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DIPARTIMENTO DI INGEGNERIA INFORMATICA, MODELLISTICA, ELETTRONICA E SISTEMISTICA
DIMES

"Cutting Machine"
Industrial Automation Systems
Project Report

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INDEX OF CONTENTS

INTRODUCTION

Laser cutting machines are great tools that offer the ability to create many different things. From simple boxes to engrave detailed wooden graphics or build complex three-dimensional objects.

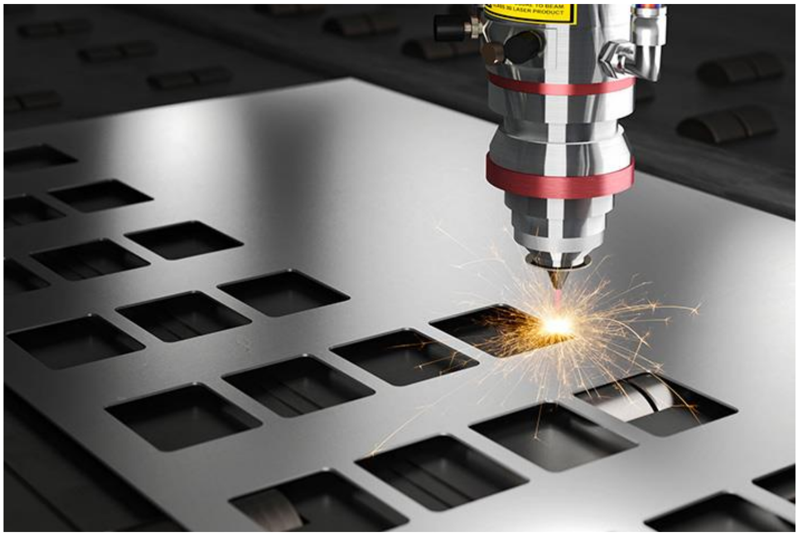


Fig 1: Example of laser cutting machine.

A laser cutting machine is a computer controlled (CNC) machine that uses a laser beam to precisely cut or engrave material. A laser is basically just highly focused, highly amplified light. The laser beam causes the material to burn, melt or vaporize locally. The type of material a laser can cut depends on the type of laser and the specific power of the machine.

Laser cutting is an incredibly flexible technology. It is possible to work a wide variety of materials and thicknesses, without any limit to the shape that can be obtained. Its programming is so fast that any modification can be applied at any stage of your production with virtually no additional cost and time. Its accuracy is the highest, the quality of the cut edge is excellent, and there is no distortion of the workpiece. The best application for laser technology is the processing of metal materials (steel, stainless steel, aluminum, copper and brass) with a thickness from 0.8 mm to 25 mm.

Chapter 1

1.1. Description. Laser cut

The Design Mechanism consists of two structures, one on the X axis and the other on the Y axis, supported on linear guides. The carriage on the X axis will move through this supporting the weight of the laser module, the carriage on the Y axis will travel together with the structure of the X axis so it will support the greatest load.

