Research on Micro-EDM Discharge State Detection Technology Based on Inter Electrode Impedance Variation Characteristics

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Abstract: Aiming at the problem that it is difficult to detect the discharge state of narrow pulse width and small duty cycle pulse, this paper studies the variation characteristics of inter electrode impedance in micro-EDM process, puts forward a detection method to distinguish different discharge states in micro-EDM based on the change of electrical signal caused by the change characteristics. The influence of pulse width and duty cycle on the quality of micro-EDM is analyzed. The surface machining quality of workpiece can be improved obviously by compressing the pulse width of pulse power supply. And designs a discharge state detection system based on inter electrode impedance variation characteristics. Experiments verify the detection method, and test the machining effect of the control strategy through the trial machining experiment, which ensures that the micro-EDM process is efficient and stable.

Keywords: micro-EDM; impedance change characteristics; discharge state; detection and identification

1. Introduction

With the increasing demand for miniaturized components in industry [1,2], terahertz vacuum devices have developed rapidly in recent years [3]. In the field of terahertz communication, the precision of micro devices is required to be high, which requires the existing micro machining technology to be more precise and efficient. At present, the main technology methods that can be used for micro structure parts machining includes micro laser machining technology [4,5], micro milling technology [6,7], micro electrochemical machining technology [8], ion beam and electron beam machining technology [9], micro ultrasonic machining technology [10,11] and so on. Micro-EDM technology [12,13] has the advantages of no macro cutting force, non-contact, low requirements for tool strength and stiffness, wide application range of materials and can process deep micro holes and special-shaped cavity dies. It shows a good technical potential in the field of micro scale manufacturing, and is one of the effective means to solve the problem of micro manufacturing of difficult processing materials and micro scale structural parts. Through the preliminary investigation, it is found that with the narrowing of pulse width, the surface quality of EDM workpiece is higher. In the field of micro-EDM, in order to further improve the surface quality, scholars are exploring the pulse power supply with narrower discharge pulse width.

In order to realize the macro control of the gap inter electrode in EDM, many scholars have carried out a lot of research on the detection and recognition technology of EDM discharge state. As shown in Fig. 1, the recognition of EDM discharge state is mainly based on the detection of discharge signal in discharge gap, and the waveform of discharge signal collected by the detection circuit is different under different discharge states. The traditional EDM state recognition

technology includes average voltage detection technology, breakdown delay detection technology, high frequency signal detection technology and so on. In recent years, many scholars have studied the intelligent recognition of discharge state from the perspective of high-speed detection, data processing and intelligent recognition. In the aspect of intelligent recognition, some scholars use neural network recognition, fuzzy logic recognition, fuzzy neural recognition and other intelligent algorithms to realize the detection and recognition of discharge state.

Fig. 1 research field of micro discharge state detection

The average voltage detection technology is to judge the inter electrode discharge state by comparing the average voltage with the set threshold voltage. As shown in Fig. 2 is a common average voltage detection technology schematic diagram. The average voltage detection technology is widely used in the discharge state recognition of EDM, and can be applied to micro-EDM. However, the discharge state recognition strategy is relatively rough, which leads to low pulse utilization and seriously affects the machining efficiency. Pamidighantam S et al. [14] proposed an inter electrode pulse recognition system based on average voltage detection technology, which detects peak voltage, breakdown delay and other parameters, and then identifies the pulse. Guangmin Liu et al. [15] carried out theoretical research on the gap average voltage detection method in micro-EDM, and established the numerical model of the relationship between the steady value of average voltage and circuit parameters and pulse parameters.

Fig. 2 Schematic diagram of average voltage detection method

S. K. Bhattacharyya et al. [16] from Birmingham University have studied the high-frequency signal detection technology. The principle of this technology is to use the high-frequency signal on the gap voltage to distinguish arc discharge and spark discharge. There is a strong and stable high frequency signal in the gap voltage of spark discharge, and the high signal is weak in other states.

This method not only distinguishes spark discharge from arc discharge, but also further divides arc discharge into stable arc discharge and transitional arc discharge. Helong Sun [17] used high frequency detection method to distinguish arc discharge and normal spark discharge.

