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FUZZY BASED WELDING SEAM TRACKING CONTROL FOR GMAW WITH ROTATING ARC SENSOR

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Abstract. This paper presents a rotating arc sensor model using Fast Fourier Transform to transform original welding current signal into frequency domain. We analyze spectrum of signal, eliminate unwanted frequencies and inverse transform signal into time domain. This signal was used to calculate input signal for the fuzzy logic controller to control a 2D table with two DC motors and two ball screws that carries a welding torch during the process of automatic seam tracking of arc welding. Input data of the controller is the deviation of average currents between the two half-cycles current corresponding to two half-cycles rotating of the torch on the left and right of centerline of the welding track. The controller were comprised of a regression model, expressing the relationship between the average current deviation and offset distance through weaving experiments. Finally, the direction and the speed of motors are calculated.

Tóm tắt. Bài báo này giới thiệu một mô hình cảm biến hồ quang quay sử dụng bộ lọc FFT để chuyển đổi tín hiệu dòng điện gốc trong miền thời gian sang miền tần số, phân tích phổ tín hiệu, loại đi thành phần tín hiệu không mong muốn và chuyển ngược về miền thời gian. Tín hiệu này được dùng để tính toán giá trị đầu vào cho bộ điều khiển mờ điều khiển một bàn máy hai trục vuông góc mang theo đầu hàn trong quá trình hàn tự động bám đường hàn. Tín hiệu vào của bộ điều khiển là độ lệch cường độ dòng điện hàn của hai nửa chu kỳ biến đổi dòng điện tương ứng với hai nửa chu kỳ quay bên trái và bên phải đường tâm rãnh hàn của đâu hàn. Dựa vào tín hiệu hồi tiếp, bộ điều khiển tính toán sự liên hệ giữa độ lệch cường độ dòng điện hàn và độ lệch đâu hàn trong rãnh hàn, cuối cùng chiều và tốc độ quay của động cơ được tính toán.

1. INTRODUCTION

In recent times, welding process is a difficult manufacturing process because of insufficiency of skilled workers as well as the decline of productivity and requirement of continuous and stable quality control. Robotic welding is widely adapted in several fields of welding shops for improvement of welding efficiency and liberating operators from severe working environment. In order to realize more compact and convenient automatic welding under complicate welding environment, an intelligent type of welding robot with ability of welding seam tracking is required[3]. Thus, seam tracking sensor becomes very important. The arc sensor has the advantages of compactness requiring no detectors around the welding torch, and of being unaffected by heat and arc light. The arc sensor weaves or rotates along the welding tip at an appropriate speed according to various welding conditions and uses electrical signal obtained from welding arc itself. The seam tracking is performed by using current patterns changed according to variation of the arc length distance on one weaving or rotating cycle. In spite of welding smog, arc light and spatter, the arc sensor can precisely achieve seam tracking and lead to a satisfactory welding bead. Moreover, it does not need a special detection device attached to the torch and its production cost is comparatively very low because it is developed by software based on arc characteristics[3].

In this paper, a 2D table experiment model uses FFT (Fast Fourier Transform) to analyze spectrum of current signal and fuzzy logic controller, which is developed to adjust the position of the torch to match the centerline of V-groove based on rotating arc sensor.

2. MATHEMATICAL MODEL OF ROTATIONAL ARC SENSOR

2.1. Principle of Arc sensor

In GMAW, welding current and the arc length had the closed relationship. Specifically, if the arc length increase, welding current will decrease, and welding current will increase if the arc length decreases. Fig.1 shows the principle of arc sensor. When the torch moves from position no.1 to position no.3, the arc length decrease and the welding current increase (the curve 123 on Fig.1). When the torch moves from position no.3 to position no.4, position no.5 and position no.1, the arc length decreases and the welding current increases. So, according to welding current signal we can determine the position of the torch on the welding groove.

