Design of a PID control for a prototype of an automated GMAW welding bench

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Abstract. This article describes parameters such as electrical currents, equipment voltage, separation distance between the welding gun and the piece to be welded, the electrode diameter, material thickness, and the travel speed of the welding application performed through the gas metal arc welding process. This is the main parameter for the automation of the process. To evaluate this parameter, a prototype of an automated gas metal arc welding bench was constructed, which consists of a mobile work table that secures the piece to be welded, and a structure that holds the welding gun in a fixed position, allowing during the welding the movement of the piece automatically at a speed estimated by the user. For this, ultrasound and speed sensors were used, together with the Labview-Arduino automation programs that simulate horizontal welding and finally, two proportional–integral–derivative calculation methods are compared: 1) Mathematical model of the system and 2) Calculation of the model of the plant based on actual data input voltage vs output speed. Unraveling with greater approximation the adjustment of parameters (Kc, Ti, Td), which allow for a speed designated by the operator, keeping stable the welding speed used in the gas metal Arc welding processes with respect to the piece to be welded.

1. Introduction
Gas-metal-arc-welding (GMAW) aims at the assembly of metal parts, by means of an electric arc, in which a metallic material is deposited, forming a cord with characteristics similar to those of welded material, backed by a gas the atmosphere suitable for the reduction of the impurities in the joints, the study of the welding that focuses on the analysis of the geometric characteristics of the bead and the variables that act at the time of its application, standing out for the GMAW processes, the temperature of the pieces, the thickness of the pieces to be welded, the electrode diameter, the voltage and the application current which depends on the electrode diameter, the feed speed of the electrode, the traveling speed of the welder, the separation between the edges to be joined and between the welding gun and the pieces to be welded [1]. The aim of the welding study is identifying the appropriate parameters, focused on obtaining a weld with quality and safety during its application, within which the welding travel speed is emphasized, since this is related to the capacity of the deposited material, the melting temperature of the material carried, the geometry of the cord and the mechanical strength of the obtained solder [2].

In order to parameterize the linear advance of the welding, an automated GMAW welding prototype was built, this allows to choose a travel speed for the application of the welding, this bench consists of
a mobile work table that secures the piece to be welded, and a structure that holds the welding gun in a fixed position [3,4]. Therefore, the welding moves on the piece automatically at a speed estimated by the user. Human error is eliminated because it allows parameterizing the amount of welding per piece in a given time. In order to control this parameter, it was necessary to design an automated bench control strategy that allows maintaining the specified speed in a constant manner during the welding application.

For this, ultrasound and speed sensors were used, together with the Labview-Arduino automation programs that simulate horizontal welding. A proportional-integrate-derivative (PID) controller was used to keep the speed constant. PID controller is an action that is executed using an algorithm in charge of regulating three different parameters that are proportional, integral and derivative based on the past, present and future error between the real output taken from the process and the expected one (set point), and finally, two methods of calculating the PID are compared: 1) Estimation by means of the mathematical model and 2) Estimation of the PID based on the real model.

The mathematical model is based on a DC electric motor coupled to a gear motor [5]. This is used to find a mathematical equation that is able to represent the behavior of two main components of the engine, one represented by an electrical circuit and the second by a mechanism composed of a motor reducer and an endless screw, in this case is the prototype of an automated welding machine, which works at high temperatures [5]. For this model, the transfer equation and the PID values related to the electromechanical characteristics are calculated. Related to the electrical behavior are the following, welding inductance of the motor, excitation source of the system or voltage source, system current and electromotive force induced MMF. For the mechanical part: moment of inertia of the motor, initial friction torque, angular velocity of the output shaft, rotor torque, viscous friction coefficient between the rotor and the stator.

The PID is estimated based on the real model, for this the Matlab Software is used, using the System Identification and PID Turner tools. The System Identification tools correlate the values of the outputs and inputs of the prototype, in order to obtain a better solution; several iterations are performed to identify the fusion of transfer of the system [6]. The set of parameters Kp, Ki and Kd, were calculated in a faster and simpler way using the PID Tuner tool of the Matlab 2014 version, which avoids extensive calculations to find the constants of the controller, in this tool, we enter the transfer function previously found with the System identification tool, and select the type of driver, in our case, a PID and the values of the constants are displayed [7-11].

