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Fractional PID controller of MIMO Gas Metal Arc Welding process.

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***Abstract*— Gas metal arc welding (GMAW) plays the great importance in the welding industry on account of high flexibility in the welding of different metals, high welding productivity, and automatic run capabilities. This paper focuses on the development of a fractional PID control of gas metal arc welding system, wherein the current and voltage of welding process are controlled using a fractional PID controller, then the system analyzed and the results compared with conventional PID controller show adequate improvement in the efficiency and performance of the proposed controller.**

***Keywords*— GMAW, MIMO system, P ID controller, Fractional PID controller**

I. INTRODUCTION

Welding is a step of joining two metal components to ensure the mechanical continuity between the parts to be assembled. It can be achieved by several welding process. Among them Gas metal arc welding (GMAW) is one of the most welding process used in industrial manufacturing [1]. There are many advantages in the welding by gas metal arc welding method, such as the only welding process consumable electrode which can be used for welding of different metals and commercial alloys, can be done in any position, unlike the submerged arc welding and automatic run capabilities [2].

In order to evaluate and ensure the weld quality in this type of welding is determined by several characteristics such as the metal transfer mode and the weld geometry [3], in this reason the control of the GMAW process can be separated into weld pool control and arc control [4]. Several control strategies for the GMAW process have been investigated; in [5] K. L. Moore et al applied PID single-input, single output and multi loop control of the GMAW process with experimental results. A feedback linearization state of GMAW process based 2 PI controllers is designed in [6]. Henderson et al [7] is successfully applied a pseudo gradient adaptive algorithm to self-tune the parameters of a PI controller for gas metal arc welding.

Smartt and Einerson [8] demonstrates a steady-state model for heat and mass transfer from the electrode to the work piece in gas metal arc welding using a computer-controlled welding machine and a proportional-integral (PI) controller. Mahdi Jalili-Kharaajoo et al proposed a feedback linearization controller based on sliding mode control action of current and arc length in Gas Metal Arc Welding systems [9]. A fuzzy-PI controller of current and arc length in GMAW systems is proposed in [10].Golob. M [11] proposed a discrete PI controller for welding current of combined simulation of GMAW process model with the simulation model of an inverter-based power machine.

Despite continuous advances in control theory, the PID controller is the most used technique in the stabilization of industrial processes for decades. The main reasons for its wide acceptance in industry are its ability to control the majority of the process, these actions are well understood and its implementation is very simple [12]. Recently a fractional order controller $PI^{\lambda}D^{\mu}$ which is a generalization of the classical PID controller was proposed by Podlubny [13], this corrector includes a fractional integration of order λ and a fractional order of derivation μ or λ and μ are real numbers.

Interest in this type of correction is justified by greater flexibility in the design of the control since two parameters in addition; fractional orders actions of integration and derivation. These parameters can be used to meet additional performance in the design of feedback control systems.

This paper studies the GMAW arc self-regulating process utilizing a nonlinear mathematical state space model of the process. In addition, a fractional order controller $PI^{\lambda}D^{\mu}$ is designed to control the wire feed speed and open circuit voltage.

This paper is organized as follows: First in section 1, the mathematical modeling of a GMAW process is presented and, then in section 2, the control objective is discussed. Subsequently, a fractional order controller $PI^{\lambda}D^{\mu}$ is designed. Applications of the fractional order control to the GMAW process and simulation results are given in the section 3.Finaly, the conclusions are drawn.

II. MODELING OF THE GMAW PROCESS

The schematic diagram of the GMAW system is illustrated in the Figure 1. The power source consists of a constant voltage source connected to the electrode and the work piece.

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The wire speed, S, travel speed of the torch, R, open circuit voltage, V_{oc}, and contact tip to work piece distance, CT, are adjusted to get the desired weld. The model used in this work is the fourth-generation of the derivative equation that originated at the Idaho National Engineering and Environmental Laboratory (INEEL) [14, 15].

The state-space representations of the resulting equation are given in the following equations. Firstly, the state variables are defined as:

$x_1 = x$ Droplet displacement (m).
$x_2 = \dot{x}$ Droplet velocity (m/sec).
$x_3 = m_d$ Droplet mass (kg).
$x_4 = l_s$ Stick-out (m).
$x_5 = I$ Current (A).

Where x is the distance of the center of the mass of the droplet above the work piece.