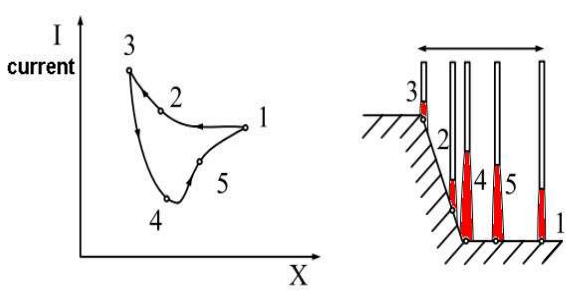


Figure 1. Principle of Arc Welding

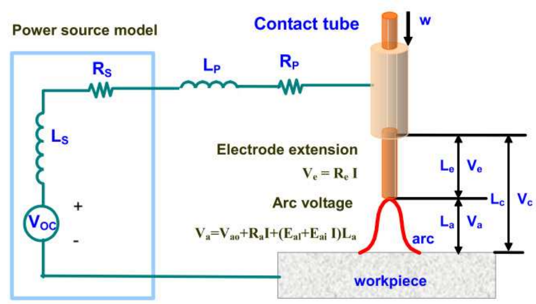


Figure 2. Equivalent Circuit of GMAW System

2.2. Rotating Arc sensor

In GMAW with consumable wire electrodes, power sources with a constant potential characteristic is employed. Fig.2 shows the equivalent circuit of a GMAW system. The resistance at wire extension R_e can be calculated as

$$R_e = \frac{V_e}{I} = \frac{aL_e}{S} - \frac{bwS}{I^2}, \tag{1}$$

where V_e is the voltage across the wire extension, a is a constant equal to the high temperature resistivity of the wire extension (Ω.mm), b is a constant depending on the room temperature resistivity of the wire, L_e is the wire extension, w is the wire feed rate, I is the welding current

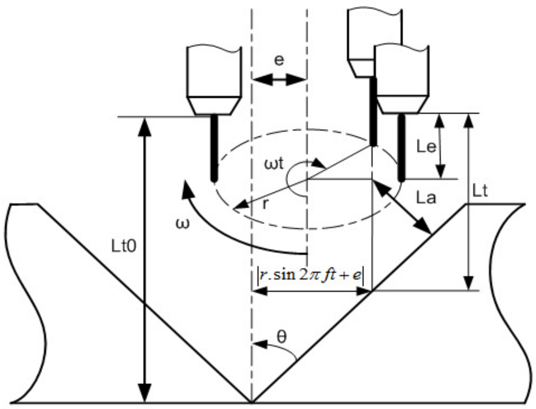


Figure 3. Model of arc length

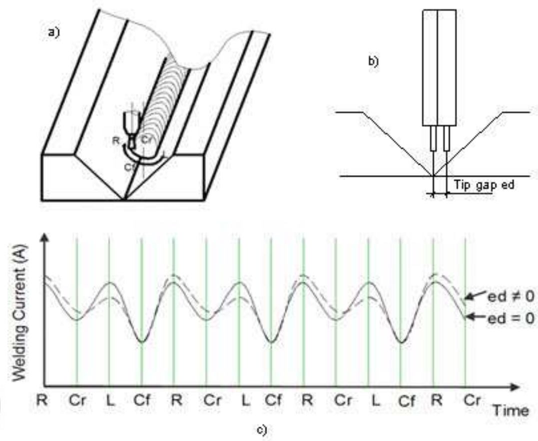


Figure 4. Welding model and correspondent current

and S is cross section area of the wire. Then, the wire extension and welding current during GMAW are given

$$\frac{dL_e}{dt} = w - \frac{AI}{1 - \frac{BL_eI^2}{w}}, \tag{2}$$

and

$$\frac{dI}{dt} = \frac{V_{oc} - V_{a0}}{L_s + L_p} - \frac{R_s + R_p + R_a + R_e}{L_s + L_p} I - \frac{E_{al} + E_{ai}I}{L_s + L_p} L_a, \tag{3}$$

where, $A = \phi/[S(H_0 + b)]$ and $B = a/[(S^2(H_0 + b))]$, F is the equivalent arc voltage for wire melting phenomenon, H_0 is the heat content per unit volume of droplet received at detachment, V_{oc}, R_s and L_s are the internal voltage, electrical resistance and inductance of the welding power source, respectively. V_p, R_p, and L_p are the voltage drop, the resistance and the inductance of the welding cable, respectively. V_{a0} is a constant in the welding model. R_a, L_a and $(E_{al} + E_{ai}I)$ are the resistance, the length and the electric field of the arc, respectively.

