MONITOR AND CONTROL OF DISCHARGE ENERGY DURING EDMING

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ABSTRACT

A pulse energy at 100MHz is verified to be able to determine the normal and abnormal discharge during electrical discharge machining (EDMing). A band pass filter is designed to detect the energy at this frequency, and can verify which discharge pulses are normal and abnormal, respectively. A field programmable gate array (FPGA) is used to implement the discharge detection circuit, including detection of the time of ignition ($T_d$) and discharge high-energy. Function analysis is used to design the proportional (P) $T_d$ controller to allow the bounded variation of reference input and the feedback signals. Energy of about 100MHz can be maintained within a specified pulse width by regulating the position of the electrode, including a slight regulation and jump motion. The rate of erosion during the roughing and finishing of a die-sinking EDM is confirmed to demonstrate the improvements obtained by the EDMing.

KeyWords: EDM, power spectrum, FPGA, filter design, energy control.

I. INTRODUCTION

When supplying high voltage between the electrode and the workpiece, electric discharge machining (EDMing) occurs in the gap between them and the metal to be removed. The conductive carbon and metal particles in the gap rapidly and stochastically change the gap length, thus changing the metal removal rate (MRR) associated with the workpiece. A motion control system for an electric discharge machine (EDM) cannot drive the electrode towards the workpiece at a constant feed rate owing to the mutually dependent erosion of the workpiece and the steel particles covering the eroded surface [1-3]. Therefore, a gap control system, which includes a motion control system, must drive the electrode forwards and backwards according to the actual discharge conditions, for example the percentage ignition delay $T_d$.

During discharge, the voltage varies as shown in Fig. 1. After the ignition delay $T_d$, the voltage reduces when the electron passes through the gap within the electrode and the workpiece. Because of the gap resistance, low voltage remains in the gap. The resistance increases and the current terminates when the metal is removed and the gap enlarges. The electron then moves from the other short path within the workpiece and electrode. The voltage varies due to the discharge positions being changed continually. The voltage varies at high frequency with rapid change in the discharge position, as shown in Fig. 1(a), where discharge does not occur at the beginning of the power supply until the termination of ignition delay $T_d$. When the gap is narrow and the discharge is spread on the surface, the ignition delay $T_d$ vanishes but the voltage varies at high frequency during discharge, as shown in Fig. 1(b). Moreover, when the discharge is located at a certain position on the surface of the workpiece, the voltage does not vary at such high frequency and it can be maintained as shown in Fig. 1(c). The voltage varies at small amplitude when the carbon powder is concentrated at a position. The $T_d$ still exists at the beginning of the discharge. When the density of the carbon powder remains high in a deep gap and the machining maintains the discharge as shown in Fig. 1(c), the concentrated powder is easily welded on the surface of the workpiece. The erosion should be terminated and...
In a commercialized die-sinking EDM, quick and frequent electrode jump thoroughly cleans the gap. The electrode jumps at a fixed preset time interval and the need to scratch the welded powder on the surface can be avoided. However, the discharge is terminated during the electrode jump. The machining time increases with frequent electrode jumping. Some discharge generator of the commercialized EDM can detect the abnormal discharge by detecting the ignition delay $T_d$. However, some discharge pulses remain normal when the ignition delay vanishes. The forced jump of the electrode wastes the machining time in this condition.

Adaptive control algorithms that regulate operating parameters can maintain their productivity when a shallow round hole is eroded. Although adaptive control algorithms [4-8] can find the optimal adaptive gain parameters, the actual discharge energy cannot be verified and controlled. The operation parameters are conservative for preventing damage of the eroded surface. However, the actual system discharge energy cannot be measured and thus the eroding speed reduces.

Since the discharge process includes high frequency variation of the discharge voltage and current [9], a radio verification is proposed in the past. Discharge pulses at high frequency can be used to effectively determine whether the discharge condition is normal or abnormal. However, the features of the high frequency cannot easily be measured due to the old electrical technology. Recently, a field-programmable gate array (FPGA) driven by a high-frequency oscillator has been extensively used in portable commercial products, such as portable computers and mobile-phones, to reduce the size of the incorporated integrated circuits. The FPGA is also used in controller implementation in numerous new control devices [10]. The easy implementation to the logical circuits is attractive to circuit and controller designers.