Then the nonlinear state equations can be written as follows:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{-kx_1 - Bx_2 + F_{tot}}{x_3} \\ \dot{x}_3 &= M_R \rho_w \\ \dot{x}_4 &= u_1 - \frac{M_R}{\pi r_\omega^2} \\ \dot{x}_5 &= \frac{u_2 - (R_a + R_s + R_L)x_5 + V_0 - E_a(CT - x_4)}{L_s} \end{aligned} \tag{1}$$

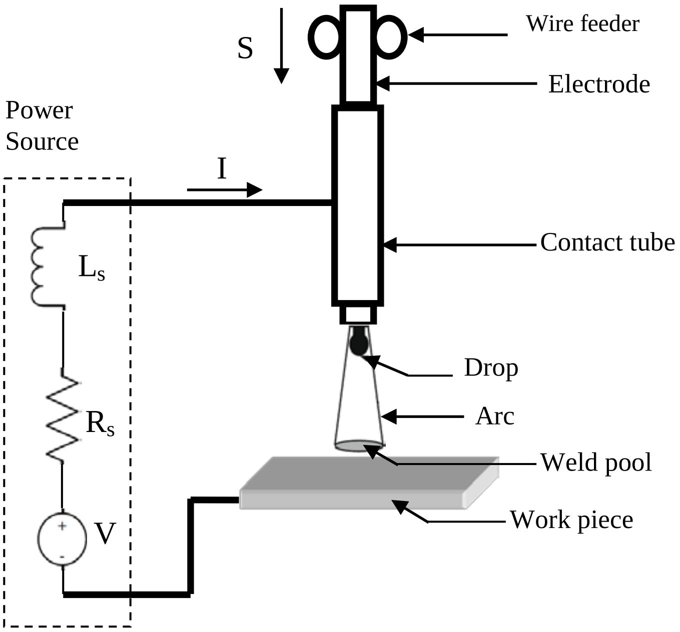

Figure 1. Schematic diagram of GMAW system.

Where F_{tot} is the force acting on the droplet given by:

$$F_{tot} = F_{em} + F_d + F_m + F_g \tag{2}$$

Where F_{em}, F_d, F_m and F_g are the electrode magnetic force, aerodynamic drag force, momentum force, and gravity force, respectively. k and B are the spring constant and damping coefficient of the droplet. R_a and R_s are the arc resistance and source resistance, respectively. ρ_ω is the electrode density, rw is the electrode radius, V_0 is the arc voltage constant, E_a is the arc length factor, L_s is the source inductance and MR is the melting rate. The melting rate, M_R is given by:

$$M_R = C_2 \rho x_4 x_5^2 + C_1 x_5 \tag{3}$$

And the electrode resistance, R_L:

$$R_L = \rho \left[x_4 + \frac{1}{2} \left(\left(\frac{3x_3}{4\pi\rho x} \right)^{\frac{1}{3}} + x_1 \right) \right] \tag{4}$$

The output equations are given by the following equations:

$$\begin{aligned} y_1 &= V_0 + R_a x_5 + E_a(CT - x_4) \\ y_2 &= x_5 \end{aligned} \tag{5}$$

And the control variables are

$u_1 = S$ Wire feed speed (m/sec),
$u_2 = V_{oc}$ Open-circuit voltage (V).

States of the system must be reset after each detachment of a drop, which means:

$$F_{tot} > F_s \tag{6}$$

Or

$$r_d > \frac{\pi(r_d + r_\omega)}{1.25\left(\frac{x + r_d}{r_d}\right)\left(1 + \frac{\mu_0 I^2}{2\pi^2 \gamma (r_d + r_\omega)}\right)^{\frac{1}{2}}} \tag{7}$$

Where:

$$r_d = \left(\frac{3x_5}{4\pi\rho_\omega} \right)^{\frac{1}{3}} \tag{8}$$

And F_s the surface tension of the droplet given as:

$$F_s = 2\pi\gamma r_\omega \tag{9}$$

Where r_d is the droplet radius, μ_0 is the permeability of free space and γ is the surface tension of liquid steel [14].