The arc length can be calculated by (Fig.3):

$$L_a = (L_{t0} - \frac{|r.\sin(2\pi ft) + e|}{\mathrm{tg}\theta} - L_{et}).\sin\theta \tag{4}$$

Fig.4 shows a relation of welding current and weaving direction and the cross-section of the V-groove welding and their corresponding current waveforms with a centered or offset rotating torch. The maximum welding currents at the left and right half cycles are equal, when the torch is in centered position ($e_d = 0$). While the welding torch is deviated from the angle bisector of the V groove, the current waveform changes. If the torch is on the left of centerline, average welding current of left haft cycle is larger than average welding current of right haft cycle, and the difference between them $(I_{left} - I_{right})$ is used for the torch offset detecting during seam tracking.

3. EXPERIMENT SYSTEM

3.1. Design of experiment model

In this paper, we developed a 2D table experiment model with two DC motor, two ball screws. The slider carried rotator and welding tip. Fig.5 shows block diagram of experiment model.

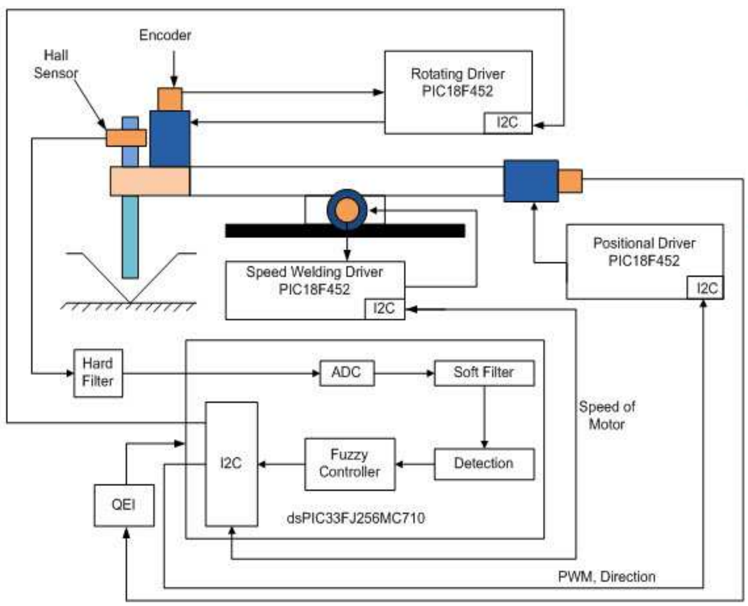


Figure 5. Block diagram of experiment model

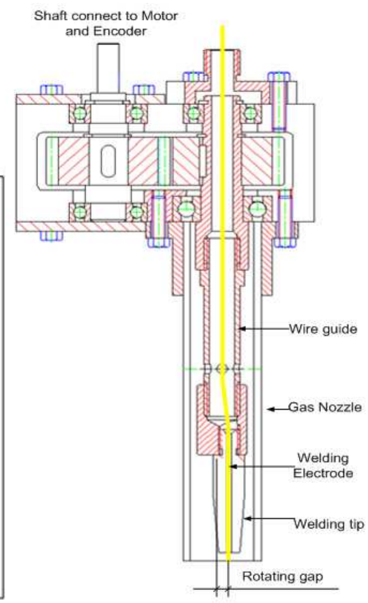


Figure 6. Geometry of Rotator

3.2. Data acquisition and processing

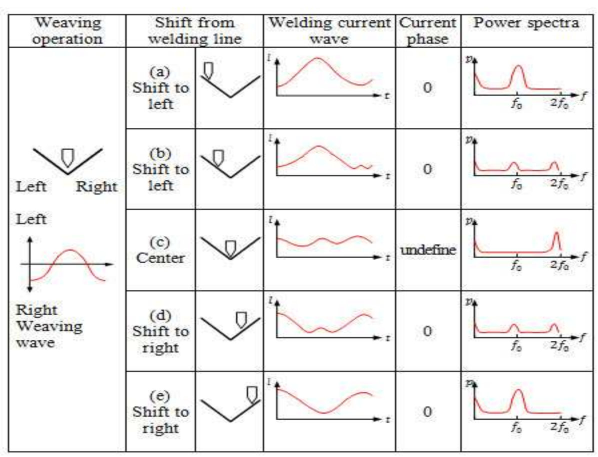


Figure 7. Welding current spectrum[1]

