

## Nonlinear Servomotor in Single Pulse Simulation of Electrical Discharge Machining System Modeling

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### Abstract

Electrical Discharge Machining, EDM is a nonconventional and high precision machining. EDM system is considered a combination of servo system and EDM process. The servo system precisely controls the gap between electrode and workpiece for the continuous electrical discharges occurrence. Machining performance and stability depend on the performance of servo system. The EDM servo system usually modeled as a linear system, which ignores the nonlinearities of the motor. An assumption that the nonlinearities are insignificant in EDM system model may leads to modeling errors and result in poor control performance. In this study, nonlinear EDM servo system model was presented and the dynamic response of the model was analyzed and compared with the linear model. Simulation result shows a slightly difference in system response and a controller used in linear model is less efficient for a nonlinear EDM servo system model. The results are very useful for control strategy and can contribute to a better machining performance and stability of EDM applications.

**Keywords:** EDM system, PID controller, DC servomotor, EDM proces

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### 1. Introduction

Electrical Discharge Machining, EDM is a nonconventional machining process for cutting complicated shape or fine hole that would be difficult to produce with ordinary cutting tools without any contact between electrode and workpiece during machining [1-2]. The history of EDM techniques was discovered by Joseph Priestly in 1770. In 1943, Dr. B. R. Lazarenko and Dr. N. I. Lazarenko developed a controlled process of machining difficult-to-machine metals by vaporizing material from the surface of metal [2-5]. In EDM system models can be arranged in two main groups, servomotor system and EDM process as shown in Figure 1. The servomotor system consists of two major subsystem; a permanent magnet DC motor with its controller and a lead-screw load. The lead-screw load consists of gear, lead-screw shaft and ram. The feedback signal in this model is the gap voltage which is calculated from EDM process. EDM process model includes three subsystems, breakdown model, material removal rate and inverse area [6-7]

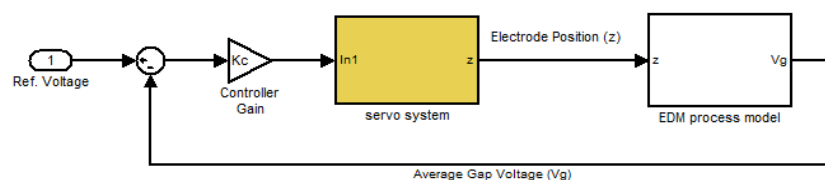


Figure 1. Model of EDM System

An electrical spark is used as an eroding tool to remove the material. The metal removal process is performed by applying of pulsed high frequency direct current through electrode to

workpiece. The electrode motion is controlled by the machine so it positioned is not to contact the workpiece [8-10]. When the gap between electrode and workpiece is sufficiently small 10–50  $\mu\text{m}$ , the gap is said being controlled by the servo system, an electrical spark occurs in the gap. In this process, current is converted into intense heat with extremely high temperatures reaching 8000° to 12000°C that could melting almost anything [2], [11-15]. The gap between an electrode and a workpiece is adjusted and maintained using servomotor system at a critical gap for the continuous occurrence of spark discharge. The machining stability and productivity depend on the performance of servomotor system [16-22]. Since the gap between electrode and workpiece is cannot be measured directly, the average voltage gap ( $V_g$ ) is implemented as the feedback signal to monitor the gap which represents voltage drop occurred during discharge phase. After that the error voltage between the  $V_g$  and the reference voltage is used as an input of EDM controller. The control gain ( $K_c$ ) and the level of  $V_s$  are manually preset manually by the EDM machine operator [23-25].

Previous studies use linear models to simulate the servo system, so the effect of nonlinearities of DC servomotor is not represented. Nonlinearities that occur in servomotor operation should be modelled to evaluate the reliability of the controller used to control the electrode position. In this paper, nonlinear servo system model used is expected to represent the nonlinearities that naturally occur during the motor operation, so that the influence of nonlinearities to the EDM system can be observed. DC servomotor model will be carried out using the transfer function approach according with a PID controllers for position controlled and will be presented in linear and nonlinear model. The simulation is then implemented using Matlab simulink. Dynamics response of each model will be analysed and compared. The dynamic response of EDM system model is simulated to identify the effects of nonlinearities in servo system to the EDM system model.