This work verifies the discharge energy via a wide-band antenna to determine the signal frequency of the normal discharge. The specification of the band pass filter at this frequency can be determined, and can be used to determine the condition of the discharge pulses. A circuit for measuring the times of $T_d$ and normal discharge is implemented using three comparators, band pass filter and a field-programmable gate array (FPGA). The detecting circuit is connected to the gap controller, and a logic input port in the computerized numerical controller (CNC) is installed on an electric discharge machine (EDM) for controlling the discharge energy of the discharge pulses. When the nonlinear and time-varying gain is expressed as an average value and a perturbation, a large robust performance control system with a fixed reference input can be obtained by applying
the \( H_\infty \) robust stability criterion \([11,12]\). The objective \( H_2 \), specified by the integral of the square of the error, is also considered to improve the tracking performance under the proposed maximal robust stability constraint. However, the bounded time-varying reference input should be considered in the energy control system. The perturbation of the reference input is seldom considered in these approaches. A robust proportional \( T_d \) control system is designed for tolerating the nonlinear and time-varying feedback signal using function analysis \([13,14]\). The high frequency energy during a discharge pulse can be maintained when the electrode position, reference input and force jump trigger are regulated by the energy control system. Furthermore, the actual erosion performance of a commercial die-sinking EDM equipped with the control system is verified. The rates of erosion of the discharge energy control system with energy and \( T_d \) feedback are compared with those of the gap control system using feedback through a traditional low-pass filter and only a pure \( T_d \) detector, to confirm the improvements of the erosion process.

II. ENERGY DETECTOR AND INTERFACE TO THE CNC

The discharge frequency is difficult to measure due to the wide band of voltage oscillation. The current variation can produce a radial signal that can be measured using an antenna. In this study, a wide-band antenna and the spectrum analyzer HP8594EM, as shown in Fig. 2, is used to measure the spectrum of the discharge signals. During a sequence of normal discharge, for example erosion at a shallow depth, a large amplitude at 100MHz presents a normal discharging process, such as shown in Fig. 3. The voltage and the current oscillate significantly at high frequency during the discharge. When many of the discharge pulses, as shown in Fig. 1(c), occur during erosion of a deep hole, the carbon powder is easily welded onto the eroding surface. The spectrum from 100MHz to 140MHz then reduces, as illustrated in Fig. 4. The discharge at these frequencies varies from high amplitude to low amplitude in cases of deep hole erosion. This study detects the amplitude at 100MHz to obtain a large signal in the circuit as shown in Fig. 5.

A band pass filter is designed for detecting the amplitude of the voltage variation at 100Mhz, the circuit of which is displayed in left part of Fig. 5. To increase the input impedance of the filter, an operational amplifier LM6365 is set before the filter. The discharge signals can be reduced to \( V'_f \) by two resistors. The output of LM6365, denoted by \( V'_f \), is filtered to the signals, \( V_f \).

The transfer function from \( V'_f \) to \( V_f \) can be expressed as:

\[
\frac{V_f}{V'_f} = \frac{1}{\frac{R_f C f_1}{s^2} + \frac{1}{R_f C f_1} s + \frac{1}{L_f C f_1}} = \frac{K_f s}{s^2 + 2\xi_\omega_n s + \omega_n^2}
\]

Fig. 2. (a) Wide-band antenna and (b) spectrum analyzer for spectrum verification.

