

Servo System to Control Arc length for Electro-Gas Welding Equipment

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Abstract: Automatic welding equipment with arc length control for electrolytic aluminum plant is designed. The servo system is composed of AC servo motor, ball screw, electro-gas (EGW) power, base material to be welded and servo controller. The welding power is installed of numerical communication port of welding current, providing information of velocity error between welding pool and gun. MIMO model of welding process is simplified into a linear error amplified. Dynamics of AC servo motor and ball screw with external load are analyzed. And a list of parameters is provided for further controlled design. The system is essentially a multi-loop control system. The internal loop of PID controller is tuned first. And then the whole system with PD controlled is tuned, so that the overshoot ($\sigma\%$) and stabilization time (t_s) is comfortable. At last, with the help of Simulink, arc control performance test is conducted. It proves that the system can keep arc length almost constant. This method is practical and easy to be realized for industrial application.

Key Words: electro-gas welding, arc length control, AC servo, ball screw

1 Introduction

As a traditional heavy industry, electrolytic aluminum plant operating environment is extremely bad: the workshop temperature is up to 50 °C; high concentration of dust contains alumina, asphalt, petroleum coke and other harmful substances; gas near the electrolytic cell contains a lot of fluoride, sulfide, carbon monoxide etc.; magnetic induction intensity is up to 125Gs. In addition, noise hazards, mechanical hazards, electrical hazards are all serious threats to the health and safety of workers. Electrolytic aluminum industry not only consume a lot of energy, especially the cathode bused are consumable, which need to be replaced regularly[1].

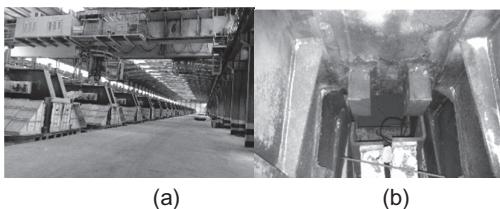


Fig. 1: Electrolytic aluminium industrial field environment
(a)electrolytic aluminium workshop;
(b)stations to be welded

The scene investigations show that the aluminum electrolysis plant scene environment is in Fig. 1. Take a 350kA electrolytic aluminum series as an example. It consists of 288 aluminum electrolytic cells in a series. There are 30 welding stations connected in parallel on

each side of each cell. As is shown in Fig. 1(b), the welding station is finished using the traditional method mentioned in literature [2]. Then each station has two points to be welded, respectively. So, we need to weld 30 pieces of steel. Overall, during a major overhaul, there are a total of $288 \times 30 \times 2 \times 60 = 103,600$ pieces of steel plate to be welded, in this way connection of the cathode bus is of good conductive properties, but the welding of the workload is very great. It is convenient to adapt the method recorded in literature[3]. But the biggest problem is that: although the initial installation of the conductivity can meet the requirements, the contact surface will deformation due to changes in ambient temperature And, the contact resistance is getting increasingly large. Literature [4] mentioned the improvement of the cathode steel bar joints: the cathode steel bar and explosive welded steel plate connecting by 30 to 50 layers of steel is transferred into a single weld. But the use of artificial filling is not inefficient. And such a small space of welding requires very skilled welders to complete this work.

Because the narrow space of the cathode bus to operate welding, the existing automatic welding equipment[5, 6] is difficult to complete that, and now rely entirely on manual welding, so this article aiming at electrolytic aluminum cathode bus welding process characteristics, design automatic welding robot systems to achieve the cathode bus. In this paper, the new fully automatic narrow gap welding technology [7, 8], using electro-gas welding [9, 10]fully filled weld, can greatly reduce the contact resistance.

*This work is supported by National High Technology Research and Development Program("863"Program) of China under Grant 2013AA041002 and National Natural Science Foundation (NNSF) of China under Grant 61305024, 61273337.

The key point of our electro-gas welding is to lift the welding gun automatically, namely an adjustment system to detect welding pool height and welding speed to control welding process. Then the welding process is adaptable to the liquid level position changes due to the gap width, pool overflow, and slope size, so that the quality of welding can be stabilized. At present, the companies are based on different principle[11-13], monitoring and controlling the systems: arc voltage, welding current and optical monitoring. In this paper, we regard the welding equipment as an error amplifier to simplify the model, but it's practical.