Other techniques to distinguish spark discharge from arc discharge in EDM also include breakdown delay detection technology [18]. R. Snoeys et al. [19] have studied the breakdown delay detection technology. The theoretical source of this method is that the breakdown delay time of arc discharge is different from that of spark discharge in EDM [20]. The schematic diagram of breakdown delay detection method is shown in Fig. 3. Using digital circuit to design the detection system can reduce the interference of switching devices on the detection results to a certain extent, but the breakdown delay detection technology cannot achieve the single pulse detection.

Fig. 3 Schematic diagram of breakdown delay detection method

Chunming Geng [21] researched the gap average pulse width voltage detection technology, as shown in Fig. 4. The basic idea of the technology is to abandon the pulse interval voltage waveform, only detect the voltage value at the pulse width, and get the average voltage detection signal through the filter circuit.

Fig. 4 Schematic diagram of average pulse width voltage detection method

In the aspect of data processing, wavelet transform can analyze the time-frequency domain of signal and express the local details of signal in time domain and frequency domain [22]. Jiang Y et al. [23,24] used wavelet transform to detect and identify inter electrode discharge state in micro-EDM small hole machining. The method distinguishes single pulse discharge based on the low frequency coefficient of wavelet transform. The schematic diagram of the EDM gap discharge state detection system is shown in Fig. 5. The basis of judging the pulse discharge state is to use the

wavelet transform results of the local peak value of the low frequency coefficient. The smaller local peak value corresponds to the shorter breakdown delay, and the higher local peak value corresponds to the longer breakdown delay, which is similar to the breakdown delay detection method. Wavelet transform is used to analyze the data collected in micro-EDM process. Compared with single detection method, wavelet transform can obtain more comprehensive information.

Fig. 5 Schematic diagram of wavelet transform detection system

The principle of fuzzy logic identification of micro-EDM discharge state is shown in Fig. 6. The voltage and gap current of input signal are fuzzy processed by fuzzy identifier. Then, according to the expert experience and knowledge, the corresponding rules are established, and the fuzzy reasoning method is used to identify the pulse type.

Fig. 6 Schematic diagram of fuzzy discharge state identification

Y. S. Tarng et al. [25,26] developed a fuzzy recognition system of micro-EDM gap state. The input of the fuzzy recognition system is gap current and voltage. At the same time, simulated annealing algorithm is applied to the fuzzy recognition system of discharge state, and the membership function structure is optimized to realize the recognition of gap discharge state. Jia ZY et al. [27] studied the step-by-step mapping detection method, which can be used to distinguish the pulse state of micro-EDM. With the development and rise of artificial intelligence, more and more researchers regard intelligent detection as a research hotspot.

Through the comprehensive analysis of the research results of scholars, it can be seen that when using narrow pulse width and small duty cycle pulse power supply for micro-EDM, the discharge state is complex, and the discharge state detection and identification circuit is greatly disturbed; At

the same time, due to the narrower pulse width, it is difficult for the detection circuit to capture the discharge process of a single pulse. Gap average voltage detection technology is the most commonly used. Although the principle of this method is uncomplicated, the way of threshold setting is relatively simple. In actual processing, the parameters of pulse power supply need to be changed, so its adaptability needs to be improved. At present, the main problems is: for the new type of narrow pulse width and small duty cycle pulse, it is difficult to realize the detection and recognition of discharge state due to the narrow pulse width and small duty cycle, so it is necessary to explore new detection methods of discharge state.

Micro-EDM technology has been considered as one of the suitable choices to meet the growing demand of miniaturization. With this unconventional processing technology, the conductive and semiconductor materials can be precisely processed. Inter electrode discharge state detection technology is a necessary technology to ensure the stability of micro-EDM.

In this paper, a new method is proposed to detect the discharge state of micro EDM with narrow pulse width and small duty cycle. A discharge state detection system based on inter electrode impedance variation characteristics is designed. The threshold setting of the detection system does not change with the change of the parameters of the pulse power supply, but is only related to the inherent parameters of the components of the detection circuit, so it has better adaptability. A control strategy based on the current direction and discharge state is proposed. It provides a new idea and technical feasibility scheme for the field of micro EDM discharge state detection, and lays a foundation for realizing the discharge state detection of narrow pulse width and small duty cycle pulse power supply.

2. Principle and simulation analysis of discharge state detection based on inter electrode impedance variation characteristics

As the inherent characteristic of electrical system, impedance does not change with the change of input signal, and its change can reflect the change of electrical system. The discharge state of EDM can be divided into open circuit, normal discharge, transitional arc discharge, stable arc discharge and short circuit [28]. Because it is difficult to identify the state of arc discharge and transition arc discharge, these two states are ignored in this study, only three discharge states are detected and identified, namely open circuit, normal discharge and short circuit, and combined with the corresponding discharge state for control.