Fig.5 shows the data acquisition model. The Hall current sensor measure welding current signal and transfer to voltage signal. Because the output voltage of Hall sensor is the analog signal containing noise and interference, we use the low pass filter to eliminate high frequency interference and noise. Therefore, microprocessor will sample and convert to digital signal. Finally, we use the soft filter to obtain the desired signal, which uses to calculate the control signal. Fig.7 shows the welding current spectrum of welding current wave when the welding torch rotates stably at frequency f_0, power spectra of welding current wave at frequency f_0 and $2f_0$ are higher than power spectra of others. So, we can use FFT filter to eliminate interference which has frequency greater than $2f_0$[1].

3.2.1. *Hard filter*

Because rotation frequency of the torch is 20Hz, frequency of received analog signal ranges from 0hz to 40Hz. So, we use the low pass filter to eliminate high frequency interference. Hard filter is designed with cutting frequency 100Hz.

3.2.2. *Soft filter*

The soft filter uses transformation FFT (Fast Fourier Transform) to transform digital signal from time domain into frequency domain. As mentioned above, when the welding torch rotates stably at frequency 20Hz, the frequency spectrum of the current signal is primary in the frequency domain from 0Hz to 40Hz, so we need to remove the signal, which has frequency greater than 40Hz to obtain the necessary current. In a rotation cycle, the microcontroller will take 64 samples of the welding current signal I(n), (n = 0 ,...,63). These samples, which are discrete signals in time domain, are converted into frequency domain using the following formula

$$Y(m) = \sum_{n=0}^{63} I(n)[cos(\frac{2\pi mn}{N}) - jsin(\frac{2\pi mn}{N})], \tag{5}$$

where $m = 0, 1, 2, ..., 63$ and $N = 64$. With a sampling rate of $f_s = 1.28kHz$, then the frequency resolution of the analysis frequency in the FFT transformation is

$$f_{analysis} = \frac{f_s}{N} = \frac{1280}{64} = 20\text{Hz}. \tag{6}$$

It means that the samples $Y(m),\ m = 0, ..., 63$, are analysis points of FFT transformation at 0,20,40,60,80,...Hz. In addition, FFT transformation has symmetrical nature

$$Y(m) = Y(N - m), m = 0, ..., 31. \tag{7}$$

Hence for the signal to removed high frequency noise over 40Hz, we assign

$$Y(m) = 0, m = 3, ..., 60. \tag{8}$$

Then we perform reversed FFT transformation, and obtain the welding current signal in time domain with 4 extreme points, corresponding to four points on the left, weld puddle, right, traces of welding. We can calculate the current deviation, which is input signal of the controller of the welding position.

3.3. Determine deviation of the torch

In each rotation cycle, we can always determine the position of the lowest current at the center front of the V groove, where there is no flow of welding arc, arc height will be the largest. Second minimum in the welding cycle locate at the center rear of the V groove, where welding spots have formed. The maximum welding current would correspond to two extreme left and extreme right position of the torch from the centerline of the V groove. Orientation of the torch is always fixed along the front from left to right and to welding beam. So the order of the extreme intensity of welding current is $left \to front \to right \to rear \to left$ ... Based on the variation of the graph function, we can identify four of these extreme values. When there are output data of the soft filter in a cycle, we consider the first two elements. If value of function is increasing, we examine the data until it decreases, then we will determine the maximum. Then we examine the data until it increases, and determine the minimum. In the process of exploring graph to find the extreme values, we observe the following principles:

- Initially, to find the maximum, we assign it is max1 then min1, then max2 and then finally min2 ($max1 \to \min 1 \to \max 2 \to \min 2$).
- Initially, to find the minimum, we assign it is min1 then max2, then min2 and then finally max1 ($min1 \to \max 2 \to \min 2 \to \max 1$).