2 Electro-Gas Welding Equipment Setup

2.1 System Architecture

Typical industrial feedback control system block[14, 15] is in Fig. 2. System, whose output closely goes after input, is so-called servo system.

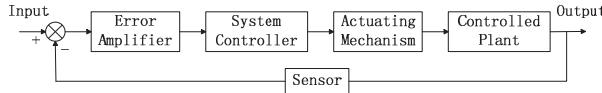


Fig. 2: Block diagram of industrial control system

As is shown in Fig. 3:input is welding pool lift velocity; output is welding gun lift velocity; error amplifier is welding system for Δv amplifier; system controller is trajectory generator; actuating mechanism is AC servo motor; controlled plant is ball screw & slide block; sensor is system feedback characteristic[16].

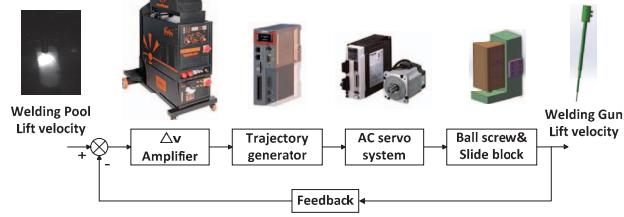


Fig. 3: Block diagram of physical welding system

3 Welding Process Model

3.1 MIMO Model for Welding Process

Welding is a typical MIMO process, which is difficult to analyze and control. System Input are: stick-out, shielding gas, nozzle angle, base material, wire feed rate and contact tube to work distance. Then welding current, welding voltage and velocity is matched or changed to influence welding quality. These factors measure welding quality: weld width, weld depth, air hole, strength, surface etc. Relationship between these input and output variables are as Fig. 4.

3.2 Nonlinear Coupled Model

The electro-gas welding(EGW) is essentially a gas metal arc welding(GMAW) process. The model equations for EGW/GMAW is thus given as the following fifth-order nonlinear form[17]:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, \mathbf{u}) \\ \mathbf{y} = \mathbf{h}(t, \mathbf{x}, \mathbf{u}) \end{cases} \quad (1)$$

The corresponding variables is listed in table1.

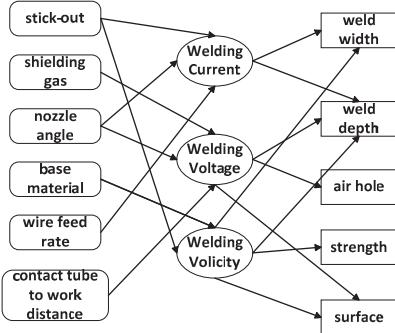


Fig. 4: Block diagram of physical welding system
Table 1: Variable list for EGW model

	Symbols	Descriptions	Units
State Variables \mathbf{x}	$x_1=l$	stick out	m
	$x_2=I$	welding current	A
	$x_3=s$	molten drop displacement	m
	$x_4=v$	molten drop velocity	m/s
	$x_5=m$	molten drop mass	kg
Input Variables \mathbf{u}	$u_1=V_o$	open circuit voltage	V
	$u_2=d$	distance between contact tube to base material	m
	$u_3=v_w$	wire feed rate	m/s
Output Variables \mathbf{y}	$y_1=V_a$	arc voltage	V
	$y_2=I$	welding current	I

Thus, the nonlinear fifth order model equations are:

$$\dot{x}_1 = u_3 - \frac{f_2(x_2, x_4)}{\pi r_w^2} \quad (2)$$

$$\dot{x}_2 = \frac{[u_1 - (R_a + R_s)x_5] - \left[x_1 + \frac{1}{2} \left(\frac{3x_3}{4\pi\rho} \right)^{1/3} \right] \rho x_5 - V_{const} - E_a(u_2 - x_1)}{L_s} \quad (3)$$

$$\dot{x}_3 = x_4 \quad (4)$$

$$\dot{x}_4 = \frac{f_1(x_2, x_5) + f_2(x_2, x_4)\rho u_3 - kx_1 - Bx_2}{x_5} \quad (5)$$

$$\dot{x}_5 = f_2(x_2, x_4)\rho \quad (6)$$

Where r_w is wire radius, R_a is arc resistance, R_s is power source resistance, ρ is wire density, E_a is arc length factor, V_{const} is arc voltage constant, k is spring constant, B is damping coefficient. The details of using this model to control welding process can been seen in [18]. But, in practice it is particularly difficult to precisely acquire all the parameters of above equations to control the welding process. So, linearization and decoupling method is introduced in following section.

