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Significant improvements of electrical discharge machining performance by step-by-step updated adaptive control laws

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A B S T R A C T

In order to obtain improved electrical discharge machining (EDM) performance, we have dedicated more than a decade to correcting one essential EDM defect, the weak stability of the machining, by developing adaptive control systems. The instabilities of machining are mainly caused by complicated disturbances in discharging. To counteract the effects from the disturbances on machining, we theoretically developed three control laws from minimum variance (MV) control law to minimum variance and pole placements coupled (MVPPC) control law and then to a two-step-ahead prediction (TP) control law. Based on real-time estimation of EDM process model parameters and measured ratio of arcing pulses which is also called gap state, electrode discharging cycle was directly and adaptively tuned so that a stable machining could be achieved. To this end, we not only theoretically provide three proved control laws for a developed EDM adaptive control system, but also practically proved the TP control law to be the best in dealing with machining instability and machining efficiency though the MVPPC control law provided much better EDM performance than the MV control law. It was also shown that the TP control law also provided a burn free machining.

1. Introduction

Electrical Discharge Machining (EDM), a non-conventional machining technology, has been widely used in industry circles after its two remarkable advantages over traditional machining had been acknowledged. One is its ability of machining conductive materials of any harness and strength. As a special and effective machining method to deal with difficult-to-cut materials like super-hard materials and high-temperature alloy materials, etc., this ability widely extends its usage in industry applications. The other is its ability to achieve high machining precisions due to the reason that EDM mechanism endows a non-contacting machining between EDM electrode and workpiece which produces no physical vibrations and deformations of machined workpiece. The vibrations and deformations of workpieces in traditional machining are quite common phenomena which are caused by cutting forces on workpieces. The cutting forces are essential in cutting off materials piece by piece from a workpiece, but produce unexpected and unnecessary vibrations and deformations of the machined workpiece, thus limiting the final reached machining precisions.

However, one essential defect of EDM which is known as the difficulty of stabilizing EDM process all the time has deterred its progress for decades though EDM tools have advanced with the advents of many new technologies but peripheral to EDM

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Nomenclature

$y(t)$	a gap state at time t
$\hat{y}(t+d\|t)$	d-step prediction of a future gap state $y(t+d)$
τ_{spark}	an accumulated number of discriminated spark states in a period of time
$\tau_{tran,arc}$	an accumulated number of discriminated transient arc states in a period of time
$\tau_{stab,arc}$	an accumulated number of discriminated stable arc states in a period of time
τ_{short}	an accumulated number of discriminated short states in a period of time
τ_{open}	an accumulated number of discriminated open states in a period of time
$\hat{\theta}$	a vector containing estimated parameters of EDM process model
$\lambda(t)$	a forgetting factor
u_c	is a reference input
$u(t)$	control variable
$e(t)$	white noise with variance σ_0

like NC, automatic position, etc. From EDM mechanism, it is known that high frequency discharges in a small gap between electrode and workpiece are likely to induce the occurrences of harmful discharging pulses named arcing pulses which are composed of stable arc pulses and short pulses when dielectric flushing condition or chips removing condition worsens. As such happens and if no proper measures are taken to impede the growth of the arcing pulses, the arcing pulses will dominate the gap making the machining process unstable and damaging workpiece surface.

For decades, many attempts have been made to improve EDM performances but mainly on material removing rate (MRR), tool wear rate (TWR), and surface quality (SR) for wide varieties of industry requirements [1–4]. Meanwhile, much of the research adopts artificial intelligence such as neural networks, genetic algorithms and fuzzy control theory to stabilize machining processes, and has achieved some effects as reported [5–10]. But these efforts have not essentially solved the stability issue and the improved machining performance was quite limited. One of the main reasons is that these studies have not researched an exact quantitative description of EDM process because of its complexity, but instead searched for ambiguous relations between gap states and control variables, thus could not theoretically explore the dynamical properties of EDM process. This tendency delayed sufficient theoretical analysis and developing effective control theories on timely varied EDM process.

Furthermore, incomplete exploitation on the nature of EDM process makes these artificial intelligent control systems unable to obtain optimal performances in different machining situations such as different materials, different shapes of workpieces and different chips removing conditions, etc. In other words, we need a highly flexible automatic control system with a consensus guideline to guide machining processes effective and efficient no matter how machining situations vary. An adaptive control system can appropriately satisfy this job [11].

Zhou built a timely-varied model of EDM process [12] and thereby developed a self-tuning regulator by minimum variance (MV) control law for on-line applications [13]. A further research by Wu focusing on stabilizing EDM process has been done [14]. In the work a minimum variance and pole placement coupled (MVPPC) control law had been established and the developed controller drives gap states to track the dynamical response of a reference model more efficiently. Experimental results showed a much more stable EDM process achieved which not only further increased the machining ability but also accelerated the fabrication. The preceding achievements provided convincing evidence that adaptive control systems behave much better than open-loop machining in improving EDM performance such as machining rates and machining capacities.

Nevertheless, there still exist instability phenomena in the above mentioned adaptive control systems, for example, oscillations of electrode discharging cycle in transitional stages where gap states vary abruptly. The fact of oscillations of electrode discharging cycle indicates that the machining processes driven by the above mentioned control laws still experience instabilities occasionally, though they are able to retrieve the machining states at last. Efforts are still needed to search for a more efficient way to stabilize EDM process. Through analysis, when the above mentioned adaptive controlled machining is trapped into unstable stages where arcing pulses dominate in the gap and gap states vary abruptly, large errors occur between actual gap states and the predicted gap states computed from the established model used in the control system. The computed values of control variable by the MV control law, or the MVPPC control law [13,14], which are strongly relying upon the predicted gap states in calculation, are either much larger or smaller than they should be at this moment resulting in stronger or weaker performances of control actions. In this case, it is not easy to regulate the actual gap states to follow a specified gap state. Consequently, the unstable machining situation cannot be recovered immediately, not only restraining both machining capability and machining rate but also more or less damaging workpiece surface.

Based on the knowledge of this, in this paper we developed a new controller driven by two-step-ahead prediction (TP) control law to improve the stability of EDM process. The effect of one more step prediction in the control law than the above mentioned two control laws equivalently acts like adding a differential term in the control law performing the function of