Introduction to the method of estimating time-domain response based on amplitude-frequency characteristics

Mingrui Wang¹ᵃ, Mei Xuᵇ, Jiangfeng Wang², Yingying Guo³

¹ Institute of NBC defence of Army
² 96901 troops
³ 96941 troops
ᵃ email: Wangmingrui25@163.com,ᵇ 13521217318@163.com

Abstract. How to use the amplitude-frequency characteristics to reconstruct the signal to obtain the time-domain response has always been a concern in the field of nuclear electromagnetic protection. So far, in practical applications, parametric modeling and non-parametric modeling have been used to solve related problems. This article summarizes the research and development of using amplitude-frequency characteristics to recover time-domain signals in the field of nuclear electromagnetic pulse protection, and briefly introduces the shortcomings of the two methods in combination with specific experiments.

1. INTRODUCTION
With the advancement of science and technology, the development of weapons and equipment has gradually shown the development characteristics of systemization, informationization, and networking, and the battlefield will also be developed in the five-dimensional space of land, sea, air, sky, and electromagnetic. For the command system, the computers, networks, power supply equipment, and various sensors it rely on are all based on electronic equipment. When a strong electromagnetic pulse acts on the electronic equipment, it can instantly cause communication interruption, computer out of control, and sensor failure. The combat command system will be greatly damaged. Therefore, strong electromagnetic pulses have become a major threat to future wars, and electromagnetic pulse protection has also become a necessary means to ensure the normal operation of the command system. Attaching great importance to the development and protection of electromagnetic pulse research to minimize the damage of electromagnetic pulse to electronic systems is a long-term and arduous task for future wars.

According to the IEC 61000-2-13 standard issued by IEC SC77C, the high-power electromagnetic environment is defined as: When the peak electric field strength in the electromagnetic environment exceeds 100V/m, the power density corresponding to the plane wave exceeds 26.5 W/m², that is Is called a high-power electromagnetic environment. Typical high-power electromagnetic environments include lightning electromagnetic pulse fields generated by ground flashback currents, electromagnetic fields near electrostatic discharges, electromagnetic pulses generated by nuclear explosions, and high-power microwaves generated by non-nuclear weapons. As an electromagnetic pulse weapon, it can be divided into three categories according to the pulse generation method: one is the high-altitude nuclear explosive electromagnetic pulse (HEMP) weapon generated by the detonation of a low-yield nuclear bomb at a high altitude; the other is the use of high explosives and related devices to generate high frequency 108-1012 Hz ultra-wideband (UWB) electromagnetic pulse weapons; third, high-power...
microwave (HPM) weapons that use high-power microwave devices such as magnetrons and virtual cathode oscillators to generate microwave peak power exceeding 100MW.

In actual application, in order to carry out the anti-electromagnetic pulse test of the equipment, people have established the corresponding test device. High-altitude nuclear explosion electromagnetic pulse field tests mainly use high-altitude nuclear electromagnetic pulse simulators, most of which are bounded wave and radiation wave simulators. The device can provide a pulse field similar to the standard waveform of the high-altitude nuclear electromagnetic pulse, so as to obtain the system-level response information of the test body to the high-altitude nuclear electromagnetic pulse. Therefore, this method is currently the closest test to the real situation except for the real nuclear environment. As a weapon, ultra-wideband uses fast switching technology to generate nanosecond or even picosecond ultrashort pulses to obtain ultra-wideband electromagnetic radiation output. It does not require electron beams as an intermediate medium, and its frequency domain is wider, while pulses The energy output of the source is relatively low. Although the above devices can meet the anti-electromagnetic pulse performance test of most weapons and equipment, their miniaturization is relatively difficult, the technology is relatively complex, and some equipment is expensive, and they are limited in use scenarios such as surface ships and fixed fortifications against electromagnetic pulse reinforcements. At the same time, the pulse field measurement system is not as popular as the continuous wave test equipment. People prefer to estimate the time domain response of the system by the amplitude-frequency characteristic curve provided by the manufacturer or actually measured. To solve the above problems, the frequency domain continuous wave irradiation test is used to obtain the test. The volume frequency response, and then the reconstruction of the time-domain impulse field response, can become an alternative, and it has strong practicability. The main purpose of the continuous wave irradiation test is to measure the transfer function from the outside of the system to the response of the reference point inside the system. Compared with the large-scale strong electromagnetic pulse simulation device, this form of measurement has the following characteristics: 1. The energy level is only a few V/m, and there is no damage to the test object; 2. The polarization mode of the antenna can be changed to simulate different The shielding effectiveness of the test body in the polarization mode; 3. The miniaturization is relatively simple, which is convenient for the measurement of the fixed test body; 4. The frequency domain measurement technology is relatively mature, and the equipment is easy to obtain.