3.3 Linearization and Decoupling

The main point of the EGW system is to maintain a constant arc length. During welding process, arc length changes due to root opening, groove size and welding pool overflow. And then change of welding current and

voltage take place to influence weld quality. As for EGW, power supply is with slow down external characteristic. To simplify the above fifth order equations, distance between contact tube to base material D and arc welding current I is output. So the following linearization method in[19] can be adapted during the small deviation range in the neighborhood of working point. According to equation (2)(3)(4)(5)(6), the nonlinear relation between I and d is:

$$I = g(D) \quad (7)$$

It is a tricky problem to solve the equations to get the analytic solution of g. The normal working state is (I_0, D_0) , thus Taylor expansion of equation(7) near here is

$$I = g(D)$$

$$=g(D_0)+\frac{dg}{dD}(D-D_0)+\frac{1}{2!}\frac{d^2g}{dD^2}(D-D_0)^2+\dots \quad (8)$$

When welding is conducted normally, D is nearly equal to D_0 all the time, or the arc will die out. So, the $D-D_0$ is tiny, and high-order items can be ignored as follows

$$I = I_0 + K(D - D_0) \quad (9)$$

Where

$$I_0 = g(D_0); K = \left. \frac{dg}{dD} \right|_{D=D_0} \quad (10)$$

So

$$I - I_0 = K(D - D_0) \quad (11)$$

Namely

$$\Delta I = K \Delta D \quad (12)$$

So equation (11)(12) indicate $\Delta I (I-I_0)$ is proportional to $\Delta D (D-D_0)$. In summary, EGW can be simplified into an error amplifier as explained in Fig. 3.

Furthermore,

$$\Delta I = K \int_0^t \Delta v dt \quad (13)$$

Applying Laplace transform

$$\Delta I(s) = \frac{K}{s} \Delta v(s) \quad (14)$$

So transfer function of Δv amplifier is $\frac{K}{s}$. This result can also be obtained in other method[11, 20]. So, this model is simple but reliable.

4 Mechanism Dynamical Description

EGW welding gun is lifted through ball screw driven by one AC servo motor. This is a 200W three-phase permanent magnet synchronous motor(PMSM). Matched screw and sliding block can move 220-300mm with precision of 0.05mm in vertical direction. It is with at most 5kg load which are welding gun and cooling copper block.

4.1 System block

Servo motor here works in velocity control model. Transfer function blocks of AC servo system and ball screw & slide block transfer[21, 22] mentioned above is as following fig.4.

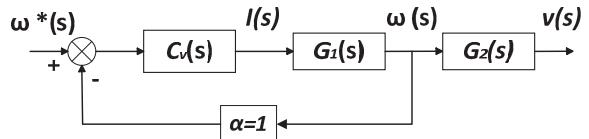


Fig. 5: Servo system and ball screw & slide block transfer
Input ω is reference rotating speed of AC servo motor, Output v is the linear sliding speed of welding gun. Synchronous motor, servo driver system and external load characteristic are included in $G_1(s)$. At the same time, $G_2(s)$ is ratio factor between linear motion and rotating motion. α is feedback coefficient. $C(s)$ is speed controller.

4.2 Servo Motor Model

AC servo motor in velocity model is with two loop: current loop and speed loop. Thus, PMSM and its driver with load is represented by

$$G_1(s) = \frac{\omega(s)}{I(s)} = \frac{A(s)}{B(s)} \quad (15)$$

where

$$A(s) = \frac{K_{pi} K_f}{JL_s}; \quad (16)$$

$$B(s) = s^2 + \frac{R_s + K_{pi} K_i}{L_s} s + \frac{K_u K_f}{JL_s}$$

Dynamical characteristics of screw have been considered above in J, and its kinematics characteristics will be included as follows:

$$G_2(s) = \beta \quad (17)$$

For example: screw pitch S is 6mm, then

$$\beta = \frac{6\text{mm}/r}{1\text{min}/r} = 0.1\text{m/s} \quad (18)$$

Finally, K_{pi} is current loop proportion coefficient. Here, $K_{pi}=100$.