Fig. 3. Spectrum during normal discharge (12A).
where \( \omega_c = \frac{1}{\sqrt{L_f C_{f1}}}, \quad \xi = \frac{1}{2R_{f1}} \sqrt{\frac{L_f}{C_{f1}}} \) and 
\[ K_f = \frac{1}{R_{f1} C_{f1}}. \]

To obtain a resonant frequency at 100MHz, the value of \( L_f C_{f1} \) should be obtained as \( \frac{1}{(2\pi 10^8)^2} \). \( L_f = 10^{-6} \text{H} \) and \( C_{f1} = 2.5 \times 10^{-12} \text{F} \) are chosen for the resonant frequency at 100MHz. The small damping ratio \( \xi \) leads to a narrow band of frequency response as shown in Fig. 6. \( R_{f1} = 100 \text{K} \) is selected to obtain \( \xi = 0.003 \). The amplitude can be amplified when the frequency is at 100MHz. The actual result during discharge is shown in the lower part of Fig. 7, where the oscillated voltage expresses the variation at 100MHz. The actual discharge voltage is shown in the upper part of Fig. 7. The large amplitude determines the normal discharge, and the small amplitude determines the abnormal discharge.

To monitor the pulse energy using a computerized energy controller, the results of the band-pass filter should be transferred to digital signals. A half-wave rectified low-pass filter following the band-pass filter is shown in right part of Fig. 5. Another operational amplifier LM6365 is set before the low-pass filter to increase the input impedance. The signals \( V'_{f2} \) and \( V_{f2} \) on input and output of the operational amplifier are similar. The signal \( V'_{f2} \) is then rectified and filtered to the signal \( V_{f3} \). Moreover, the transfer function from \( V'_{f2} \) to the output \( V_{f3} \) is expressed as

\[
\frac{V_{f3}}{V_{f2}'} = \frac{1}{1 + R_d / R_{f2}} \frac{1}{1 + R_{f2} C_{f2} / (1 + R_d / R_{f2})} = K_{f2} \frac{1}{1 + \tau}
\]

where the time constant \( \tau = \frac{R_d C_{f2}}{1 + R_d / R_{f2}} \) and 
\[ K_{f2} = \frac{1}{1 + R_d / R_{f2}}. \]

Furthermore, \( R_d = 0.686 \Omega \) is the forward resistance of the diode \( D_f \). Additionally, \( R_{f2} = 330 \Omega \) and \( C_{f2} = 1000 \times 10^{-12} \text{F} \) are used in the circuit to obtain a time constant \( \tau = 7 \times 10^{-10} \) seconds. The voltage, as shown in the lower part of Fig. 7, is filtered to a positive voltage above 0V, as shown in the lower part of Fig. 8 while the discharge voltage is shown as the upper
part of Fig. 8. The low pass filter can maintain the signal amplitude at 100MHz.

The signal duration expresses the discharge maintained at 100MHz, which can be detected via a comparator CMP401, as shown in right part of Fig. 5. The signal, \( V_{ref} \), produced by the low pass filter is compared with a reference voltage to express the signal duration with large amplitude. The resulting signal, \( V_{c3} = 5V \), is produced using the comparator, as shown in the lower part of Fig. 9, when the filtered signal as shown in the upper part of Fig. 9 exceeds the reference voltage. The duration of the 5V signals indicates the duration of the normal discharge. The 0V signals express that the amplitude at 100MHz is small.

The result of \( V_{c3} \) triggers the timer in the FPGA. If the result of the timer exceeds the preset value, the output of the FPGA, \( O_{n} \), is set to a high voltage (5V) which expresses a high discharge energy. If the result of the timer is below the preset value, the output of the FPGA is set at 0V to denote the abnormal discharge maintained over the preset time. The whole energy detecting circuit is connected with a logic input of the motion control board in the EDM CNC. The energy controller in the motion control board is designed to maintain the energy during EDMing.

The ignition delay \( T_{d} \) varies with the actual gap length. To maintain the discharge energy, the \( T_{d} \) should also be detected and controlled at a certain value. Two comparators, as shown in Fig. 10, can be used to measure the \( T_{d} \) values during discharge. A comparator rises the output voltage to set the input port \( I_{2} = \text{on} \) of FPGA when the voltage is higher than the high threshold. The time interval during \( I_{2} = \text{on} \) expresses the ignition delay \( T_{d} \). A voltage above a low threshold of another comparator can be used to determine the duration of the discharge pulse \( T_{on} \). The output voltage of the comparator sets the input port of FPGA \( I_{1} = \text{on} \) under this status. A voltage below the low threshold can be considered to represent a short circuit or pulse-off.