2.1 Equivalent model of inter electrode impedance

The pulse discharge process can be divided into three stages: ionization preparation stage, discharge thermal etching stage and deionization stage. In the ionization preparation stage, no discharge channel is formed, because there is no breakdown inter electrode under the current voltage, the electric field strength inter electrode increases, but no current is formed, and the capacitor between the positive and negative electrodes is in the process of charging. When the electric field intensity inter electrode increases to a large enough level, the dielectric inter electrode will break down and form a discharge channel, which is the stage of discharge heat etching, and a large amount of plasma will be produced. Under the influence of electric field, the charged particles in the dielectric collide with the dielectric violently, and the plasma is hindered in the process of high-speed motion between the electrodes, so there is impedance inter electrode. In the stage of

discharge thermal etching, charged ions form conductive channels, and there is current inter electrode, which proves that there is a magnetic field between the positive and negative electrodes, so the inductance also exists in the channel. In the deionization stage, the inter electrode plasma channel disappears and the inter electrode plasma channel returns to the state before discharge. The analysis of the pulse discharge process above shows that the capacitor state exists independently before the formation of the discharge channel, so the capacitor should be independent. When the discharge channel is formed, the inductance and resistance characteristics are caused by the behavior of the inter electrode plasma discharge channel, so the equivalent resistance and inductance between the electrodes are connected in series [29,30], as shown in Fig. 7. The equivalent model of inter electrode impedance as shown in the figure is obtained, including typical resistance, inductance, capacitance and other principle devices. The impedance at a certain time between the positive and negative poles P + and P - can be expressed as equation (1).

Fig. 7 Equivalent model of inter electrode impedance

$$Z(t) = \frac{1}{\frac{1}{R(t) + j\omega L(t)} + j\omega C(t)} \quad (1)$$

2.2 Analysis of variation characteristics of inter electrode impedance

Electrical impedance is a very important characteristic of electrical system. For electrical system, impedance Z is usually the ratio of voltage V and current I in frequency domain. In the time domain impedance calculation, the voltage and current in the actual representation are converted into the corresponding complex representation, and the converted signal is called the analysis signal. Then the impedance can be calculated by dividing the analytical voltage by the analytical current. The impedance can be expressed by the real and imaginary parts of the complex number. The real part represents resistance and the imaginary part represents capacitance and inductance.

$$Z(t) = R(t) + jX(t) \quad (2)$$

Combined with the fast Fourier transform FFT, the impedance at a given frequency is obtained. In order to get the impedance in time domain and study its changing trend with time, the measured voltage and current are converted into corresponding analysis signals by Hilbert transform, and then the impedance is calculated. Finally, the following equation (3) is obtained to evaluate the electrical impedance.

$$Z = \frac{V(t)}{I(t)} e^{j(\phi_1 - \phi_2)} \quad (3)$$

It can be seen from equation (3) that under different states of micro EDM, the value of inter electrode impedance is different. The inter electrode impedance in open circuit is greater than that in spark discharge, and the inter electrode impedance in spark discharge is greater than that in short circuit.

It can be concluded that before the dielectric breakdown between the electrodes, the impedance between the electrodes is high; When a discharge channel is formed inter electrode [31], they are in a medium impedance state; When the inter electrode gap is zero, the inter electrode impedance is low. In the process of machining, the formation and disappearance of inter electrode plasma channel will affect the voltage amplitude between positive and negative poles, which is the characterization of the change of inter electrode impedance.

2.3 Principle of discharge state detection based on inter electrode impedance variation characteristics

Based on the characteristics of the inter electrode impedance analyzed above, a new detection circuit is designed, as shown in Fig. 8. Its principle is to set an independent constant voltage power supply DC in the detection circuit as the detection reference source. In the open circuit state, the current cannot flow through the diode D2 because of the large impedance, and the resistance R1 and R2 form a loop with the power supply DC; When the inter electrode gap is zero, that is, after the short circuit between positive and negative electrodes, the inter electrode impedance is close to zero, and the voltage U_s will decrease. At this time, diode D2 and resistance R3 are also connected to the detection circuit; In the spark discharge state, the dielectric is broken down, and the inter electrode impedance changes. The impedance value is greater than that in the short circuit state but less than that in the open circuit state. The magnitude of the voltage U_s in the detection circuit varies with the impedance value or the inter electrode discharge state. Therefore, the discharge state between electrodes in micro-EDM can be obtained by measuring the amplitude of U_s .