## 2. Research Method

### 2.1. DC Servomotor Model

DC servomotor is a permanent magnet DC motors that are modified to work using a closed loop control system in which the shaft position or angular velocity are the control variables [26-27]. A controller can be used to direct the operation of the servo motor by sending position or velocity signals to drives the motor. In modelling the DC motor, the aim is to find the governing differential equations that express the motor characteristics and relate the applied voltage to the torque produced by the rotor. The DC motor equivalent circuit is shown in Figure 2.

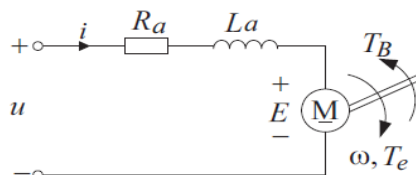


Figure 2. DC motor equivalent circuit

The voltage balance equation of DC motor armature circuit based on Kirchhoff's law is expressed as:

$$u = R_a i + L_a \left( \frac{di}{dt} \right) + K_e \omega \quad (1)$$

The torque balance equation of DC motor based on Newton's law is expressed as:

$$K_t i - K_e \omega = J \left( \frac{d\omega}{dt} \right) \quad (2)$$

Where,  $i$  is armature current (A);  $L_a$  is equivalent inductance of armature circuit (H);  $R_a$  is equivalent resistance of armature circuit ( $\Omega$ );  $u$  is terminal voltage of armature circuit (V);  $K_e \omega$  is

back electromotive force (Vs/rad);  $J$  is the inertia moment of the rotor ( $\text{Kg.m}^2$ );  $K_t$  is the torque coefficient of DC motor ( $\text{Nm/A}$ ) and  $\omega$  is angular velocity ( $\text{rad/s}$ ).

The transfer function of DC servomotor model is obtained by combining equation 1 and 2. The Laplace Transform of both equations gives the simulink model depicted in Figure 3. The angular position,  $\theta$  of the motor is obtained by taking the integral of the motor velocity,  $\omega$ .

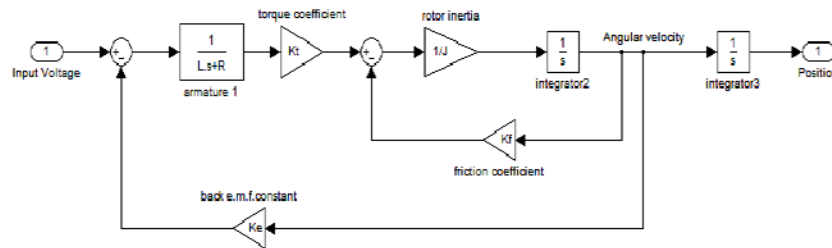


Figure 3. Linear DC motor Simulink Model

**2.2. Nonlinear DC Servomotor Model**

DC servomotor is always having nonlinearities that need to be considered in controller design. In presence of this nonlinearities behaviour, it is difficult to tune a controller as the nonlinear effects are difficult to predict and vary with the system load [28-30]. The performance of controller will not be close to optimal and not be satisfactory. The nonlinear effects are dominant at low motor speeds and gradually get less prominent with higher motor speed. When a DC motor operates in two directions and high precision control is needed for the application, the assumption that the nonlinear effects on the system are negligible may lead to insufferably high modelling errors and result in poor control performance [31-33].

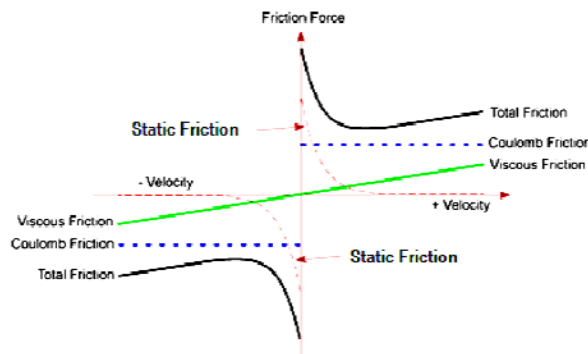


Figure 4. Force vs velocity for friction [28]