2. Theoretical basis

In terms of continuous wave test, large-scale continuous wave irradiation test equipment was established in foreign countries in the 1980s. The U.S. Air Force Weapons Laboratory has developed a low-level continuous wave test system to conduct electromagnetic protection evaluation and electromagnetic reinforcement research on civil and military aircraft. Similar tests have also been conducted in the United Kingdom. The domestic research on using frequency domain measurement to reconstruct the impulse field response started relatively late. In 2000, Professor Shi Lihua and Zhou Bihua first proposed in the field of high-altitude nuclear electromagnetic pulse protection, based on the minimum phase system, to solve the impulse response problem of the amplitude spectrum estimation system. It mainly adopts two methods: non-parametric modeling and parametric modeling based on Prony method. Since then, the theoretical research and practical application of estimating the impulse response of the system from the amplitude frequency spectrum are also carried out around these two ideas.

The key to the problem of extrapolating electromagnetic impulse response in continuous wave irradiation experiment is how to use frequency domain measurement results to estimate the electromagnetic impulse response of the test body, which involves signal reconstruction theory. In 1991, academician Li Yanda edited and published the book "Signal Reconstruction Theory and Its Application"[1]. In the chapter Reconstructing Signals from Partial Data of Fourier Transform, it explained in detail how to determine the minimum phase signal from the amplitude spectrum and reconstruct the mixed phase signal. The conditions, methods and algorithms have laid the theoretical
basis for estimating electromagnetic impulse response from frequency domain measurement data Li Yanda, Chang Jiong. Signal reconstruction theory and its applications. For a causal sequence, after Fourier transform, the real part and imaginary part satisfy the Hilbert transform. We set the system as the minimum phase system, and its frequency domain transfer function is, which can be expressed as:

$$H(k) = |H(k)|e^{j\theta(k)}$$ (1)

After taking the logarithm of the above formula, the following formula can be obtained:

$$\ln H(k) = \ln |H(k)| + j\theta(k)$$ (2)

Then meet the Hilbert transformation between and. Therefore, when we know the signal amplitude spectrum, we can get the phase spectrum and transfer function according to the above formula.

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3. Non-parametric modeling method

Non-parametric modeling, that is, after obtaining the amplitude spectrum, directly sample the data at equal intervals, and obtain the real cepstrum of the sampled data, and use the real cepstrum to obtain the complex cepstrum, thereby recovering the minimum phase signal. The specific process is as follows:

Fig. 1 Minimum phase recovery process

Among them is the real cepstrum of the sampled data, is the complex cepstrum of the sampled data, is the minimum phase signal of the original signal, and is the result of time domain convolution.

In 2004, Xie Yanzhao used this method to perform minimum phase recovery on commonly used excitation signals and analyzed the results [2]. The results show that the reconstructed waveforms of HEMP waveforms, cosine damped oscillation waveforms and other signals are in good agreement with the original waveforms. However, for non-minimum phase signals, the detail parameters such as the front (rear) edge and peak value of the reconstructed waveform are quite different. At the same time, in the process of using this method, the sampling time and sampling frequency have a greater impact on the waveform reconstruction effect. Generally speaking, the higher the sampling frequency, the longer the sampling time, the better the reconstruction effect. In 2011, Cao Jingyang used this method to study the signal reconstruction problem of the current probe in order to obtain the phase frequency characteristics of the sensor. In experiments on HEMP waveforms, it is found that the reconstructed waveform of this method is sensitive to Gaussian white noise. When the sampling points at the tail of the measured pulse wave signal are few, the reconstructed waveform after convolution with the transfer function will produce a larger amount at the end of the pulse. Big fluctuations [3].
2015, Hu Xiaofeng and others evaluated the shielding effectiveness of metal cavities against electromagnetic pulses, and used this method to simulate and test the slotted cavities. When reconstructing the internal waveform of the cavity, the pulse waveform trend can be roughly reflected, but the superimposition of the reconstructed signal noise is more serious.