Fig. 8 Circuit diagram of impedance detection method

In the open circuit state, the value of U_s is U_{open} :

$$U_{open} = E \frac{R_2}{R_1 + R_2} \quad (4)$$

In the state of spark discharge, the value of U_s is U_{spark} :

$$U_{spark} = E \frac{R_2 // (R_3 + Z(t))}{R_1 + R_2 // (R_3 + Z(t))} \quad (5)$$

In the short circuit state, the value of U_s is U_{short} :

$$U_{short} = E \frac{R_2 // R_3}{R_1 + R_2 // R_3} \quad (6)$$

According to the characteristics of impedance change inter electrode, the state change of micro-EDM process can be effectively identified by means of external power supply, which provides the basis of control strategy for micro EDM process.

2.4 Simulation analysis of discharge state detection circuit

According to the change characteristics of inter electrode impedance and the principle of detection circuit mentioned above, the simulation circuit as shown in Fig. 9 is constructed to simulate the circuit model. The schematic diagram of the simulation model of the inter electrode state switching module is shown in Fig. 10. The voltage controlled switch is used to realize the change and switching of the inter electrode impedance state. Through the setting of the model, the effective rate of inter electrode spark is 40%, and the periodic pulse waveform of spark discharge, open circuit and short circuit can be obtained. As the detection object, the effectiveness of impedance detection method can be judged by circuit simulation.

Fig. 9 Simulation principle diagram of impedance detection method

Fig. 10 Simulation model of inter pole state switching

Using the simulation circuit model of discharge state detection designed in the previous paper, the simulation experiment is carried out for the detection effect of pulse power supply under different duty cycle conditions. In the actual simulation process, the cycle of pulse power supply is $10\mu\text{s}$. The pulse width is $1\mu\text{s}$, 500ns , 100ns , 50ns , 10ns , get the detection waveform as shown in Fig. 11.

Fig. 11 Simulation waveform of impedance detection method

It can be seen from the detection waveform of oscilloscope that the detection circuit based on impedance change characteristics can achieve good detection effect for different duty cycle of pulse power supply.

3. Design of micro-EDM discharge state detection system

Based on the detection principle in the previous paper, the circuit design and the design of each part of the function module are carried out, and the discharge state detection system is constructed to realize the complete detection and control function of the system.

3.1 Overall design of detection system

The overall functions of the detection system include inter electrode voltage signal acquisition function, detection system and pulse control board communication function and control signal output function. The overall hardware scheme of the detection system is shown in Fig. 12.

Fig. 12 Hardware system architecture of impedance detection module

STM32F103 is selected as the core chip of the detection system. 232 unit realizes the communication function between the detection system and the pulse control board, and obtains the power control parameters related to the pulse control board. The state signal inter electrode is transformed into voltage signal after being processed by impedance detection circuit, and then enters ADS8681 data acquisition chip after isolated operational amplifier. The main control chip STM32 communicates with ads8681 data acquisition chip and obtains voltage data through SPI bus.

According to the hardware system scheme, the modular design is carried out, and the main function modules are shown in Fig. 13.

Fig. 13 Function module of detection system

3.2 Module design of detection system

(1) System power module

The positive and negative 12V voltage is provided by the external interface, and the voltage parameters used in the detection system are: 12V, 5V, 3.3V, etc., so it is necessary to design the power conversion module of 12V to 5V, 5V to 3.3V, 5V to 12V.

In order to realize the voltage conversion from 12V to 5V, LM2596 [32] switching voltage regulator is selected, AMS-1117 low-voltage linear regulator is used to realize the voltage conversion from 5V to 3.3V, and WRA0512SDC / DC module power supply is used to realize the voltage conversion from 5V to 12V.