**2.2.1. Friction**

Figure 4 showed frictions of the motor torque. Static or stiction friction characterizes a starting point over which the motor torque must cross with the purpose of smooth motion. Stiction is the effect where, if the interface has remained still for any length of time, the amount of force required to start the relative motion is greater than the amount required to sustain it. Viscous or kinetic friction represents a torque that always in the opposite direction of shaft rotation. However, the viscous friction is proportional to the change of the angular velocity and in the model it is always considered as a linear function with respect to the change of the angular velocity [6]. Coulomb or dry friction represents a constant torque that is always in the opposite direction of shaft rotation. It can be modeled as a current source in parallel to the motor with constant current. Moreover direction of this current equals the motor's current direction every time. Coulomb friction is expressed imposed as a signum function dependent on the rotational speed [34] as below:

$$sgn(\omega) = \begin{cases} 1, & \omega > 0 \\ 0, & \omega = 0 \\ -1, & \omega < 0 \end{cases}$$

In order to simplify applications and reflect the real nonlinear friction of the motor accurately, a simplified friction model [35] was expressed in the Equation (3) as below:

$$T_f = J_m \cdot \frac{d\omega}{dt} + T_{fvisc} + T_{fcoul} \cdot sgn(\omega) \tag{3}$$

Where,  $T_{fcoul}$  is the coulomb friction torque (Nm);  $T_{fvisc}$  is viscous friction torque (Nm);  $\omega$  is the angular velocity of the rotor (rad/s);  $sgn(\omega)$  is signum function of angular velocity. The coulomb friction causes mechanisms to be resistant to move from rest. A rotational system will not start to move apparently until the driving torque is large enough to break the static friction torque. Such characteristics of coulomb friction form dead zone nonlinearity in the system [30, 34]. The dead zone nonlinearity is depicting in Figure 5.

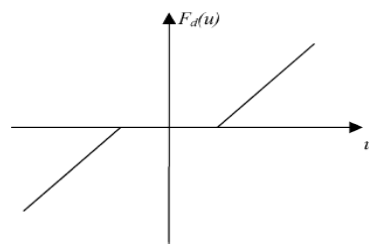


Figure 5. Dead zone nonlinearity

**2.2.2. Backlash**

The speed required by the load is too low as compared to the nominal speed of the motor. In such cases, gears are introduced between the motor and the load, thus reducing by a factor,  $n$  the angular velocity of the load itself. When a gear is inserted in servo system, backlash is experienced on its output due to the coupling between the cogwheels of the gear. This gives rise to nonlinearities and discontinuities in the force/velocity relationships. Backlash is the term that is commonly used to describe any sort of coupling that has slack when it is unloaded. Devices such as gear trains, or mechanical linkages that contain pinned hinges, will exhibit backlash to some extent or another as illustrated in figure 6(b). The nonlinear EDM servo system model usually fixed with leadscrew load as shown in figure 6(a). A leadscrew load containing the motor and leadscrew gears, leadscrew shaft and ram to hold an electrode. The calculation of the mechanical system inertias for the lead screw load is carried out using Newton's second law of motion [6, 36].

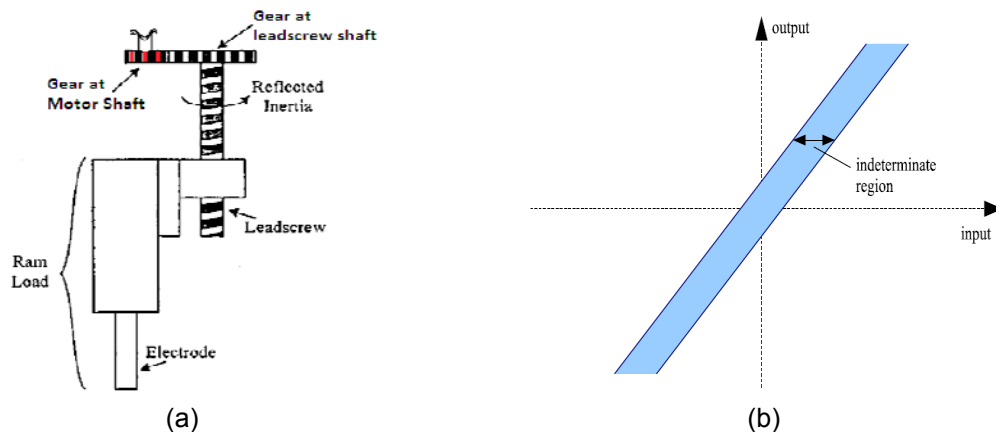


Figure 6. (a) Servomotor leadscrew load (b) Input-output for element with backlash

