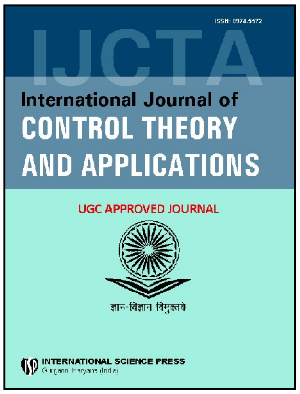

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Robust Fractional Control of Current and ARC Voltage in Gmaw Systems

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Abstract: Gas metal arc welding (GMAW) plays 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 is analyzed and the results are compared with conventional PID controller show adequate improvement in the efficiency and performance of the proposed controller.

Keywords: GMAW, MIMO system, PID controller, Fractional PID controller.

1. 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 preferred for its versatility, speed and relative ease of adapting to robotic automation. This process has been used extensively by many industrial environments especially, the automobile industry. [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. A model predictive control (MPC) based on ARMarkov has been designed to control the welding current and arc voltage in a linearized GMAW process in [12].

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 [13]. Recently a fractional order controller $PI^{\lambda}D^{\mu}$ which is a generalization of the classical PID controller was proposed by Podlubny [14], this corrector includes a fractional integration of order λ and a fractional order of derivation μ or λ and μ are real numbers.

Applications of fractional calculus in control are numerous. In [15] the control of viscoelastic damped structures is presented. Control applications to a flexible transmission [16], an active suspension [17], a buck converter [18], and a hydraulic actuator [19] are also found in the literature. The fractional-order control of a flexible manipulator is the objective in [20], rigid robots are treated in [21], and the fractional-order control of a thermal system in [22].

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 modelling 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.

2. 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. 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) [23, 24].

The main parts of the model will be presented as follows. Basically, the important aspects with respect to control are the electrical circuit, the drop dynamics, the drop detachment criteria and the melting rate.

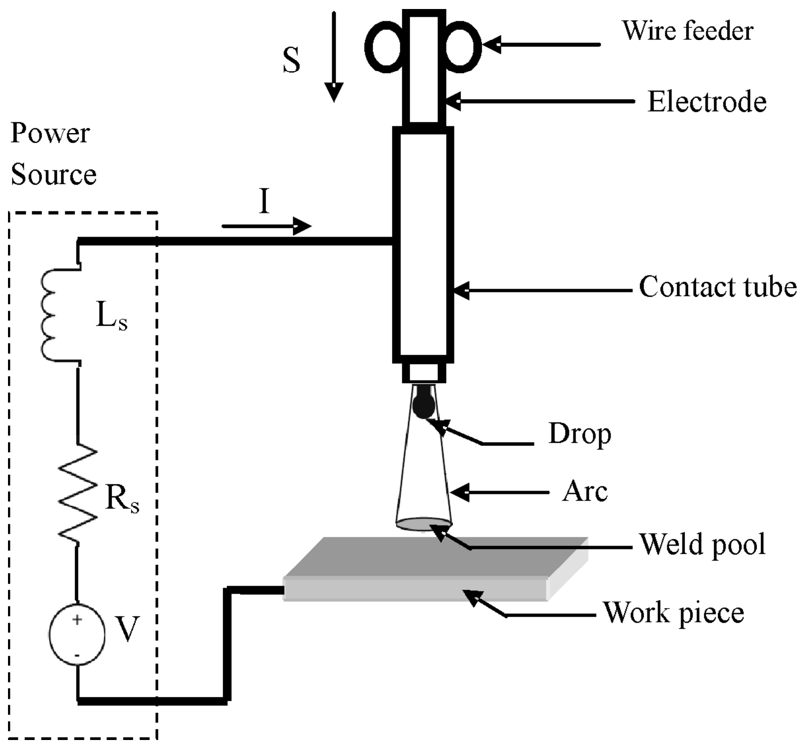

Figure 1: Schematic diagram of GMAW system

The current is obtained from a simple electrical circuit principle as [25]:

$$\dot{I} = \frac{V_{oc} - R_L I - V_{arc} - R_s I}{L_s} \tag{1}$$

$$V_{arc} = V_o + R_a I + E_a(CT - l_s) \tag{2}$$

$$R_L = \rho\left[l_s + \frac{1}{2}(r_d + x_d)\right] \tag{3}$$

The pendant drop attached to the tip of the electrode canbe modelled as a mass-spring-damper system as describedby [26-28] and Wu *et al.* given by the following equation :