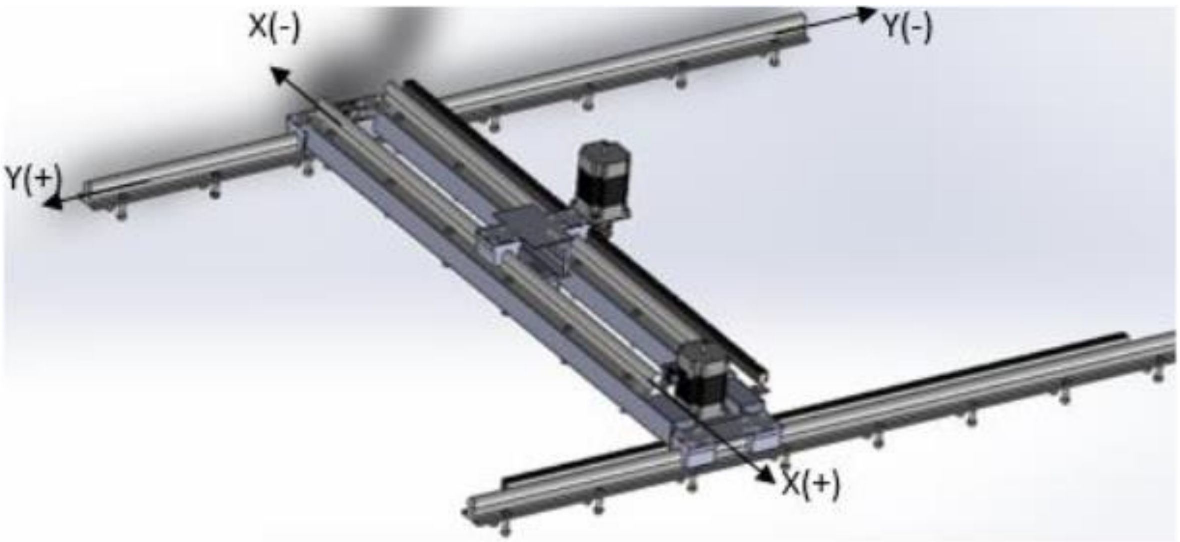


Fig 2: Movement mechanism.

1.2. Technical specifications of the design to be made

Two-axis plane laser cutting machine was considered for this work. The machine has two equal DC motors that allow it operates in a two-dimensional workspace.

The mechanical system must cut three meters long by two in height rectangular slab, and extract the assigned geometric shapes, moving along the two coordinated axes.

The shapes are describing in the figure 3. There are a triangle, a circle, and semicircle:

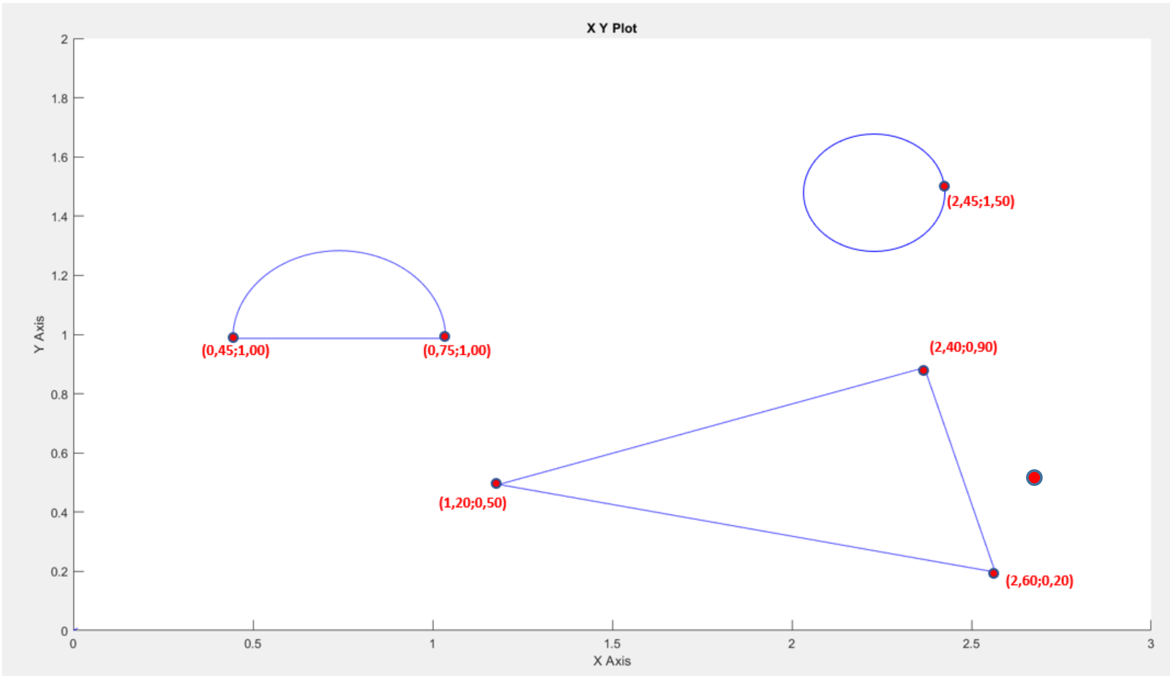


Fig 3: Cut to be made.

