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Improved Electrical Discharge Machine (EDM) Servomechanism Controller for Machining Micro Pits

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Abstract **- This research work is aimed at designing a better and more suitable servo control system to maintain an accurate spark gap between the electrode and the workpiece. A poor performance of EDM servo controller results in longer Ignition Delay Time, and inadequate speed of EDM machines in the micromachining process. Also, harmful arcing and short circuit as a result of inaccurate position control of the machine electrode in relation to the work piece are undesirable machining cases experienced in poorly controlled EDM process. The objective of this paper is to design a good servo system with a very good precision to obtain a better settling time. A PID controller is designed and fine-tuned with SIMULINK and MATLAB PID tuner to obtain suitable gains for faster and accurate response of the EDM process. Verified results obtained from the step response and Bode plot of the servo control system include: a settling time of 3.52 seconds, the rise time of 1.05 seconds, the percentage overshoot of 7.68%, the phase gain of 62 degrees at a frequency of 1.27rad/s, and a steady-state error less than 2%. The research work produced a better design and simulated results proved the accuracy and precision of the servo controller.**

Key Words: **Micromachining, Servo-control, Electrical discharge, Delay- Time, Ignition.**

I INTRODUCTION

The Electrical Discharge Machining (EDM) is a controlled process where pulsed of electrical discharge is used to erode metal in a work-piece. In other words, Electrical Discharge Machining is the machining method in which voltage is applied through a dielectric medium between the tool electrode and work-piece [1]. EDM can also be defined as the process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a work-piece in the presence of a dielectric fluid [2]. In typical industrial terms, EDM is a controlled metal removal process that is used to remove metal by means of electric spark erosion [3]. Electric discharge machining provides an effective manufacturing technique that enables the production of parts made of special materials with complicated geometry which is difficult to produce by conventional machining processes [2].

Modern day EDM (also known as spark machining or Spark Erosion) process has been given a significant amount of research focus in manufacturing micro components and highly advanced electrical discharge machines which are available for most machine applications. The working principle of EDM process is based on the thermoelectric energy created between a workpiece and an electrode submerged in a dielectric fluid with the passage of electric current [2]. The workpiece and the electrode are separated by a specific small gap called spark gap. In the EDM process, there is no mechanical contact between the electrodes and workpiece, and spark erosion is produced by electrical discharge. This process has as its basic requirement the electrical conductivity of electrode and work-piece. A resistivity ranging from 100Ω/cm to 300Ω/cm is also required for the electrodes. The dielectric must have low viscosity, high dielectric strength, and quick recovery after breakdown, effective quenching/cooling and flushing ability [4].

The electrical discharge in the EDM process causes strong heating of the workpiece material and electrode material tool, rapidly creating a small molten metal pool at the surface of the workpiece. The molten metal pool at the workpiece surface is flushed with dielectric in the form of debris. The material removal rate is determined by the crater size and the frequency of crater generation (i.e. discharge energy and the frequency of discharges). Also, the cavity produced in the work piece is approximately the replica of the tool [4]. A better explanation of EDM principle is provided by the EDM process. EDM is employed in industrial micromachining processes that require high precision to produce best quality products involving micro pits with complex geometry. The electrode-to-workpiece spark gap is controlled by a servo control system. A poor performance of this EDM servo controller results in longer Ignition Delay Time, and inadequate speed of EDM machines in the micromachining process. Also, harmful arcing and short circuit as a result of inaccurate position control of the machine electrode in relation to the work-piece are undesirable machining cases experienced in poorly controlled EDM process.

