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GAP CONTROL OF ELECTRICAL DISCHARGE GRINDING WITH HIGH BANDWIDTH DUAL STAGE ACTUATORS

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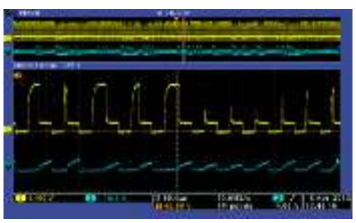
Graphical abstract



Abstract

Electrical discharge grinding process has four types of discharge states and abnormal states, such as arcs and short circuits have great impact on the machining efficiency and the surface finish of workpieces, for example, polycrystalline diamond cutting tools. The aim of this study had been to develop a new servo system with high bandwidth dual stage actuators, which can quickly change the gap width to eliminate these harmful discharge states. The structure of the dual stage system is that a piezoelectric actuator stands on a linear actuator and both move along one axis. The piezoelectric actuator, which has high bandwidth but short travel distance, was used for the gap width control and the linear actuator, which is relatively slow but has long travel distance, tunes the feed rate of the workpiece to match the erosion rate. The gap information obtained from the electrical discharge waveform was used as a feedback signal. The linear actuator system adjusted its velocity based on the average piezoelectric displacement value. Hence, an electrical discharge machine was developed with a one-axis dual stage system. The results from simulations and experiments showed that the new system provided a high bandwidth response, as well as enhanced the machining rate and stability.

Keywords: Electrical discharge grinding; gap control; dual stage actuator

Abstrak

Tujuan kajian ini adalah untuk membangun sistem servo baru dengan jalur lebar tinggi penggerak peringkat dua, yang dengan cepat boleh menukar lebar jurang untuk menghapuskan pelepasan berbahaya. Struktur sistem peringkat dual ialah penggerak piezoelektrik berdiri pada penggerak linear dan kedua-dua bergerak di sepanjang satu paksi. Penggerak piezoelektrik, yang mempunyai lebar jalur yang tinggi tetapi jarak perjalanan yang pendek, digunakan untuk mengawal lebar jurang dan penggerak linear, yang agak perlahan tetapi mempunyai jarak perjalanan yang panjang, menala kadar suapan bahan kerja kepada kadar hakisan. Sistem penggerak linear menyesuaikan halajunya mengikut purata nilai anjakan piezoelektrik. Sebuah mesin nyahcas elektrik telah dibangunkan dengan sistem dwi peringkat satu paksi. Hasil daripada simulasi dan eksperimen menunjukkan bahawa sistem baru yang disediakan mempunyai jalur lebar tinggi dan peningkatan dalam kadar pemesinan dan kestabilan.

Kata kunci: Pelepasan elektrik pengisaran ; kawalan gap ; dual penggerak peringkat

1.0 INTRODUCTION

Electrical discharge machining/grinding (EDM/EDG) has been widely used to machine the parts of aerospace, automotive, and mold, which are often made in those difficult-to-machine materials, such as polycrystalline diamond (PCD) and tungsten carbide[1, 2]. EDG erodes the part materials by thermal energy. It supplies a series of discrete electrical pulses between the electrode and the workpiece in a dielectric medium. The electrical discharges occur on the discharge spot, the plasmas exert extreme thermal energy to melt and evaporate the workpiece material [3]. The fast adjustment of the EDG gap width is critical to keep the efficient EDM process. The large gap width extends ignition delay time and the small gap causes the high rate of short circuit and arcs, which are related to the poor expulsion of debris particles. All of those abnormal discharge states reduce the EDG removal rate and some can worsen the surface finish.

Moreover, many attempts have been made to improve the EDM gap width control for high removal rate. Adaptive control algorithms were applied to EDM servo systems for the optimal gap width adjustment based on identification of its discharge states [4-6]. Robust control, sliding mode control [7], and fuzzy control [8, 9] were used to enhance the robustness to variation of EDM machining conditions and minimize the abnormal discharge states due to the stochastic characteristics of EDM process. However, the traditional EDM servo actuators showed slow response and the coarse position resolution. Therefore, piezoelectric actuator was introduced for fast adjustment of the gap width of EDM because its high bandwidth can achieve 1 KHz, higher than those of the conventional DC or linear motor, lower than 20 Hz. Besides, Kunieda [10] installed a piezoelectric actuator under a workpiece to control the gap width of dry EDM and its simulation results showed that the piezoelectric actuator improved the material removal rate. This fast response actuators, which also had a nanometer resolution, were used in micro-EDM machining to fabricate microstructures on workpieces, for example, drill micro holes, whose diameters can be less than 45 μm[11], or cut 200μm×200μm grooves on PCD with good surface roughness of 0.10 μm Ra [1]. Assisted by the piezoelectric actuator or an ultrasonic wave generator, many researchers improved the EDM removal rate by ultrasonic vibration, which can also lower heating damage with better flushing [12, 13]. To synchronize piezoelectric movement and EDM pulses, Tong [14] proposed a macro/micro-dual-feed structure that consisted of a linear motor as the macro-drive and a piezoelectric actuator as micro-feeding mechanism to keep the favorable discharge gap. The good surface finish with an Ra value of 0.37 μm was reported in contrast to the conventional roughness of 0.5~4.5 μm [1] and the high machining repeatability error of <0.7%. Therefore, the method of combining the dual actuators for good performance and robust stability is critical. Ding [15] used two steps: the first step was to design the macro-drive system for basic performance, while the second step was to design the micro-drive system by loop shaping for superior performance of the overall system. Meanwhile, Schroeck [16] reduced the dual stage system into a single loop system by adding an auxiliary compensator. This paper presents a design of high pass filter to decompose the gap width error to the two-stage actuators to increase the servo system response. The new control algorithm had been forecasted to improve the stability and the efficiency of the EDM process.

