Precision Engineering xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Improving electrical discharging machining efficiency by using a Kalman filter for estimating gap voltages

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ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form 6 July 2016
Accepted 23 August 2016
Available online xxx

Keywords:
Kalman filter
Stochastic process
Gap voltage
Electrical discharging machining (EDM)

ABSTRACT

Gap voltage can be used as an indicator on the direction of the electrode movement along a desired tool path in electrical discharging machining (EDM) processes. However, due to the noise induced by electrical discharges, the estimation of gap voltages is difficult due to the lack of an appropriate state space model. In this paper, gap voltage signals are considered to be generated as a summation of colored noise through a linear filter and measurement noise. Obtained by the Yule–Walker auto-covariance method, the transfer function of the linear filter can be converted into a state space model. The composite process noise and the composite measurement noise are defined to derive the composite noise covariance matrices. A Kalman filter can thus be designed based on the state space model and the noise covariance matrices. Experimental results showed that, as compared with the traditional 10-point moving average filter, the Kalman filter can decrease the average machining time as well as improve the discharging gap status.

1. Introduction

Electrical discharging machining (EDM) is a process which can remove workpiece materials by a series of electrical discharges occurring between an electrode and a workpiece [1,2]. Unlike in a milling machining, the movement of servo axes of an EDM machine are not only dependent on movement commands, but also determined by the gap status between an electrode and a workpiece [3]. From the control point of view, there are two control loops in an EDM process: the inner loop is the servo control loop, whose function is to position the servo axes; and the outer loop is the gap width control, whose function is to maintain an appropriate gap width. To maintain a stable machining, the gap width between the tool electrode and the workpiece should be kept to a distance of 10–100 μm [3]. As a direct measurement of the gap width during discharging is difficult, average gap voltage [4] and ignition delay [5] and time ratio of each gap state [6–8] are the three types of variables that can be used as feedback signals to control the gap width. Average gap voltage is more commonly used for its simplicity in implementation.

A gap width control block diagram when gap voltage is used to maintain the gap width is shown in Fig. 1. V_s is the preset servo voltage and V_{est} is the filtered gap voltage. Given the voltage difference $\Delta V = V_{est} - V_s$, a function $K_e(\Delta V)$ is used to compute the feedrate f_r for the next servo period. Thus $f_r T_s$ is the displacement calculated by an interpolator that should be traveled during the next servo period, where T_s is the servo period. When the gap voltage is higher than the servo voltage ($V_{est} > V_s$), the electrode should move forward along the trajectory to reduce the gap width. By contrast, when the gap voltage is lower than the servo voltage ($V_{est} < V_s$), the electrode should retract to increase the gap width so as to leave a deteriorated gap condition. The integrator $1/s$ in the block diagram means that the integral of the feedrate within the servo period is the position command to the servo loop, and the gain of -1 reflects the fact that a positive error will reduce the gap width, and vice verse. In this paper, the existing gap width control strategy was used, which, as shown in Fig. 2, is a nonlinear function $f_r = K_e(\Delta V)$ relating feedrate (f_r) to gap voltage difference (ΔV). This function was obtained empirically by the EDM machine manufacturer.

In an ideal scenario, when a short pulse or an arc is detected, the electrode will retract quickly so as to move away from the occurrence of arcs. In practice, however, it is not easy to achieve such an ideal scenario. To keep a stable gap width, there are basically two tasks involved: one is the design of a gap width controller, and the other is the estimation of feedback signals, such as gap voltage signals.

To design a gap width controller, it is important to build a dynamic model for EDM processes. Due to the difficulties in modeling EDM processes, fuzzy logic [9–11], neural networks [12,13], and genetic algorithm [14] are often used to model the dynamics of EDM processes and to help to design a gap width controller. Many researchers developed various servo controllers for EDM

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http://dx.doi.org/10.1016/j.precisioneng.2016.08.003
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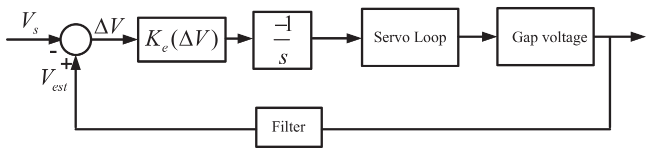

Fig. 1. Block diagram of gap width control for EDM processes.

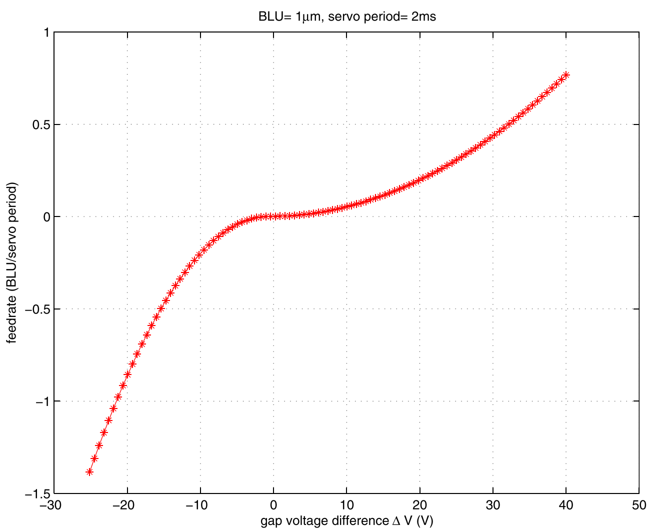

Fig. 2. Nonlinear function relating feedrate to gap voltage difference for gap width control.

processes. Due to its time-varying and stochastic nature, an online identification algorithm was used to obtain the process model, and then a controller was designed based on the model parameters [6,7,15,16]. Wu et al. used an adaptive control system to directly control electrode discharging cycles [17]. A variable structure system (VSS) controller was reported to control the gap width and achieve a good machining performance [18] and later robust gap width control was applied to compensate for the electrode wear in an electric discharge scanning (ED-Scanning) process [19].