If $\min 1 < \min 2$ corresponding the torch derived from the left side of the V-groove, $\Delta I = \max 1 - \max 2$. If $\min 1 > \min 2$ corresponding the torch derived from the right side of the V groove, $\Delta I = \max 2 - \max 1$. Because ΔI is always $(I_{left} - I_{right})$, the torch is left deviation if ΔI is positive and the torch is right deviation if ΔI is negative.

3.4. Fuzzy controller

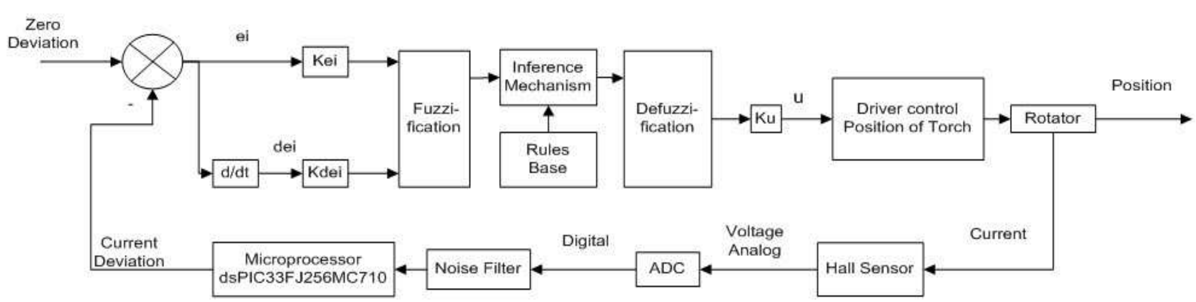
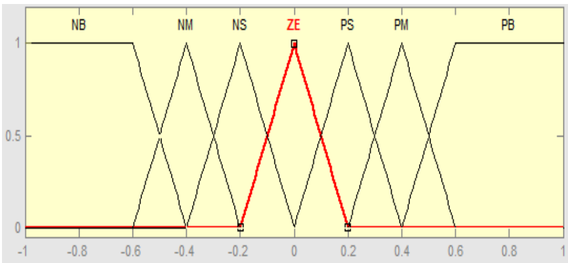
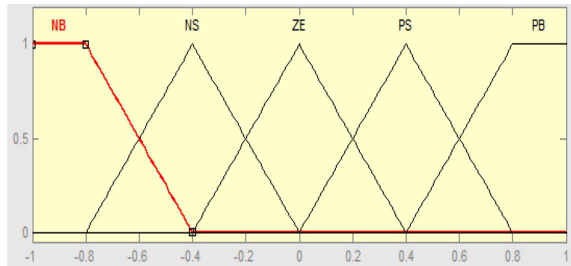


Figure 8. The principle of fuzzy tracking control system

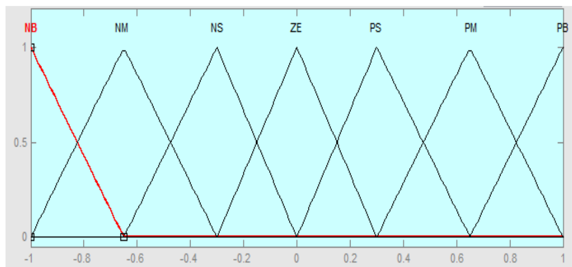
The fuzzy controller can be divided into three parts: fuzzification, inference mechanism, and defuzzification. Fuzzification encoded input values to linguistic descriptions. Inference mechanism determined conclusions based on rules base. Finally, defuzzification converted decisions into actions or controlled values. Fig.8 shows the process in which microprocessor get input values from hall sensor calculate controlled values by fuzzy controller.