The GMAW dynamics model, given by Equations (1), is highly nonlinear. Based on some approximations the simplified model of GMAW is [14]:

$$\begin{aligned} \dot{x}_4 &= u_1 - \left(\frac{C_2 \rho}{\pi r_\omega^2} x_4 x_5^2 + \frac{C_1}{\pi r_\omega^2} x_5 \right) \\ \dot{x}_5 &= \frac{u_2 - (R_a + R_s + \rho x_4)x_5 + V_0 - E_a(CT - x_4)}{L_s} \end{aligned} \tag{10}$$

III. A FRACTIONAL ORDER PID CONTROLLER OF MIMO GMAW PROCESS

To improve the performance of GMAW systems, the researcher has proposed a generalization of the conventional PID controller to $PI^\lambda D^\mu$ form [13] called fractional PID, where λ and μ are positive real such that $0 < \lambda < 1$ and $0 < \mu < 1$, it showed that performance was significantly improved compared to those obtained by a fractional order PID.

The analytical expression of the fractional $PI^\lambda D^\mu$ is given by the following equation:

$$G_c(s) = K_p + T_i s^{-\lambda} + T_d s^\mu \tag{11}$$

$PI^\lambda D^\mu$ structure consists of a parallel connection of the three actions, proportional, integral and derived, as shown in the Figure 2.

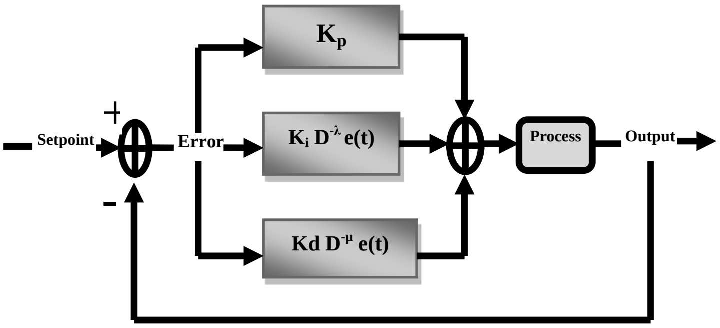

Figure 2.Closed loop control process with fractional $PI^{\lambda}D^{\mu}$ controller.

Fractional $PI^{\lambda}D^{\mu}$ controller's output is used to control the plant and the proposed control scheme is illustrate in the Figure 3.

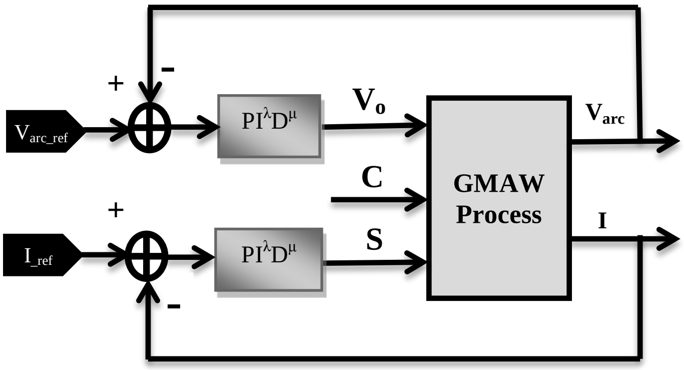

Figure 3. Fractional order $PI^{\lambda}D^{\mu}$ controller of MIMO GMAW process.

IV. PROCESS SIMULATION AND RESULTS

The above design procedures are implemented and simulation studies are carried out using MATLAB.

The most important parameter values, which are considered in the GMAW process, are presented in Table1.

The current response with different controller for a series of step changes is depicted in the figure 4. The different controllers are turned on with a set point of 240A between 3 and 5 micro seconds and a set point of 260A after that time.

The arc voltage output with different controller for a series of step changes is depicted in the figure 5. The step change varies of desired arc voltage V_{arc}= 30 volts between 3 and 5 micro seconds and a desired arc voltage V_{arc}= 35 volts between 5 and 10 micro seconds. The effectiveness of the fractional PID controller is clearly illustrated and the system tracks the desired signal quickly.

Figure 6 and Figure 7 show the controlled open-circuit voltage signal with different controller that ensured that the arc voltage be maintained at 34 volts between 3 and 5 micro seconds and at 35 volts between 5 and 10 micro seconds.

This simulation show satisfactory robustness of the system with fractional PID controller under the mechanical parameters uncertainty.

Table 1. The GMAW parameters.