Three counters \( q_{1}, q_{2} \) and \( q_{3} \) are implemented within a short period in the FPGA. As plotted in Fig. 11, during the period when \( I_{2} = \text{on} \), count value \( q_{2} \) increases. Count value \( q_{2} \) increases until the voltage falls below the reference voltage \( V_{2} \). Count \( q_{2} \) is treated as the ignition delay \( T_{d} \). Meanwhile, during the period when \( I_{1} = \text{off} \), the count value \( q_{1} \) increases. The count continues to increase until the voltage falls below reference voltage \( V_{1} \). Count \( q_{1} \) is considered the time within \( T_{on} \). Count \( q_{3} \) fixed at the end of the discharge pulse can be sent to an EDM CNC via a digital-to-analog converter (D/A) when the input port \( I_{1} \) is off. When the value \( q_{3} \) is fixed at the input of the D/A, the contents of \( q_{1} \) and \( q_{2} \) are then reset to zero. The period for which the gap voltage is 0V should be measured. The output of D/A must be reset to zero; otherwise, the previous \( T_{d} \) causes motion control problems when the circuit is shorted. The input of D/A should be reset in the FPGA to eliminate the previous \( T_{d} \) when \( I_{1} \) is off for sufficiently long. Count \( q_{1} \) measures the time for which the voltage is off. The short circuit is detected when count \( q_{1} \) exceeds the preset threshold \( n_{m} \). The time required for the count \( q_{1} \) to increase to the value \( n_{m} \) is the pulse-off time \( T_{off} \). Subsequently, the output of D/A should be set to zero voltage if the count \( q_{1} \) remains zero.
The gap controller regulates the position of the electrode to maintain the actual ignition delay. In this work, the $T_d$ counter is implemented in the FPGA, as illustrated in Fig. 11, to maintain the duration of the discharge through the $T_d$ controller in the motion control system. A robust proportional (P) controller is designed to permit the perturbation of the feedback gain, which can be expressed as:

$$f_c(t) = k_g (T_d \%) (t) - R_{e}(t).$$  \hfill (3)

where $R_{e}$ denotes the reference input of the $T_d$ control system, $T_d \% (t)$ represents a percentage of the ignition delay $T_d \% = \frac{(100T_d/T_{on})\%}{(100T_d/T_{on})\%}$ which can be obtained from the $T_d$ detector and the preset duration of the discharge pulse $T_{on}$, and $k_g$ denotes the gain parameter of the P controller. In this study, the reference input $R_{d}(t)$ is regulated by the energy controller. The reference input $R_{e}(t)$ then can be expressed as:

$$R_{e}(t) = (1 + \Delta_x) R_{e}',$$ \hfill (4)

where the nominal value $R_{e}$ varies in $\Delta_x$. The varying ratio $\Delta_x$ is bounded by the generator specification. The output, $f_c(t)$, of Eq. (3) represents the required feed rate during control. A servo system drives the servo motor on the EDM along the negative direction of the main axis. The actual speed $\dot{y}(t)$ can be expressed as:

$$\dot{y}(t) + 2\zeta\omega_n\dot{y}(t) + \omega_n^2 y(t) = -k_c f_c(t)$$ \hfill (5)

where $k_c$ denotes a magnification constant. The terms $\zeta$ and $\omega_n$ represents the damping ratio and natural frequency of the servo system, respectively.

When the electrode is driven towards the workpiece using the dynamic equation Eq. (5), and the actual gap length, $d(t)$, measured from the original surface of the workpiece, varies according to the following dynamic equation.

$$d(t) = \int_{0}^{t} V(u)du,$$ \hfill (6)

which also specifies the actual electrode position.