$$m_d \ddot{x}_d = F_T - b_d \dot{x}_d - k_d x_d \tag{4}$$

where F_T is the total external force affecting the droplets is as follows:

$$F_T = F_g + F_{em} + F_d + F_m \tag{5}$$

where F_g, F_{em}, F_d and F_m are the gravity force, electromagnetic force, plasma drag force, and momentum flux force, respectively. The gravity force F_g is defined as

$$F_g = m_d g \tag{6}$$

where g is the acceleration due to gravity and m_d is the mass of the droplet, which can be computed in terms of the droplet radius r_d (Fig. 2). It is assumed that the droplets have a spherical shape.

$$m_d = \frac{4}{3}\pi\rho_e r_d^3 \tag{7}$$

ρ_e describes the density of the liquid electrode material. Considering uniform distributed current and a spherical dropletwith a radius larger than the solid electrode, the electromagnetic force F_{em} can be written as

$$F_{em} = \frac{\mu_0 I^2}{4\pi}\left[\ln\left(\frac{r_d \sin\theta}{r_e}\right) - \frac{1}{4} - \frac{1}{1-\cos\theta} + \frac{2}{(1-\cos\theta)^2}\ln\left(\frac{2}{1+\cos\theta}\right)\right] \tag{8}$$

where μ_0 is the permeability of free space, I is the welding current, θ is the angle of the arc-covered area, and r_e is the radius of the electrode (Fig. 2). The plasma drag force F_d is determined as follows.

$$F_d = 0.5\left(c_d A_d \rho_p v_p^2\right) \tag{9}$$

where c_d is the drag coefficient, ρ_p is the density of the plasma, v_p is the shielding gas velocity, and A_d is the area of droplet hit by the shielding gas

$$A_d = \pi\left(r_d^2 - r_e^2\right) \tag{10}$$

The momentum flux F_m is determined as follows [29].

$$F_m = \frac{\mu_0}{4\pi}\left(\left(\frac{I}{\sigma}\right)^2 - I_2\right) \tag{11}$$

where σ is defined as r_d / r_e and I_2 is determined as

$$I_2 = \int J_0 dA_d \tag{12}$$

where J_0 is the uniform current density on the arc-covered area of the drop surface (Fig. 2).

The meltingrate M_R is expressed by the following equation :

$$M_R = C_2 I_a^2 \rho l_s + C_1 I \tag{13}$$

The stick-out evolution is controlled by

$$\frac{dl_s}{dt} = S - \frac{M_R}{\pi r_e^2} \tag{14}$$

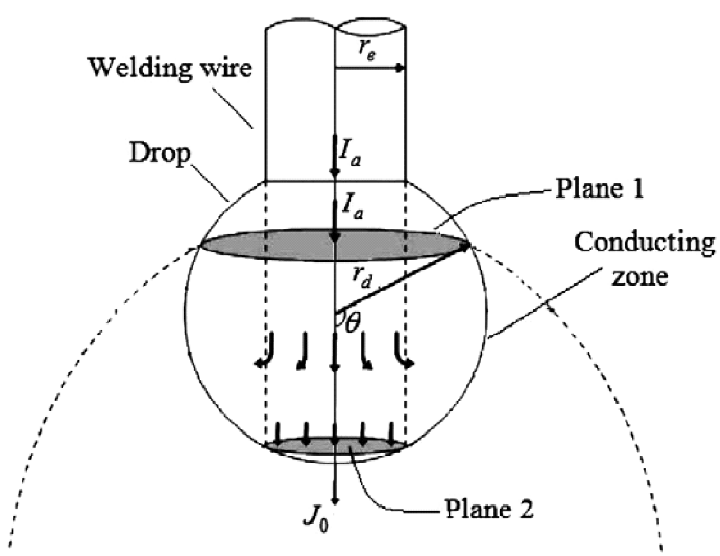

Figure 2: Schematic diagram of droplet and electrode

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

$x_1 = x_d$: Droplet displacement (m).

$x_2 = \dot{x}_d$: Droplet velocity (m/sec).

$x_3 = n$: Droplet mass (kg).