A good number of previous researches have been done in the field of Electrical Discharge Machining (EDM). [5] applied an intelligent approach for process modeling and optimization of electric discharge machining (EDM), Micro Electrical Discharge Machine machining (Micro-EDM) as a powerful bulk micromachining technique that is applicable to any type of electrical conductor was described in [6], including all kinds of metals and alloys as well as doped semiconductors, in a research by [7] an experiment to

analyze the effect of machining parameters such as discharge current (I_p), pulse on time (T_{on}), voltage (v) over the responses of Material Removal Rate (MRR) and Surface Roughness (SR) was performed. In the experiment, various techniques were applied to improve the material removal rate (MRR), surface roughness (SR) and tool wear rate (TWR) with different electrode combination, [3] carried out a research on how servo control system can be used to maintain the gap between Electrode and workpiece in Electrical Discharge Machining (EDM), improving the performance of the machine.
In this paper, the modelling and simulation of the Electrical Discharge Machining (EDM) and a servo system controller will be carried out in order to have a better performance of micro-machining positioning.

II EDM DC SERVO MOTOR MATHEMATICAL MODEL

A servomechanism (or simply Servo) is an automatic device that uses error-sensing feedback to correct the performance of a control system. Figure 1 shows the block diagram of an EDM servo control system.

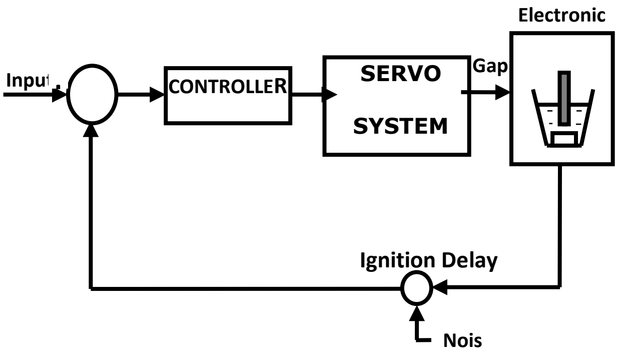

Figure 1: Block diagram of an EDM Servo Control System.

A servo is mostly employed in systems where the feedback or error-correction signals are applied to controlling mechanical position or other parameters. Servomechanisms are primarily driven by servo motors, especially DC servo motors. Figure 1 shows the block diagram of an EDM servo control system.The circuit diagram of a servo motor is shown in figure 2.

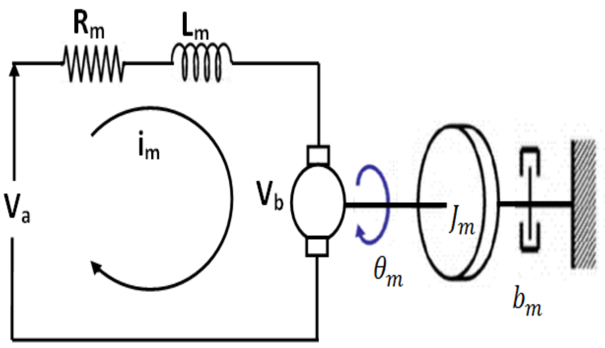

Figure 2: A servomotor circuit Diagram.

A DC servo motor is an actuator that converts electrical energy to mechanical rotation using the principles of electromagnetism. DC servomotors are one of the main components of automatic systems. Any automatic system should have an actuator module that makes the system to actually perform its function [8].
Figure 2 shows that a DC servomotor has two main components, the electrical and the mechanical components. The electrical components consists of resistance, inductance, input voltage and the back electromotive force. The mechanical component determines the mechanical rotational movement at the servomotor shaft. The mechanical component consist of the motor's shaft, inertia of the motor or load inertia and damping.
Most DC Servomotors have good torque and speed characteristics and are controlled by changing the voltage signal connected to the input. The parameters considered in figure 2 are denoted as follows:
R_m = resistance, L_m = inductance, V_a = applied or input voltage, V_b = the back electromotive force (emf), J_m = load or shaft inertia, b_m = damping, θ_m = angular position of the output shaft, ω_m = the angular speed of the shaft, T_m = the motor torque, i_m = the current, K_m = the torque constant.
From figure 2, the transfer function of the DC servomotor can be derived using Kirchhoff's voltage law and Laplace transforms as follows:
Applying Kirchhoff's voltage law,

$$V_a = R_m i_m + L_m \frac{di_m}{dt} + V_b \quad (1)$$

The angular speed of the shaft, ω_m and the angular position of the output shaft θ_m are connected by equation (1)

