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An on-line pulse trains analysis system of the wire-EDM process

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ABSTRACT

Ignition delay time (Td) has been widely used to distinguish the abnormal discharges from the normal ones in wire electrical discharge machining (WEDM) process. In this paper an on-line analysis system for the causality of the Td data sequences was developed to evaluate the machining performance of WEDM process. The system is composed of a stand-alone Td processing circuitry and a user-friendly computer program for data analysis. The Td processing circuitry calculates and records the Td of every single electrical discharge in the first place, and then transmits the Td data via an embedded communication port to a desktop or notebook computer. The computer program, after performing the analysis tasks, will display the result in a graphic way. Two mathematical algorithms were employed for the analysis: autocorrelation function and Fourier transform. Through experiments under different working conditions, it was found that the autocorrelation function could be used to detect if arc or short circuit discharges take place consecutively, and to distinguish the WEDM process with similar Td distributions. On the other hand, the spectral analysis revealed that several factors were identified to be able to induce certain periodic patterns of Td data. These factors include the length of wire electrode, the water pressure, etc.

1. Introduction

The machining performance of the wire electrical discharge machining (WEDM) process lies in the discharging condition between the electrodes. However, since the gap between the electrodes is too small to be observed directly, the discharging condition can only be monitored by way of examining the discharge waveforms, i.e. the waveforms of the gap voltage and the discharge current.

The beginning of waveform analysis in EDM process dates back to 1970s. Snoeys and Cornelissen (1975), by comparing the variation of gap voltage, classified the discharging condition into four categories—effective discharge, arc, short circuit and open circuit. In the CIRP conference in 1979, the CIRP Scientific Technical Committee E, in its Summary Specification of Pulse Analyzer for Spark-Erosion Machining, suggested that the types of discharge waveforms could be divided into four categories to represent the normal, arc, short circuit, and open discharges. For the WEDM process, Watanabe et al. (1990) proposed that the discharge waveform could be put into three categories – normal, deion and arc – through the study of current peak, spark voltage, current pulse length and pulse energy. Later on, Liao and Woo (1997) developed a waveform discrimination system by way of measuring the time period from the rising of gap voltage to the starting of ignition current.

The researches mentioned above were mostly based on the waveform discrimination and the statistics of discharge pulse trains. From the mathematical point of view, the physical nature of the electrical discharges in WEDM is a stochastic process. On the other hand, the process is made up by a series of electrical discharges. Since the discharge is ignited one after another, the discharges are also a sequence of events with causality themselves. Hence the electrode gap condition made and left by the previous discharges would inevitably affect the present and following discharges.

This study is devoted to develop an on-line system to investigate the causality of the electrical discharges in WEDM process. The system includes both hardware and software components. The hardware component is a microcontroller-based circuitry for recording the Td data during the WEDM process and then, via RS-232 interface, transferring the data to a personal or notebook computer for further processing by the software component. The software component is a multi-window calculation and displaying program, performing the autocorrelation function and the spectral analysis of the Td data received form the hardware component. Several experiments were conducted, with the developed system, to confirm the validity of the system.

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2. Algorithms

In order to investigate the causality of the Td data, two of time series methods were employed in this study: autocorrelation function and the spectral analysis. The autocorrelation function is to identify the possible existence of consecutively repeated sequence in the Td data trains. The spectral analysis, based on the technique of Fast Fourier Transform (FFT), is to explore the periodic patterns, if any, in the Td data trains. In addition to these two mathematical methods, the Td distribution is also presented by the developed system to reveal the statistic nature of the Td data.

2.1. Autocorrelation function

The autocorrelation function of Td data is expressed as Eq. (1).

$$\rho_k = \frac{(1/(n-k))\sum_{t=1}^{n-k}(\mathrm{Td}_t - \overline{\mathrm{Td}})(\mathrm{Td}_{t+k} - \overline{\mathrm{Td}})}{(1/n)\sum_{t=1}^{n}(\mathrm{Td}_t - \overline{\mathrm{Td}})^2} \quad (1)$$

where n is the size of the Td data series ($n = 1024$ in this study). Td time series data is denoted as Td_t with subscript t as the sequence number. $\overline{\mathrm{Td}}$ is the mean value of the Td_t, and k is the sequence shift (or time lag). The resulted ρ_k means the autocorrelation coefficient of time lag k.

