

Acoustic Signal Characteristics Analysis of Underwater Plasma Source Pulse Discharge based on Variational Mode Decomposition Algorithm

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Abstract. In order to study the variational mode decomposition (VMD) algorithm for the analysis of acoustic signal characteristics of underwater plasma sound source pulse discharge, a simulation model of central control module is established by using VMD algorithm. The whole hardware circuit takes the FPGA (Field Programmable Gate Array) chip as the intelligent control center of the central control module, and combining with the minimum composed of basic power supply circuit, clock circuit, reset circuit and configuration circuit, the model is used to analyze the characteristics of acoustic signals. The results show that the uncertainties of these parameters also affect the performance of VMD. In VMD decomposition, the smaller the equilibrium constraint parameters are, the larger the bandwidth of each modal component is, the more likely the phenomenon of center frequency overlap and mode aliasing will occur. The larger the equilibrium constraint parameters are, the smaller the bandwidth of each component signal will be, and the phenomenon of center frequency overlap and mode aliasing will disappear. Through analysis, it is proposed that the general equilibrium constraint parameters can be taken as sampling frequency f_s in practice. The acoustic signal of VMD applied to underwater plasma sound source pulse discharge is analyzed, and the results are as expected. It provides a theoretical basis and practical basis for its application in underwater plasma acoustic signal characteristics analysis. This is of great significance to the study of VMD as an underwater plasma source for the analysis of acoustic signal characteristics of pulse discharge.

Keywords: VMD algorithm, underwater plasma, simulation model, spectrum.

1. Introduction

Underwater plasma sources are easy to control, convenient to carry, and have high sound levels. In recent years, with the increasing strategic significance of the ocean and the increasing demand of the world for the development of marine resources, countries around the world have begun to invest a lot of manpower and material resources to research and develop high-power underwater pulsed sound sources. High-power pulsed sound source with good performance can not only be used in seismic exploration, deep well geophysical exploration and rock drilling, but also meet the application requirements of underwater remote communication, underwater instrument remote control, sea surveillance, and naval military confrontation [1].

The characteristics of the acoustic signal produced by underwater high voltage discharge are narrow pulse width, wide frequency band and quick mutation. Since the structure of the signal itself and its spectrum are time-varying, the Fourier transform, which is good at analyzing periodic or quasi-periodic signals, does not apply. Therefore, it is necessary to find another method to process such pulse signals. On the basis of obtaining acoustic signals of underwater plasma sound source, this paper will explore the application of variational mode decomposition in underwater plasma sound source acoustic signal analysis, and provide reference for underwater high voltage pulse discharge feature extraction.

Variational mode decomposition (VMD) is a new adaptive signal processing method [2]. It assumes that each eigenmode function has a finite bandwidth with different central frequencies. In order to minimize the sum of estimated bandwidth of each eigenmode function, the variational problem is solved by conversion. The eigenmode functions are demodulated to the corresponding baseband, and the eigenmode functions and corresponding central frequency are finally extracted [3].

In view of the above findings, the application of VMD algorithm to underwater plasma acoustic signal characteristic analysis has become a research hotspot of scholars all over the world, but it is only a trend, and there are still great limitations if it is implemented. The model is built based on VMD algorithm and applied to underwater plasma acoustic signal characteristics analysis. Finally, the data integration is realized, the utilization of data information is improved, and the development process is promoted.

