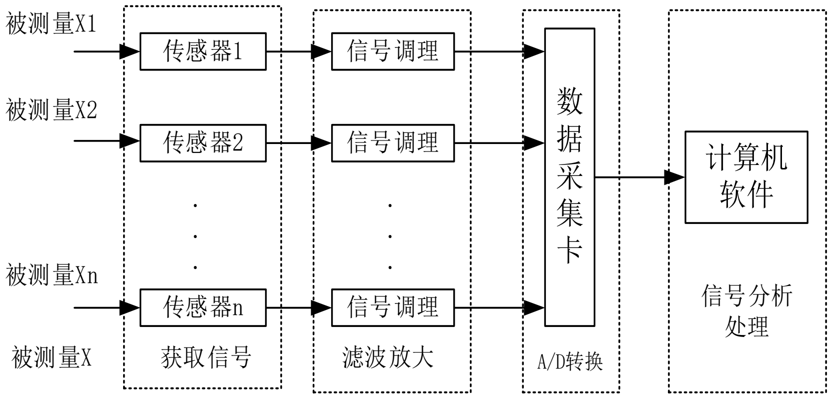

Fig. 1 Tested system diagram

3. The Principle of Wavelet Transform

Assume $\varphi(t) \in L^2 R$ and the Fourier transform of $\varphi(t)$ is $\psi(\overline{\omega})$, $L^2 R$ is the signal space of finite energy. When $\psi(\overline{\omega})$ meets:

$$C_\varphi = \int_R \frac{|\varphi(\omega)|^2}{|\omega|} d\omega < \infty . \tag{1}$$

$\varphi(t)$ is referred to a basic wavelet or a mother wavelet. If scale or translate the Mother Wavelet Function, then a wavelet basis can gotten.

For continuous wavelet transform, $\varphi(t)$ wavelet sequence is:

$$\varphi_{a,b}(t) = \frac{1}{\sqrt{|a|}} \varphi\left(\frac{t-b}{a}\right) a, b \in R, a \neq 0 . \tag{2}$$

In which a is a (scaling) stretching factor and b is a translation factor.

For arbitrary function $f(t) \in L^2(R)$, its continuous wavelet transform is:

$$W_f(a,b) = < f, \varphi_{a,b} > = \int_{-\infty}^{\infty} f(t) \overline{\varphi\left(\frac{t-b}{a}\right)} . \tag{3}$$

In which $< f, \varphi_{a,b} >$ is the inner product of $f(t)$ and $\varphi_{a,b}$. $\overline{\varphi\left(\frac{t-b}{a}\right)}$ and $\varphi\left(\frac{t-b}{a}\right)$ are conjugate function mutually.

The wavelet inverse transform is:

$$f(t) = \frac{1}{C_\varphi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{a^2} W_f(a,b) \varphi\left(\frac{t-b}{a}\right) dadb . \tag{4}$$

According to the define of continuous wavelet transform, compared with Fourier transform, the wavelet transform can control the size of time frequency through scaling factor ‘a’, translation factor ‘b’. The results of the Wavelet transform show the characteristic of no longer a certain frequency point or a point in time, but of some frequency period or time period. In addition, the continuous wavelet transform coefficients have a large amount of redundancy, which is an advantage for continuous wavelet transform. The redundancy can achieve the purpose of signal denoising and data recoverying.

Using wavelet transform, arbitrary signal $f(t) \in V_0$ can be divided into the low frequency signal a_i (proximate signal) and high frequency signals d_i (detail signal).For further study, a_i can be decomposed at any scale which is beneficial to the signal analysis. Fig. 2 is a picture of three-layer structure of wavelet analysis.In this picture a_i, represents a low-frequency signal and d_i is a high frequency signal. The digital serial number represents the wavelet decomposition layers, and the whole bunch's relationships can be expressed by this formula: $S = a3 + d3 + d2 + d1$. If the signal frequency band is $[0, \omega]$, after first layer decomposing, signal frequency band is decomposed into two parts: $[0, \omega/2]$ and $[\omega/2, \omega]$. And then the signal has been decomposed for further which belongs to the frequency band $[0, \omega/2]$, then we can get another two frequency bands of signals those belong to $[0, \omega/2^2]$ and $[\omega/2^2, \omega/2]$. After N times' decomposition, we can get N times' Wavelet decomposition results [5].

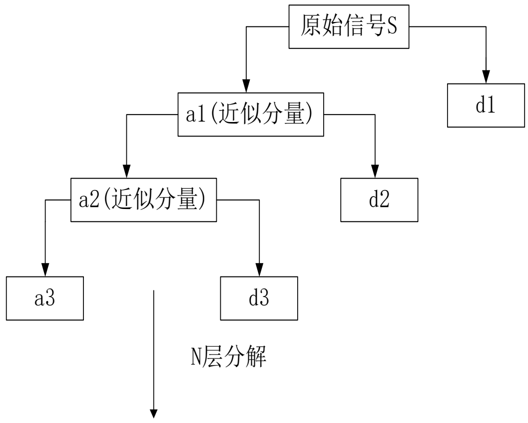

Fig. 2 Principle of Wavelet Decomposition

4. Data Processing and Simulation Analysis

4.1 Wavelet Analysis

In muzzle blast overpressure test, due to the outside interference or test equipment's vibration caused by gun launching and other reasons, the collected shock-wave signals will inevitably superimpose various noise. In order to extract effective muzzle blast wave signals, the signals need to be preprocessed. The clutter signals need to be filtered out and the useful signals can be remained. In this paper, Butterworth Filter and wavelet filtering are used to preprocess the wave signals and two different shock filter denoising waveforms are given.