The autocorrelation function of a data series describes the correlation between the different data points in sequence. If the ρ_k is zero regardless the lag k, it means the Td data series are inter-independent and implies that the electric discharge process of WEDM is a genuine random process. Otherwise, the Td data series might be inter-correlated to each other in some extent.

2.2. Spectral analysis

In electrostatics, the intensity of the electrical field between a pair of electrodes is inversely proportional to the gap width between the electrodes, given the electrical potential across the electrodes is fixed. Since the electrical discharges would be easier to be ignited in an intensive electrical field, a narrower electrode gap width would result in a shorter corresponding Td, and vice versa theoretically.

There are many factors that may impose influences on the discharge gap (electrode gap) width, so as the Td duration. These factors include the vibration of the WEDM machine itself, the machining debris in the discharging process, the spraying pressure of working fluid (de-ionized water), the external vibration onto the workpiece from any sources, and even the intrinsic feedback oscillation of the ignition circuitry (Fig. 1).

One of the widely suspected factors imposing influences on the Td duration is the mechanical wave induced over the wire electrode.

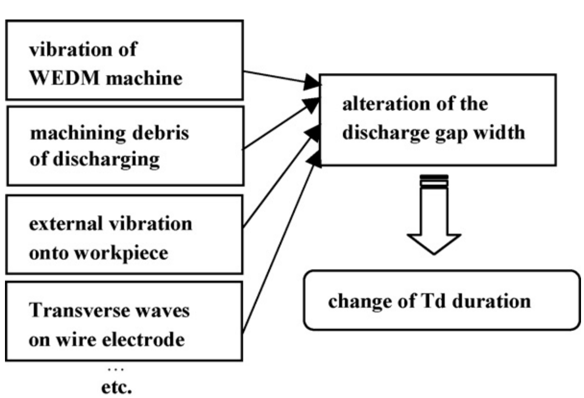

Fig. 1. The probable causes contributed to the discharge gap width, so as to the Td duration.

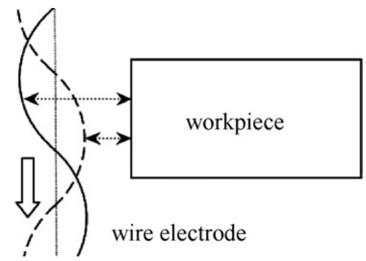

Fig. 2. Illustration of the change of the gap width between the electrode and the workpiece due to running waves along the wire electrode. The arrow represents the moving direction of the waves.

In WEDM machines, the wire electrode is constantly maintained in a fixed length with predetermined longitudinal tension throughout the machining process. During the short period of ignition "on time," an external electromagnetic force due to the ignition current is exerted onto the wire electrode. Since the wire electrode can be taken as a simple string, this intermittent external force may, in theory, induce a transverse mechanical wave running along the wire electrode, imposing a periodical alternation the gap width between the wire electrode and the workpiece, as illustrated in Fig. 2.

However, how much influence would be imposed onto the Td duration by every individual factor is a complicated question to be answered, because these factors may confound with each other among themselves. From a systemic point of view, the electric discharging process itself could be taken as a black box with input variants such as the servo voltage, the discharge energy, the feed rate of workpiece, the speed and tension of wire, etc. In the mean while, the output of the black box could be the Td data or some other index regarding the machining performance, as designated.

Under such presumption, the major question raised herewith is that: Are these factors, together or separately, could induce periodic patterns of Td data which can be revealed in spectrum? To answer the prerequisite question, Fast Fourier Transform was introduced for spectral analysis of the Td data in this study.

3. System configuration

The system developed in this study is composed of hardware and software, whose configurations will be introduced respectively as followings.

3.1. Hardware configuration

The stand-alone hardware device for Td measuring and recording is a combination of four subunits as displayed in Fig. 3:

1. High-voltage differential probe.
2. Ignition current detection probe.
3. Waveform rectification circuit.
4. Td measuring/recording unit.