2. Literature Review

There are numerous studies on the application of the algorithm to underwater plasma acoustic signal analysis at home and abroad. Pei of Nanjing university of science and technology reward used Mallat algorithm, the discrete wavelet transform is adopted to underwater explosion signals are analyzed in layered extraction, continuously discussed continuous underwater explosion signals in each frequency band energy distribution, Welch method was adopted to realize the continuous explosion signal power spectrum feature extraction of underwater, and uses the discrete wavelet transform spectrum characteristics of acoustic signal analysis[4]; Sheng zhenxin analyzed the underwater continuous explosion signals with the combination of wavelet transform, energy statistics and power spectrum estimation, and the results showed that the energy of the two groups of underwater continuous explosion signals with a time interval of and was the same within. Within a certain time interval, the energy of continuous underwater explosion signal with time interval is larger than that of continuous underwater explosion signal with time interval. Then, the underwater continuous explosion signal is processed and analyzed by using transform[5]. According to the interference of different frequency bands of wideband sound source signals, Wen Hongtao adopted the filtering algorithm of adjacent scale correlation for the small scale high frequency wavelet coefficients with high signal-to-noise. For the large scale wavelet coefficients with low SNR, the cross-scale correlation filtering algorithm is adopted, and the selection method of threshold coefficient in the algorithm is modified. It is proved that the wavelet algorithm is suitable for wideband underwater acoustic signal processing under narrow band strong background noise[6]. Kang Jiaying has deeply studied the basic principle of VMD, and compared one-dimensional and two-dimensional VMD with one-dimensional and two-dimensional EMD by processing theoretical data and actual seismic data. In parameter selection, decomposition accuracy, noise resistance and other aspects of the similarities and differences and the advantages and disadvantages of related algorithms. The results show that VMD is superior to EMD in both decomposition accuracy and noise resistance. However, VMD fails to effectively improve the endpoint effect in EMD, and there are certain human factors in the selection of parameters in VMD. The above problems still need to be further studied[7]. Chen Lijun proposed a new time-frequency analysis method based on variational mode decomposition (VMD) and Hilbert spectrum analysis (HSA) for the detection and parameter estimation of acoustic frequency hopping signals under the condition of low SNR in underwater acoustic communication. VMD is a newly developed adaptive signal decomposition technique, which can decompose multi-component signals into many quasi-orthogonal intrinsic mode functions completely without recursion. Firstly, the VMD algorithm is analyzed, and then the HSA method is briefly introduced. Finally, the method combining VMD and HSA is applied to the analysis of underwater acoustic frequency hopping signals. The numerical simulation results show that the proposed method can obtain high resolution and high aggregation time-frequency graphs[8].

In 2016, Sachin Gupta et al. used high-speed three-dimensional digital image correlation (DIC) experiments to study the fluid-structure interaction during confined implosion. The results show that the collapse of the explosive body in the enclosure will cause the strong oscillation of water hammer wave. The study also shows that the increase of collapse pressure will lead to faster implosion. With the increase of collapse pressure, the peak velocity and average velocity of the structure increase linearly. Finally, a single-degree-of-freedom theoretical model is established to predict the pulse pressure scheme of the research problem [9]. In 2017, Zettergren et al. used the numerical model of ionospheric-neutral coupling to study the disturbances of plasma density, vertical integral total

electron content (TEC), neutral velocity and neutral temperature produced by the initial ocean surface displacement caused by strong seabed earthquakes. Finally, the TEC perturbation obtained from the case study seems to be consistent with the observed data, reproducing obvious TEC losses, which have been proved to be the result of the influence of non-linear dissipative acoustic waves [10]. Sylvain Amailland et al. studied the decomposition of trans-spectral matrix based on wall pressure in 2018, using the low rank of trans-spectral matrix and the sparsity of BLN-type trans-spectral matrix to analyze the characteristics of acoustic signals. The results show that this method can effectively reduce the BLN of large hydrodynamic tunnels [11]; Peter Harris et al. studied a statistical method for long-term trend analysis and uncertainty evaluation of the estimated trend in 2019, and finally verified the uncertainty by bootstrap resampling. The experimental results show that the sound pressure level decreases significantly after using this method [12].

3. Method

3.1 Key Technology

VMD is the latest proposed in 2014. Signal estimation method is essentially different from the layer-by-layer filtering mode adopted by recursive mode decomposition (EMD, LMD) [13]. Its overall framework is the solution of variational problems, and has a solid theoretical foundation.