$x_4 = l_s$: Stick-out (m).

$x_5 = I$: Current (A).

Where x_d 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:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{-kx_1 - Bx_2 + F_T}{x_3} \\ \dot{x}_3 &= M_R \rho_w \\ \dot{x}_4 &= u_1 - \frac{M_R}{\pi r_e^2} \\ \dot{x}_5 &= \frac{u_2 - (R_a + R_s + R_L)x_5 + V_0 - E_a(CT - x_4)}{L_s} \end{aligned} \tag{15}$$

Where 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_w is the electrode density, V_0 is the arc voltage constant, E_a is the arc length factor and L_s is the source inductance.

The output equations are given by the following equations:

$$\begin{aligned} y_1 &= V_0 + R_a x_5 + E_a(CT - x_4) \\ y_2 &= x_5 \end{aligned} \tag{16}$$

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:

$$F_T > F_S \tag{17}$$

Or

$$r_d > \frac{\pi(r_d + r_e)}{1.25\left(\frac{x + r_d}{r_d}\right)\left(1 + \frac{\mu_0 I^2}{2\pi^2 \gamma (r_d + r_e)}\right)^{\frac{1}{2}}} \tag{18}$$

Where:

$$r_d = \left(\frac{3x_5}{4\pi\rho_w}\right)^{\frac{1}{3}} \tag{19}$$

And F_S is the surface tension of the droplet given as:

$$F_s = 2\pi\gamma r_e \tag{20}$$

Where γ is the surface tension of liquid steel [23].

The GMAW dynamics model, given by Equations (1), is highly nonlinear. Based on some approximations the simplified model of GMAW is [23]:

$$\dot{x}_4 = u_1 - \left(\frac{C_2\rho}{\pi r_e^2} x_4 x_5^2 + \frac{C_1}{\pi r_e^2} x_5\right)$$
$$\dot{x}_5 = \frac{u_2 - (R_a + R_s + \rho x_4) x_5 + V_0 - E_a(CT - x_4)}{L_s} \tag{21}$$

3. BASIC DEFINITIONS OF FRACTIONAL CALCULUS

The fractional-order integrodifferential operator can be seen as the extendedconcept of the integer-order integrodifferential operator. The commonly useddefinitions in literatures are Grunwald-Letnikov, Riemann-Liouville, and Caputodefinitions. In the literature we find different definitions of fractional differ-integral, but the commonly used are:

The Riemann– Liouville definition of order $\alpha \in \mathbb{R}^+$ has the following form:

$$D_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_0^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \tag{22}$$

An alternative definition for the fractional-order was introduced by Caputo as

$$D_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^m(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \tag{23}$$

where α is the fractional order, and *m* is an integer satisfying $m - 1 < \alpha <$ and $\Gamma(\cdot)$ represents the Euler's Gamma function expressed by the following equation :

$$\Gamma(x) = \int_0^\infty e^{-t} t^{(x-1)} dt, \quad x > 0 \tag{24}$$

Due to its importance in applications, we will consider here the Grunwald– Letnikov's definition, based on the generalization of the backward difference. This definition has the form :

$$D_t^\alpha f(t) = \lim_{h\to 0} \frac{1}{h^\alpha} \sum_{k=0}^{(t-\alpha)/h} (-1)^k \binom{\alpha}{k} f(t-kh) \tag{25}$$

Because the numerical simulation of a fractional differential equation is not simple as that of an ordinary differential equation, so Laplace integral transforms is fundamental tools in systems andcontrol engineering. For this reason, we will give here the equation of thesetransforms for the defined fractional-order operators. The Laplace transform of Riemann– Liouvilledefinition is as follow [30, 31]:

$$L\{D_t^\alpha f(t); s\} = s^\alpha F(s) - \sum_{k=0}^{m-1} s^k \left[D_t^{(\alpha-k-1)} f(t)\right]_{t=0} \tag{26}$$

Where the Laplace transform of Caputo's definition is given by [14]:

$$L\{D_t^\alpha f(t); s\} = s^\alpha F(s) - \sum_{k=0}^{m-1} s^{\alpha-k-1} f^k(0) \tag{27}$$

where $s = j\omega$ denotes the Laplace operator. For the zero initial conditions, the Laplace transforms of fractional derivative of Riemann-Liouville, Caputo and Grunwald-Letnikov are reduced to (7) [32,14].