(2) Serial communication module

In order to realize the communication between the detection system and the pulse control board, so that the detection system can obtain the inter electrode pulse parameters and other information, including perception or processing, whether the inter electrode chip removal environment is good or not, need to design the serial communication between the detection system and the pulse control board. This paper uses TD301D232H single channel high-speed RS232 isolated transceiver module. The function of serial communication is to realize the communication between the detection system and the pulse control board. The pulse control board sends the pulse parameters such as duty cycle to the detection system, and the detection system sends the threshold information to the pulse control board. With this module, TTL level can be converted to RS232 level to realize signal isolation and RS232 protocol network connection function. The circuit principle is shown in Fig. 14.

Fig. 14 Hardware circuit of serial communication

The protocol of serial communication is shown in Table 1, with 0XFF as the start flag, and the consecutive 9 bytes after the start flag contain the data of communication between the detection system and the pulse control board. When the detection board sends the serial port receiving interrupt, it judges whether it is the start flag and carries out data receiving processing. After receiving a group of data, it sends the received data to the pulse control board for data verification. When the pulse control board sends the 0X01 confirmation character to the detection system, the flag data transmission is correct. At this time, the detection system will store the received data.

Table 1 Data communication protocol

Array elements	parameter information
RXBUFFER[0]	0xff data frame start identification
RXBUFFER[1]	SVH open circuit voltage threshold
RXBUFFER[2]	SVL short circuit voltage threshold
RXBUFFER[3]	SIH_H open circuit voltage threshold high byte
RXBUFFER[4]	SIH_L open circuit voltage threshold low byte
RXBUFFER[5]	SIL_H circuit voltage threshold high byte
RXBUFFER[6]	SIL_L circuit voltage threshold low byte
RXBUFFER[7]	ax duty cycle
RXBUFFER[8]	Imax_h Max short circuit current high byte
RXBUFFER[9]	Imax_l Max short circuit current low byte

(3) Data acquisition module

In the data acquisition module, ADS8681 is used as the acquisition chip in this system. The inter electrode signal processing path is shown in Fig. 15. The inter electrode voltage signal X1 is filtered by the impedance detection circuit. The processed signal X2 is isolated by the isolated operational amplifier after passing through the resistance capacitance low-pass filter. The signal X4 is used as the input signal of ADS8681 chip by the operational amplifier; STM32's SPI is used to communicate with ADS8681, which is used to obtain the voltage data collected by the data acquisition chip.

Fig. 15 Inter electrode signal processing path

(4) DAC output module

TF6550GN high precision signal conditioning module is used to realize control signal output. The schematic diagram of DAC output circuit designed in this paper is shown in Fig. 16.

Fig. 16 Hardware circuit of DAC output module

3.3 Program design and control strategy analysis

Based on the hardware design, the software system design of the detection system is shown in Fig. 17. The main function, 232 interrupt function and timer interrupt function handle different tasks respectively. The system software is based on Keil μ Vision5 development system is completed by C language, including main program and subroutine. The flow chart of main program is shown in Fig. 18.

Fig. 17 Overall design of detection system software

Fig. 18 Main function flow chart

Fig. 19 Flow chart of state detection

The flow chart of state judgment program in micro-EDM process is shown in Fig. 19. Using STM32's SPI bus to read the data acquisition results, and accumulates the results. After reaching the set number, the average value is calculated, and the inter electrode discharge state is obtained by comparing the average value with the threshold value. According to the scheme in the control strategy table, different control strategies are selected according to the state and the feed direction of the axis of the CNC system, and the control signal is output to control the feed of the axis of the CNC system.

In order to realize high efficiency and high quality machining of micro EDM, different control strategies are proposed based on the feed direction of CNC system axis in different states of micro EDM process. As shown in Table 2,

Table 2 Control strategy table

state	stage	Strategy number
open circuit	In progress ($V > 0$)	1-Slow acceleration
	Falling back ($V < 0$)	2-Speed up
discharge	In progress ($V > 0$)	3-Slow down
		4-Slow acceleration
	Falling back ($V < 0$)	5-Speed up
short circuit	In progress ($V > 0$)	6-Slow down
	Falling back ($V < 0$)	7-Maximum value of return speed

4. Experimental verification of discharge state detection system

4.1 Experimental scheme and test platform

Build the test environment as shown in Fig. 20 to carry out the test experiment of the discharge state detection system, select the function signal generator as the signal source, PI power amplifier to amplify the signal source, and use the amplified pulse as the pulse source. The workpiece and electrode are connected to the discharge circuit, and the input signal is obtained by collecting the voltage signal between electrodes through the discharge state detection system. The discharge state detection system judges the state of the input signal and outputs the control signal to the feed shaft to control the tool electrode forward or backward.