3.1.1. High-voltage differential probe

To detect the voltage gap between two electrodes, PINTEK DP-100 high-voltage differential probe was used in the study. This voltage probe is the only commercial product employed in the system. The bandwidth of the probe is 100 MHz which guarantees the fidelity of the input voltage signal. Along with the input voltage tolerance of 6500 V, the input impedance is as high as 54 MΩ which ensure that the WEDM process is not interfered by the proposed system.

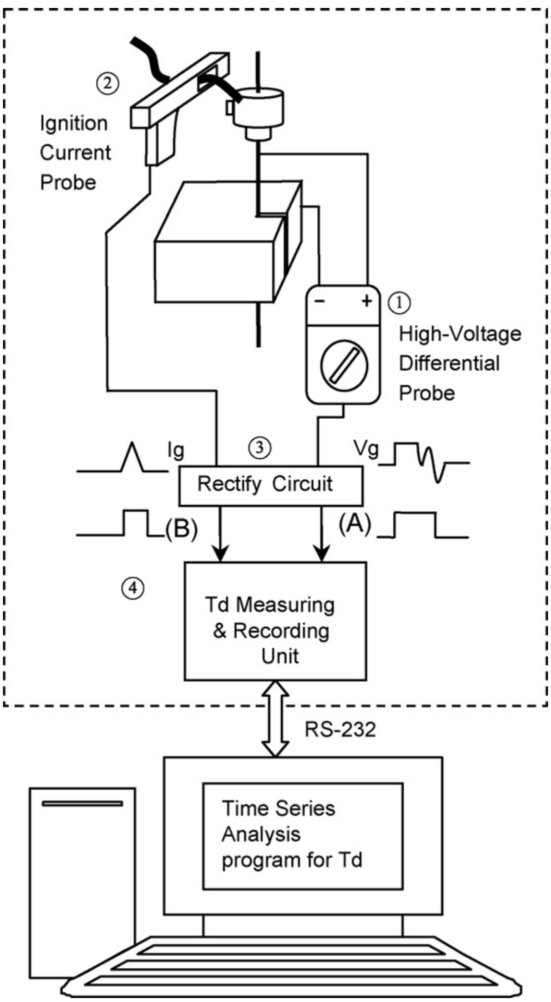

Fig. 3. Configuration of the developed on-line analysis system and its connection to the WEDM machine and the personal computer.

3.1.2. Ignition current detection probe

Td is defined as the time interval from the beginning of voltage applied across the electrodes to the occurrence of ignition current between the electrodes. The voltage across the electrodes is measured through the PINTEK DP-100 probe described above, while the start of ignition current is detected by the ignition current detection probe developed in another related study conducted by the authors of this paper. The probe is comprised of an induction coil and a concise high-speed op-amp circuit. In previous studies regarding the detection of ignition current, high-precision current probes and amplifiers are indispensable for acquiring accurate current measurement. However, these two equipments are both very expensive. Since the major concern of the ignition current in this study is not its current value but its occurrence time, the induction coil of the clamp meter is capable enough of being a current sensor to serve the purpose. At the moment of ignition, the inducting coil will generate a responding current spike which was rectified into a square wave pulse. The validity of the developed probe is showed in Fig. 4. The ignition current signals acquired by TEKTRONIX AM503S current probe (channel 1) and by the developed probe system (channel 2) are shown in Fig. 4 for comparison. The "homemade" ignition current detection probe was found as good as the high-precision and high-price current probe and amplifier combination, in terms of detecting the occurrence time of the ignition current.

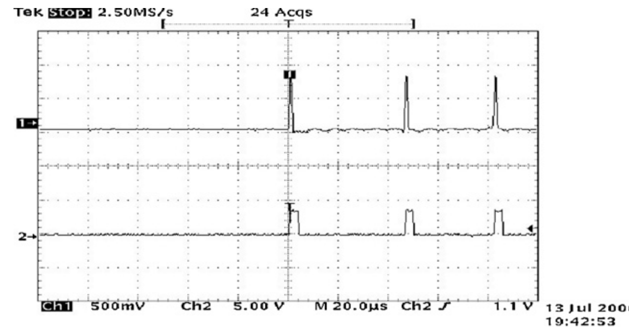

Fig. 4. The ignition current signals acquired by TEKTRONIX AM503S current probe system (channel 1), and by the developed probe (channel 2).