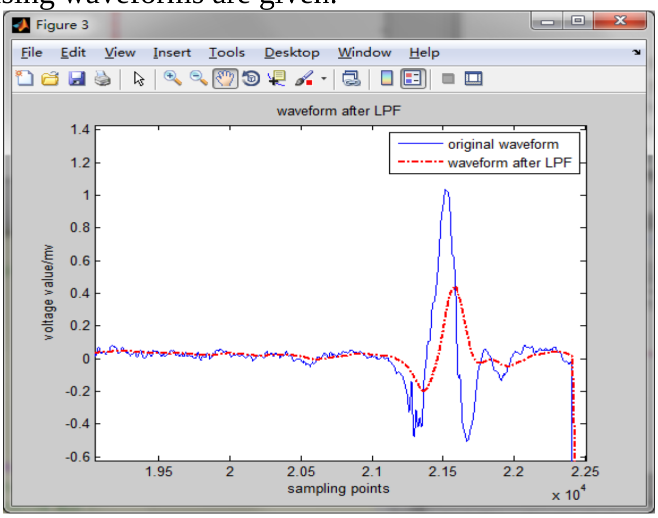

Fig. 3 Butterworth digital filter for the being filtered waveform

A part of Butterworth digital filter for the being filtered waveform is shown in Fig. 3. From it, using Butterworth filter for preprocessing, most of shock wave noise is filtered, but the signal has a certain degree of time delay. Repeated experimental data show that if Butterworth filter's order number is set to be improper, there will be a bad filter effect, an increasement of time delay and a loss of a part of useful signals. Wavelet analysis has characteristics of good time frequency and multi-resolution, so the selection of wavelet basis function, the number of decomposition levels, thresholds and threshold functions can be gained flexibly in order to get a better approximation the original signals[6]. Based on the comparative analysis of wavelet bases, thresholds as well as threshold functions, the bior2.2 wavelet basis, heursure threshold value, soft and hard compromise threshold function are selected to decompose and reconstruct signals. The effect of denoising is shown in Fig. 4:

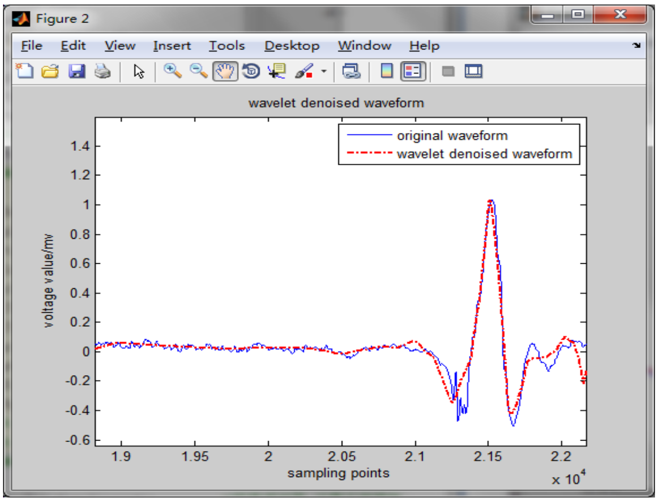

Fig.4 Figure of wavelet denoising effect of shock wave waveform

And Fig. 4 is a part of wavelet denoising effect of shock wave waveform.From it, denoised shock wave signal by wavelet analysis, the anastomosis degree between processing signal and original signal is special high, almost no time delay phenomenon. It not only filter the signal impurities, but also retain the signals of information of sudden change. It guarantees the follow-up computational accuracy of signal duration, overpressure peak value and shock wave pressure field analysis.

The experiment data show that the wavelet denoising method is more suitable for the denoising of non-stationary muzzle blast signals [7].

5. Analysis of Shock Wave Pressure Field

5.1 The Layout of Position Sensors

In order to accurately test overpressure damage power field, the same type of sensors need to be placed for shock wave signal collecting from different angles and different distances when the testing system works. Fig. 5 is a sensor layout diagram of this test system in which the polar positions of the sensors is shown. In this figure, central point is the position of the muzzle. The radial distance from sensors to the position of the muzzle is 5 m to 10 m. Sensors have been laid out every 30 degrees direction on both sides of the muzzle.

