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ORIGINAL ARTICLE

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Self-tuning fuzzy control with a grey prediction for wire rupture prevention in WEDM

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Abstract Wire rupture in the wire electrical discharge machining (WEDM) process is one of the most troublesome problems in practical applications. In this paper, the abnormal ratio R_{ab}, defined as the proportion of abnormal sparks in a sampling period, is taken to represent the gap state in machining. The grey predictor is adopted to compensate the time-delayed R_{ab} caused by the low pass filter data processing. A gain self-tuning fuzzy control system has been developed to cope with the conditions that often occur with wire rupture in the WEDM process, such as an improper setting of machining parameters, machining the workpiece with varying thickness, etc. Experimental results of several cases show that the proposed controller results in a satisfactory performance. Not only can it immediately suppress transient situation once there is a sudden change of workpiece thickness, but a stable performance can also be achieved during machining a workpiece of constant thickness. As a result, wire rupture problems in most WEDM processes can be successively solved by the proposed control strategy.

Keywords Self-tuning fuzzy controller · Grey predictor · Wire rupture prevention · Wire electrical discharge machining · Abnormal ratio

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1 Introduction

Wire electrical discharge machining (WEDM) is one of the fastest growing and accepted manufacturing technologies in non-traditional machining processes [1]. Instead of direct contact, machining is accomplished by a series of discharges between a wire electrode and the workpiece; it is particularly suited for machining difficult-to-cut materials such as die steels. Due to its special material removal mechanism, a long time is generally required for WEDM to complete the entire machining process. Consequently it is imperative that the WEDM process be automated, including unattended operation, automatic wire threading, etc. In order to achieve this objective, it is of great importance to keep the WEDM process stable and efficient.

Wire rupture is the most undesirable event in the WEDM process, because it increases machining time, and deteriorates the quality of final products. There have been diverse efforts to this issue in the past years. Kinoshita et al. [2] found that the percentage of micro short circuit is closely correlated with wire rupture. As a result, they suggested to control the work feed rate by holding this percentage at a certain level. Tanimura and Heuvelman [3] found that wire breaking is associated with the unusual increment of the short-circuit pulses. Liao et al. [4] suggested that abnormal ratio R_{ab}, defined as the proportion of abnormal sparks in a sampling period, could be taken as a parameter to monitor machining state including wire rupture and machining efficiency. As for controlling wire from rupture, based on the duration of unusual discharges rise prior to the wire rupture, two types of wire rupture are categorised: one is that the duration is in the order of mini-second, for example, at the moment of the restart the machine again [5] or in machining a thin workpiece under high speed [6]. Kinoshita et al. [6] proposed to stop power supply temporarily as soon as the pulse frequency dramatically increased. By this control strategy, preventing wire from rupture can be achieved but the process stability and the quality of the product cannot be assured. Lawyers et al. [7] developed a thermal model to estimate the temperature distribution of the wire. Control strategies were to provide a temporary reduction or stop of the pulse energy whenever the estimated temperature over the wire exceeded a critical value.

The other type is that the duration is in the order of second, for example, machining a workpiece with varying thickness and so on. For problems of this sort, the control strategy can be employed to improve machining efficiency as well as to prevent the wire from rupture. Rajurkar and Wang [8] developed an on-line estimator of the workpiece height. Based on the estimated thickness, the optimal reference spark frequency can be determined experimentally. According to a linear model for WEDM process, an integral controller was adopted to adjust the pulse off time to keep the spark frequency at optimal level. Experimental results show that the proposed control system can successfully control the spark frequency at the optimal value without the risk of wire rupture, when cutting a workpiece with variable thickness. However, it is known that the WEDM process is a complex dynamic system and difficult to be mathematically modelled. Those model-based control strategies [5,8] are inapplicable to the wide range variation of machining condition in WEDM. Yan and Liao [9] proposed a multi-region fuzzy controller to augment the range of the working situation. Liao and Woo [10] developed a DSP-based on-line pulse monitoring system, and both short ratio and discharging energy were taken as controlled variables. Experimental results show that a high machining efficiency as well as system stability can be achieved in machining workpiece of constant thickness. The condition where there is a change of workpiece thickness is not taken into account.

In the last two decades, fuzzy logic controllers (FLC) [11,12,13] have been applied successfully to a wide variety of industry applications. Essentially, the FLC offers a method for representing and implementing the engineer's control strategy by IF-THEN rules. Thus, FLC provides an alternative method for such plants as the WEDM process that is difficult to be mathematically modelled. In general, the conventional FLC with constant scaling factors cannot effectively cope with the transient and steady state machining condition at the same time. Specifically, at machining a workpiece with thickness suddenly changing, especially under the high-speed machining, in which the gain should be large enough to suppress the transient response, but this high gain will also cause instability during machining a workpiece of constant thickness. Consequently, a gain self-tuning fuzzy controller to further expand the range of the working situation is proposed in this paper.

According to the previous studies of one of the present authors [4], the abnormal ratio R_{ab} can be taken as a sensing parameter to the gap state in the WEDM control system. Due to the stochastic feature of the WEDM process, and the EMI coming from the adjacent electronic device, there is extreme and random oscillation exhibited in the measured R_{ab} signal. It is inappropriate to send the on-line measured R_{ab} directly to the fuzzy controller. Instead, it is usually pre-processed by a low pass filter. But the filtered signals often have time-delayed problem, especially when it is processed by a low pass filter having a low cut-off frequency. In order to immediately detect the symptom of impending wire rupture, the dramatic increment of the R_{ab}, and let controller take instant control actions to reduce the risk of wire rupture, the grey predictor [14] was used to compensate the delayed filtered signal. Finally, the simultaneous adjustment of the arc off time, and the servo reference voltage to regulate the R_{ab} at a proper level is adopted to solve the problem of wire rupture in WEDM process.