**2.3. PID Controller**

The PID controller is a common controller used in EDM system [37]. It includes three term parameters comprised of proportional (P), integral (I) and derivative (D). PID controller algorithm does not need complicated mathematics and can be calculated more easily. The relationship between control signal and process error in PID controller is presented in equation 4 below:

$$u = K_p + K_i \int e dt + K_d \frac{di}{dt} \tag{4}$$

Based on the Equation (4), the proportional gain ( $K_p$ ) is depend on the present error value and have direct relationship to the controller sensitivity. The integral gain ( $K_i$ ) depends on the summation over time of the present error and the previous error. The derivative gain ( $K_d$ ) will considered the current error and the duration of error. By inserting nonlinearities of friction, dead zone and backlash to the linear servomotor model that connected to leadscrew load will represent a complete nonlinear EDM servo system model [38]. The dead zone nonlinearity can be appeared as a characteristic between the overall system input and output. The manufacturer data for a particular DC servomotor and experimental data in paper [6] are used for the simulation purposes. A complete nonlinear model of DC servomotor is shown in Figure 7.

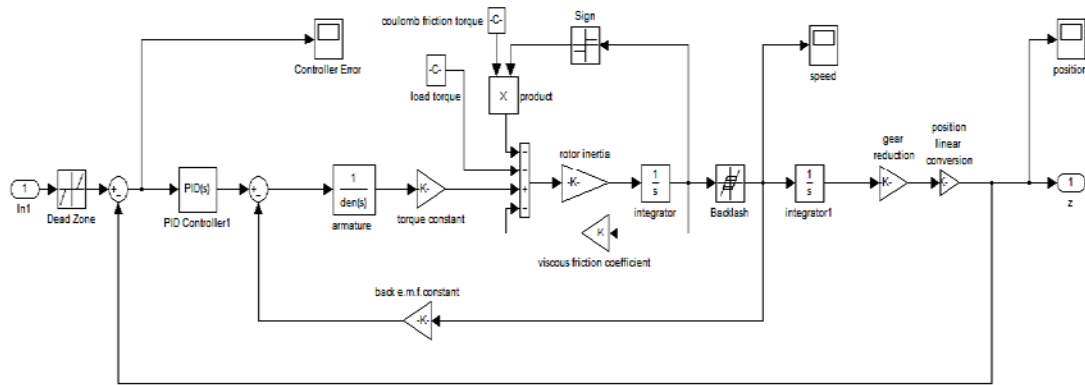


Figure 7. Simulink of Servo System model

**2.4. EDM Process Model**

EDM process block is a model for EDM discharge phenomenon [6], [39-41]. The simulation of EDM process consists of material removal rate model, breakdown model and voltage average gap model. The mathematical material removal rate (MRR) model is developed using Dimensional Analysis to examine the most effective parameters on the material removal rate or efficiency of the machining according to the Equation (5) as below:

$$\dot{V} = C \times \alpha \times V_{arc} \times I_{gap} \times F_s \times t_{on} \tag{5}$$

Where  $C$  is experimental dimensionless constant,  $\alpha$  is a material properties factor,  $V_{arc}$  represent gap voltage,  $I_{gap}$  is gap current,  $t_{on}$  represent discharge pulse on-time, and  $F_s$  is represent sparking frequency. Then by integrating and then dividing the surface area of electrode, the position of the workpiece ( $\xi$ ) is obtained. After that the position of workpiece is subtracted from the electrode position ( $z$ ) established in servo block. Then the result is used in empirical breakdown model to calculate ignition delay time ( $t_d$ ) [42-44]. In this subsystem,  $t_d$  can be calculated according to nonlinear model as according to the equation 6 as follow

$$t_d = 1.04 \times 10^{25} \times \delta^{6.57} \tag{6}$$

Where, the gap position  $\delta$  is nonlinearly related to the ignition delay time  $t_d$  and to a less important point on dielectric fluid flushing velocity. Ignition delay is in ( $\mu\text{s}$ ) and the gap width in ( $\mu\text{m}$ ) for a typical flushing velocity of 1m/s [45-48]. Next, ignition delay time is used as input of average gap voltage model. For the regulation of the gap between electrode and workpiece the average gap voltage is employed as an indirect measured factor [49-50]. An average gap voltage ( $V_g$ ) is calculated according to the Equation (7) as below:

$$V_g = \frac{(V_{max} \times t_d) + (V_{arc} \times t_{on})}{(t_{on} + t_{off} + t_d)} \tag{7}$$