Fig. 20 Schematic diagram of verification experiment system

As shown in Fig. 21, the discharge state detection system designed in this paper integrates the gap average voltage detection method and the detection methods based on inter electrode impedance variation characteristics. Firstly, the functional modules of the detection system are tested, including data acquisition module test and serial communication test; In order to ensure the safety of the electrode, the corresponding delay time of different positions of the detection system was tested; Test and verify the control strategy mentioned above, when different states appear between poles, check whether the output control signal of the system conforms to the set rule.

Fig. 21 Micro-EDM discharge state detection system

Fig. 23 Serial port test result chart

4.3 Test of output control strategy of test board

After the detection system identifies the inter electrode state through data acquisition and processing, the strategy adopted is not only related to the current discharge state and processing environment, but also related to the CNC feed direction at this time. The feed direction under different discharge states is distinguished, and different control strategies are adopted. As shown in Fig. 24, it is a typical waveform of control signal output in case of continuous short circuit.

Fig. 24 Waveform between poles and DAC output waveform during continuous short circuit

When there are multiple short circuits and continuous open circuits inter electrode, the detection system will dynamically adjust the upper limit value of the control signal according to the corresponding discharge state, as shown in Fig. 25, which shows the inter electrode DAC output waveform under different states. As shown in Fig. 25 (a), when there are multiple short circuits inter electrode, the upper limit value of the speed decreases continuously. When the short circuit inter electrode begins, the DAC decreases rapidly. However, due to the multiple short circuits inter electrode, the upper limit value of the speed has been adjusted. When there is an open circuit, the DAC keeps the adjusted upper limit value output. As shown in Fig. 25 (b), when the inter electrode are in continuous open circuit, if the upper limit of speed has not been adjusted to the maximum value, the detection system will dynamically adjust the upper limit of speed, so when the inter electrode are in continuous open circuit, the DAC output waveform presents the shape of ladder rise.

Fig. 25 DAC output waveforms in different states between poles

4.4 Detection effect under different pulse power parameters

(1) Amplitude of pulse power supply

The signal generator + PI power amplifier is used as the pulse source to test the detection board. Different voltages are set to test the threshold setting of resistance partial voltage detection method and impedance detection method respectively. The schematic diagram of the test circuit is shown in Fig. 26. The oscillography is used to collect the waveform images of different positions. Channel 1 is the collected inter electrode voltage, channel 2 is the DAC output, and channel 3 is the waveform after the resistance partial voltage detection filter module or impedance change detection filter module.

Fig. 26 Schematic diagram of test circuit of detection system

Function signal generator and PI power amplifier are used as pulse power supply to test gap average voltage detection method and detection method based on inter electrode impedance variation characteristics. The peak to peak parameters of signal source are set as shown in Table 3. Under this condition, using gap average voltage detection method and detection method based on inter electrode impedance variation characteristics to set threshold respectively. The threshold setting is shown in Table 4. When the peak to peak value of the signal source is 5V, the processing state is judged after the threshold is set, and the waveform when the continuous short circuit occurs is shown in Fig. 27. From top to bottom, it is the collected inter electrode voltage, the waveform after the detection and filtering module and the DAC output waveform.

Table 3 Power amplifier output when tested by different detection methods

Serial number	Signal source peak to peak / V	Frequency / kHz	Duty cycle / %	Power amplifier output value / V	
				Average voltage detection	Impedance change detection
1	1	10	50	20	20
2	2	10	50	36	40
3	3	10	50	52	46
4	4	10	50	68	66
5	5	10	50	84	88

Table 4 Threshold setting under different amplitude conditions

Serial number	Gap average voltage detection method				Detection method based on impedance change			
	VOS	SEC	VH	VL	VOS	SEC	VH	VL
1	0.0194	3.0432	2.8932	2.0311	0.0278	6.1260	5.9760	4.1915
2	0.0402	5.5313	5.3813	3.7790	0.0237	6.1254	5.9754	4.1899
3	0.0211	8.0067	7.8567	5.5060	0.0181	6.0971	5.9471	4.1684
4	0.0335	8.2919	8.1419	5.7094	0.0115	6.1164	5.9664	4.1799
5	0.0439	8.2928	8.1428	5.7131	0.0118	6.1197	5.9672	4.1823