<u>Description of the cut</u>

1. Initially the machine is located in the position (0; 0) meters.
2. To reach your initial or resting position you must move to the position (3; 2) meters.
3. The first cut to be made is a circle with a 20 centimeters radius and a center in (2,25;1,50) meters. For this purpose, the cutting path has to move to the point (2,45;1,50) meters which is the begging of the circle (see coordinate points, figure 3).
4. Second, the machine moves to the point (2,40;0,90) meters to starts the cutting of a triangle with its three vertices in the points (2,40;0,90) meters, (2,60;0,20) meters, and (1,20;0,50) meters. To accomplish this, the machine must cut in a straight line from the first vertex to the second, from the second to the third and from the third back to the first.
5. Then, a semicircle shape has to be cut. It has a radius of 30 centimeters and a center in (0,75;1) meters. Hence, the machine moves to the point (1,05;1) meters and starts the cut until the point (0,45;1) meters (the half of the circle) and cut a line between the point (1,05;1) meters and (0,45;1) meters.
6. Finally, the machine moves towards the point (3; 2) meters to reach the resting position.

1.3. Generation of the trajectory

Due to the possibility to fix the position of each geometric shape on the laminated plate the waste of resources reduces. For this reason, the cutting path is provided to define, point by point, the operations that the machine must perform to cut the designed shapes. The machine moves its axes when the mechanical parameters, such as the position, the speed, and acceleration are assigned. In this work this trajectory parameters are given by Simulink. And all the process has straight and circular movements which follow this explication:

1. Initially, the necessary specifications for each movement are given by a state machine made with a Matlab's tool: Staflow. In this section eleven state give all the sufficient data for each movement. For example, in the figure 4 we can see the state two and three that give us the data of a straight and a circular trajectory (initial point, final point, times, center, radius).

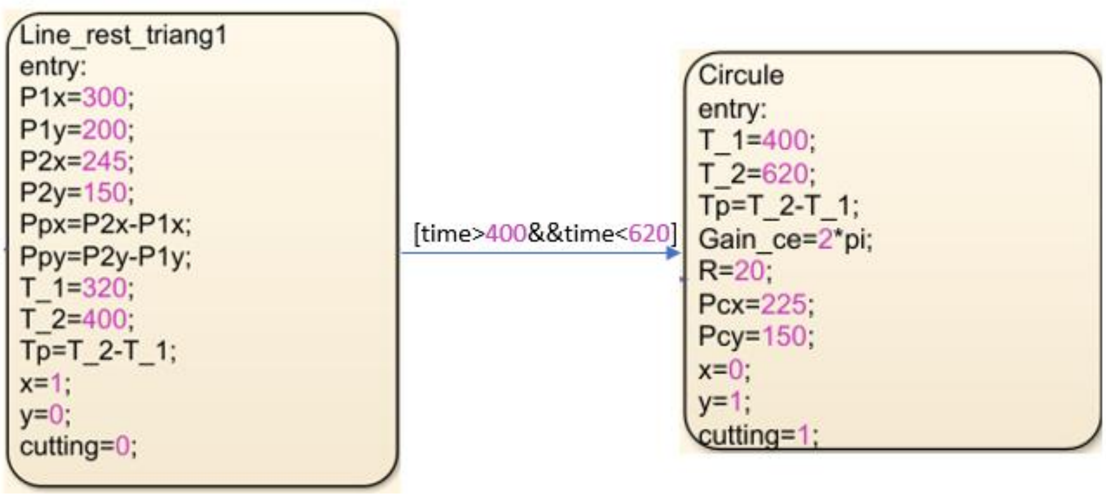


Fig 4: Stateflow's states.

2. When all the necessary trajectory data are collected, the movement has been described by means of the polynomial interpolation between two adjacent points, using a polynomial of five degree for the generation of the reference. The degree of the polynomial was chosen to be sure the continuity of position, velocity, and acceleration. A third order polynomial or greater fulfills this purpose.

   The chosen polynomial to describe de position is the follow:

$$X(t) = a_0 t^5 + a_1 t^4 + a_2 t^3 + a_3 t^2 + a_4 t + a_5$$

For the facility of calculus of a_n is necessary a normalization as it is shown in the figure 5.