3.1.3. Waveform rectification circuit

The measurement of Td is carried out by the digital circuitry of the Td measuring/recording unit, which will be described later. However, the original voltage and current waveforms taken through the probes are both analog. Therefore, a waveform rectification circuit is deigned to convert the original analog waveforms into the digital ones before they are introduced into the Td measuring/recording unit.

3.1.4. Td measuring/recording unit

When the rectified voltage and current waveforms are introduced into the Td measuring/recording unit, the Td is measured by the microcontroller and recorded in the embedded memory chips of the unit. After certain electric discharges, for example 1000 discharges, are recorded, the unit will transfer the Td data in a lump sum, via RS-232 interface, to the personal computer for time series analysis of Td.

This unit plays a central role in the whole system. The key component is an 89C52 microcontroller, which was chosen for its cost-effectiveness. Although 89C52 cost only $4 USD per piece, its clock rate can be raised up to 66 MHz, a speed able to serve the need of this study. It also comes with a build-in serial port (RS-232), which can transfer data to the computer at as high as 115,200 bps.

3.2. Software configuration

The analysis program developed in this study is based on the design of software modules. The "front panel" of the program, as shown in Fig. 5, is a combination of several "windows." Each window represents a software module performing a specific function. That is to say, if there is a need of a new function, the only thing has to do is just to write a software module to replace any one of the existed module on the panel.

In Fig. 5, window ②, and ③ are for monitoring the incoming Td data to make sure that there is no data lost during the data transfer process. Window ④ is the graphic representation of Td pulse trains, in which the *x*-axis is the time scale, and the *y*-axis is the duration of Td. A total of 1024 Td data are presented in the graphic chart, through which the user could have a general idea about the nature of the incoming Td data trains. In order to get a closer observation of the Td data trains, there is a moving window for the user to choose the data segment wanted to be enlarged in the window ⑤. Window ⑥ is the Td distribution chart of the incoming 1024 Td data. To its right is window ⑦, which is the FFT of the Td data series, a Fourier transform of the graphic chart of window ④. Window ⑧, located at the right lower corner of the panel, is for the showing of autocorrelation.

4. Experiments

In order to verify the validity of the system, several experiments were conducted under controlled machining conditions.