5 System Parameters

Model equation of the whole has been acquired, this section will sustain the parameter number for further controlled design.

5.1 Motion Mechanism Parameters

Parameters of above will be explained in detail in Table 2.

Table 2: Mechanism Parameters

Symbol	Description	Value	Units
P_n	rated power	200	W
v_n	rated speed	3000	r/min
U_ϕ	rated phase voltage	87	V
I_ϕ	rated phase current	1.6	A
f	supply frequency	200	Hz
n_p	pole pairs	4	pair
R_s	stator resistance	0.15	Ω
L_s	stator inductance	0.25	H
K_i	current coefficient	2.21	—
K_f	moment coefficient	0.04	—
K_u	potential coefficient	0.3393	—
J	rotary inertia;	0.18	$\text{kg} \cdot \text{m}^2$

5.2 Welding Device Parameters

According to [23], welding parameters for EGW will be as in Table 3.

Table 3: Welding Parameters

Parameter	Value	Units
welding current	380-400	A
welding voltage	38-42	V
wire diameter	1.6	mm
gas flowing speed	15-20	L/min

6 Controller Design

6.1 Velocity loop

In

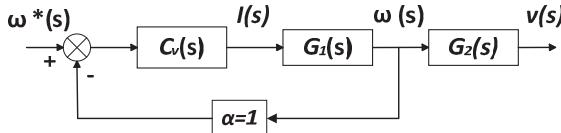


Fig. 5, $C_v(s)$ is Proportion Integration Differentiation (PID) regulator of velocity loop. These coefficients are tuned repeatedly to acquire satisfying and cost effective performance.

$$C_v(s) = K_{pv} \left(1 + \frac{1}{T_{iv}s} + T_{dv}s \right) \quad (19)$$

This is a traditional controller design problem. According to Ziegler and Nichols method, we first only consider the influence of Proportion, assuming that

$$T_i = \infty; T_d = 0 \quad (20)$$

The close loop transfer of system is

$$\frac{\omega(s)}{\omega^*(s)} = \frac{26.67K_{pv}}{s^2 + 265.8s + 26.67K_{pv}} = \frac{\omega_{vn}^2}{s^2 + 2\xi_v\omega_{vn}s + \omega_{vn}^2} \quad (21)$$

$$2\xi_v\omega_{vn} = 265.8 \xrightarrow{\xi=1} \omega_{vn} = 132.9 \quad (22)$$

Then ultimate gain:

$$k_{cr} = \frac{\omega_{vn}^2}{26.67} = 662.3291 \quad (23)$$

Oscillation period:

$$T_{cr} = \frac{2\pi}{\omega_{vn}} = 0.0473 \quad (24)$$

So, K_{pv} , T_{iv} and T_{dv} are as follows:

$$K_{pv} = 0.6K_{cr} = 1305$$

$$T_{iv} = 0.5T_{cr} = 0.0071 \quad (25)$$

$$T_{dv} = 0.125T_{cr} = 0.0018$$

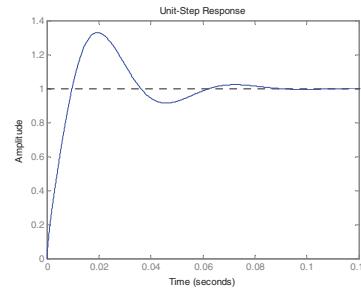


Fig. 6:Unit-Step Response ($K_{pv}=1305$, $T_{iv}=0.0071$, $T_{dv}=0.0018$)

The unit-step response is as Fig. 6. From that, a stable system is acquired, but overshoot ($\sigma\%$) is over 25%, and stabilization time (t_s) is over 0.1s. Furthermore, we tune this three parameters repeatedly. In Fig. 7, system is of more high performance ($\sigma\% < 15\%$, $t_s < 0.1s$).