2 Experimental setup and monitoring system

2.1 Experimental setup

A flushing-type WEDM machine developed by ITRI (Industrial Technology Research Institute) and CHMER Company, Taiwan, was used as our experimental machine. This machine comprises four major subsystems that include an isoenergy power supply, a dielectric regeneration system, a computer numerical control system with a five-axis motion system, and a wire drive system having semiautomatic wire threading function. The discharge power supply system of this machine consists of a low power circuit, and a high power circuit. The low power circuit supplies a 110 V voltage low power to break the insulation in the gap. Subsequently, a 220 V voltage is supplied by the high power circuit to generate the high current discharge and to erode the workpiece. A control circuit board performs the switching of the two power circuits. The peak value of a triangular discharge current waveform can be calculated by a constant slope of 380 A/μsec, and the value of on-time. The workpiece, and electrode were as follows: (1) workpiece (anode)-SKD11 alloy steels, (2) electrode (cathode), ϕ0.25 mm brass wire. The adjustable parameters of this machine are listed in Table 1. These parameters include on-time, off-time, arc on-time, arc off-time, servo reference voltage, wire speed, wire tension, and flushing pressure.

2.2 WEDM discharge frequency monitoring system

The waveforms of the gap voltage and the associated current are shown in Fig. 1. There are three types of discharges namely normal discharge, arc, and short circuit. In order to prevent wire breaking and maintain an appropriate machining performance, it is necessary to develop an on-line monitor to classify these sparks.

From Fig. 1 it is apparent that a normal discharge has a relatively longer ignition delay time than the others. Based on this observation, a WEDM sparking frequency monitor system has been developed. Due to the large interference of noises, the voltage level between arc and short circuit is difficult to differentiate. Hence, without loosing too much information for control purpose, the short circuits are categorised in the arc pulse group. Accordingly, only two types of pulse namely normal discharge and abnormal discharge (including arc and short circuit) are discriminated in our sparking monitoring system. Details of the discriminating principles can be found in our previous work [4]. The AX5216 count card in the PC recorded the numbers of discharges, normal pulses, and abnormal pulses. By dividing these numbers by the sampling period yields frequency of total discharge, normal pulses and abnormal pulses, respectively. In our system the sampling period ranges from 2 to 65535 ms.

3 Self-tuning fuzzy inferences and grey prediction control systems

3.1 Effects of the tuneable machining parameters on the controlled variable

As mentioned previously, the abnormal ratio R_{ab} has a close connection with machining efficiency as well as wire rupture [4]. It is taken as the controlled variable in the developed WEDM control system, and its on-line measured signal will be used as a feedback signal to reflect the gap state. In this section, effects of the tuneable machining parameters on the controlled variable will be investigated, which can be used to aid the design of the fuzzy controller. Figure 2 shows the effect of arc off-time on the feedrate and the abnormal ratio R_{ab}. When the arc off-time is set to be a large value, the feedrate and the abnormal ratio R_{ab} is small. Although the wire rupture in this case will not occur, the machining speed is too low. By stepwise reducing the arc off-time, the machining speed can be improved, but the wire rupture will take place at last. Similar results by changing the tuneable machining parameter, the servo reference voltage, are given in Fig. 3. In summary, the tuneable machining parameters are highly correlated with the R_{ab} and the feedrate, which is in proportion with the machining efficiency. The higher the machining speed, the more likely the wire rupture would occur. Hence the appropriate setting of the R_{ab} depends on the compromise between the ultimate machining speed and

Table 1 Adjustable parameters of the WEDM machine (CW-430F)

Item	Range
On-time	1 ~ 9steps (unit: 0.1 μs)
Off-time	8 ~ 50steps(unit: 1 μs)
Arc on-time	1 ~ 5steps(unit: 0.1 μs)
Arc off-time	9 ~ 50steps(unit: 1 μs)
Servo reference voltage	30 ~ 70 V
Feedrate override	0 ~ 310%
Wire feed	1 ~ 16 m/min(15 step)
Wire tension	300 ~ 1600 gf(15 step)
Flushing	0 ~ 20 kg/cm^2 (7 step)