$$L(D_t^\alpha f(t)) = s^\alpha F(s) \tag{28}$$

4. FRACTIONAL-ORDER PID CONTROLLER OF 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 integro-differential equation defining the control action of a fractionalorderPID controller is given by:

$$u(t) = K_p e(t) + K_i \mathcal{D}^{-\lambda} e(t) + K_d \mathcal{D}^{\mu} e(t) \tag{29}$$

Applying Laplace transform to this equation with null initial conditions,the transfer function of the controller can be expressed by

$$C_f(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} = k\,\frac{(s/\omega_f)^{\lambda+\mu} + s\delta_f s^{\lambda}/\omega_f + 1}{s^{\lambda}} \tag{30}$$

Figure 3 shows the frequency response of this controller for $k = 1$, $\omega_f = 1$, $\delta_f = 1$ and $\lambda = \mu = C$

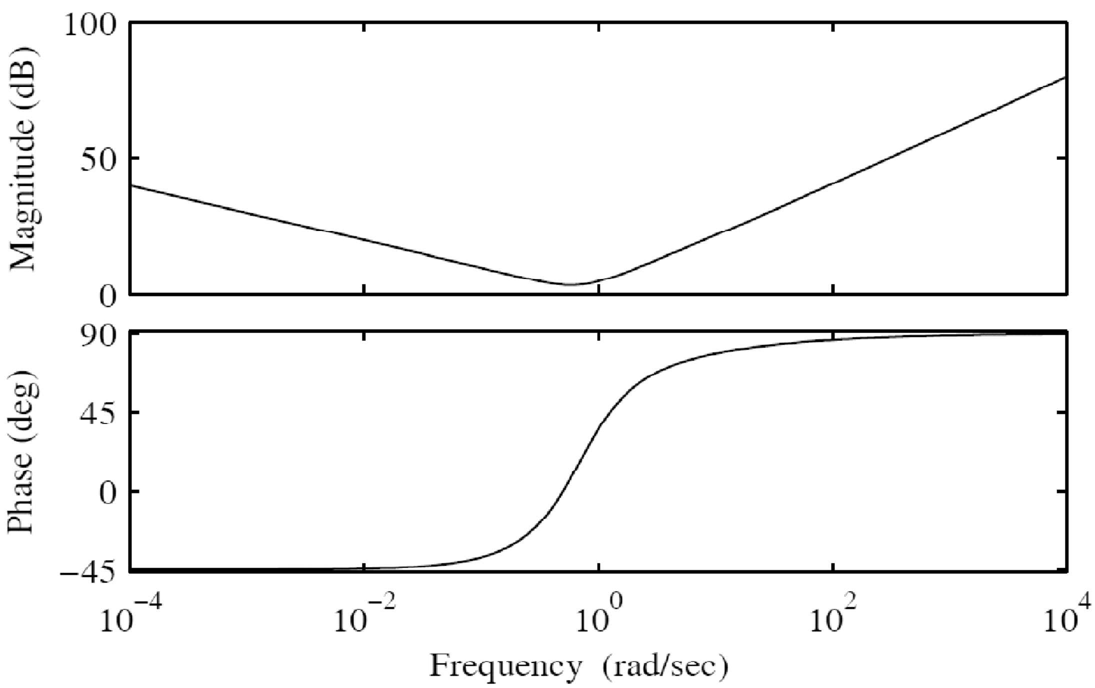

Figure 3: Frequency response of the fractional-order PID controller with k = 1, $\omega_f = 1$, $\delta_f = \lambda$ and $\lambda = \mu = 0.5$

As can be observed, this fractional-order controller allows us to select boththe slope of the magnitude curve and the phase contributions at both highand low frequencies.

In a graphical way, the control possibilities using a fractional-order PIDcontroller are shown in Figure 4, extending the four control points of theclassical PID to the range of control points of the quarter-plane defined byselecting the values of λ and μ.

Fractional $PI^{\lambda}D^{\mu}$ controller's output is used to control the plant and the proposed control scheme is illustrate in the Figure 5.