$$\omega_m = \frac{d\theta_m}{dt} = \dot{\theta} \quad (2)$$

The Back-electromotive force (emf), V_b can be expressed in terms of θ_m or ω_m as shown in equation (2)

$$V_b(s) = K_m \frac{d\theta_m}{dt} = K_m \omega_m \quad (3)$$

Putting equation (3) into (1),

$$V_a = R_m i_m + L_m \frac{di_m}{dt} + K_m \omega_m \quad (4)$$

Taking the Laplace transform of equation (4),

$$V_a(s) - R_m(s) I_m(s) - L_m(s) I_m(s)s + V_b(s) \quad (5)$$

Expressing the current $I_m(s)$ in terms of the other parameters in equation (5),

$$I_m(s) = \frac{V_a(s) - K_m(s)\omega_m(s)}{L_m(s)s + R_m(s)} \quad (6)$$

The mechanical component of the servomotor can be represented by equation (7)

$$J_m \frac{d^2\theta_m}{dt^2} + b_m \frac{d\theta_m}{dt} - T_m = 0 \quad (7)$$

But the motor torque T_m can be written as in equation (8)

$$T_m = K_m i_m \quad (8)$$

Substituting equation (8) into (7) gives

$$J_m \frac{d^2\theta_m}{dt^2} + b_m \frac{d\theta_m}{dt} - K_m i_m = 0 \quad (9)$$

$\frac{d\theta_m}{dt}$ in equation (9) can be replaced with equation (2) to obtain equation (10).

$$J_m \frac{d\omega_m}{dt} + B_m \omega_m - K_m i_m = 0 \quad (10)$$

Taking the Laplace transform of equation (10),

$$J_m(s)\omega_m(s)s + B_m(s)\omega_m(s) - K_m(s) I_m(s) = 0 \quad (11)$$

Expressing the current in equation (11) $I_m(s)$ in terms of other parameters,

$$I_m(s) = \frac{J_m(s)\omega_m(s)s + B_m(s)\omega_m(s)}{K_m(s)} \quad (12)$$

Combining equations (6) and (12) gives the Transfer Function of the servo motor, $G_{(s)}$ as shown in equations (13).

$$\frac{J_m(s)\omega_m(s)s + B_m(s)\omega_m(s)}{K_m(s)} = \frac{V_a(s) - K_m(s)\omega_m(s)}{L_m(s)s + R_m(s)} \quad (13)$$

$$\omega_m(J_m(s)s + B_m(s))(L_m(s)s + R_m(s)) = K_m(s)(V_a(s) - K_m(s)\omega_m(s)) \quad (14)$$

$$\omega_m(J_m(s)s + B_m(s))(L_m(s)s + R_m(s)) = K_m(s)V_a(s) - K_m(s)^2\omega_m(s) \quad (15)$$

$$\omega_m(J_m(s)s + B_m(s))(L_m(s)s + R_m(s)) + K_m(s)^2 = K_m(s)V_a(s) \quad (16)$$

$$\omega_m[(J_m(s)s + B_m(s))(L_m(s)s + R_m(s)) + K_m(s)^2] = K_m(s)V_a(s) \quad (17)$$

$$\frac{\omega_{m(s)}}{V_a(s)} = \frac{K_m(s)}{[J_m(s)s + B_m(s)].[L_m(s)s + R_m(s)] + K_m(s)^2} \quad (18)$$

$$G(s) = \frac{\omega_{m(s)}}{V_a(s)} \quad (19)$$

$$G(s) = \frac{K_m(s)}{[J_m(s)s + B_m(s)].[L_m(s)s + R_m(s)] + K_m(s)^2} \quad (20)$$

Equations (22) shows that the Transfer Function of the servo motor is the ratio of the angular speed of the shaft and the angular position. The standard parameter values of a typical Die-Sinking EDM servomechanism obtained experimentally from a previous research (Ananya et al., 2011) are given as: R_m = 4.0 Ω, L_m = 2.75 x 10^{-6} H, J_m = 3.22 x 10^{-6} Kgm^2, B_m = 3.508 x 10^{-6} Nm/(rad/s), K_m = 0.027 V/(rad/s)