2. Materials and methods
Description of the two methods used to determine the parameters of the controller, in this case, a PID:

2.1. Mathematical model of the system
The electromechanical system has a voltage source which is connected to the motor; a resistance and coil (see Figure 1). The motor moves the piece to be welded in the mobile plate; the electrode holder guarantees a quality welding adjusting the movement (see Figure 2). The prototype has some of the considerations of linear modeling considered by the author [12,13]. An electric motor coupled to a motor reducer was selected for the model, which are modeled mathematically in the following way.

The variables that are related according to Figure 1 such as: R=Ohmic resistance of the motor windings, L=Inductance of the motor windings, J=Moment of inertia of the motor, β=viscous friction coefficient between the rotor and the stator, U(t)=System excitation source, Γ(t)=Rotor torque, i(t)=System current, Vfem=Electromotive force induced FEM, ω(t)=Angular velocity of the output shaft, Ti=Initial friction torque, Kt=Electrical to mechanical conversion constant, Ke=Mechanical to electrical conversion constant.

2.2. Electrical analysis
Kirchhoff’s law applies to the scheme of Figure 1. In Equation (1), the sum of the voltages of each element is obtained, which is equal to the voltage of the excitation source, which is obtained from the electrical analysis of the DC motor.
\[ U(t) = R * i(t) + L \frac{di(t)}{dt} + V_{\text{fem}} \]  

(1)

**Figure 1.** Diagram of DC electric motor.

2.3. Mechanical analysis

For the mechanical part, the sum of the couples is calculated that rotate the rotor with respect to the symmetrical axis, it is equal to the sum of the moments that oppose the movement as presented in Equation (2).

\[ \Gamma'(t) = \beta * \omega'(t) + J \frac{d\omega'(t)}{dt} + T_i \]  

(2)

Equation (3) and Equation (4) relate the electrical part and the mechanical part of the system. Where \( K_t \) is a constant of proportionality that converts a mechanical scalar to electric.

\[ \Gamma'(t) = K_t * i(t) \]  

(3)

\[ V_{\text{fem}} = K_\text{e} * \omega'(t) \]  

(4)

Known as the induced electromotive source equation, and \( K_\text{e} \) is the electric constant. Replacing Equation (4) in Equation (1), Equation (5) is obtained:

\[ U(t) = R * i(t) + L \frac{di(t)}{dt} + K_\text{e} * \omega'(t) \]  

(5)

Considering it very small, taking \( T_i=0 \)

\[ K_t * i(t) = \beta * \omega'(t) + J \frac{d\omega'(t)}{dt} \]  

(6)

Clarifying that angular velocity is defined as the change of angle with respect to time.

2.4. Transfer function

Applying Laplace transform to Equation (5) and Equation (6) with zero initial conditions, we obtained Equation (7) and Equation (8).

\[ U(s) = R * i(s) + L * s * i(s) + K_\text{e} * \omega'(s) \]  

(7)

\[ K_t * i(s) = J * s * \omega'(s) + \beta * \omega''(s) \]  

(8)
It is cleared $i(s)$ in Equation (8) and it is replaced in equation (9), simplifying and grouping some terms, the transfer function is obtained to the prototype, in relation of $\omega'(s)$ and $U(s)$, the transfer function is shown in Equation (9).

$$\frac{\omega'(s)}{U(s)} = \frac{Kt(s)}{(R+Ls)(s+\beta)+(Ke+Kt)}$$ (9)

3. Experimental setup

Equation (9) models the dynamics of the system, the model will be conditioned to a particular solution for the experimental prototype, where the physical parameters of that system are identified, and these are shown below:

3.1. Experimental data collection made to the prototype

Table 1 shows measurements of the voltage and current made to the motor-reducer of the experimental prototype. Also, it shows the variations of voltage and current data collection with the weight of the mobile table and an additional load to the motor-reducer of the experimental prototype.