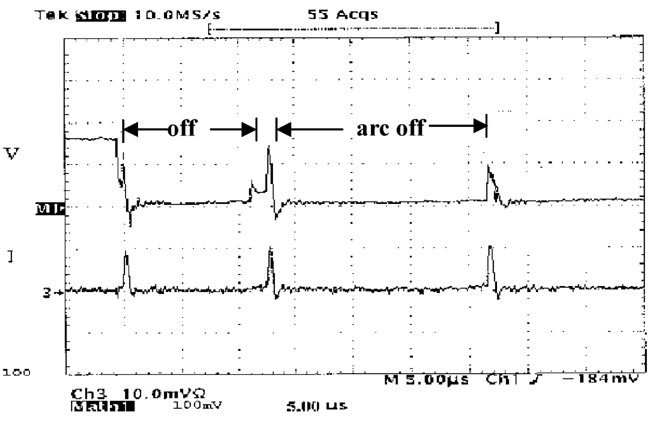


Fig. 1 Typical gap voltage and current waveforms of the WEDM process

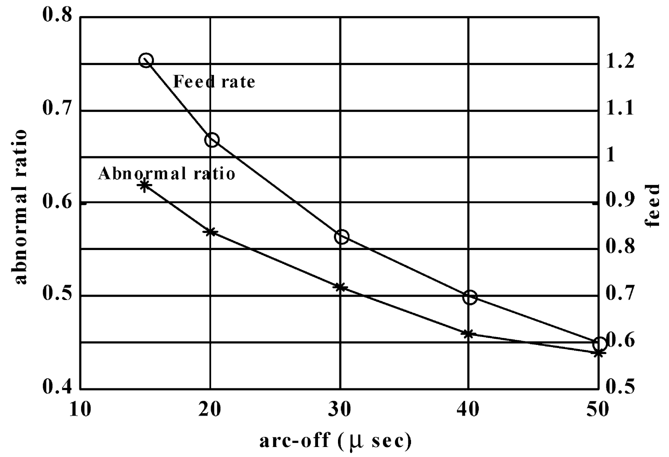


Fig. 2 Effect of the arc off-time on feedrate and abnormal ratio

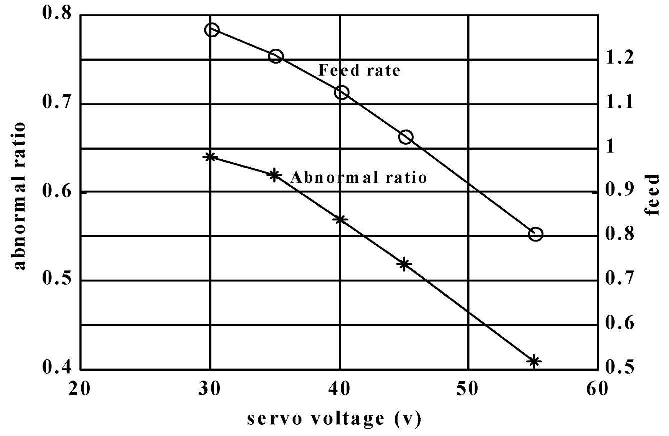


Fig. 3 Effect of the servo reference voltage on feedrate and abnormal ratio

the occurrence of wire breaking. Finally, the desired setting of the R_{ab} can be achieved by concurrently tuning the arc off-time and the servo reference voltage.

3.2 The compensation of time-delayed signal by the grey predictor

Figure 4 shows the obvious oscillation of the R_{ab} that is measured in real time. It is denoted by the original data. In order to attenuate the fluctuation of the original R_{ab}, a low pass filter is usually employed. The filtered data, also shown in Fig. 4, is processed by the low pass filter having a cut-off frequency of 0.012 times one half of sampling frequency of the original R_{ab}. Compared with the evolution of the original signal, the filtered signal has an apparent time-delayed phenomenon, and cannot represent the real-time evolution for gap state, hence increases the risk of wire rupture if it is used as the control signal.

In order to compensate this associated time-delayed problem, a grey predictor [14] is applied to the filtered data. By the theory of grey prediction and associated data generating, the compensated value of $\hat{y}^{(0)}(k+p)$, through grey model GM (1,1), can be calculated by [15]

$$\hat{y}^{(0)}(k+p) = (1-e^{c})\left[y^{(0)}(0)-\frac{b}{c}\right]e^{-c(k+p)} \tag{1}$$

where p is the compensated step size, $y^{(0)}$ is a filtered data sequence, c and b are the development coefficient and the grey input, respectively [14].

An appropriate compensated step size p can be determined by the following off-line signal process. Firstly, the objective signal, which stands for the instantaneous evolution of the R_{ab} but has no apparent fluctuation, is obtained by the moving average with 50 steps to attenuate the fluctuation. Then moving 25 steps ahead is conducted to cope with the delay problem, caused by the previous moving average calculation. By considering the various combination of the compensated step size of the grey predictor, and the cut-off frequency of the low pass filter, the optimal parameters can be obtained, in the sense of the least square error in Eq. 2. Table 2 shows the optimal compensated step size in different cut-off frequency. It is found that the smaller the cut-off frequency, the longer the compensated step size is required. When the cut-off frequency is taken too large and then the more frequency component is included, the compensated result was not well on the contrary and the resulting error is very large. The optimal combination is that the cut-off frequency for the 2nd order low pass digital Butterworth filter is 0.012 times one half of sampling frequency of the original data, and the compensated step size for the grey predictor is 37 steps in our case. These parameters are adopted in this paper. As a result, the compensated data, shown in Fig. 4, has good synchronism with the progression of the original signal.

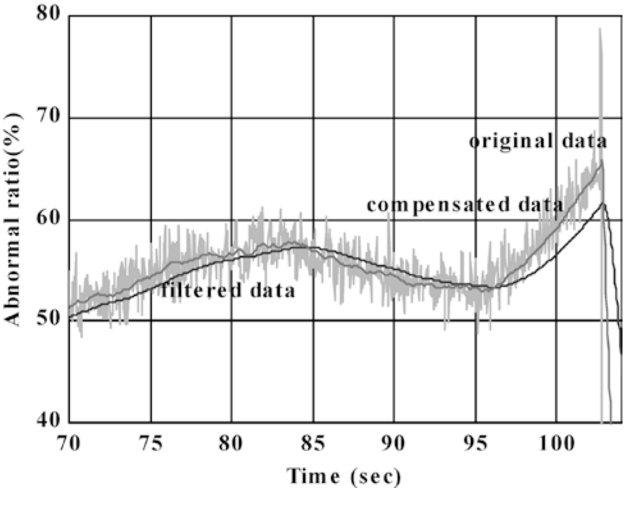


Fig. 4 The original, filtered and compensated R_{ab} data

$$\text{error}(p,\omega_c) = \sqrt{\frac{1}{N}\sum_{k}^{N}\left[y^{*}(k) - \underset{p,\omega_c}{y}(k)\right]^2}, \tag{2}$$

Where

y^*: the objective signal
y: the signal previously processed by low pass filter and then grey predictor
N: the total number of sampling data