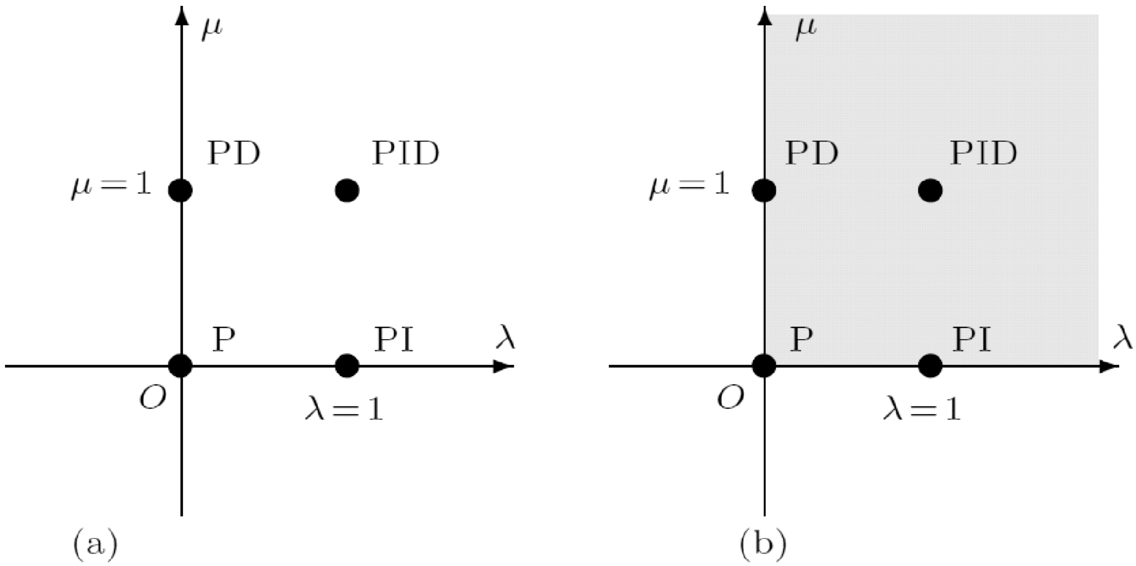

Figure 4: Fractional-order PID vs classical PID: from points to plane: (a) integer-orderand (b) fractional-order

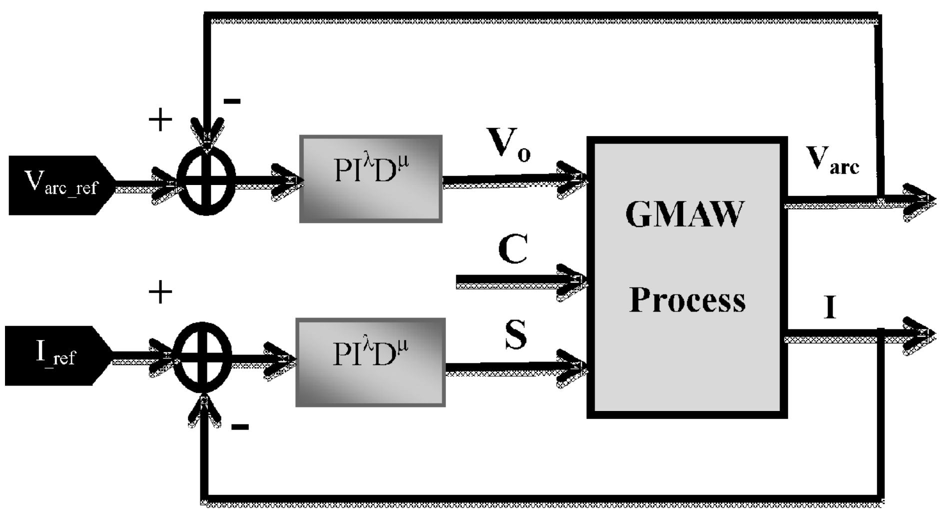

Figure 5: Fractional order $PI^{\lambda}D^{\mu}$ controller of MIMO GMAW process

5. 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 inTable1 in APPENDIX.

The current response with different controller for a series of stepchanges is depicted in the figure 6. 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 7. The step change varies of desired arc voltage Varc= 30 volts between 3 and 5 micro seconds and a desired arc voltage Varc= 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.

Figures 8 and 9 show the controlled open-circuit voltage signal with different controller that ensured that the arc voltage be maintained at 34 voltsbetween 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.