Within two years, VMD has been applied in many fields, such as machinery, power, medicine, economy and so on. However, plasma discharge in water is different from general rotating machinery, and it has the characteristics of complex and changeable working conditions, low speed and variable speed. At present, there is no report on the application and research of VMD in underwater acoustic field. It is introduced into the acoustic signal characteristic analysis of underwater plasma sound source pulse discharge. Underwater plasma sound source is a technology of plasma discharge in water or pulsed discharges in water. An important application of underwater acoustics and seismic exploration technology is also called sparker.

In the VMD algorithm, the intrinsic mode function (IMF) is defined as an AM (amplitude modulation)-FM (frequency modulation) signal whose expression is:

$$u_k(t) = A_k(t) \cos(\varphi_k(t)) \quad (1)$$

In Formula (1): $A_k(t)$ is the instantaneous amplitude of $u_k(t)$ and $W_k(t)$ is the instantaneous frequency of $u_k(t)$:

$$w_k(t) = \varphi_k(t) = \frac{d\varphi(t)}{dt} \quad (2)$$

$A_k(t)$ and $w_k(t)$ are slowly varying relative to the $\varphi_k(t)$, i.e., within the interval of $[t-\delta, t+\delta]$ (where $\delta = 2\pi/\varphi_k(t)$), $u_k(t)$ can be regarded as a harmonic signal with an amplitude of $A_k(t)$ and a frequency of $w_k(t)$.

3.2 Experimental Model

The underwater plasma acoustic source system is designed according to the VMD algorithm. Finally, the following model is designed. As the control core of the whole underwater plasma sound source control platform, the central control module is mainly responsible for charging voltage control, feedback voltage acquisition, charging speed (current) control, feedback speed (current) acquisition, charging full feedback signal acquisition, and switch trigger pulse generation. The main central control module can be designed separately or embedded in the sub-central control module, and the second design method is chosen here. The central control module designed can be used as both the main central control module and the sub-central control module.

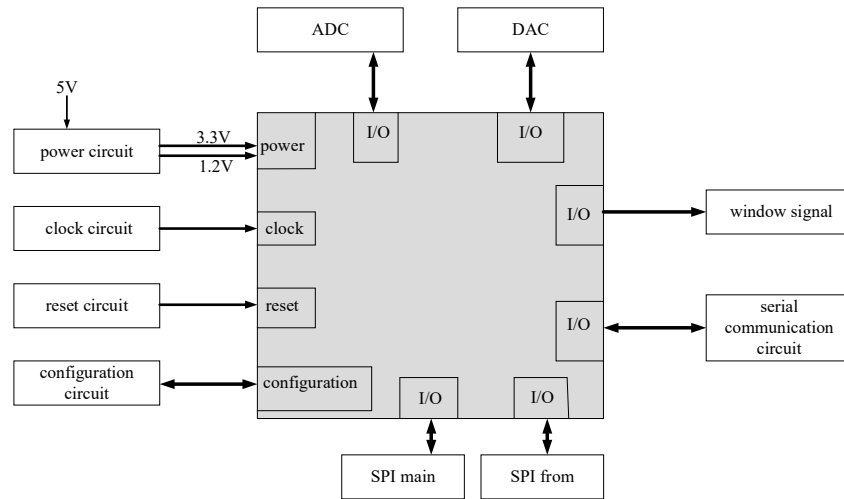


Figure. 1 Structural block diagram of central control module

According to the functional requirements of the central control module, the structure of the central control module is shown in Figure 1. The whole hardware circuit takes the FPGA chip as the intelligent control center of the central control module, and combines with the basic power supply circuit, clock circuit, reset circuit and configuration circuit to form a typical minimal system. The system needs to be responsible for the setting of charging voltage and charging speed (current) in the three-way charging and discharging circuit at the same time. It also needs to monitor the changes of voltage and current and the feedback signals such as charging full in real time. Therefore, 6-way digital-to-analog converter circuit and 9-way analog-to-digital converter circuit are used for parallel output and input in the design. Another important task of the system is to precisely control the triggering and discharging time of each sound source. According to the specific triggering mode, the central processing unit (CPU) FPGA generates the triggering pulse signal of the switch through the precise logic sequential circuit, and finally outputs it to the corresponding interface. In order to realize real intelligent control, human-computer interaction interface is essential. The system uses traditional serial communication to realize data exchange between central control module and host computer display and control software. In the design of the hardware structure of the control platform, the idea of one master and three slaves is adopted. In order to facilitate data exchange and hardware wiring, the communication mode between the main central control module and the sub-central control module is SPI (Serial Peripheral Interface) serial synchronous bus communication with high transmission performance.