(a) Membership Functions of EI



(b) Membership Functions of DEI



(c) Membership Functions of DISTANCE

Figure 9. Membership functions

3.4.1. *The input and output of the controller*

Two-dimensional fuzzy controller is chosen for this system. The first input signal is the deviation of average current of two haft-cycles ($e_i = I_{left} - I_{right}$), when the torch on the left and right of center to the center line of the welding V-groove. The second input signal is the differential of this deviation $de_i = d(e_i)/dt$. The output is distance of the torch and bisector of V-groove, which decided values of PWM and direction supplied to motor controlling position of the torch. Membership functions of the input e_i and the output distance are negative big (NB), negative middle (NM), negative small (NS), zero (ZE), positive small (PS), positive middle (PM), and positive big (PB). And membership functions of input de_i are NB, NS, ZE, PS, and PB. Because output signals of fast fourier transfer (FFT) filter are fractional numbers (16 bits has ranged from -1 to 1), we design the range of two input i (-1;1), and the same range for output distance with the output scale factor, which we can adjust in the experiments. The universes of discourse the input e_i and the output distance are divided into thirteen subnets between [-1;1]. The universe of discourse input de_i is divided into eleven subnets between [-1;1]. The membership functions are set as isosceles triangle which is shown in Fig.9.

3.4.2. *Fuzzy control rules*

The fuzzy rule base consists of a group of IF-THEN control rules with two input EI, DEI and output is DISTANCE. Table.1 shows all fuzzy rules. It consists of 35 IF-THEN rules for fuzzy tracking controller:
Rule 1: If EI is NB and DEI is NB then DISTANCE is PB.
Rule 2: If EI is NB and DEI is NS then DISTANCE is PB.
Rule 3: If EI is NB and DEI is ZE then DISTANCE is PB.

Table 1. The Fuzzy Control Rules

DISTANCE		EI						
		NB	NM	NS	ZE	PS	PM	PB
DEI	NB	PB	PB	PM	PM	ZE	NS	NM
	NS	PB	PB	PM	PS	ZE	NM	NB
	ZE	PB	PM	PS	ZE	NS	NM	NB
	PS	PB	PM	ZE	NS	NM	NB	NB
	PP	PM	PS	ZE	NM	NM	NB	NB

...

Rule 35: If EI is PB and DEI is PB then DISTANCE is NB.

The fuzzy rule base consists of IF-THEN control rules, that is If $EI = A_i$ and $DEI = B_j$ then $DISTANCE = C_{ij}$ $(i = 1, ..., 7; j = 1, ..., 5)$, where A_i, B_j and C_{ij} are membership functions. The fuzzy relation can be expressed as

$$R = \bigcup_{i=1,j=1}^{i=7,j=5} R_{ij} = \bigcup_{i=1,j=1}^{i=7,j=5} (A_i.B_j \Rightarrow C_{ij}). \tag{9}$$

In this paper, we use the inference rule max - product and the defuzzification method is the centre of gravity. Given input $e_i = x$ and $de_i = y$, the output $distance = z$ can be determined. We have

$$\mu_{R_{ij}}(z) = [\min(\mu_{A_i}(x), \mu_{B_j}(y))].\mu_{C_{ij}}(z_k), \tag{10}$$

where, $z_k \in [-1; 1]$ is range of output.
$k = 1, ..., N$. (the value of N belongs to calculating ability of microprocessor). Thus, we have

$$\mu_R(z_k) = \bigcup_{i=1,j=1}^{i=7,j=5} \mu_{R_{ij}}(z_k), \tag{11}$$

where, $\bigcup$ is maximum operation. Finally, we get

$$z = \frac{\sum_{k=1}^{N} \mu_R(z_k) z_k}{\sum_{k=1}^{N} \mu_R(z_k)}. \tag{12}$$

4. EXPERIMENT

The experiments are done to check the reliability of the received signal from the sensor and assess the possibility of using welding current signal from rotating arc sensor to control the welding robot and estimate tolerance of welding robot control problem using the fuzzy logic controller. The welding conditions were used in the experiments are shown in Table 2. The material is used in this study is low-carbon steel plates. Angle of welding line (V-groove) and direction of vertical ball screw is 45^0. The welding current signal which is shown on Fig. 11