3.3 The gain self-tuning fuzzy controller

In order to prevent wire rupture under different machining conditions, a gain self-tuning fuzzy controller is proposed. Figure 5 is the configuration of the proposed self-tuning fuzzy inference with grey prediction control system, in which the PI-type Fuzzy Logic Controller (FLC) is involved. In order to keep the R_{ab} at a desired level, the inputs to the controller including the error e and the change of error ce, are described as follows:

$$e(k) = (R_{ab})_{ref} - (R_{ab})_{p}(k)$$
$$ce(k) = (R_{ab})_{p}(k-1) - (R_{ab})_{p}(k)$$

Table 2 The optimal compensated step size in different cut-off frequencies

2*cut-off frequency/ sampling frequency	Compensated step size	Error
0.010	46	1.07e−2
0.012	37	0.98e−3
0.015	27	1.03e−2
0.020	17	1.19e−2
0.030	6	1.40e−2
0.050	1	1.74e−2
0.100	1	4.70e−2

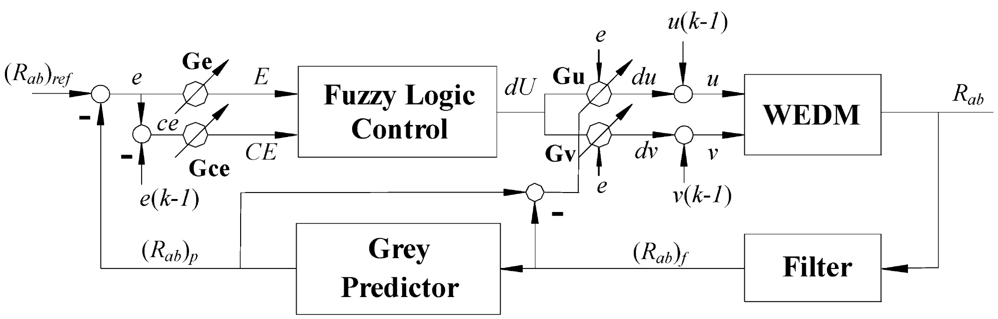


Fig. 5 Self-tuning fuzzy logic and grey prediction control system

$$E = e(k) \times \mathrm{Ge} \tag{3a}$$

$$CE = ce(k) \times \mathrm{Gce} \tag{3b}$$

Where $(R_{ab})_{\mathrm{ref}}$ is the reference of the abnormal ratio, $(R_{ab})_f$ is the abnormal ratio processed by the low pass filter from the original R_{ab}, and $(R_{ab})_p$ is the abnormal ratio compensated by the grey predictor from the $(R_{ab})_f$. Ge and Gce are input scaling factors and in our cases their values are Ge = 5 and Gce = 40 respectively. E and CE in Eq. 3a and 3b are corresponding fuzzy variables. Each fuzzy variable is quantified into seven term sets: NB-Negative Big, NM-Negative Medium, NS-Negative Small, ZE-Zero, PS-Positive Small, PM-Positive Medium, and PB-Positive Big. The triangular membership functions for each fuzzy term set and the universes of discourse for each fuzzy variable, including input and output variable, are shown in Fig. 6.

According to Lee [11], the rule bases can be derived from a dynamic system response. A typical response of the R_{ab} in WEDM process is shown in Fig. 7, where the dash line stands for the desired set point. For the point *a*, the R_{ab} error, *E*, is PB and the change of the R_{ab}, *CE*, is *ZE* and then the change of control action *dU*, the arc off-time, should be reduced to improve the machining speed. This linguistic control strategy can be described in fuzzy inference, as

IF *E* is PB and *CE* is ZE, THEN *dU* is NB

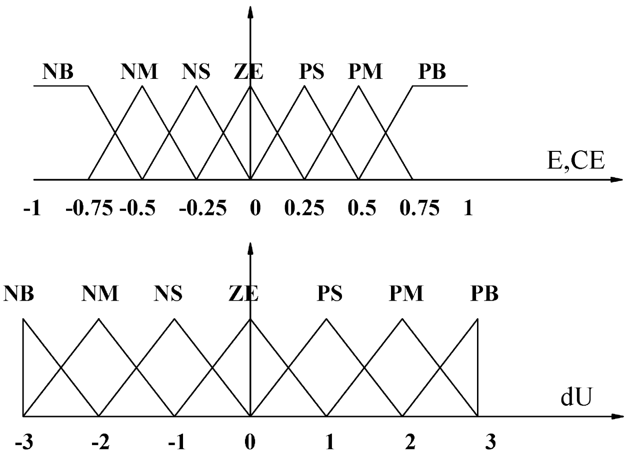


Fig. 6a,b Membership function of **a** E, CE and **b** dU

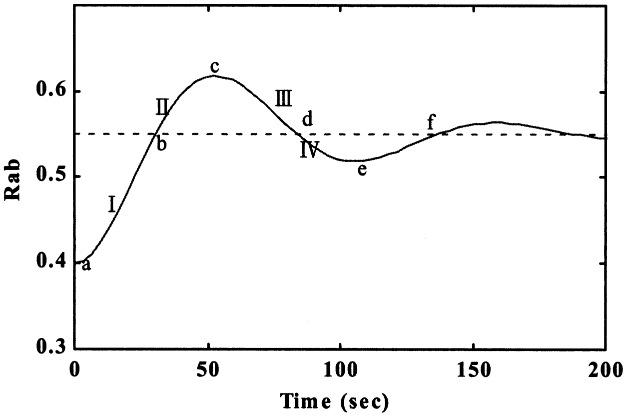


Fig. 7 A typical example of the R_{ab} response for WEDM processes

In the same way, the other points such as *b, c, d....* can be described and the rule bases are summarised in Table 3. In addition, from Figs. 2 and 3, the effect on the R_{ab} by adjusting arc off-time is the same as that by the servo reference voltage. Consequently, the rule bases for arc off-time can be directly applied to those for the servo reference voltage without any modification. As a result, the design procedure of the controller can be greatly simplified.