2.0 ARCHITECTURE OF SERVO SYSTEM WITH DUAL STAGE ACTUATORS

Electrical discharge grinding process has four types of discharge states: open circuit, arc, normal discharge, and short circuit during eroding PCD workpieces. Bigger gap width leads to longer ignition delay time, which increases the time ratio of ignition time with high voltage, such as 120 V. However, it leads to higher voltage [3]. Therefore, the average voltage of EDG gap was used as the feedback signal of gap width. To achieve good surface finish, EDG erodes tiny craters on the PCD workpiece every pulse at high frequency: each pulse had very short duration time of the order of microseconds. However, the conventional servo system of EDM machines showed slow dynamic time response, around 1~20 Hz. Consequently, the traditional servo system cannot satisfy the change rate of EDG gap states and the ratio of abnormal discharges, such as high arc, as illustrated in Fig.1.

Meanwhile, Fig.2 shows a new servo system of EDG machine, which consisted of a linear actuator in a series of a piezoelectric actuator. The linear actuator supported big displacement of the order of centimeters, but it was dynamically slow when adjusting the EDG gap width for quick debris flushing. Conversely, the piezoelectric actuator just had a maximum displacement of 100 micrometers, but had a very precise resolution and fast response. By combining two actuators, a large stroke servo system with fast response was built to quickly adjust the EDG gap width for high efficient eroding process. Each actuator had its own position feedback signal: the piezoelectric actuator used a strain gauge, which was attached to the piezoelectric element and resistance was in proportional to its length; as the linear actuator had an encoder to indicate the movable part displacement. Besides, the PCD workpiece was installed on the end of the second actuator. A waterproof insulated motor drove a copper tungsten wheel rotating at a fixed speed. Both the workpiece and the electrode wheel were submerged in the dielectric tank. The position of feedback signal of the PCD workpiece is the mean gap voltage, which is the average value of each pulse voltages in a fixed time period.

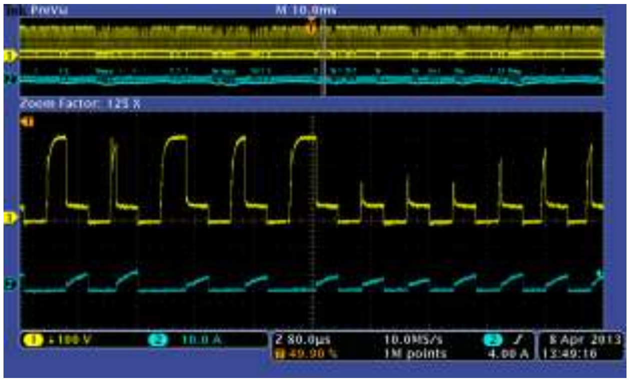


Figure 1 Pulse pattern of electrical discharge grinding

Fig.3 illustrates the control algorithm of this EDG servo system. Assuming that the electrode wear was slow, only the EDG servo system changed the gap width by controlling the PCD workpiece position. The model of the linear actuator can be expressed as:

$$M_1(x_1,t)\ddot{x}_1(t)+C_1(x_1,\dot{x}_1,t)\dot{x}_1(t)+g_1(x_1,t)=u_1(t) \quad (1)$$

where is the inertia matrix, is the vector relating centrifugal and Coriolis force, is the gravitational vector, and are the displacement and driving force vector. During the eroding period, the linear actuator was required to track the slow and time-varying material removal rate of EDM by maintaining the gap width between 10 and 50 μm. The error can be expressed as:

$$e_1(t)=Y(t)-X(t)\rightarrow 0, as\ t\rightarrow\infty \quad (2)$$

The controller was

$$f(t)=k_p e_1(t)+k_i\int_0^{\infty} e_1(t)dt \quad (3)$$

The transfer function of the linear actuator was

$$\frac{Y_1(s)}{X_1(s)}=\frac{C_1(s)G_1(s)}{1+C_1(s)G_1(s)} \quad (4)$$

Where

$$C_1(s)=K_p+\frac{K_i}{s}$$
$$G_1(s)=\frac{k_s}{s^2+2\xi\omega_n s+\omega_n^2} \quad (5)$$