| Voltage (Volts) | Current (Amperes) | Speed (cm/s) | Current with additional load (Amperes) |
|-----------------|-------------------|--------------|---------------------------------------|
| 1               | 0.01              | 0.25         | 0.01                                  |
| 2               | 0.01              | 1.00         | 0.01                                  |
| 3               | 0.02              | 1.70         | 0.02                                  |
| 4               | 0.02              | 2.5          | 0.02                                  |
| 5               | 0.02              | 3.3          | 0.02                                  |
| 6               | 0.02              | 5.0          | 0.03                                  |
| Average         | 0.02              | 2.29         | 0.02                                  |

3.2. Transfer function parameters

Other additional measures are: 1) the measurement of the internal resistance of the rotor that was performed directly with the multimeter, which gave a value of 70.8 Ohms; 2) the measurement of the rotor inductance was made directly with the multimeter, which gave a value of 38 mH (Milli Henrios).

The constant $Ke$ is determined (mechanical to electrical constant). This constant is shown in Equation (10).

$$Ke = \frac{V_{fem}}{\dot{\omega}}$$ (10)

Taking Equation (11) [14].

$$V_{fem} = U - Ra \times Ia$$ (11)

Table 2 shows the voltage value in the electromotive source $V_{fem}$. The average of the values of $V_{fem}$, $\dot{\omega}$, $Ia$ (see Table 1) and $Ra = 70.8$ are taken, we calculate the constant of electric to mechanical time conversion (see Equation 12).

$$Ke = \frac{V_{fem}}{\dot{\omega}} = \frac{2.32}{121} = 1.923 \frac{V_{rms}}{rad}$$ (12)

The inductance $La$ is determined, the inductance calculation is carried out directly from the measurement on the motor which yields a value of $L = 38$ mH. The electric time constant $Te$ is calculated, see Equation (13).
\[ Te = \frac{L}{R} = \frac{38}{70.8} = 7.5 \mu s \]  

(13)

Table 2. Variations of the voltage and data collection of linear speed, angular and calculation of the average values of Vfem and \( \dot{\omega} \) with only the weight of the mobile table.

| Voltage (volts) | Linear speed (cm/s) | Angular speed (rad/s) | Vfem = U − Ra * Ia |
|----------------|---------------------|-----------------------|-------------------|
| 1              | 0.25                | 0.132                 | 0.292             |
| 2              | 1.00                | 0.256                 | 1.292             |
| 3              | 1.70                | 0.895                 | 1.584             |
| 4              | 2.50                | 1.316                 | 2.584             |
| 5              | 3.30                | 1.737                 | 3.584             |
| 6              | 5.00                | 2.632                 | 4.584             |
| Average        | 2.29                | 1.21                  | 2.32              |

For the determination of the coupling constant \( K_t \), expressions that have a direct dimensional parametric relation between \( K_e \), have units \( V/\text{(rad.s)} \) and \( K_t \) with units \( N\cdot m/A \), assimilating that \( K_t = K_e = 1.923 \, N\cdot m/A \) [13]. The parameter of the mechanical time constant will take an approximate value of \( t_m = 1.8 \, ms \) (milli-seconds) to perform the simulation in the Matlab software (see Equation 14).

\[
J = \frac{tm+Kt\cdot Ke}{R} = \frac{1.8 \, ms+1.923+1.923}{70.8} = 9.4 \times 10^4 \, kgm^2
\]

(14)

The starting torque of the motor is determined by taking the value of the starting \( I_{arrq} = 0.001 \, A \) and the value of \( K_t = 1.923 \, N\cdot m/A \) (see Equation 15).

\[
T_m = K_t \cdot I_{arrq} = 0.001 \cdot 1.923 = 0.001923 \, N\cdot m
\]

(15)

The friction constant \( \beta \) is determined by Equation (16).

\[
T_m = K_t \cdot I_a = J \cdot \alpha + \beta \cdot \omega + Ti
\]

(16)

The steady state angular acceleration is zero, then, \( \alpha = 0 \), see Equation (17).

\[
T_m = J \cdot \alpha + \beta \cdot \omega + Ti
\]

(17)

The average values of the current \( I_a \) and angular velocity are calculated by the approximate value of \( \beta \) using the previous values obtained of \( T_m − Tf, \dot{\omega}, \) and \( I_a \), as shown in Table 3.