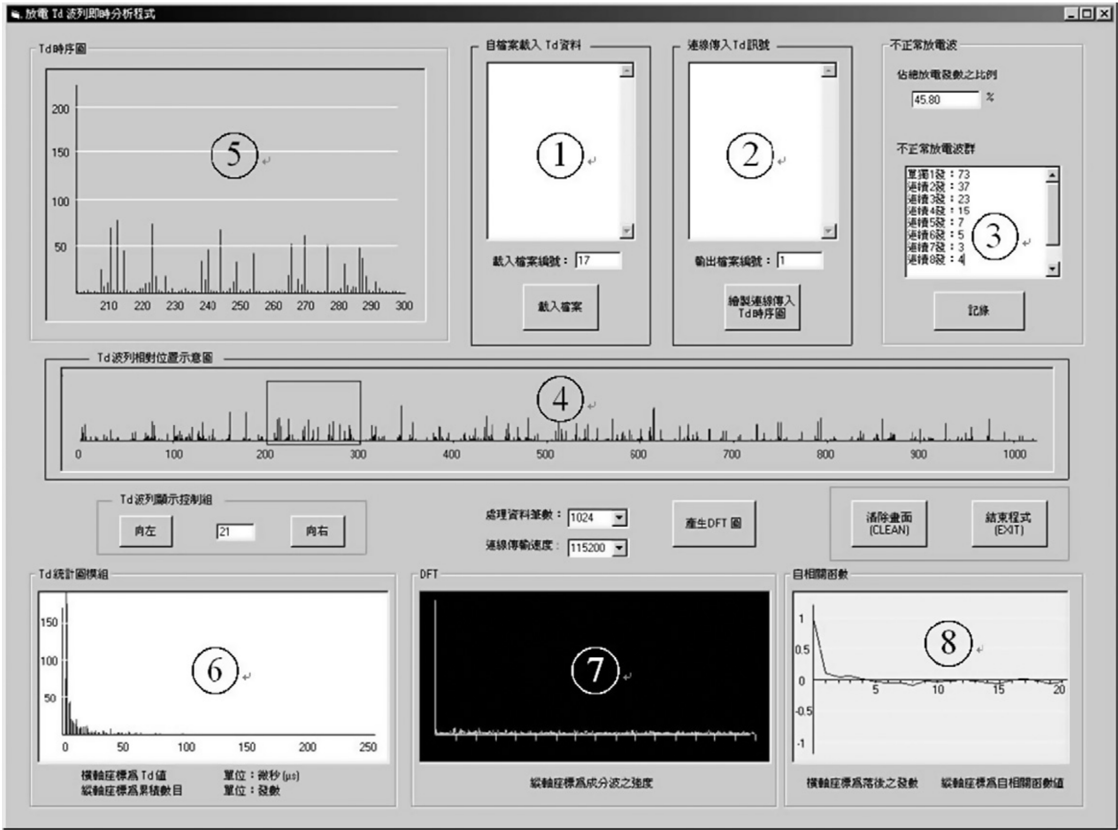

Fig. 5. The multi-window "front panel" of the developed analysis program.

These experiments were conducted on the WEDM machining tool (model CW-430F) manufactured by Ching Hung Machinery & Electric Industrial Co., Ltd., Taiwan. The wire used in the experiments was 0.25 mm brass wire. The workpiece material was SKD11 alloy steel of 16-mm thickness. The machining fluid was deionized water.

4.1. Autocorrelation function for various servo voltages

The workpiece was cut under servo voltage of 30, 50, and 70 V, respectively. The Td duration and distribution for a total of 1024 discharges recorded for these conditions are shown Figs. 6 and 7, respectively. The average Td duration is found prolonged as the servo voltage is increased. It is because when the servo voltage is set to a higher value, the feed rate of WEDM machine will be slowed down by the control system of the machine. As a result, the discharge gap becomes wider and the Td duration will be increased accordingly.

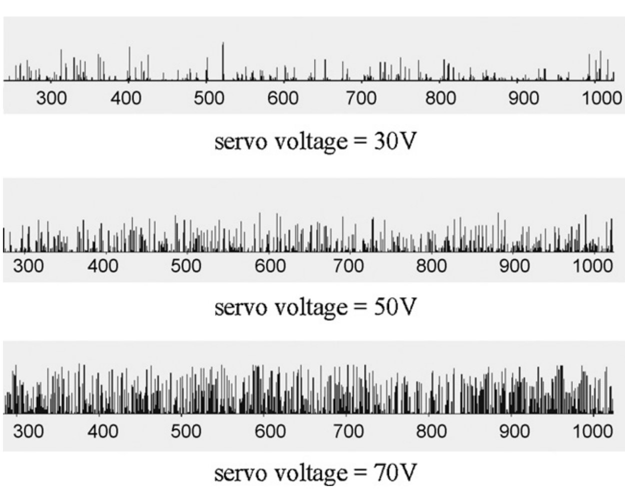

Fig. 6. Td duration for a total of 1024 discharges recorded. The *y*-axis represents the Td and the *x*-axis is the Td sequence number.

The autocorrelation function, as shown in Fig. 8, reveals that, at lower servo voltage, the Td data will present a higher possibility of correlation. When servo voltage is set to 30 V, it is found that the autocorrelation coefficient still not yet to reach zero even with a 5-data-sequence shift. In contrast, when servo voltage is at 50 or 70 V, the autocorrelation coefficient will soon reach to zero with only 1-data-sequence shift. The correlated data could be due to the arc or short circuit discharges coming in a row.