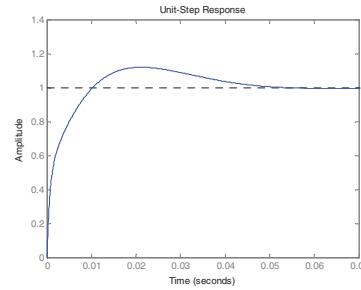


Fig. 7: Unit-Step Response ($K_{pv}=2641$, $T_{iv}=0.0142$, $T_{dv}=0.0036$)

The velocity loop transfer function block is in Fig. 8. And its closed loop transfer is equation(26).

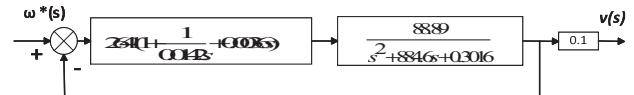


Fig. 8:velocity loop block

$$G_{v\omega} = \frac{v(s)}{\omega^*(s)} = \frac{1.184s^2 + 333.5s + 23480}{0.01421s^3 + 24.41s^2 + 3335s + 234800} \quad (26)$$

6.2 Servo System Performance Test

In this section, the whole system controller is discussed. It is difficult to get its analytical solution, so we tune the parameters annually. Because error amplifier is an integral block, PD controller is enough, namely $C_w(s)$:

$$C_w(s) = K_{pw} (1 + T_w s) \quad (27)$$

And the transfer function block of the whole welding system is in Fig. 9. Unit-step response of the system is in Fig. 10 under careful design.

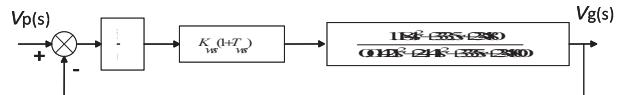


Fig. 9: Transfer function of physical welding system

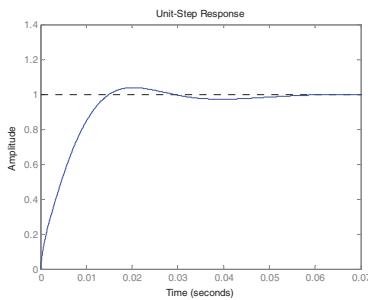


Fig. 10:Unit-Step Response ($K_{pw}=367$, $T_{pw}=0.0017$)

7 Arc Control Performance Test

With the help of Simulink, arc control performance test is conducted. Simulink model is in Fig. 11.

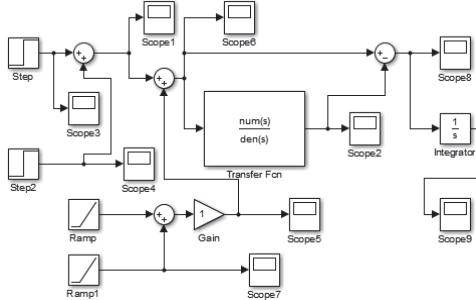


Fig. 11:Simulink model for Arc Control

As is shown in Fig. 12(a), welding pool lift velocity changes in step or slope. Fig. 12(b) shows welding gun lift velocity. Fig. 12(c) shows velocity error. Fig. 12(d) shows arc length error, which is less than 0.015mm. So, arc length is almost constant to fulfill welding process.

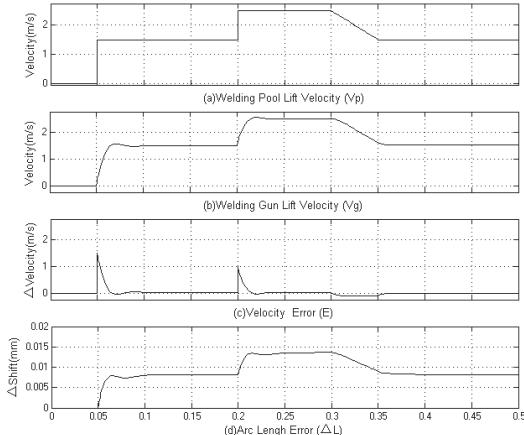


Fig. 12: Arc Length Control Experiment

8 Conclusion

In this paper, servo system to control arc length for electro-gas welding is designed and analyzed. First, electro-gas welding model equations are simplified into an error amplifier, which provides a reliable base for theoretical analysis. Then, this method is practical and easy to be realized for industrial application. Last, a multi-loop control system is designed to control arc length, surviving workers from harsh environments.

There are still some drawbacks of linearization method, which is not able to provide full information of control object. It is impossible for us to solve the stable working

point, but is essential to test repeatedly. So, we will study this problem in future.