When the gap within the electrode and the workpiece is sufficiently narrow, the discharge occurs in the gap and the metal of the workpiece is removed. Figure 12 shows the actual measurement that determines the relationship between the gap length, $d(t)$, and the actual percentage ignition delay, $T_d \%$. A short gap $d(t)$ yields a small $T_d \%$, which vanishes if the electrode contacts the workpiece. Because the ignition delay $T_d$ is always shorter then the duration of the discharge pulse $T_{on}$, $T_d \%$ increases with the gap length, and saturates at the full 100% of the discharge pulse. Consequently, the feedback values of $T_d \%$ will saturated at 100% when the gap within the electrode and the workpiece is large enough. The carbon and steel powders generate in the gap quickly and stochastically during discharging, so the relation on Fig. 12 can not actually shows the linear relation when the signals below the saturation. However, the measuring data is within the dotted lines and is near the dashed line. The relation can be expressed as,

$$T_d \% (t) = N d(t),$$ \hfill (7)

where $N$ denotes the nonlinear and time-varying gain. The relationship is expressed via a saturation type nonlinearity and the time-varying perturbation. This perturbation is considered in relation to the nonlinear and time-varying disturbed element $\Delta_x$. The feedback signal $T_d \% (t)$ is rewritten as,

$$T_d \% (t) = (N_c + \Delta_x) d(t),$$ \hfill (8)

where $N_c$ denotes the average gain, plotted as the dashed line in Fig. 12. Furthermore, the term $\Delta_x$ is the gain perturbation of the $T_d$ detector. According to the results of the experimental data in Fig. 12, the bounds of the perturbation $\Delta_x$ is obtained as $\pm 60\%$ of the average gain $N_c$.

The block diagram of the $T_d$ control system is represented in Fig. 13 using the dynamic equations from Eq. (3) to Eq. (8). Using the symbols $x(t) - d(t), x(t) - V(t)$
\[ \dot{X}(t) = AX(t) + BR_{x} + F_{1}(x(t)) + F_{2}(R_{x}) \]  
\[ A = \begin{bmatrix} 0 & 1 & 0 \\ -k_{1} & k_{2} & N_{k} \end{bmatrix} \]
\[ B = \text{transpose of } [0 \ 0 \ k_{2}] \]
\[ F_{1}(x(t)) = \text{transpose of } [0 \ 0 \ k_{2} \Delta_{b}(x(t))] \]
\[ F_{2}(R_{x}) = \text{transpose of } [0 \ 0 \ k_{2} \Delta_{r}(R_{x})] \]

The solution to Eq. (9) is:
\[ X(t) = e^{At}X_{0} + \int_{0}^{t} e^{A(t-u)} BR_{x} d\nu + \int_{0}^{t} e^{A(t-u)} F_{1}(x(u)) d\nu + \int_{0}^{t} e^{A(t-u)} F_{2}(R_{x}) d\nu \]  

Fig. 12. Gain distribution of the feedback signals.

Fig. 13. Block diagram of the EDM \( T_{\beta}\% \) control system.
which gives the boundaries on $X(t)$ as $t$ approaches infinity. From the definition of $-k$ in Eq. (20), the eigenvalues should satisfy
\[ -k < -k_i k_j N_{rad} \]

(28)

Then, the gap-control system is robustly stabilizable. If the system is linear, so that $N_{rad} = 0$, the criterion $-k < 0$ satisfies the stability theory using the Routh-Hurwitz Criterion [14]. When $-k$ is smaller than $-C$, the eigenvalues are on the left side of $\text{Re}(s) = -k_i k_j N_{rad}$. The system has sufficiently robustness to override a non-linear and time-varying perturbation in the gap-control system. For convenience of design and to ensure the robustness of the gap-control system, the gain parameter $k_g$ with a minimum of $-k$ can be used, supporting the asymptotical stability of the linearized system with a central gain $N_c$. If the minimum $-k$ does not yield the required robustness and thus maintain the system stability, then no other control parameters can be found that satisfy the robust criterion, Eq. (28), to override the non-linear and time-varying perturbation in the gap-control system. According to Eq. (26), the norm of the system states $|X(t)|$ settles to the results of Eq. (27) fast as decrease of $-k$. The optimal transient performance can also be obtained using the minimum $-k$. To avoid the need to find the minimum $-k$ along a wide spread of $k_g$, the system can first be treated as linear time-invariant. The stable region of the gain parameter $k_g$, satisfying $-k < 0$, can be obtained via a Routh-Hurwitz test on the determinant $(\lambda A) = 0$, where $\lambda$ denotes the eigenvalues and I denotes the unit matrix. The minimum $-k$ can then be found by continuously checking $-k$ in the linearized stable region.