Table 3. Coefficient of friction, angular velocity and current.

| Voltage (V) | Angular speed (rad/s) | Current | \( T_m = K_t \cdot I_a \) | \( T_m − Tf \) | \( \beta = T_m − Tf/\dot{\omega} \) |
|------------|-----------------------|---------|--------------------------|----------------|-----------------|
| 1          | 0.13                  | 0.01    | 0.019                    | 0.01           | 0.076           |
| 2          | 0.53                  | 0.01    | 0.019                    | 0.01           | 0.019           |
| 3          | 0.89                  | 0.02    | 0.038                    | 0.02           | 0.032           |
| 4          | 1.32                  | 0.02    | 0.038                    | 0.02           | 0.022           |
| 5          | 1.74                  | 0.02    | 0.038                    | 0.02           | 0.016           |
| 6          | 2.63                  | 0.02    | 0.038                    | 0.02           | 0.011           |

Table 3 shows the averages of the coefficient of friction for each voltage variation. The calculated data are represented, \( T_m − Tf \) versus \( \dot{\omega} \) and the linear regression.
The equation obtained by linear regression, the slope of the line is taken to obtain the value of $\beta$, then, the value of $\beta = 0.0084 \text{ N.m.s}$ is calculated. The parameters obtained are used in the transfer equation from the mathematical model that regulates the movement of the linear table according to equation (10). They are $K_e = 1.923 \text{ V/s/rad}$, $K_t = 1.923 \text{ N.m/s}$, $\beta = 0.0084 \text{ N.m.s}$, $L = 0.038 \text{ H}$, $R = 78 \Omega$ and $J = 9.4 \times 10^{-4} \text{ kg.m}^2$. Matlab software is used for the transfer function with the following constants (see Equation 18):

$$G_s = \frac{1.923}{3.572 e^{-3} s^2 + 0.07364 s + 4.353}$$

Equation (18) is a second-order transfer function, because the maximum exponential in its denominator is two. The simulation of Equation (18) is carried out using the Matlab software, using the Simulink tool [15]. Figure 3 shows the transfer function with feedback, the system of the transfer function is stable, however, it has an attenuated response (see Figure 4), that is, and it is below the step signal.

The closed loop of the system is stable; however, it has an attenuated response. Using the Simulink PID Tuner tool, the parameters of a PID controller that improve the step response of the transfer function are observed in Equation (5) and Figure 6. Subsequently, in Figure 5, the parameters $P = 17.85$, $I = 2784.13$ and $D = 0.017$ are obtained.

3.3. System estimated model

The data acquisition from LabView program shows the change of speed in cm/s versus the input voltage (from 0 V to 6 V, see Figure 7). A new engine model is obtained with the system identification tool and the step-signal response is shown with the transfer function $H$ (See Figure 8 and Equation 19).

$$H_s = \frac{-2.286 s + 1.352}{9.792 s + 1}$$
The PID control values are estimated using the Matlab PID Turner tool according to Equation (19), which is used to the bench automation. The outcome obtained from PID control is $K_p = 1.5968$.

**Figure 7.** System Identification Tool.  
**Figure 8.** PID control of the transfer function H.

### 4. Conclusion

The calculations of the PID controller were made with an automated bench for GMAW welding. To improve the stability of the speed a PID control was adapted; the parameters are found using the mathematical model. Also, by means of an experimental assembly a transfer function was obtained, this allows, in an estimated way, simulating the real behavior of the system, for an input voltage, an output speed is obtained. In turn, the system stability is improved with new parameters of a PID control; these are calculated with the estimation model, which yields data from a proportional type control, which allows stabilizing a speed in a desired range. With the two methods used, a transfer equation of the model was obtained, which governs the behavior of the prototype of an automated bench, in the observation of the operation tests, it is concluded that the estimation method had a better compartment for the stability of the speed estimated. In conclusion, the determination of the PID control makes it possible to carry out welding tests, repetitive and good-looking tests.

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