4.2. The usefulness of autocorrelation function

Autocorrelation function provides extra information that cannot be obtained by the traditional statistics approaches. With traditional statistics analysis of Td, if two WEDM processes present similar Td distributions such as the ones shown in Fig. 9, they will be considered identical in machining performance. However, since the continuous arc or short circuit discharges will lead to wire breaking during the WEDM process, the one with higher occurrence rate of repeated short circuit or arc discharges should be considered inferior to the other one. Only by way of autocorrelation function, can the repeated pattern be detected as shown in Fig. 9.

4.3. Spectral analysis of Td data by FFT

The experiments of spectral analysis conducted were aimed at verifying the validity of the system and to identify the factors which may induce cyclic patterns of the Td data.

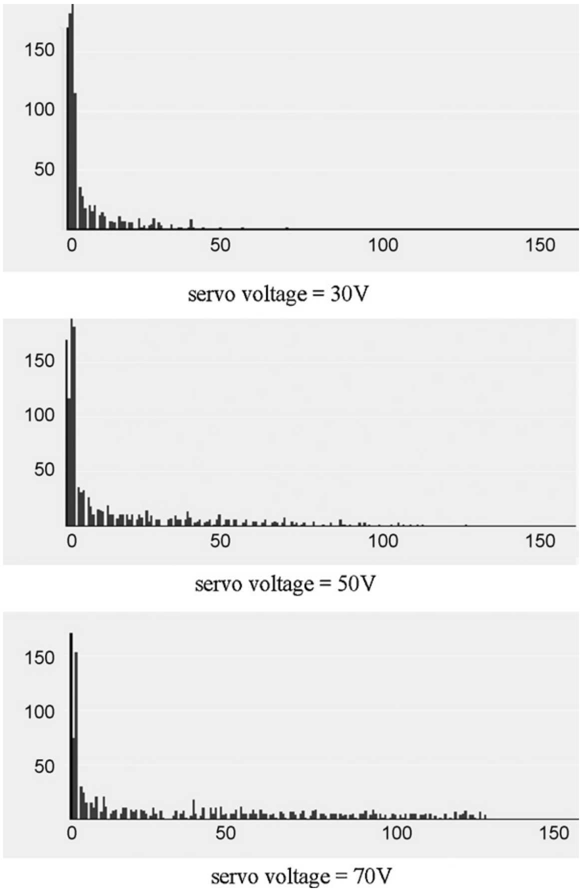

Fig. 7. Td distributions for the data in Fig. 6. The x-axis is the Td duration in μs, and the y-axis is the number of discharges at every duration.

The unit of the horizontal axis of the spectrum is dubbed as RPR, which stands for the "repeated pattern rate" within the 1024 Td data sequence put into Fourier transformation. For example, a peak appearing at RPR = 36 suggests that a certain repeated pattern occurs periodically for 36 times throughout the 1024 Td data put into calculation. The full scale of the RPR is 1024 and it is equally divided into 16 subscales, each of which represents a 64-RPR interval.

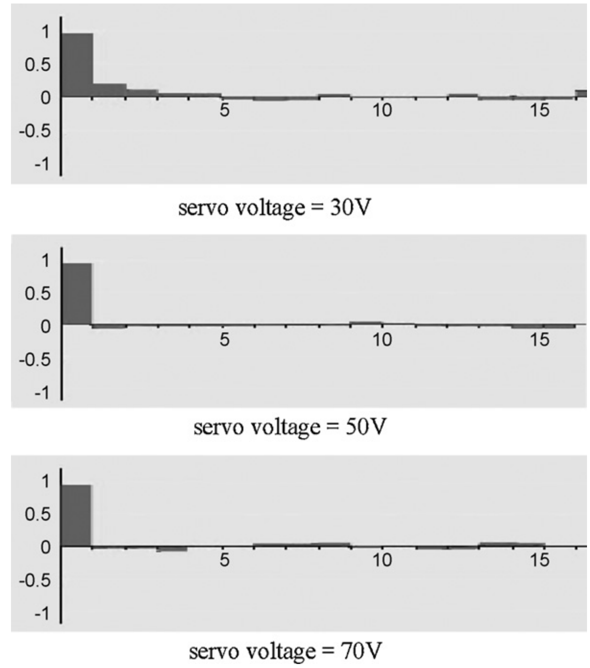

Fig. 8. Autocorrelation function of data in Fig. 6.