To maximize the robustness and transient performance to tolerate the nonlinear and time-varying feed back signals, as illustrated in Fig. 12, the optimal gain parameter $k_g$ in Eq. (3) can be determined through as follows,

\[ \max_{k} (-\max(\text{Re} \lambda_j(A))) \]

(29)

When $T_d$ is controlled by the $T_g$ controller, the energy controller, as shown in Fig. 14, receives the output signals $O_n$ of FPGA denoting the normal discharge and then regulates the reference input of the $T_g$ controller according to the following:

\[ R_g(t) = \begin{cases} R_g(t-1) + 1 & \text{when } O_n = 0 \\ R_g(t-1) - 1 & \text{when } O_n = 1 \end{cases} \]

(30)

The values of $R_g(t)$ are constrained within the maximum $R_{max}$ and minimum $R_{min}$ as specified by the discharge generator. When the abnormal discharge is maintained for a long time, the value of $R_g(t)$ reaches the maximal value $R_{max}$. The controller then raises the “Jump” flag that triggers the jumping motion created by the interpolator. The powder is thoroughly swept from the gap during the jump motion.

IV. EXPERIMENTS

The energy controller is installed in a computerized numerical controlled (CNC) die-sinking EDM, as shown the lower right portion of Fig. 15, where the $T_d$ and energy detectors are connected to a DSP-based (ADSP21062) motion control board installed in the industrial personal computer (80486 CPU). The DSP receives the $T_d$ signal via an analog-to-digital converter (A/D). The proposed energy and $T_d$ detector, which is implemented using a Xilinx FPGA, type-Spartan XCS10, is connected to the energy controller in the DSP. The P controller can determine the feed rate of the interpolator that drives the electrode either towards or away from the workpiece along the desired path. The energy controller increases the reference input of the $T_d$ controlled system and triggers the jump motion of the electrode for cleaning the gap between the electrode and the workpiece.

The damping ratio $\xi$ and natural frequency $\omega_n$ of the servo can be determined in a dynamic test using a function generator and an oscilloscope. After setting $R_g(t) = 0$ and $k_g = 1$, the square signals from the function generator are fed to the input of the analog-to-digital converter (A/D), which digitizes the gap voltage. The resulting speed $V(t)$ can be measured using the tachometer mounted on the back of the servomotor. Moreover, the parameters $\xi$ and $\omega_n$ can be obtained by comparing the results of a simulation with those detected on an oscilloscope. Following the dynamic test, the parameters of the servo driving system can be obtained as

\[ \xi = 0.3 \]

\[ \omega_n = 150 \text{ rad/sec} \]
The mean feedback gain is $N_c = 1.3767\%/\mu m$, as plotted in Fig. 12. The reference input is 30%, such that the controller can maintain the electrode 22 $\mu m$ away from the workpiece.

After obtaining the parameters $N_c$, $\xi$ and $\omega_n$, the region of the gain parameter, $0 < k_g < 65$, can be determined using a Routh-Hurwitz test [14]. Because the maximal boundaries of the gain parameter are determined by treating the system as linear time-invariant, the gain parameter $k_g = 65$ near the boundary yields the almost undamped responses illustrated in Fig. 16, for which the 20 $\mu m$ step disturbance and $\Delta_N = 60\%$ were set to 1.2 seconds. The responses diverge after 1.2 seconds due to the increase of the feedback gain. During the actual erosion, the speed also oscillates as displayed in Fig. 17 where the left part represents the speed of jump motion produced by the interpolator. The nonlinear and time-varying signals are fed back to the actual system. In Fig. 16, the plot simulates actual nonlinear and time-varying feedback element installed in the simulated system block.