Parameter	Value
C_1	2.8855e-10 m^3/A
C_2	5.22e-10 m^3/A^2.Ohm
ρ	0.2821 Ohm/m
E_a	1500 V/m
V_a	15.7 V
R_a	0.022 Ohm
R_s	0.001 Ohm
L_s	0.35 mH
R	8 m/s
CT	0.01 m
r_w	0.001 m

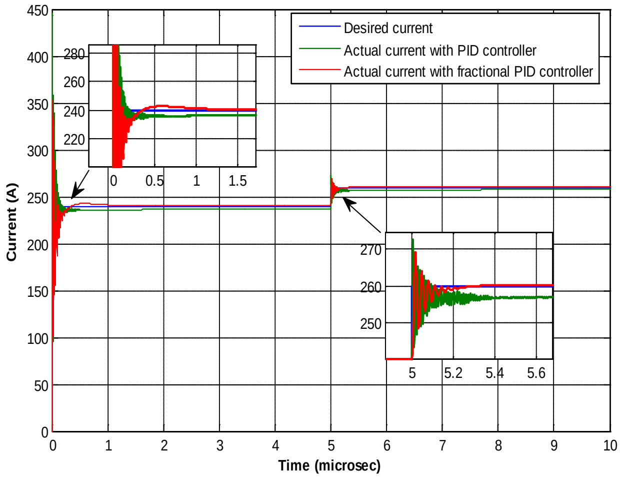

Figure 4.Current response with different controller

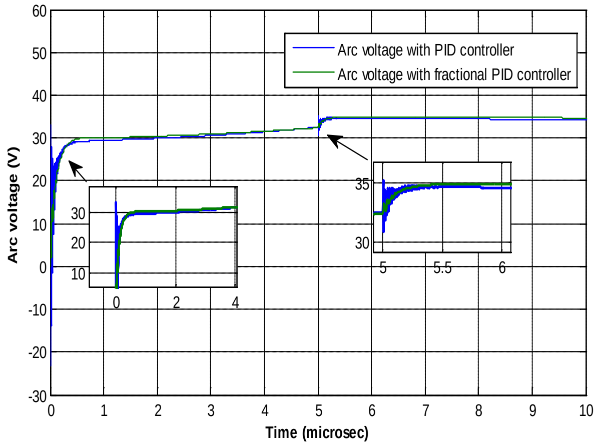

Figure 5.Arc voltage response with different controller

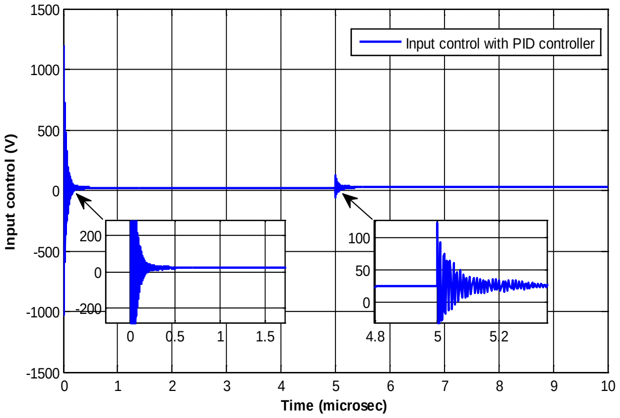

Figure 6.input control signal with PID controller

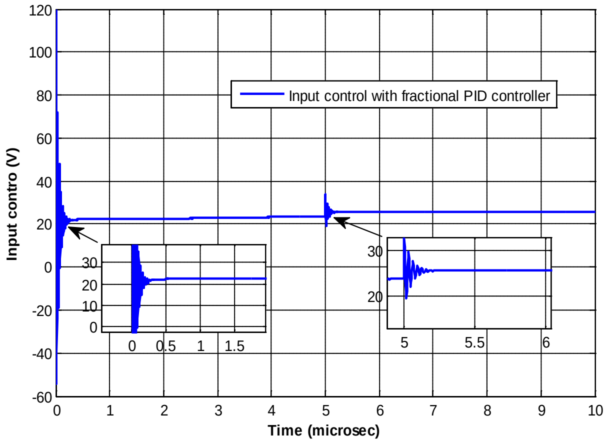

Figure 7.input control signal with fractional PID controller

V. CONCLUSIONS

In this paper, the modeling of a nonlinear gas metal arc welding was addressed. Advanced control strategies, including fractional order PID controller of MIMO gas metal arc welding system have been used to accomplish control tasks for both voltage and current arc welding, together. From the implemented control algorithm based fractional PID controller, it can be seen that very good performance in the weld and the controller's performance and robustness are improved, compared to a conventional PID controller.

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