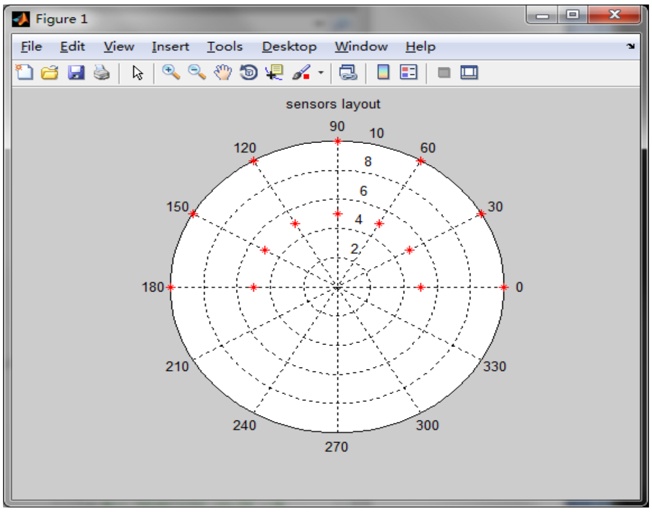

Fig. 5 Sensors placement diagram

6. Pressure Field Analysis

Using denoising shock waves signal collected from each sensor, waveforms of shock waves have been obtained, and overpressure peak value has been calculated. Finally according to the exact location of sensors, the shock wave pressure model has been established.

The muzzle blast overpressure signal from sensor is made up of discrete point. Using Interpolation, the approximation of this function on other points can be estimated. Because it's impossible to place sensors at every point on the propagation path. Therefore, it provides great convenience for our shock wave signal pressure Isobar drawing using interpolation method.

By comparing the algorithms of linear interpolation, polynomial interpolation 'cubic' and 'V4' splines interpolation algorithm[8], in this paper, 'V4' splines interpolation algorithm has been chosen to reconstruct the field model. Fig. 6 is the contour diagram.

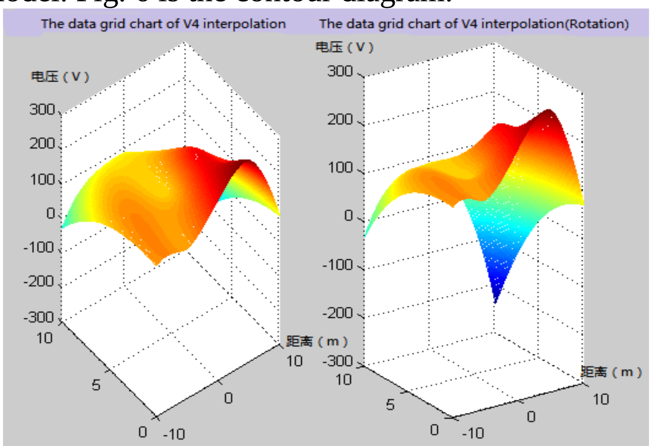

Fig. 6 V4 interpolating surfaces diagram

From fig. 6 ,it can be found that shock wave in the process of transmission decays in wavy, and it is accord with the characteristics of the muzzle shock wave pressure field.

6.1 Error Analysis

To assess the established model, it is assumed that there is a damaged sensor in the test site and the sensor cannot provide data for this shock wave field. Then the following method is used to build the model of shock wave field tested by those sensors.

Operating steps are followed:

Assume that an arbitrary one of those sensors has a problem and the procedure doesn't read in the sensor's data. The model of shock wave field has built by the estimated value from other sensor's data. To compare the model data with the measured ones,the modeling error is calculated according to the formula(5):

$$\delta = \left|\left(L-R\right)/R\right| \times 100\% . \quad (5)$$

In which, δ is the relative error, L is the interpolation value, R is the measured value.

Calculating the relative error's absolute value between the interpolation value and the measured value. The larger the absolute value, the larger the error and vice versa. Adopting V4 interpolation methods and comparing the different modeling errors of discarded different data of different positions sensors after removing the corresponding position sensor's value, four experiments data of relative errors between the measured data and estimated ones have been listed in Table 1.

Table 1 the interpolation error of getting rid of different position sensor's data

The position of sensors(ω ,r)	(0°,5) Number1	(60°,5) Number3	(180°,10) Number8	(120°,10) Number10
error	0.1243	0.0021	0.1588	0.0026

Note: in the table ω (degrees) represents the layout angle of sensors, r(m) represents these sensor's distance from the muzzle.

From the above chart, it can be seen that when we get rid of the sensors laid out on the border position, such as No.1 and No.8 sensors in table 1, the error between the estimated values and measured values is large. When getting rid of sensors laid out on the middle position, such as No. 3 and No. 10, the interpolation errors are relatively small and the estimated values are very closer to measured values. The analysis of data shows that it is more accurate to estimate the test data of sensor which is laid out on the middle position. So in actual tests, this method can be used to estimate the test data of sensor which is laid out on the middle position.

7. Summary

Aiming at the characteristics of shock wave signal, through comparing the traditional digital filter method with the wavelet analysis method, unsteady shock wave signals collected by the sensors have been denoised by wavelet analysis method and then, the overpressure peak value - the main characteristic parameter of shock-wave signal is calculated. V4 spline interpolation method is used to establish a model of shock wave pressure in the following. It shows intuitively the propagation rule of the muzzle shock wave. Finally, through error analyzing, the modeling errors are estimated when sensors which laid out in different position are failure.

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