Substituting the above parameter values into eqation (20) gives the actual Transfer Function of the servo motor as shown in equation (4).

$$G(s) = \frac{0.027}{[3.22 \text{ x } 10{-}6\, s + 3.508 \text{ x } 10{-}6].[2.75 \text{ x } 10{-}6s + 4.0] + 0.027^2}$$
(21)

$$G(s) = \frac{\omega_{m(s)}}{V_a(s)} = \frac{0.027}{s^2 + 1.086s + 0.000779} \quad (22)$$

III DESIGN SPECIFICATIONS

a) Percentage overshoots less than 10% to a unit step input.
b) Settling time less than 5 seconds to a unit step input.
c) Rise time of less than 2 seconds to a unit step input.
d) Steady-state error less than 0.2%.
e)

A *EDM Controller (PID) Design*

A Proportional Integral Derivative (PID) controller is a generic control loop feedback mechanism widely used in industrial control systems and is regarded as the standard control structures. A PID controller, sometimes called three-term control, calculates an error value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process through the use of a manipulated variable. The PID controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. Figure 3 shows the control system model with general PID controller.

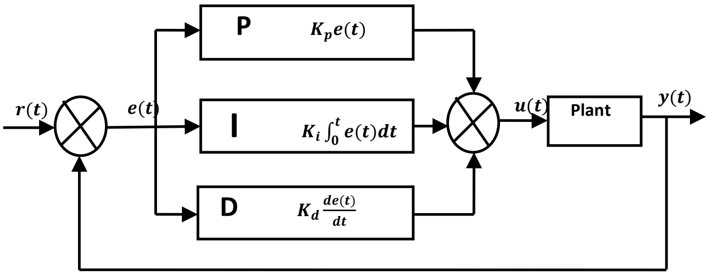

Figure 3: The Model of a PID Controller Configuration.

From Figure 3, the mathematical expression for the three controller gains can be written as follows:

- The proportional controller is an amplifier with adjustable proportional gain, K_p. The action of this controller depends on the error present . The equation is:

m(t) = K_pe(t) (23)

Where m(t) = controller output, K_p = Proportional gain/sensitivity, and e(t) = actuating error signal

- In the integral gain K_i or integral controller action (also known as Reset Control), the output of the controller changes at a rate proportional to the actuating accumulation of past error signal e(t).
 integral gain, as shown in equation (24).

m(t) = $K_i\int_0^t e(t) + m(0)$ (24)

Where K_i = Integral gain, m(0) = Control output.

- In the derivative control action or derivative gain K_d, the output of the controller depends on the rate of change of the actuating prediction of future error signal e(t). The equation for D is written as

m(t) = $K_d\frac{d}{dt}e(t)$ (25)

The three separate controller gains parameters involved in PID controller algorithm can be combined as in equation (26).

$$u(t) = K_pe(t) + K_i\int e(t)dt + K_d\frac{de(t)}{dt} \quad (26)$$

T_i = integral time and T_d = derivative time.

Applying the PID controller to any control system involves adjusting the values of gain K_p, K_i and K_d in order to get the best response of the system. The selection of PID controller gain values causes the variation of observed response with respect to desired response.

IV RESULT AND DISCUSSION

The analysis and discussion of the results obtained from the design of the Electrical Discharge Machining (EDM), process mathematical model, servo control system modelling, and controller design and simulation is presented below. The results include the step responses of the EDM servomechanism, mathematical model transfer function as well as the improving effects of the controller on the overall system.