4. Results and Discussion

The results of the simulation model are analyzed, and in terms of the simulation signals: $x(t) = x_1(t) + x_2(t) + x_3(t)$:

$$x_1(t) = \cos(4 * \pi * t) \quad (3)$$

$$x_2(t) = 1 / 4 * \cos(48 * \pi * t) \quad (4)$$

$$x_3(t) = 1 / 16 * \cos(576 * \pi * t) \quad (5)$$

The simulation signal $x(t)$ is decomposed by VMD. The simulation signal and its VMD decomposition diagram are shown in Figure 2.

After VMD decomposition, the three modal components of the simulation signal are recorded as u_1 , u_2 and u_3 , respectively. u_1 , u_2 and u_3 correspond to x_1 , x_2 and x_3 in the input signal respectively. Comparing the modal components u_1 , u_2 , u_3 and u ($u = u_1 + u_2 + u_3$) decomposed by VMD with x_1 ,

x_2 , x_3 and x in the input signal, as shown in Figure 2, it can be seen that u , u_1 , u_2 , u_3 are similar to x , x_1 , x_2 and x_3 in magnitude and frequency, respectively.

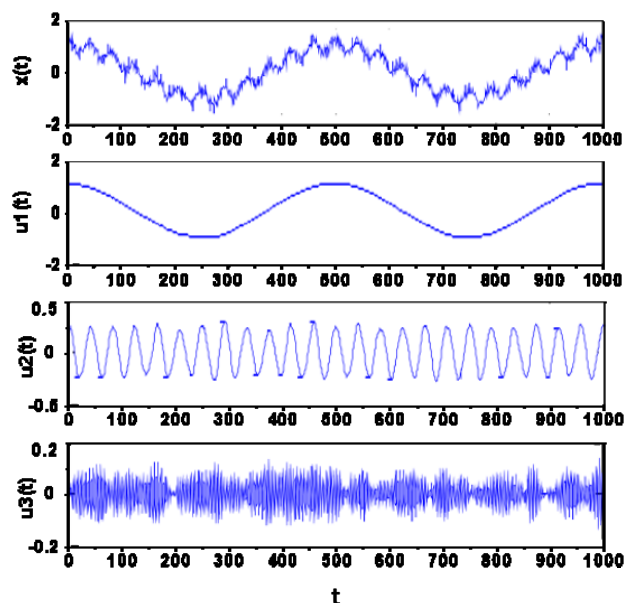


Figure. 2 Simulation signal and VMD decomposition

Furthermore, the spectrum distribution of the input signal (Figure 3) and the decomposed modal signals (Figure 4) are drawn. From the comparison between Figure 3 and Figure 4, it can be seen that the decomposed three modes are in good agreement with the frequency of the original signal in the frequency range.