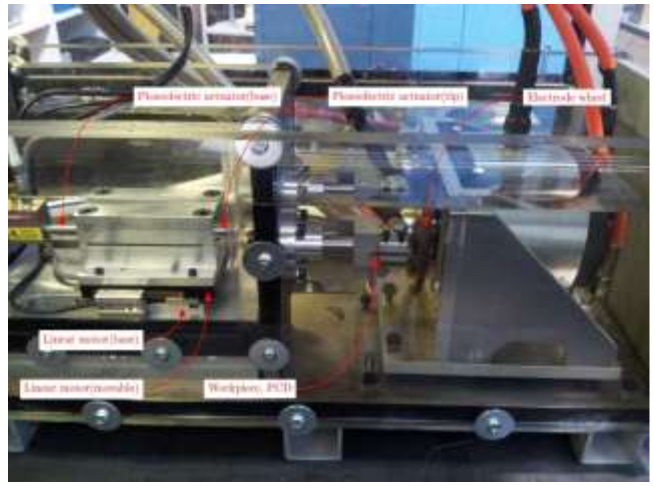


Figure 2 Electrical discharge grinding with dual stage actuators

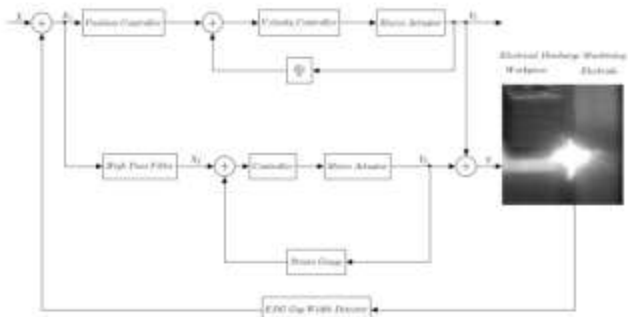


Figure 3 Block diagram of controller for dual stage actuators

The discharge state variation at high frequency was adjusted by the piezoelectric actuator by compensating the high frequency error signal of the gap voltage, which was processed by a high pass filter. The transfer function of this high pass filter was:

$$H(s)=\frac{s}{s+1} \quad (6)$$

The position reference of the piezoelectric actuator was:

$$x_2=H(s)e_1 \quad (7)$$

Considering that the PCD workpiece with a mass is on the top of the piezoelectric actuator (PZT), the following equation can describe the motion of the PZT [17]:

$$M_2\ddot{x}_2(t)+C_2\dot{x}_2(t)=u_2(t) \quad (8)$$

where are the dielectric damping coefficient, the PZT displacement, and the force from the expansion of PZT element. The transfer function of the PZT control loop was:

$$\frac{Y_2(s)}{X_2(s)} = \frac{C_2(s)G_2(s)}{1 + C_2(s)G_2(s)} \tag{9}$$

where

$$C_2(s) = K_{p2} + \frac{K_{i2}}{s}$$
$$G_2(s) = \frac{k_s}{s^2 + \xi_2 s} \tag{10}$$

The PCD workpiece position was:

$$Y = y_1 + y_2 \tag{11}$$

Besides the servo system, the EDG machine also had a pulse generator, a dielectric cooling, and a filter system, as well as a user interface, as shown in Fig. 4 & 5.