Through the height defuzzification method [12], the crisp output of fuzzy inference *dU* can be obtained. The actual increment control actions in Eq. 5a and 5b, the change of arc off-time and the change of servo reference voltage, can be calculated by multiplying the scaling factors, Gu and Gv, respectively. The actual control actions at the *k*th sampling instant are calculated by

$$u(k) = u(k-1) + du(k) \tag{4a}$$

Table 3 Rule bases of the FLC

CE E	NB	NM	NS	ZE	PS	PM	PB
PB	ZE	NS	NM	NB	NB	NB	NB
PM	PS	ZE	NS	NM	NB	NB	NB
PS	PM	PS	ZE	NS	NM	NB	NB
ZE	PB	PM	PS	ZE	NS	NM	NB
NS	PB	PB	PM	PS	ZE	NS	NM
NM	PB	PB	PB	PM	PS	ZE	NS
NB	PB	PB	PB	PB	PM	PS	ZE

$$v(k) = v(k-1) + dv(k) \tag{4b}$$

where

$$du(k) = dU(k) \times \mathrm{Gu} \tag{5a}$$

$$dv(k) = dU(k) \times \mathrm{Gv} \tag{5b}$$

$$\mathrm{Gu} = \mathrm{Ku}|e|\Phi(\alpha, E, CE)\Psi(ol, d_{pf}) \tag{6a}$$

$$\mathrm{Gv} = \mathrm{Kv}|e|\Phi(\alpha, E, CE)\Psi(ol, d_{pf}) \tag{6b}$$

$$\Phi(\alpha, E, CE) = g1 + g2 \times f(CE, 5 * E) \tag{7}$$

$$\Psi(ol, d_{pf}) = ol(1 + 100.0 * d_{pf}) \quad e < 0.01 \tag{8}$$

$u(k)$, $u(k-1)$: arc off-time at the kth, $(k-1)$th sampling instant respectively
$v(k)$, $v(k-1)$: servo reference voltage at the kth, $(k-1)$th sampling instant respectively
$du(k)$: increment of arc off-time at the kth sampling instant
$dv(k)$: increment of the servo reference voltage at the kth sampling instant
$dU(k)$: crisp output of fuzzy inference at the kth sampling instant
Gu: output-scaling factor for the arc off-time
Gv: output-scaling factor for the servo reference voltage

$$g1 = 0.5 \times (1.0 + \alpha)$$

$$g2 = 0.5 \times (1.0 - \alpha)$$

$$f(x, \alpha) = \frac{1 - \exp(-\alpha * x)}{1 + \exp(-\alpha * x)}: \quad \text{hyperbolic tangent function} \tag{9}$$

$$d_{pf} = (R_{ab})_p - (R_{ab})_f$$

Ku, Kv: the global gain about control actions
α: III region tuneable parameter
ol: overloading parameter
sampling time Δt = 40 ms

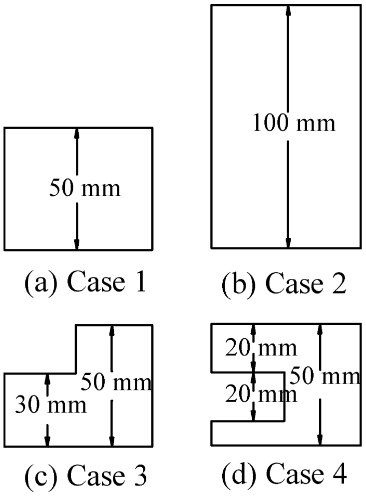
Each of the tuneable output-scaling factors, Gu and Gv, has three factors: (1) The R_{ab} error, $|e|$, is called the attraction-causing factor. Its function is to attract R_{ab} so that it can reach and remain at the set-point, $(R_{ab})_{\mathrm{ref.}}$ (2) The overshoot-attenuating factor Φ(α,E,CE) which will attenuate impending overshoot or undershoot by reducing control actions in regions I and III (referring to Fig. 7). Instead of tuning the massive rule bases [13], this factor Φ(α,E,CE) in Eq. 7, is synthesised by a hyperbolic tangent function given in Eq. 9. Since a few parameters would be tuned, the task of design can be apparently simplified. The smaller the parameter α and the more the level to be attenuated. But too small a value will reduce the system response. (3) The overloading factor $\Psi(ol,d_{pf})$ which will suppress the overloading phenomenon by enhancing the control actions once the R_{ab} apparently exceeded the safety level. For instance at the instant of sudden change of workpiece thickness during machining, the d_{pf} in the Ψ will increase drastically and accordingly enhance control actions to prevent the wire from breaking. Effect of Ku and Kv is similar to the gain of a general controller where a larger gain results in faster but unstable response. The relative magnitude between Ku and Kv will determine which control action will be dominantly tuned. For instance, when Kv is chosen larger, the servo reference voltage is mainly regulated.

4 Experimental results and discussion

In order to verify the feasibility of the self-tuning fuzzy control with grey prediction proposed in the paper, four cases where wire rupture often occurs are tested. They are: (1) improper setting of machining parameters, (2) machining of a thick section workpiece, (3) machining of a workpiece with varying thickness, and (4) machining of a workpiece with a hole. In the following experiments, Fig. 8 shows the cross-section of workpiece used and Table 4 gives the corresponding machining parameters initially set. The fuzzy control algorithms are implemented in the PC using C language. A RS485 interface card installed in the PC is used for the data communication between the PC and the machine. The sampling time used in the experiments is 40 ms. Table 5 shows the parameters of the controller for the four cases under study.