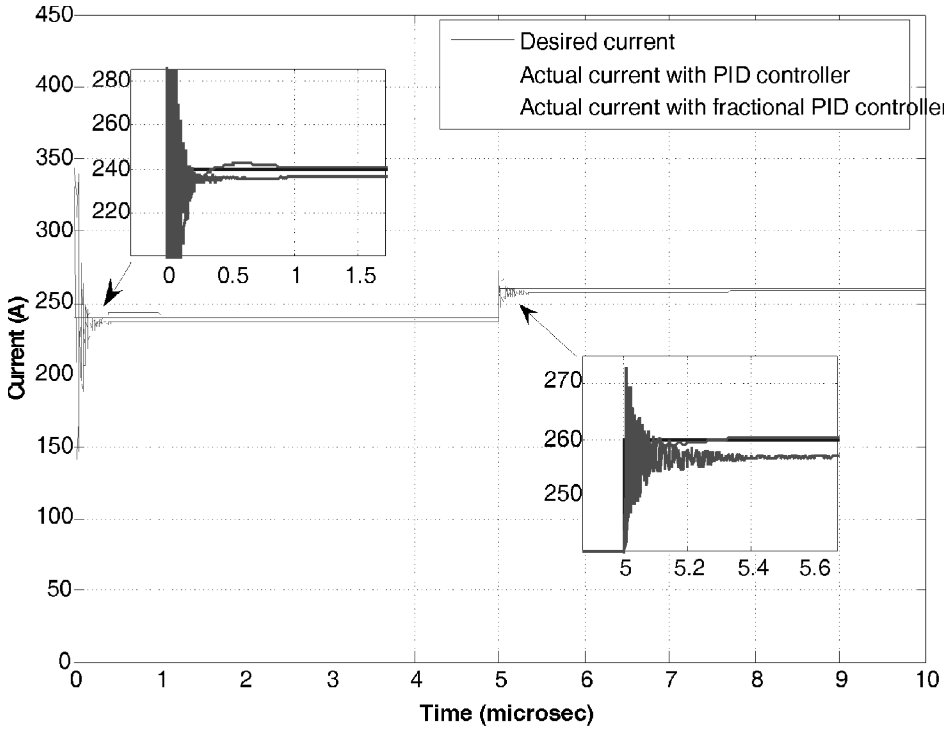

Figure 6: Current response with different controller

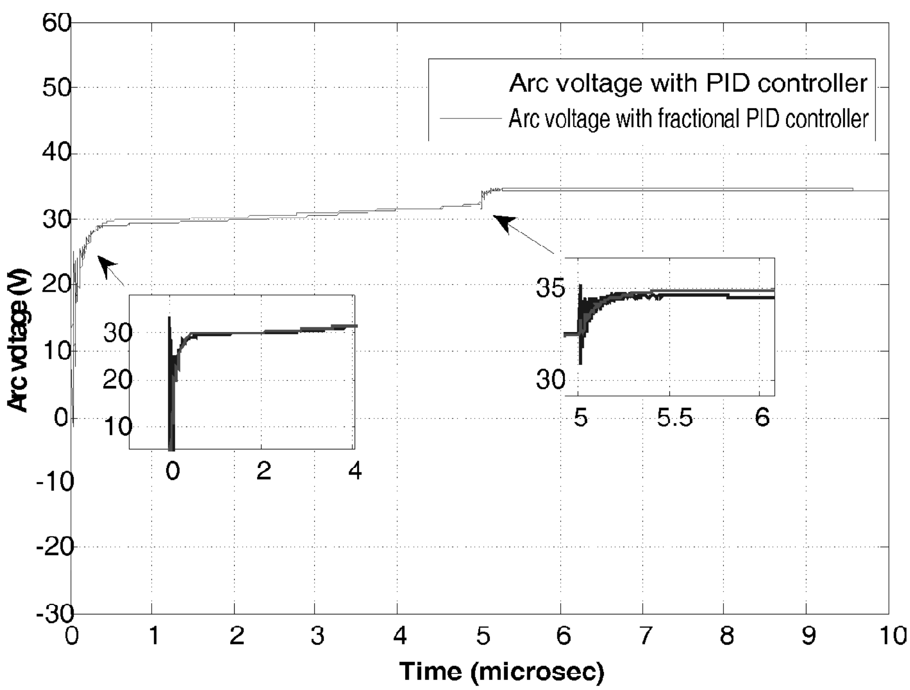

Figure 7: Arc voltage response with different controller

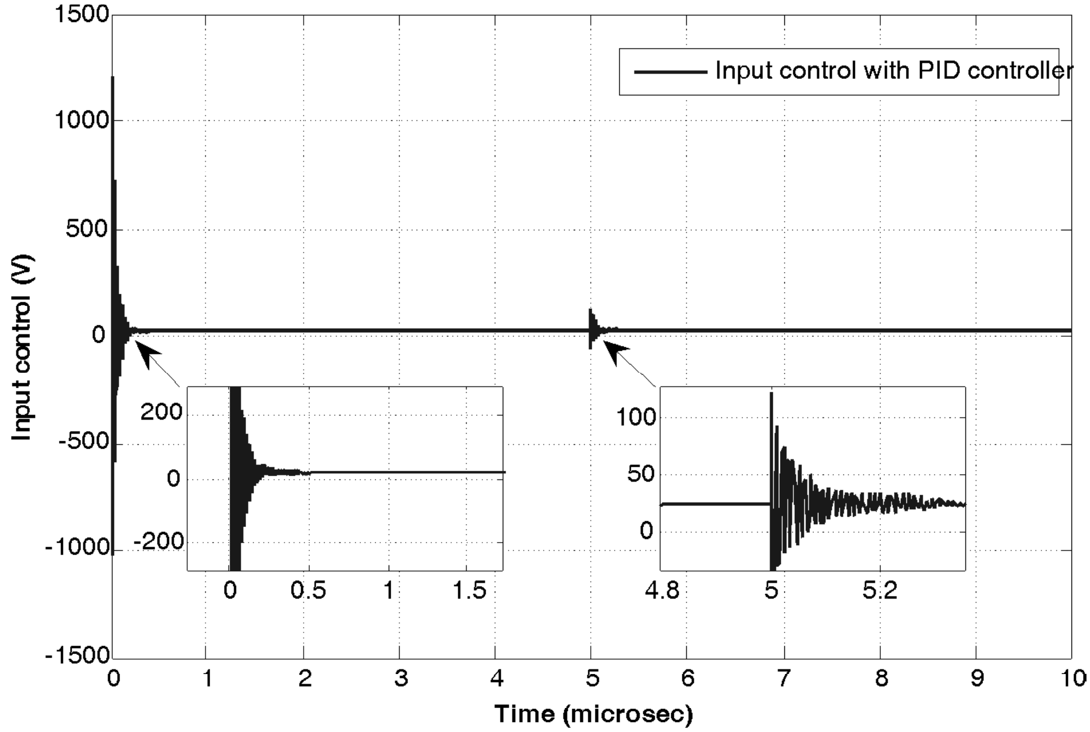

Figure 8: Open circuit voltage withPID controller

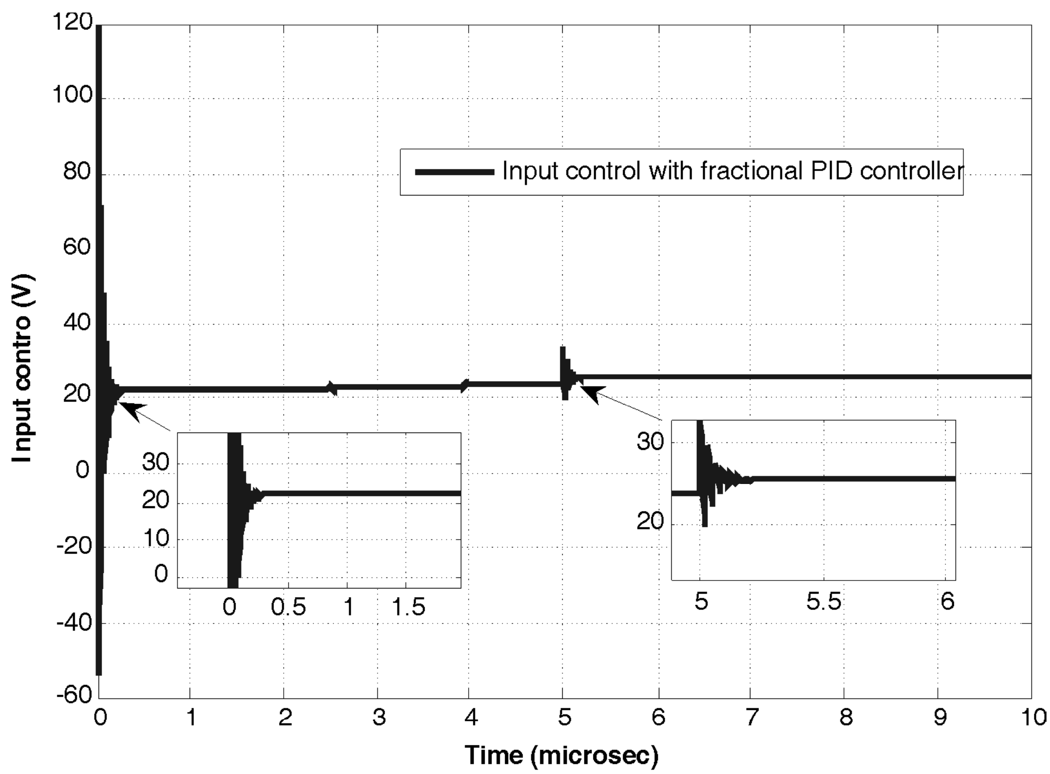