4.3.1. Spectrum under various lengths of wire electrode

The WEDM processes were performed with the wire electrode length of 25, 50, and 70 mm. The result of the experiment is shown in Fig. 10. It is observed that there is a prominent peak in the spectrum when the length of wire electrode is 70 mm. The peak is located at around 100 RPR, which means a certain pattern repeated 100 times periodically within the series of 1024 Td data in the experiment.

What is the physical meaning behind the peak shown in the spectrum? Since one of the suspected factors for periodical Td is

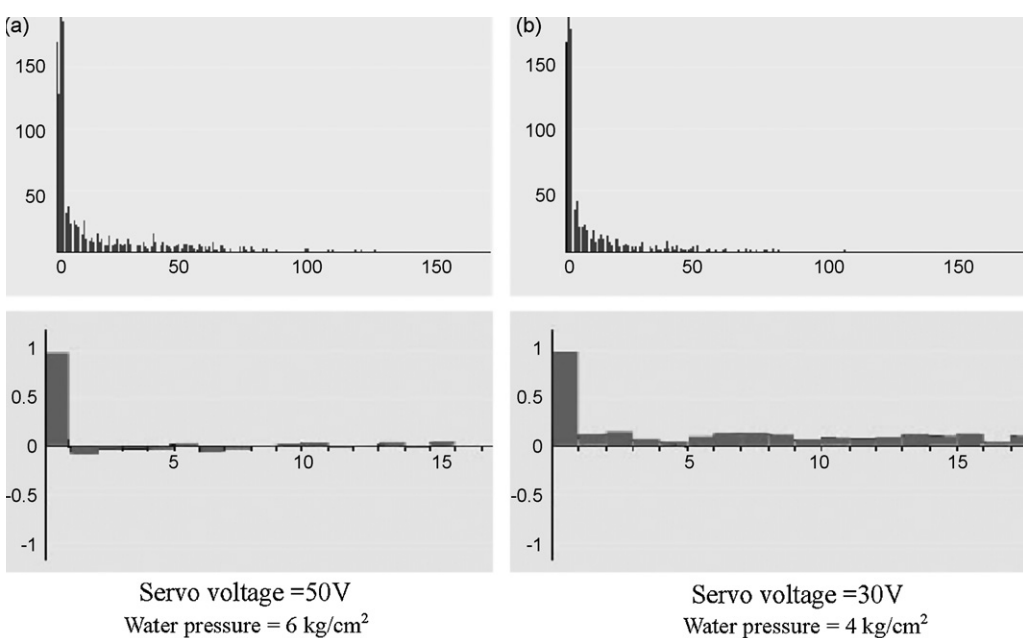

Fig. 9. Td distribution (upper row) and autocorrelation function (lower row) under different working conditions.

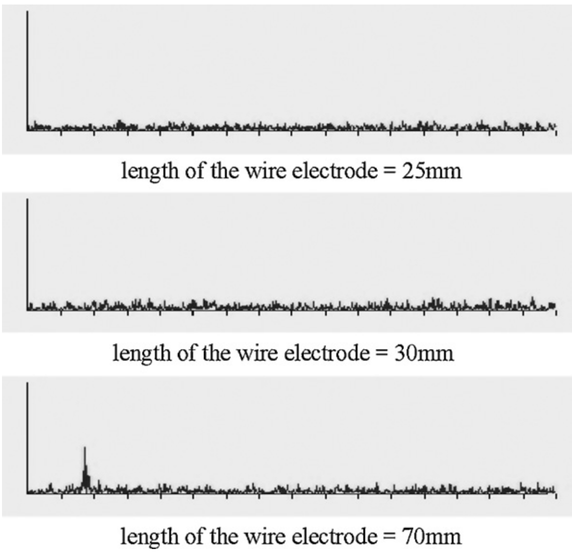

Fig. 10. Spectrum of Td data for various lengths of wire electrode.