4.1 Case1—improper setting of machining parameters

The WEDM process is characterised by many machining parameters. An improper setting of machining parameters may be occurred, especially to a beginner. Figure 9a



(a) Case 1
(b) Case 2
(c) Case 3
(d) Case 4

Fig. 8a–d The cross-sections of workpiece (cases 1 to 4)

Table 4 Machining parameters in the experiments

Case no.	On-time	Off-time	Arc on-time	Arc off-time	Servo voltage	Wire speed	Wire tension	Flushing pressure
1	6	15	4	13	35	4	10	2
2	6	15	4	15	40	4	10	2
3	6	15	4	30	40	4	10	2
4	6	15	4	35	45	4	10	2

Table 5 Parameters in the controller

Case no.	Ge	Gce	α	*ol*	Ku	Kv	$(R_{ab})_{ref}$
1	5	40	0.7	2.0	0.06	0.03	0.6
2	5	40	0.7	2.0	0.06	0.03	0.6
3	5	40	0.7	2.0	0.08	0.16	0.42
4	5	40	0.7	3.0	0.07	0.14	0.42

shows the time variations of R_{ab} when a 50 mm thickness SKD11 workpiece shown in Fig. 8a is machined under the machining conditions of case no. 1 in Table 4. The fluctuating signal of R_{ab} in Fig. 9a indicates the original on-line measured R_{ab}, while the solid line stands for the filtered and compensated one. Form Fig. 9a, it is observed that the compensated R_{ab} is continuously above 60%. Because of too many abnormal discharges, the wire electrode endured about 55 seconds and ruptured at last. Figures 9b and 9c show the control actions and the resulted time record of the R_{ab} respectively, under the same machining condition as that of Fig. 9a. The associated parameters of the controller are given in Table 5 (case no.1). As shown in Fig. 9b, when the machining parameters are set improperly and hence the R_{ab} is over the safety level, the proposed controller can rapidly lengthen the arc off-time and the servo reference voltage to improve the gap state. By so doing, R_{ab} is promptly controlled and remained around the set point in Fig. 9c. As a result, not only can the chance of wire rupture be eliminated, the allowable machining can be also achieved by employing the developed control strategy.

4.2 Case 2—the machining of a workpiece with a thick section

Machining thick section of a workpiece is often required in industry applications. However, in this cutting condition wire rupture is likely to occur due to the poor flushing condition resulted from the nature of the thicker workpiece. This experiment is conducted to test the proposed controller in this situation. A workpiece of 100 mm thickness in Fig. 8b is tested in this case and the corresponding machining parameters are listed in Table 4 (case no. 2). Fig. 10a shows the same phenomenon as Fig. 9a but it lasts for a shorter duration before wire breaking because of the poor flushing condition. Figs. 10b and 10c show the control actions and the resulted time record of R_{ab}, respectively for the same machining condition as Fig. 10a. The associated parameters of the controller are given in Table 5 (case no.2). Similar to case 1, through the concurrent adjustments of the arc off-time and the servo reference voltage, R_{ab} can be controlled around the set

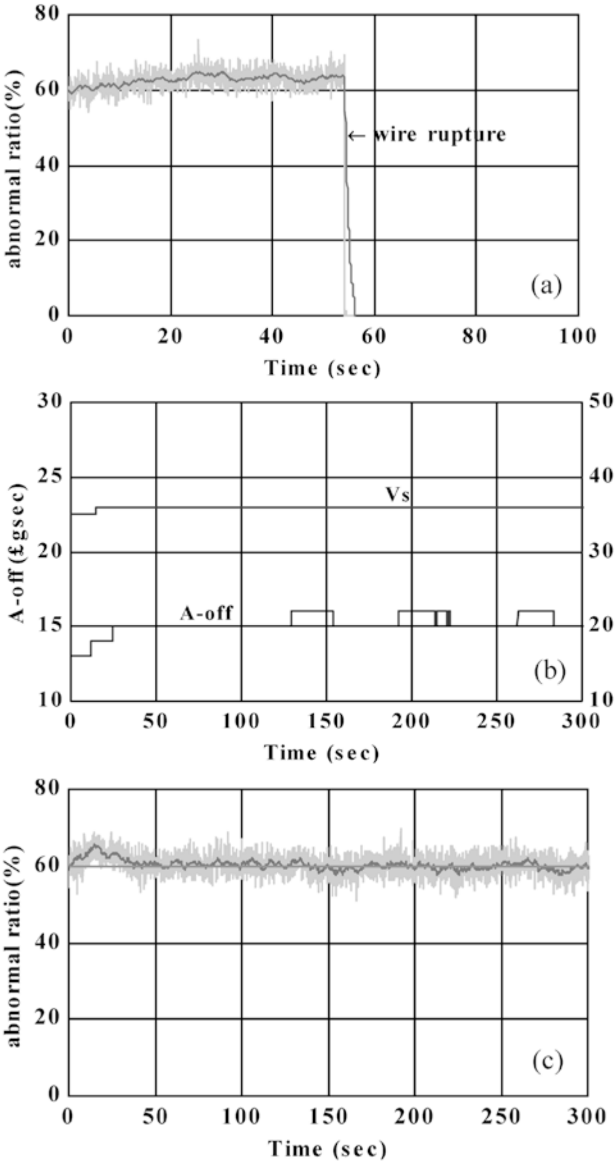


Fig. 9 **a** A wire rupture phenomenon-abnormal ratio without control actions **b** the control actions, the arc off-time and the servo reference voltage and **c** abnormal ratio with control actions under the improper machining parameter setting