The Routh-Hurwitz test implies that the test region of the gain parameter $k_g$ can be below 65. Moreover, a robust gain parameter $k_g = 20$ can be determined from the maximal $-(\omega)\lambda$ along the gain region from 0 to 65, as shown in Fig. 18. Figure 19 illustrates the simulated gap response, where the response of part (b) is well-damped. A simulated step disturbance of 20 $\mu m$ and $\Delta_N = 60\%$ also occurs at 1.2 second. The simulated gap length $d(t)$ decreases after 1.2 seconds because of the increase of the feedback gain. A large $k_g$ causes the oscillated response, as displayed in Fig. 19(a). When the oscillation gap is large, the large $T_d$ reduces the portion of the discharge and so reduces the eroding speed. A small $k_g$ causes the slow response, as displayed in Fig. 19(c). The sudden increasing powders can not easily escape from the narrow gap because the gap enlarges slowly. The powder is easily welded on the surface of the workpiece owing to the increase of powder density. Figure 20 shows the actual speed responses when the gain parameter $k_g = 20$ is used; $T_d$ remains approximately 30% of a discharge duration when the electrode interacts with the discharge field. A slight oscillation occurs during the actual erosion process for the powder generation. At the mean time, the D/A, receiving the actual values of $T_d$ from FPGA, generates the signals for the $T_d$ control as shown in Fig. 21. The low signal in the lower part of the figure denotes the low ignition delay on the fifth discharge pulse as shown in the upper part.
Fig. 18. $-(\dot{k})$ variation with respect to the gain parameter $k_g$.

The energy controller controls both roughing erosion using parameters $(I = 6A, T_{on} = 450 \mu s, T_{off} = 350 \mu s)$ and finishing erosion using parameters $(I = 1A, T_{on} = 20 \mu s, T_{off} = 140 \mu s)$. The above erosion results are compared with those produced by a traditional gap controlled system using a low-pass filter designed by a resistor and capacitor (RC) as a feedback device. The system is also compared with the system containing only the $T_d$ controlled system where the reference input is a constant.

The variety of the erosion depth is expressed in Figs. 22 and 23. The erosion speeds are large, and are marked by circles in both figures when the energy controller controls the system. The discharge energy at 100MHz can be maintained as indicated in the lower part of Fig. 24. However, the discharge energy reaches that shown in Fig. 25 when the energy controller does not work in the EDM following 30min. The stars in Figs. 22 and 23 indicate the variety of the erosion depth. The discharge energy at 100MHz reduces as shown in the lower part of Fig. 26 when the low-pass filtered discharge voltage is fed back to the EDM for 30min. The variety of the erosion depth reduces as indicated by the dots in Figs. 22 and 23.

When the discharge exhibits median energy, the low signals are sent to the energy controller, as shown in Fig. 27. The reference input of the proposed system is increased as calculated by Eq. (30), after which the energy increases. If the discharge energy remains low then the jumping motion is triggered. The erosion rate can be maintained as shown in the circles in Figs. 22 and 23.

V. CONCLUSIONS

The amplitude at 100MHz can be used to confirm the discharge characteristics. A band pass filter, rectified low pass filter and a comparator can implement the energy detecting circuit. The $T_d$ detecting circuit, which is implemented by two comparators, can detect the duration of the $T_d$. The signals following both detecting circuits can be measured using an FPGA. The signals pro-
produced by the FPGA, representing the abnormal discharge, can increase the reference input of the \( T_d \) control system. The other signals produced by the FPGA, representing the actual \( T_d \), can serve as the feedback signal of the \( T_d \) control system. A perturbation with an average gain should be considered when designing a robust P controller. The optimal performance, obtained with maximal \((-k)\) can be determined by seeking the gain parameter \( k\) in the nominally stable region. Both simulation and an actual die-sinking EDMing process with optimal \((-k)\) exhibit optimal robust and transient control performance. When the energy controller is used,
the discharge energy can be maintained and the rate of erosion in the system with the $T_d$ feedback and abnormal discharge announcement exceeds that obtained using a low-pass filter or a pure $T_d$ control.

Other adaptive controllers can also operate with the nonlinear and time-varying system. The robust $P$-controller integrated with an adaptive law is one potential method to enhance the performance of the discharge energy control on EDM. High frequency discharge pulses, such as those generated in wire-cutting electric discharge machines (WEDMs), can be diagnosed via high-speed FPGA. Further research on corner cutting is required to determine how the operating parameters influence the corner accuracy.

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**REFERENCES**


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