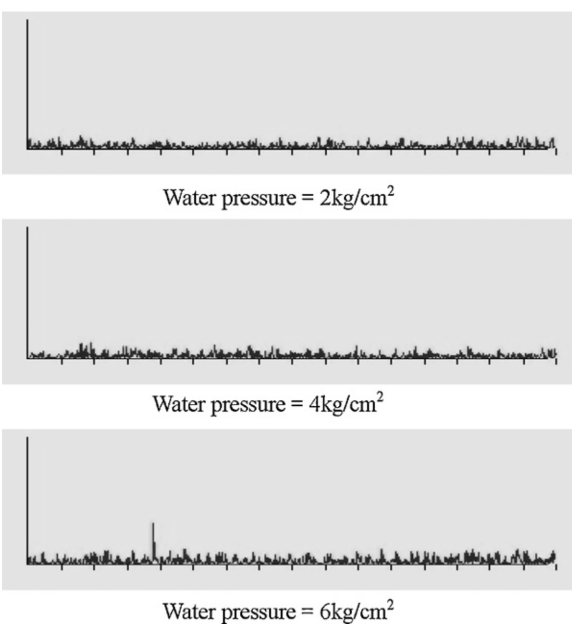

Fig. 11. Spectrum of Td data under various water pressures.

the mechanical running wave along the wire electrode, as suggested previously in the text, the peak in the spectrum might be associated with the vibrating frequency of the mechanical running wave. The underlying cause of the mechanical running wave may come from the disproportional ratio of the thickness of workpiece (16 mm) to the length of the electrode (70 mm), which was deliberately arranged to create a critical working condition in the experiment.

4.3.2. Spectrum under various water spraying pressures

With the wire electrode length of 50 mm, the WEDM process was conducted under different water spraying pressures of 2, 4, and 6 kg/cm^2, respectively.

It is found that, as shown in Fig. 11, a peak of around 240 repeated rate is noted when the spraying pressure is 6 kg/cm^2. In contrast, when the spraying pressure is 2 or 4 kg/cm^2, the spectrum looked “white noise” with no dominant frequency component. The result may suggest that only when the spraying pressure is elevated to a certain level, will a mechanical running wave be induced.

Although the stronger spraying pressure of 6 kg/cm^2 and the longer wire electrode of 70 mm both induced a peak in the spectrum respectively, the two peaks are not located at the same place in the spectrum. This might suggest that they are out of different modes of vibration generated by the suspected mechanical wave along the wire electrode.

It is noted that the information extracted by the autocorrelation function and by the spectral analysis is complimentary. Autocorrelation function reveals if there is correlation of the Td data. The spectral analysis can display all the spectral components of periodical repeated patterns. The different spectral components not only represents different periodical repeated patterns, but may also be related to different physical properties involved in WEDM process.

5. Conclusion

This study successfully developed an on-line analysis system for investigating the causality of the Td in the WEDM process. The merits of the system are its cost-effectiveness hardware and its user-friendly software interface. Through experiments, the system was proved to be valid and reliable. In terms of the algorithms adopted in the system, the autocorrelation function is able to detect the consecutive arc or short circuit discharges. Since the consecutive arc or short circuit discharges could lead to wire breaking during the WEDM process, the system can be used by the operator of the WEDM machine as an on-line wire-breaking monitoring system. The autocorrelation function is also an effect tool for distinguishing the WEDM process with similar Td distributions. With the aide of the system, the operator of the WEDM machine can have a more clear idea to choose the relatively superior process among several processes with similar abnormal discharge ratio. On the other hand, the spectral analysis availed in the system reveals the spectrum of Td data sequence, helping the user of the WEDM machine to sort out the unwanted repeated pattern that may be induced by any factors involved in the machining process. That is to say the system can be used as a diagnosis tool for examining the quality of electric discharges in the WEDM process. Although the experiments conducted in the study showed that several factors were able to induce periodically repeated patterns in Td data sequence, it still too early to conclude that a certain component appearing in the Td spectrum can be exclusively attributed to any unique factor. Since the factors influencing the Td spectrum may confound with each other among themselves, a more scrutinized and thorough research has to be designed and conducted in order to establish the models for system identification, and it is underway.

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