Figure 9: Open circuit voltage with fractional PID controller

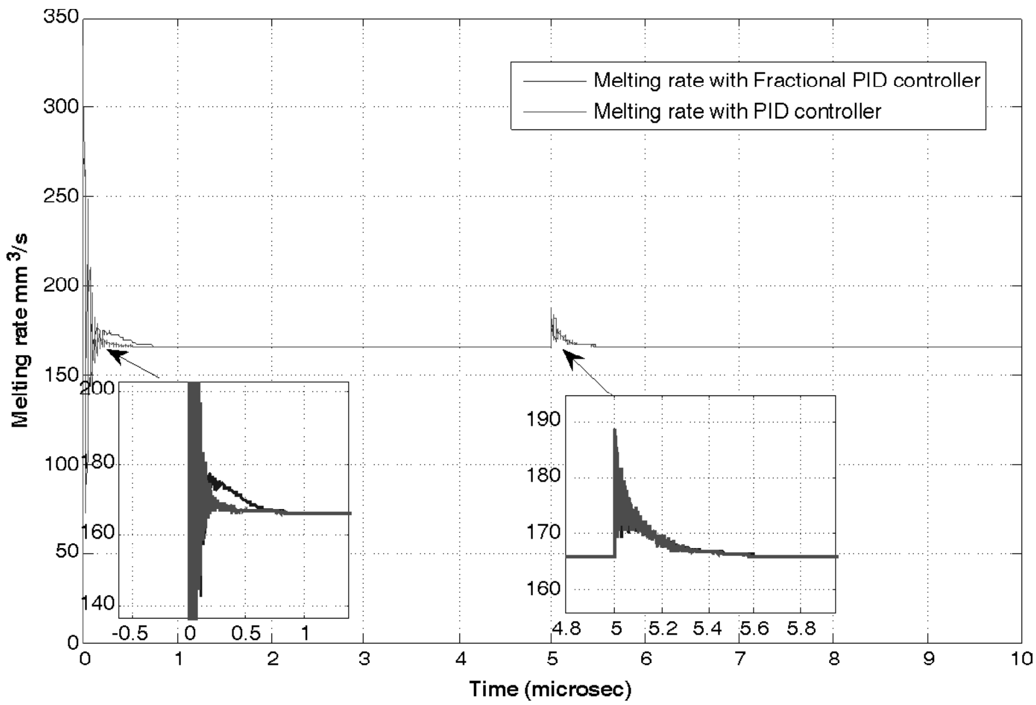

Figure 10: Melting rate response with different controller

Figure. 10 demonstrates the variations of melting rate obtained by the proposed different controller that ensured that the arc voltage be maintained at 170 mm^3/s. According toFigure. 10, the estimated melting rate signal is almost the same asthe one obtained by solving the nonlinear model.

4. CONCLUSIONS

In this paper, the modelling 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.

APPENDIX

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_e	0.001 m

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