This method uses Fourier transform to perform time domain frequency domain conversion many times, which will introduce errors. At the same time, if you want to improve the simulation accuracy, you need to increase the number of points of the frequency domain amplitude spectrum, increase the sampling frequency, and increase the sampling time, which causes certain inconvenience to the use of this method.

4. Parametric modeling method

The difference between the parametric modeling method and the non-parametric modeling method is that the method combines the effects of electromagnetic waves and the test body to find a mathematical model in the frequency domain or time domain to approximate the transfer function of the test body. In this way, fewer data points can be used to realize the description of the pulse wave transfer characteristics of the system.

The Prony method used by Professor Shi Lihua and Zhou Bihua is based on the time domain point of view. The parameters of the discrete transfer function model correspond to the differential equation of the discrete system representing the input-output relationship. However, the model is very sensitive to noise and is very sensitive to the cavity. The effect of the test body with severe electromagnetic wave reflection is not good. In 2004, Guo Jian aimed at the shielding problem of cylindrical thin metal shells and proposed using vector fitting method to model the transfer function in the frequency domain as a rational function. After performing the inverse Laplace transform, the excitation signal and the transfer function are used for recursion in the time domain. Convolution calculation. The function model fits well with the measured signal, and the method of recursive convolution also improves the calculation efficiency. In 2009, Guo Dongyi directly aimed at the excitation and response of the system, within the allowable error range, optimized the approximation of the filter parameters, and obtained the filter model of the transfer function. However, the model of the digital filter is simple, and its applicability is not strong for the establishment of the transfer function of the cavity. In 2015, Chen Xiang compared the vector fitting method with the non-parametric modeling method based on the infinite plane material. It superimposes noises of different intensities on the spectrum of the shielding effectiveness of infinite plane materials. Two methods are used to reconstruct the time-domain waveform. The results show that the anti-noise performance of the vector fitting method is better than that of the minimum phase method. In 2018, Liu Xu used the EML over-limit learning machine neural network to fit the frequency domain transfer function. When debugging large-scale irradiation equipment, the method was tested for whip antennas. The induced current estimated by the neural network is basically consistent with the induced current generated by the antenna in the bounded wave simulator, which proves that it is a feasible method to use the neural network model for function fitting, but the article does not compare the test results with other parameters. A method based on the continuous wave irradiation test to extrapolate the HEMP response of the system.

Compared with non-parametric modeling, parametric modeling has a reduced amount of calculation and higher accuracy, but it requires users to have a clearer understanding of the mathematical operation process of the model, so as to better predict model errors. Find the rational function approximation according to a set of frequency sampling values of the transfer function. The basic method is through rational interpolation, which can be completed by solving a set of linear equations. But the problem is that this system of equations is highly ill-conditioned, and the higher the order of the rational approximation and the wider the frequency range of the approximation, the more serious the ill-conditioned degree. The vector fitting method does not solve a set of equations about the coefficients of the numerator and denominator when approximating, but directly solves the poles and residues of the rational function, and through the introduction of an auxiliary function, the
The problem is converted into the solution of a linear equation system. It solves the problem of "ill-conditioned equations" that arises when the rational interpolation method fits high-order or wide frequency bands. The call flow of the algorithm based on MATLAB is summarized as follows Fig.2. At the same time, the development of intelligent algorithms such as neural networks has also opened up new directions for parametric modeling.

![Fig. 2 VF method flow](image)

**5. CONCLUSION**

This article introduces the development and application of the method of estimating the pulse field response based on the amplitude-frequency characteristics in the field of nuclear electromagnetic pulse protection. Two methods of non-parametric modeling and parametric modeling are introduced, and the shortcomings of the two methods are briefly explained in combination with specific experiments. In terms of specific applications, the current test bodies are mostly holes, antennas, and new materials. As a widely used shield, the cavity has not been studied much. At the same time, compared with other test objects, electromagnetic waves will be reflected in the cavity and there will be resonance problems at specific frequency points in the cavity. How to use the amplitude-frequency characteristics to better estimate the pulse field response of the cavity is also a problem that needs to be solved in the future.

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