(a) Gap average voltage detection method**(b)** Detection method based on inter electrode impedance variation characteristics**Fig. 27** Continuous short circuit waveform

(2) Duty cycle of pulse power supply

Different duty cycle of pulse power supply are set, and the influence of different duty ratios on the threshold setting of detection method based on inter electrode impedance change characteristics is analyzed. The experimental data are shown in Table 5. The duty cycle ranges from 2% to 50%, as shown in Fig. 28. The voltage values VOS, SEC, VH and VL collected in short circuit, open circuit under different duty cycles are relatively smooth horizontal lines, which proves that the threshold setting of the detection method based on the change characteristics of inter electrode impedance is not affected by the duty cycle of pulse power supply.

Table 5 Threshold setting under different duty cycles

Serial number	Duty cycle%	VOS	SEC	VH	VL
1	50	0.0111	6.1220	5.9720	4.1837
2	40	0.0013	6.1173	5.9673	4.1805
3	30	0.1129	6.1167	5.9667	4.1800
4	20	0.0112	6.1117	5.9617	4.1766
5	10	0.0112	6.1179	5.9679	4.1809
6	5	0.0112	6.1175	5.9671	4.1806
7	2	0.0113	6.1162	5.9662	4.1797

Fig. 28 Threshold setting under different duty cycles

4.5 Experimental verification of trial machining based on Inspection Board

The detection system based on inter electrode impedance variation characteristics is applied to the micro modular electrical machining machine tool to test the feasibility of the system for measuring and controlling the discharge process. As shown in Fig. 29, after the discharge pulse is applied to the positive and negative poles, the velocity displacement curve appears when the positive and negative poles are quickly short circuited by wires. In the open circuit, keep the maximum speed forward under the limit of the upper speed threshold. When there is a short circuit or spark discharge, adjust the speed dynamically in time.

(a) The process of speed Continuous reduction

(b) The process of speed dynamic adjustment

Fig. 29 Velocity displacement curve during machining

Using the detection system based on the variation characteristics of inter electrode impedance for drilling trial processing. The voltage signal information in the processing process is collected by the oscilloscope, and the waveform as shown in Fig. 30 is obtained. From top to bottom, the collected inter electrode voltage, the waveform after the detection and filtering module and the DAC output waveform are respectively obtained.

Fig. 30 Waveforms at different positions during machining

As shown in Fig. 31, the velocity displacement curve of the machining process, because the electrode does not rotate during the machining process, the electrode retreats many times, and the velocity changes and fluctuates greatly.

Fig. 31 Velocity displacement curve during machining

5. Conclusion

In order to solve the problem that the adjustment of pulse parameters will affect the accuracy of threshold setting when the existing detection technology is applied to the state detection and recognition of narrow pulse width and small duty cycle pulse electrical discharge machining process, this paper analyzes the change characteristics of inter electrode impedance in micro-EDM process. A detection method is proposed to distinguish different discharge states of micro-EDM based on the change of electrical signal caused by the change. The main contents of this paper include: the research on the change characteristics of inter electrode impedance of micro-EDM, the design of discharge state identification and detection system, and the test of discharge state detection system. The main research work and conclusions are as follows.

(1) The characteristics of inter electrode impedance of micro-EDM are analyzed. The influence of pulse width and duty cycle on the quality of micro EDM is summarized, and the breakdown

mechanism of micro-EDM is analyzed. From the mechanism of micro-EDM, the equivalent model of inter electrode impedance is analyzed, and the inter electrode equivalent model composed of variable resistance, variable capacitance and variable inductance is established.

(2)The discharge state detection system is designed. This paper puts forward the overall design scheme, carries out the peripheral circuit design with STM32F103 core, and completes the design of each functional module according to the overall design scheme. The overall design of the program, divided into functional modules, completed the realization of the main function and peripheral driver, analyzed the control strategy of the discharge state detection system, and proposed the control strategy based on the current electrode feed direction and discharge state.

(3)The test of the discharge state detection system is carried out, and each functional module of the detection system works normally through the modular test. Through the output control strategy test, the control strategy based on the given direction and discharge state of the spindle is realized. The threshold setting of the gap average voltage detection method will change with the change of voltage amplitude, while the detection method based on the inter electrode impedance variation characteristics is almost unaffected. And the threshold setting of the detection method based on the inter electrode impedance variation characteristics has nothing to do with the duty cycle of the pulse power supply.

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