Figure 4 Sub-systems of the electrical discharge grinding

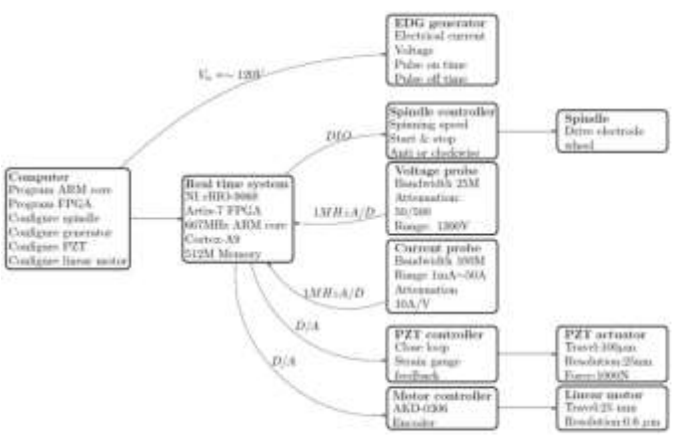


Figure 5 Main components of the electrical discharge grinding

3.0 SIMULATION RESULTS

To demonstrate the performance of the proposed dual stage servo system, a simulation model was developed in Matlab/Simulink environment, as shown in Fig. 6. This model used the parameters of the linear actuator, shown in Fig. 2, which had a maximum velocity of 5 m/s and a maximum acceleration of 5G. The piezoelectric actuator was simplified as a pure proportional element, whose hysteresis characteristics were ignored. The simulation result is shown in Fig. 7. The dual stage servo system showed fast dynamic response performance, which had the capability to follow a square wave position reference of 20m. The red signal represents the PCD workpiece position, which was driven by both actuators, while the blue signal represents the linear motor's response. These results indicated that the dual stage servo system can quickly adjust the EDG gap width to prevent those abnormal discharge states, such as arcs and short circuit from happening.

4.0 CONCLUSION

Because of its stochastic characteristics, the EDG process needs a fast dynamic response servo system to adjust its gap width for the high ratio of normal discharge state. To achieve it, the paper presents a new servo structure, which consisted of a linear actuator with large displacement and a piezoelectric actuator with fast response. Besides, a new control algorithm was proposed to avoid the impact of their disadvantages of both actuators, for instance, the short stroke of the piezoelectric actuator and the slow response of the linear actuator. The simulation demonstrated that this system can drive the workpiece to follow the square wave position reference signal exactly and quickly compared to the conventional single stage actuator.

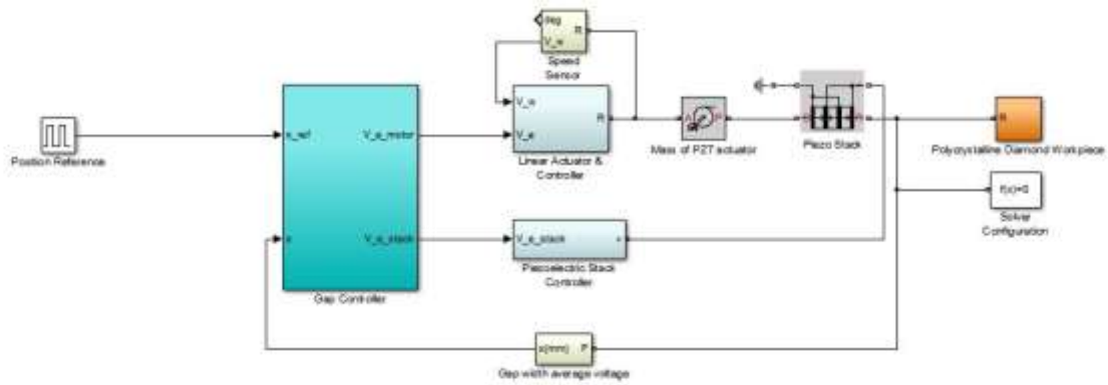


Figure 6 Simulink block diagram for the dual stage actuators

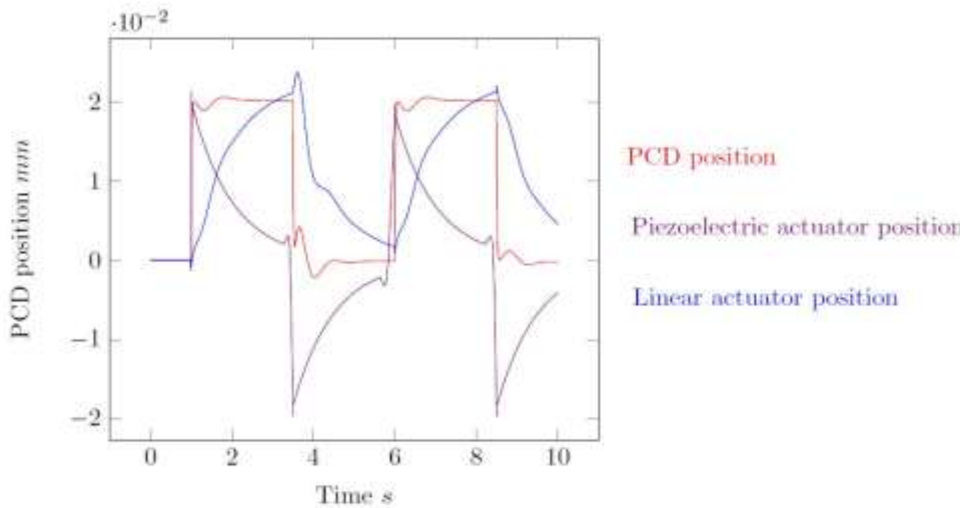


Table 7 Simulated PCD workpiece position response with dual stage actuators

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