A *PID Controller Tuning Using Mathlab/Simulink*

The actual PID controller gains from tuning Using MATLAB/SIMULINK are: $K_p = 59.3$, $K_i = 0.655$ and $K_d = 28.1$. Putting these controller gains obtained from the tuning into a standard controller equation, this gives equation (27).

$$G_c(s) = 59.3 + 0.655\frac{1}{s} + 28.1s \qquad (27)$$

B Initial Step Response of EDM Servo Control System Model

The initial performance of the EDM servo control system without a well tuned PID Controller was investigated by simulating equation 14 using MATLAB/SIMULINK. The step response plot of the result are shown in figure 4. From the plot, the open-loop response of the EDM servo control system does not satisfy the design criteria at all. The settling time of 520 seconds, the rise time of 355 seconds, the percentage overshoot of 0%, the phase gain of -120 degrees at a frequency of 113.5rad/s, and a steady-state error less than 5%. This describes a very poor stability of the system. It can be inferred from the plot that with the open-loop response the system is partially unstable. It can also be interpreted that the response of the EDM) servo control system without a well tuned PID is practically very slow and a longer ignition delay time. This can lead to uncontrolled performance of the EDM process as a result of non-linearities.

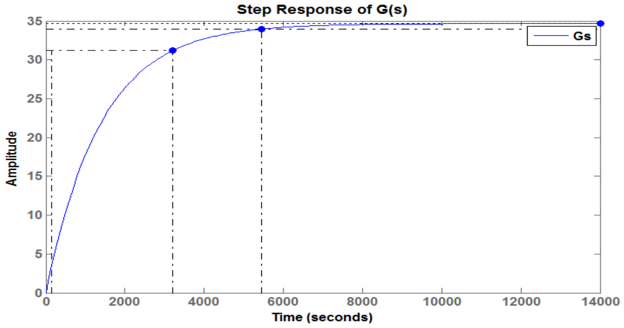

Figure 4: Initial Step response the Servo Transfer Function, G(s).

C EDM Servo Control System Model with Tuned PID Controller

The step response and Bode plot of the EDM servo control system with a well tuned PID controller as shown in figure 1 was simulated using MATLAB/SIMULINK. The PID controller was tuned with a Matlab/Simulink PID tuner application. The results of the simulation for the system with transfer function and state equation are shown in figure 5. From the step response plot for the EDM servo control system with the transfer function, G(s) is shown in figure 5

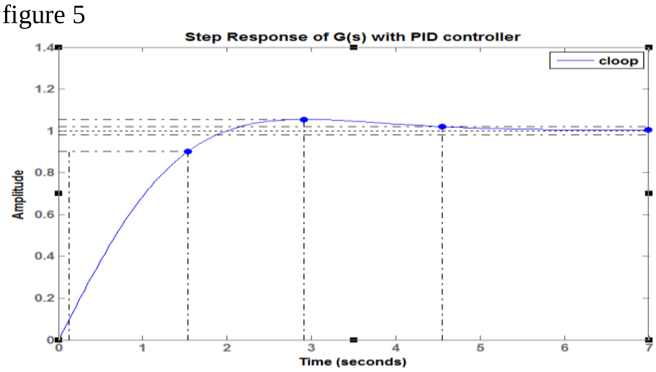

Figure 5**:** Step Response of the Overall EDM Servo Control System.

The control parameters obtained in figure 5 are: a settling time of 3.52 seconds, the rise time of 1.05 seconds, the percentage overshoot of 7.68%, the phase gain of 62 degrees at a frequency of 1.27rad/s, and a steady-state error less than 2%. These servo control parameter values indicate significant improvements in the performance of the system. Such improvements include a shorter and constant ignition delay time corresponding to the reduced rise time, and a higher speed and accuracy of the EDM tool electrode positioning to achieve the appropriate spark gap.

V CONCLUSION

In this research the servomechanism have been successfully developed and simulated based on the initial, ignition and discharge phase of current and voltage gap. Also, the design of a classical servo controller that optimizes the performance of the EDM process is presented. The ultimate goal of the research is to improve the servomechanism of an EDM process for a better efficiency of the EDM micromachining process. The PID controller has been successfully designed and fine-tuned with MATLAB/SIMULINK and MATLAB PID tuner to obtain suitable gains for faster and accurate response of the EDM process. The PID controller gains obtained were integrated with a servo control system to achieve a better result. Moreover, the overall control system was improved to establish a more intelligent and robust response of the EDM process especially in our modern industries.

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