A complete simulink model of the EDM process and simulation parameters is shown in Figure 8. The numerical data in paper [51] are used for the simulation purposes.

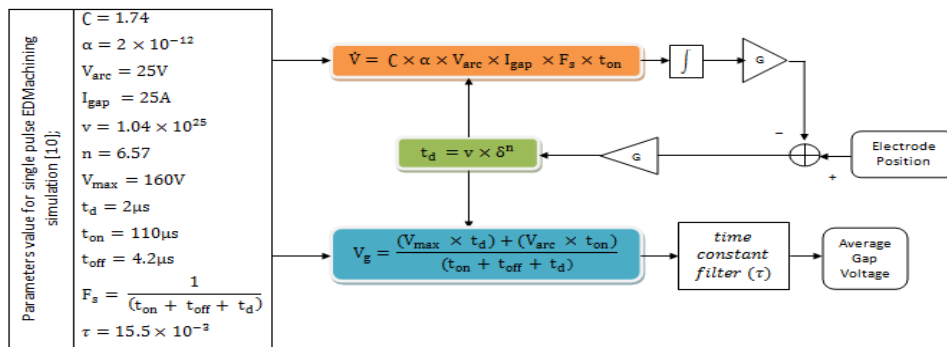


Figure 8. Simulink of EDM process model

### 3. Results and Analysis

Simulation of EDM system model that consist of nonlinear servo system and EDM process model has been carried out using MATLAB Simulink in order to analyse the system response for single pulse machining process. At first, linear and nonlinear servomotor model is simulated in open loop system to analyse the dynamic response of each model. At steady state, nonlinear servomotor model have shows a lower maximum electrode velocity compared to a linear model as illustrated in Figure 9. The settling time for nonlinear servomotor model also slightly higher compare to linear model that indicates nonlinear effect in resulting slower system response.

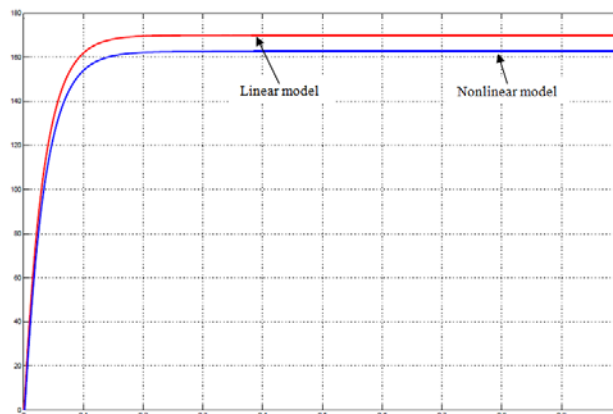


Figure 9. Angular velocity vs time

Figure 10 and 11 illustrate the temporal velocity and position of the electrode in a closed loop system with a PID controller respectively. For linear model system, the controller is

sufficiently controlled the electrode velocity and position and give fast system response with zero steady state error. However, for nonlinear model system, similar controller gives a slightly different in system response. The nonlinearities effect caused the controller are not at optimum performance with slower system response compare to linear system model and having higher steady state error.