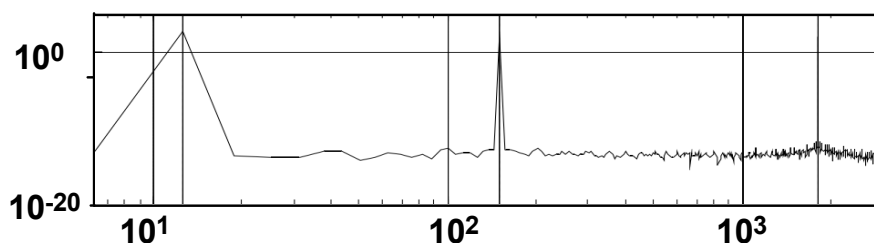


Figure. 3 The frequency spectrum distribution of the input signal

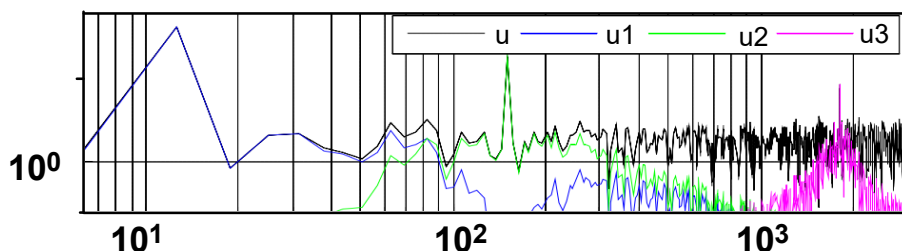


Figure. 4 The mode signal spectrum with VMD

Continue to use the periodic simulation signal of the above model, sampling frequency is $f_s = 1000\text{Hz}$, $K = 3$; take $a = 1/8f_s$, $1/4f_s$, $1/2f_s$, f_s , $2f_s$, respectively, to make the central frequency curve under different a value and the spectrum distribution of each mode signal after VMD decomposition.

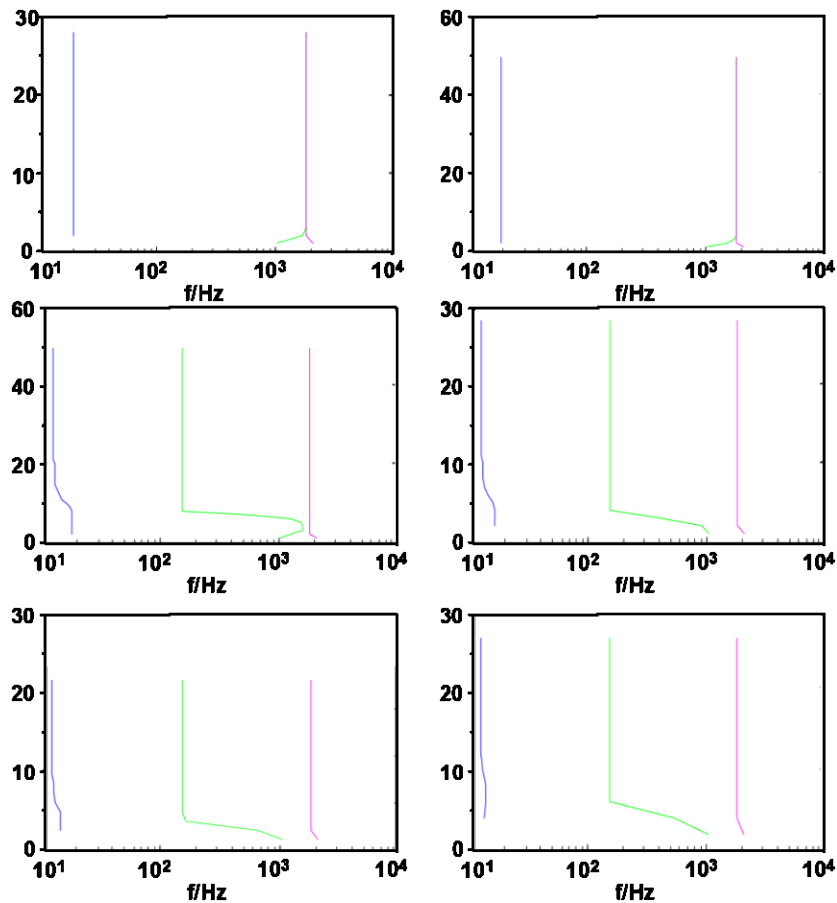


Figure. 5 The change of center frequency under $a=1/8fs$, $1/4fs$, $1/2fs$, fs , $2fs$, and $4fs$