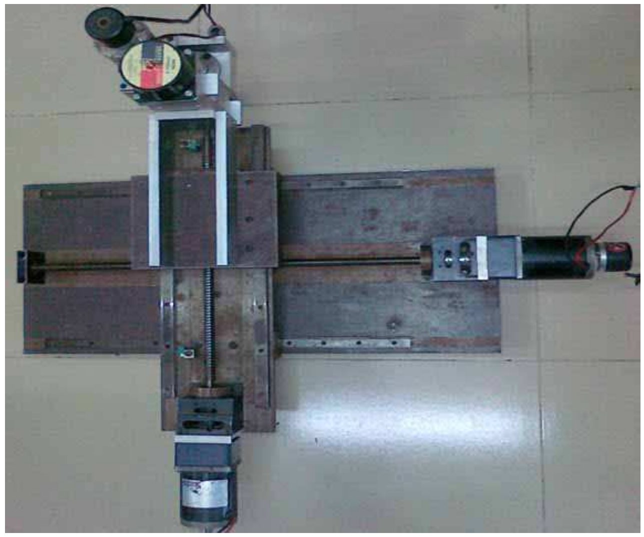


Figure 10. Experiment Model

Table 2. Welding Conditions

Dimensions (mm)	500x40x5	Electrode wire	1,2mm
Seam geometry	V-groove	Shield gas	CO_2 gas
Thickness of base metal	5mm	Arc rotating speed	20hz
Welding voltage	30V	Rotating radius	2,5mm
Welding speed	6mm/s	Control cycle	50ms
Wire feed speed	95mm/s		

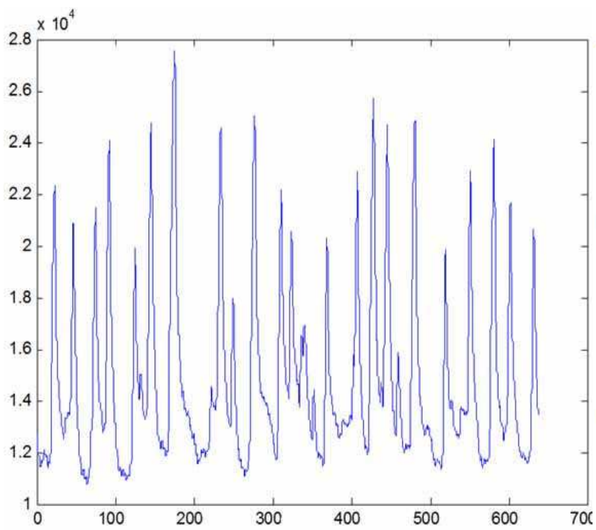


Figure 11. Signal before filtering

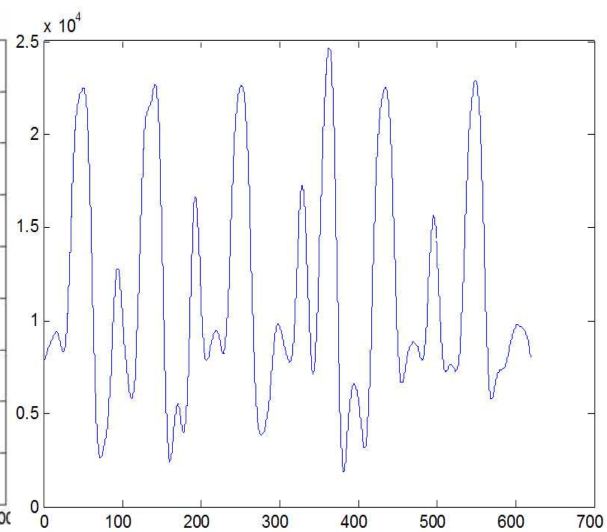


Figure 12. Filtered signal

(or Fig. 12) has many big peaks and frequency of signal is not stable. It means the current signal is affected greatly by short circuit phenomenon. Some reasons of this phenomenon are

Figure 13. Result of seam tracking

followed:

- The limit of Hall sensor which was used is not suitable with maximum current of the welding power source.

- Mechanical model is not stable.

Fig.13 shows result of the fuzzy based seam tracking controller. We hope the improvement model can achieve better result and the proposed controller can be applied for straight welding line (V-groove type) in real industrial system.

5. CONCLUSIONS

The fuzzy controller can adapt to lots of environments. It can help sliders carry the torch to track to various profiles of welding line. Ability of the fuzzy controller has been tested by simulation but experimental control has not had good result yet because of some restrictions from the received signal from the rotating arc sensor. However, we are trying to determine and eliminate short circuit frequency and improve experiment model.

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