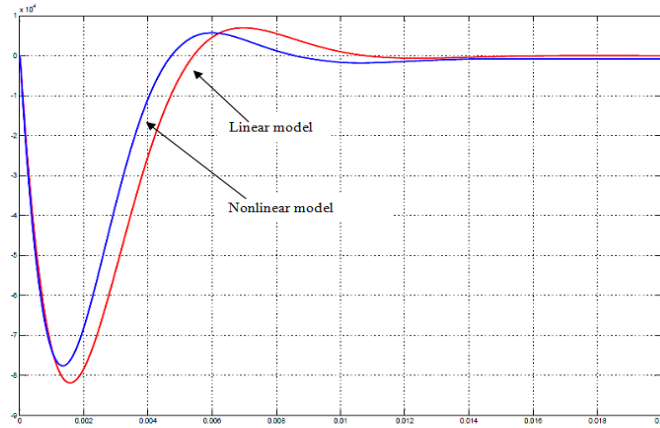


Figure 10. Temporal electrode velocity vs time for closed loop servo system

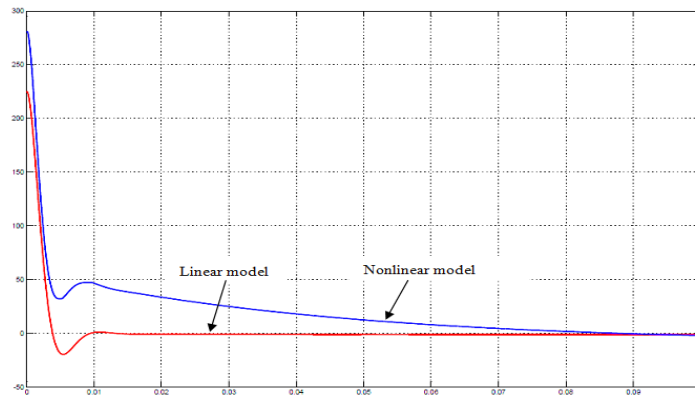


Figure 11. Temporal electrode position vs time for closed loop servo system

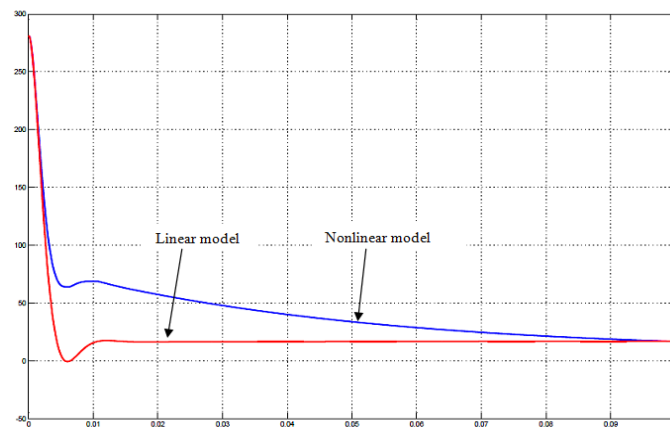


Figure 12. Temporal electrode position of EDM system model

Figure 12 illustrates the simulation response of electrode position from the complete EDM system model at fixed  $t_d = 2\mu\text{s}$ . Time for electrode position to settle down at closed to reference gap ( $21.13\mu\text{m}$ ) is measured. At this gap the position is said being controlled by the servo system and the discharge phase is takes place. Temporal electrode position for linear EDM system model is adjusted from initial position,  $280\mu\text{m}$  to  $17.5\mu\text{m}$  in  $10\mu\text{s}$  compared to nonlinear model need longer time which is approximately at  $90\mu\text{s}$  to meet  $17.5\mu\text{m}$ . It can be conclude that a nonlinear EDM system model give insufficient control performance and slower response system due to higher steady state error and longer settling time compared to linear EDM system model. However, nonlinear model showing more stable system compared to linear model based on the lower in overshoot value. The linear control strategy in this case is less effective to ensure the nonlinear EDM system model performs well and need to be improved.

#### 4. Conclusion

This work presents a nonlinear EDM system model that consists of nonlinear servo system model and EDM process model. The main goal of this study was to investigate the effect of nonlinearities in servo system model to the EDM system model. Dynamic response from a linear servomotor model is used to compare with the nonlinear servomotor model. An Open loop test for a motor model was implemented in order to identify a nonlinear behavior of servomotor model. An adequate PID controller that had been proved in linear DC servomotor model was inserted into the nonlinear DC servomotor model. A closed loop test was then implemented in order to obtain the dynamic response on the EDM system. As a result from the closed loop test indicates that slower response system with poor control strategy for nonlinear EDM system and linear PID controller is insufficient for controlling a nonlinear EDM system model and need to be improved. The simulation of nonlinear model is represented closely to the real EDM machine operation.

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