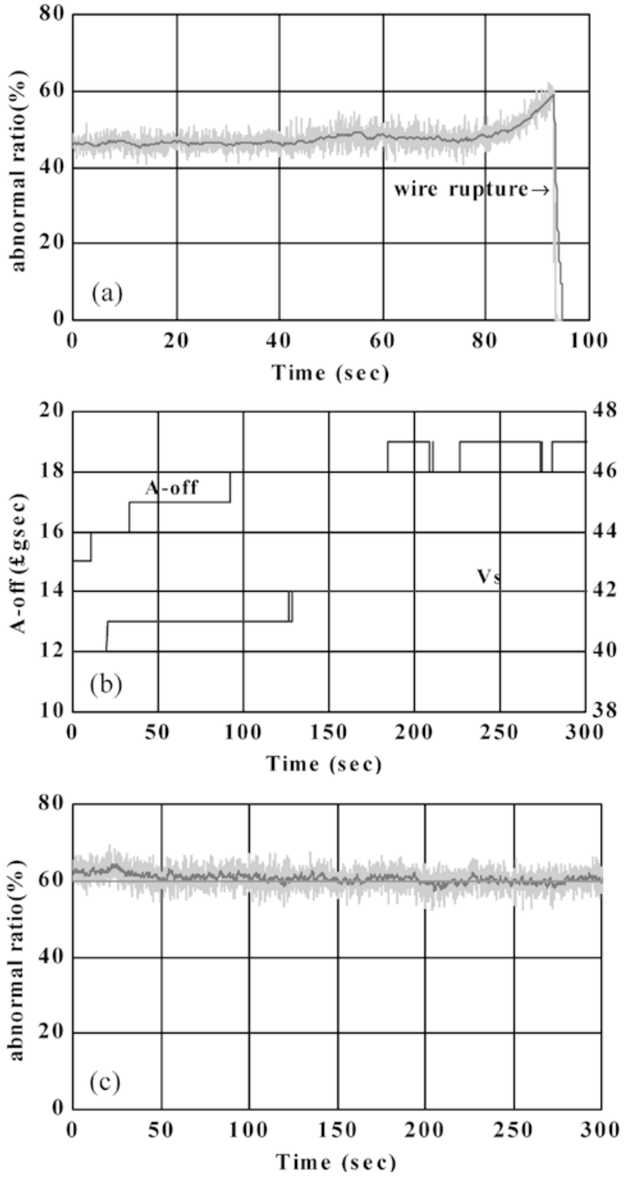


Fig. 10 a A wire rupture phenomenon-abnormal ratio without control actions **b** the control actions, the arc off-time and the servo reference voltage, and **c** abnormal ratio with control actions in machining a thick section workpiece

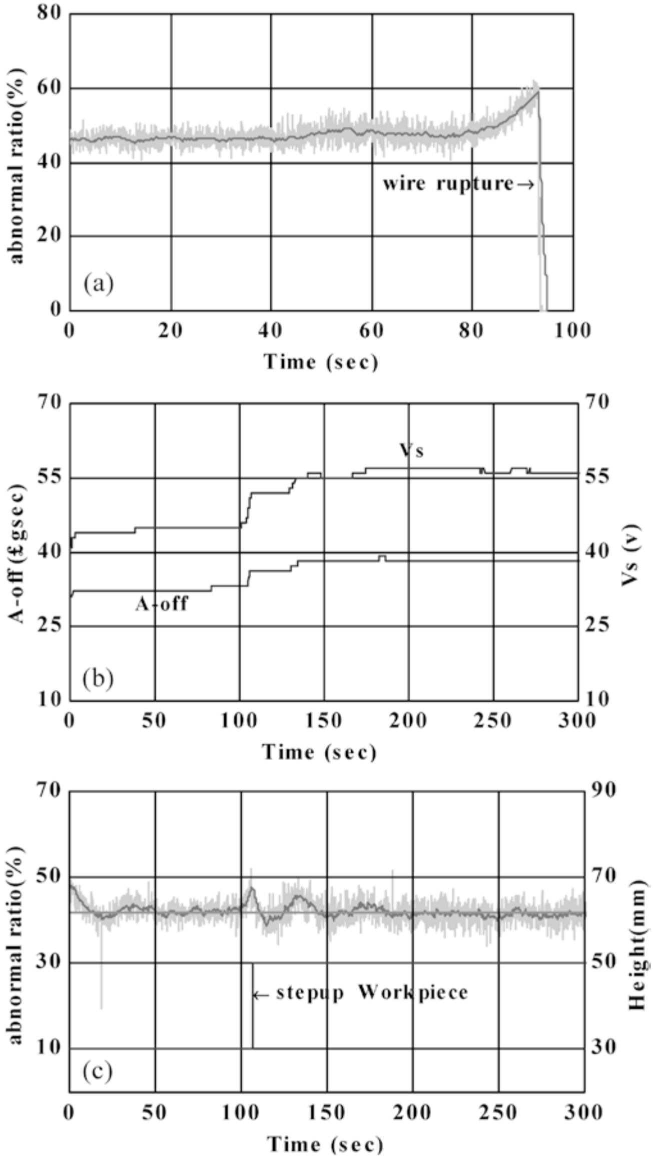


Fig. 11 a A wire rupture phenomenon-abnormal ratio without control actions **b** the control actions, the arc off-time and the servo reference voltage and **c** abnormal ratio with control actions in machining a workpiece having a step change of thickness

point. Comparing Fig. 10b with Fig. 9b, it is noted that larger control actions are automatically tuned in this case.