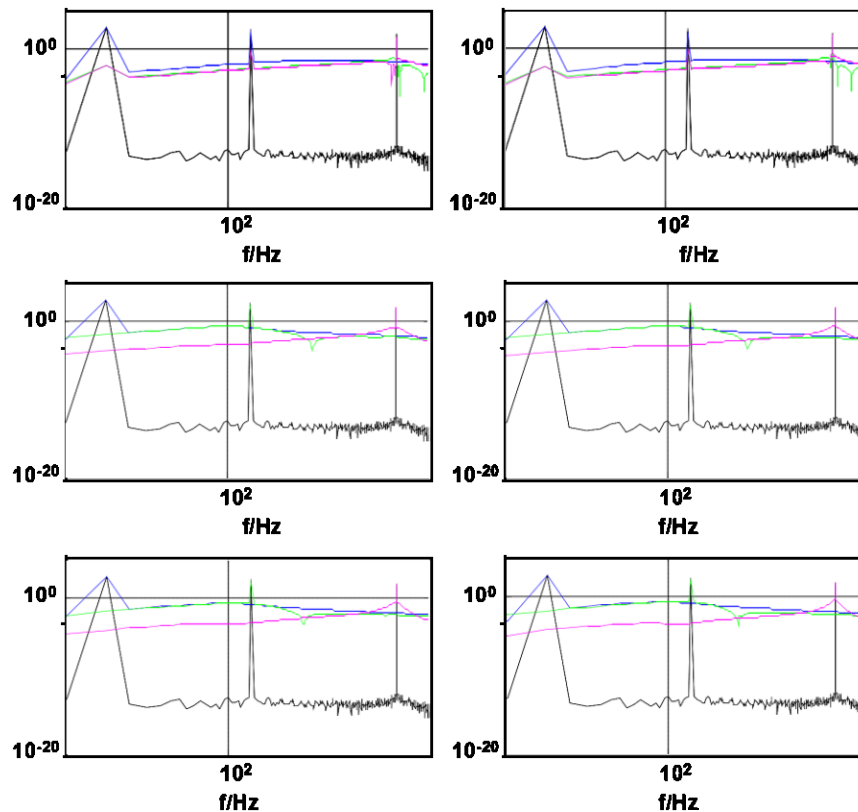


Figure. 6 The modal signal spectrum distribution under $a=1/8fs$, $1/4fs$, $1/2fs$, fs , $2fs$, and $4fs$

It can be seen from the central frequency change curve (Figure 5) under different a value and the spectrum distribution of each mode signal after VMD decomposition (Figure 6), when $a = 1/8f_s$ and $1/4f_s$, the phenomenon of center frequency overlap can be seen from the central frequency change curve. The phenomenon of mode overlap can also be seen in the spectrum distribution of each mode signal. With the increase of a value, $a = 1/2f_s$, f_s and $2f_s$ are selected. In VMD process, the phenomenon of overlapping central frequencies disappears, and the phenomenon of mode aliasing will not appear in the frequency spectrum of each mode signal.

5. Conclusion

Based on the above model analysis data, it can be seen that there is no theoretical guidance for the selection of some key parameters in VMD: the selection of decomposition mode number and the determination of equilibrium constraints parameters, and the uncertainty of these parameters will also affect the performance of VMD. Through the analysis of simulation examples, it is proposed that the correlation between each mode after VMD decomposition and the original signal is the most important guidance. The smaller the equilibrium constraint parameter is, the larger the bandwidth of each modal component is, and the more likely the phenomenon of center frequency overlap and mode aliasing will occur. The larger the equilibrium constraint parameter is, the smaller the bandwidth of each component signal will be, and the phenomenon of center frequency overlap and mode aliasing will disappear. Through analysis, it is proposed that the general equilibrium constraint parameter can be taken as sample frequency f_s in practice.

In conclusion, the application of VMD algorithm to the acoustic signal characteristics of underwater plasma acoustic source pulse discharge is in line with the expectations, and the analysis of its acoustic signal characteristics is indeed enhanced. The algorithm for analyzing the acoustic signal characteristics of underwater plasma sound source pulse discharge is discussed, which can be used as a reference for the future development.

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