The second task in the design of a gap controller is the estimation of feedback signals. In this paper gap voltage is chosen as the feedback signal. When making a judgment on whether to move forward or backward, the gap voltage is a crucial measure. As EDM machining is a stochastic process, there exists strong noise in measured gap voltage signals. In the gap width control loop as shown in Fig. 1, a filter or an estimator is designed to estimate the gap voltage from a noisy environment. To minimize the estimation error in a statistical sense, an optimal filter can be used to remove the noise components. Conventional EDM machines simply use moving average filters. Though working smoothly, a moving average filter cannot be considered as an optimal estimator for gap voltages.

Kalman filters have long been considered as optimal estimators for noisy signals [20–22]. Kalman filters are designed based on state space models. Though a Kalman filter can be applied in a stochastic EDM machining process, the building of a state space model for a Kalman filter is not a trivial task. Give a sequence of noisy signals, the challenge for the design of a Kalman filter is to build a state space model. Zhou et al. [23] used two interactive Kalman filters based on an instrumental variable approach to obtain unbiased model parameter estimates online for an EDM process.

In this paper, a Kalman filter is designed and used together with a gap width controller to form a closed loop as illustrated in Fig. 1. A state space model for a Kalman filter is first built based on an autoregressive (AR) model for gap voltage signals. A discrete–time transfer function, or an autoregressive model, is built by using the Yule–Walker auto-covariance method. A discrete–time stochastic state space model is then obtained from the transfer function. To alleviate the online computational burden, a steady-state Kalman filter is used. A steady-state gain from the measurement to the estimated signal is calculated so that the estimated value can be scaled back to the original range of the measurements. By collecting gap voltage signals from an EDM test, a Kalman filter can be built for the EDM machine. The filtered gap voltage by the Kalman filter is then used as the feedback signal to the gap width controller. Experimental tests showed that, the machining time by using the Kalman filter is less than that by using the traditional moving average filter. The Kalman filter is also found to be able to improve the gap status.

2. Modeling of gap voltage dynamics

Kalman filter is an optimal linear filter which estimates a signal from a noisy environment in a minimal statistical error sense. Considering the fact that noise contained in measured gap voltage signals, it is helpful to use a Kalman filter to optimally estimate the gap voltage. To design a Kalman filter, a state space model is needed. To this end, the gap voltage signal $y(k)$ is regarded as a summation of two components

$$y(k) = y_0(k) + v(k) = G_w(q^{-1})w(k) + v(k) \tag{1}$$

where $w(k)$ is the process noise, $v(k)$ is the measurement noise, $G_w(q^{-1})$ is a linear filter, and q^{-1} is the unit delay operator. It is first assumed that both $w(k)$ and $v(k)$ are white noise, and are uncorrelated with each other, i.e., $E[w(k)v(k)] = 0$, and $w(k)$ and $v(k)$ have the same variance, i.e., $\sigma_w^2 = \sigma_v^2$. It is noted from Eq. (1) that $y_0(k)$ is the colored noise obtained by feeding $G_w(q^{-1})$ with the process noise $w(k)$. To obtain the transfer function $G_w(q^{-1})$, the Yule–Walker method can be used [22] by using the signal sequence $y_0(k)$.

The transfer function $G_w(q^{-1})$ from $w(k)$ to $y_0(k)$ can be written as

$$G_w(q^{-1}) = \frac{y_0(k)}{w(k)} = \frac{b_0}{1 + a_1q^{-1} + a_2q^{-2} + \cdots + a_{n-1}q^{-(n-1)} + a_nq^{-n}} \tag{2}$$

where n is the order of the transfer function, a_i, $i = 1, \ldots, n$ are the coefficients of the denominator, and b_0 is a constant which can be chosen such that the steady-state gain is unity.

To the use the Yule–Walker method, it is necessary to use the covariance matrix R_0 of $y_0(k)$, which is

$$R_0 = \begin{bmatrix} r_0(0) & r_0(1) & \cdots & r_0(M-1) \\ r_0(1) & r_0(0) & \cdots & r_0(M-2) \\ \vdots & \vdots & \ddots & \vdots \\ r_0(M-1) & r_0(M-2) & \cdots & r_0(0) \end{bmatrix} \tag{3}$$

where $r_0(k) = E[y_0(t)y_0(t+k)]$, and E is the expectation operator. However, the colored noise $y_0(k)$ is unavailable. What is available is the measured gap voltage $y(k)$, which contains both the colored noise $y_0(k)$ and the measurement noise $v(k)$. The covariance $r(k)$ of $y(k)$ can be computed as

$$\begin{aligned} r(k) &= E[y(t+k)y(t)] = E[(y_0(t+k) + v(t+k))(y_0(t) + v(t))] \\ &= E[y_0(t+k)y_0(t) + y_0(t+k)v(t) + v(t+k)y_0(t) + v(t+k)v(t)] \\ &= \begin{cases} r_0(0) + \sigma_v^2, & k = 0 \\ r_0(k), & k \neq 0 \end{cases} \end{aligned} \tag{4}$$