4.3 Case 3—the machining of a workpiece having varying thickness

Figure 11a shows the phenomenon of wire rupture during machining of a workpiece having varying thickness shown in Fig. 8c. Machining parameters are also listed in Table 4 (case no. 3). At the instant of a sudden change of workpiece thickness in machining, there is an abrupt rise of abnormal discharge and this would result in the burnt out of wire electrode instantaneously. Apparently, the larger the change of workpiece thickness, the lower the safety level of R_{ab} should be set to avoid wire rupture. But too low a reference level of R_{ab} will sacrifice the machining efficiency. Taking these into consideration, it is found from our experiments that the proper level of R_{ab} for the 20 mm step increase in workpiece thickness is 42%. Figs. 11b and 11c show the control actions and the resulted time record of R_{ab}, respectively under the same machining condition as that of Fig. 11a. The associated parameters of the controller are given in Table 5 (case no.3). Viewing from these figures, it is noted that there are excessive abnormal discharges as soon as the wire electrode contacted the step change wall of the workpiece. The arc off-time and the servo reference voltage were quickly elongated to suppress the fast increasing R_{ab} and hence avoid the wire rupture which may occur as that shown in Fig. 11a.

4.4 Case 4—the machining of a workpiece with a hole

Machining a workpiece with a hole as shown in Fig. 8d may be encountered in manufacturing industries. Although the upper and lower flushing pressure can be maintained at a constant level during machining, the centre part of wire undergoes poor flushing condition due to the impediment of the upper and lower part of the workpiece. Similar to the case 3, there is an abrupt rise in R_{ab} as shown in Fig. 12a as soon as the wire electrode contacts the internal wall of the workpiece. Machining parameters and associated parameters of the controller for this case are also listed in case no. 4 of Tables 44 and 5, respectively. The control actions and the resulted time record of R_{ab}, respectively under the same machining condition as that of Fig. 12a are displayed in Figs. 12b and 12c. Once again, as R_{ab} suddenly rises due to the workpiece geometric discontinuity, controller can rapidly respond and the arc off-time and the servo reference voltage are adjusted accordingly to overcome the poor gap condition. By so doing the appropriate machining can be maintained in the following cutting process.

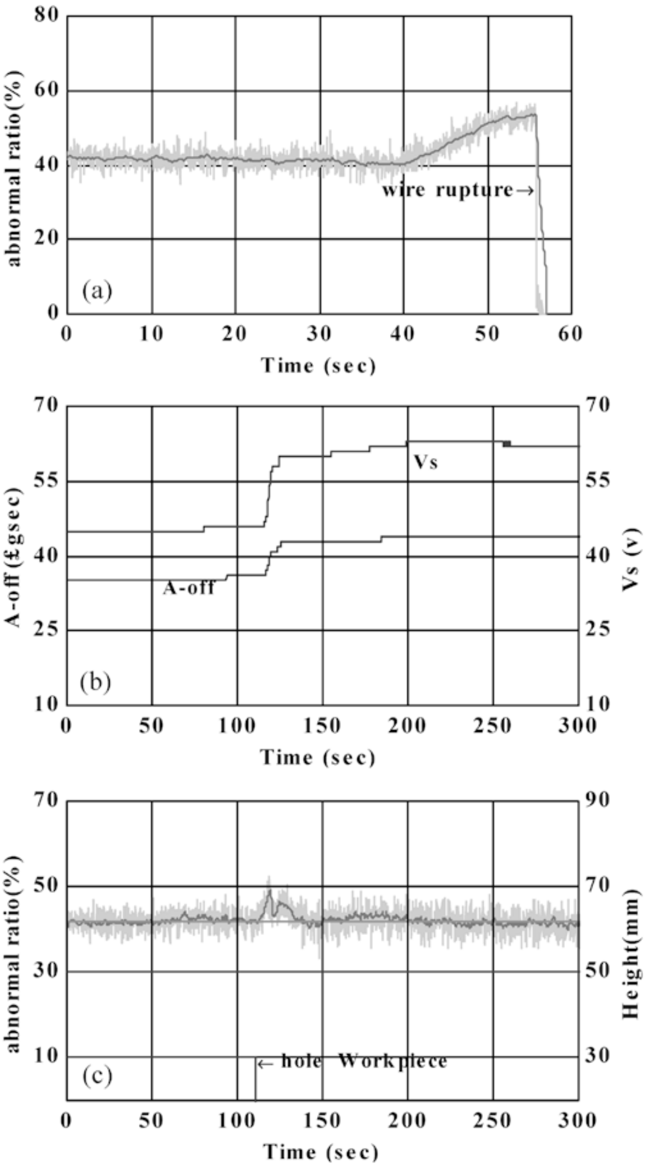


Fig. 12 **a** A wire rupture phenomenon-abnormal ratio without control actions **b** the control actions, the arc off-time and the servo reference voltage and **c** abnormal ratio with control actions in machining a workpiece with a hole in cross-section

5 Conclusions

With the objective of preventing wire rupture in the WEDM process, a gain self-tuning fuzzy controller has been developed. It provides a solution to the control system for the WEDM process. The proposed tuning algorithm consists of three factors including the attraction-causing factor, the overshoot-attenuating factor, and the overloading factor. The output scaling factor of the fuzzy controller can be adaptively tuned in a wide variety of machining conditions. Experimental results show that not only can it immediately suppress transient situation once there is a sudden change of workpiece thickness, a stable performance can be also achieved during machining a workpiece of constant thickness. In the proposed control system, the grey predictor is adopted to compensate the time-delayed R_{ab} caused by the low pass filter data processing, and hence the gap state can be reflected in real time. By the concurrent adjustment of the arc off-time and the servo reference voltage, the controlled variable R_{ab} can be regulated at the proper level. As a result, the problems of wire rupture in most WEDM processes can be successively solved by the proposed control strategy.

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