References

- [1] Y. Liu, and L. Jie, *Modern aluminum electrolysis*: Metallurgical Industry Press, 2008.
- [2] W. Ziqian, C. Bin, and Y. tao, "All current welding aluminum reduction cells drop test of magnetic technology research".
- [3] Y. Yongtao, "Aluminum electrolytic cell cathode steel stick type pressure connection application".
- [4] H. Yingke, and L. Yunqing, " Improvement of aluminum electrolytic cell cathode steel stick between the head and block explosion welding way affect energy " *Journal of Shanghai metal: non-ferrous pathol*, no. 1, pp. 50-52, 1991.
- [5] D. N. Manh, L. C. Tan, K. K. Hak, B. K. Sang, and S. O. Myung, *NONLINEAR CONTROL OF WELDING ROBOT FOR TRACKING A 3D RECTANGULAR WELDING LINE*, 2015.
- [6] C. S. Kim, K. S. Hong, and Y. S. Han, *Welding Robot Applications in Shipbuilding Industry: Off-Line Programming, Virtual Reality Simulation, and Open Architecture*, 2006.
- [7] J. Norrish, *Narrow-gap welding techniques*, 2006.
- [8] H. C. Cui, Z. D. Jiang, X. H. Tang, and F. G. Lu, "Research on narrow-gap GMAW with swing arc system in horizontal position," *The International Journal of Advanced Manufacturing Technology*, vol. 74, no. 1-4, pp. 297-305, 2014.
- [9] S. Y. Hwang, Y. Kim, and J. H. Lee, "Finite element analysis of residual stress distribution in a thick plate joined using two-pole tandem electro-gas welding," *Journal of Materials Processing Technology*, vol. 229, no. 2016, pp. 349-360, 2016.
- [10] Q. Li, M. Yin, and H. Cui, "Control and optimal design of auto electro-gas welding swing oscillator," *Journal of Jiangsu University of Science & Technology*, 2010.
- [11] J. Zheng, Z. Liu, L. Chen, B. Cheng, T. University, and Beijing, "Arc length control study for crawl-type electrogas arc welding robot," *Transactions of the China Welding Institution*, 2008.
- [12] S. May, J. Vignollet, and R. D. Borst, "A new arc-length control method based on the rates of the internal and the dissipated energy," *Engineering Computations*, vol. 33, no. 1, pp. 100-115, 2016.
- [13] D. J. Leith, and W. E. Leithead, "On microprocessor-based arc voltage control for gas tungsten arc welding using gain scheduling," *Control Systems Technology IEEE Transactions on*, vol. 7, no. 6, pp. 718-723, 1999.
- [14] R. C. Dorf, and R. H. Bishop, "Modern Control Systems, 11th Edition," *Pearson (Addison-Wesley)*, vol. 11, no. 8, pp. 580, 2007.
- [15] P. Corke, "Robotics, Vision and Control: Fundamental Algorithms in MATLAB," *Industrial Robot*, vol. 39, no. 6, pp. págs. 75-85, 2012.

- [16] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic System*: Addison-Wesley, 1986.
- [17] D. S. Naidu, S. Ozcelik, and K. L. Moore, "Modeling, Sensing and Control of Gas Metal Arc Welding," *Modeling Sensing & Control of Gas Metal Arc Welding*, pp. 281–346, 2003.
- [18] K. L. Moore, D. S. Naidu, R. Yender, and J. Tyler, "Gas metal arc welding control: Part I : Modeling and analysis," *Nonlinear Analysis Theory Methods & Applications*, vol. 30, no. 5, pp. 3101-3111, 1997.
- [19] Katsuhiko Ogata, *Modern control engineering*, 2011.
- [20] J. Pan, "Arc Welding Control," *Arc Welding Control*, pp. 582–600, 2003.
- [21] Z. Shu, "AC Servo Motion Control System," Tsinghua University Press, 2006.
- [22] X. Chen, Z. Shu, and Y. Zhao, "Mathematic Model and Performance Analysis of PMSM Based Servo System [J]," *Machinery & Electronics*, vol. 1, pp. 41-43, 2005.
- [23] *Welding handbook: welding processes* 9ed.: American Welding Society, 2004.