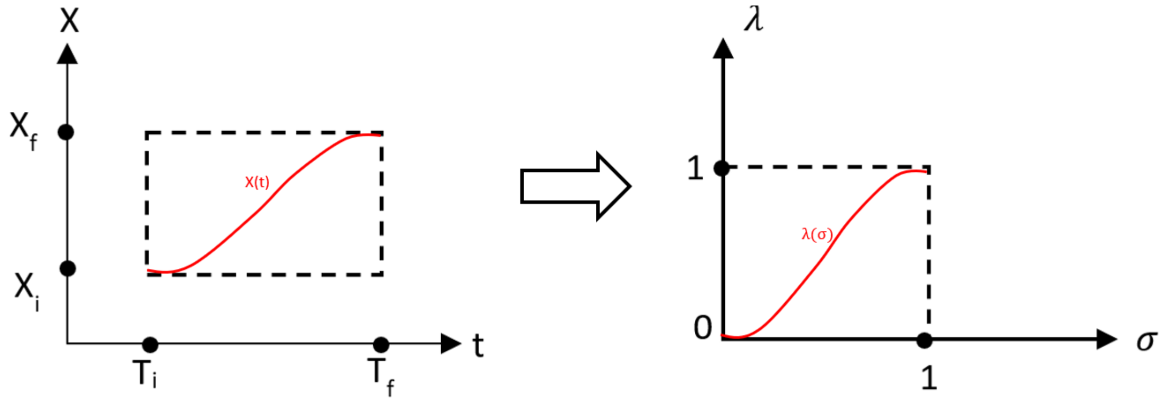


Fig 5. Normalization of trajectory

Starting with the process $\sigma(t)$ is calculated.

$$t = T_i + \sigma(T_f - T_i)$$

$$\sigma = \frac{t - T_i}{T_f - T_i}$$

Then, $\lambda(\sigma)$ and its values of a_n are obtained. As the trajectory from 0 to has been regulated now the extremes are $T_i = 0$ y $T_f = 1$ the speed and acceleration must be 0 in $\sigma = 0$ and $\sigma = 1$.

Then to calculate a_n, the position, velocity and acceleration polynomials are evaluated for:

$\lambda(0) = 0$ $\qquad$ $\dot{\lambda}(0) = 0$ $\qquad$ $\ddot{\lambda}(0) = 0$

$\lambda(1) = 1$ $\qquad$ $\dot{\lambda}(1) = 0$ $\qquad$ $\ddot{\lambda}(1) = 0$

We have the following system of linear equations:

$$\begin{cases} \lambda(0)=a_5=0 \\ \dot{\lambda}(0)=a_4=0 \\ \ddot{\lambda}(0)=a_3=0 \\ \lambda(1)=a_0+a_1+a_2=1 \\ \dot{\lambda}(1)=5a_0+4a_1+3a_2=0 \\ \ddot{\lambda}(1)=20a_0+12a_1+6a_2=0 \end{cases}$$

After to solve the system the found solution was:

$a_0 = 6$ $\qquad$ $a_1 = -15$ $\qquad$ $a_2 = 10$

$a_3 = 0$ $\qquad$ $a_4 = 0$ $\qquad$ $a_5 = 0$

In consequence the $\lambda(\sigma)$ is:

$$\lambda(\sigma) = 6\sigma^5 - 15\sigma^4 + 10\sigma^3$$

Due to the circular movement needs an angle for its argument, is needed another transformation to this kind of movement as it is shown in the figure 6.

$$\lambda(\sigma) = \frac{\theta - \theta_i}{\theta_f - \theta_i}$$

$$\theta = \theta_i + \lambda(\sigma)(\theta_f - \theta_i) \; where \; \theta_i = 0 \; and \; \theta_f = 2\pi$$

$$\theta = 2\pi\lambda(\sigma)$$

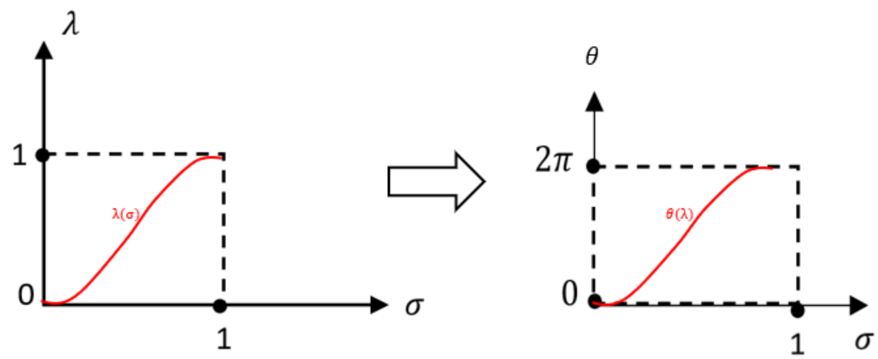


Fig 6. Normalization for a circular trajectory

This part of the of the process was made in Simulink as it is shown in the figure 7.

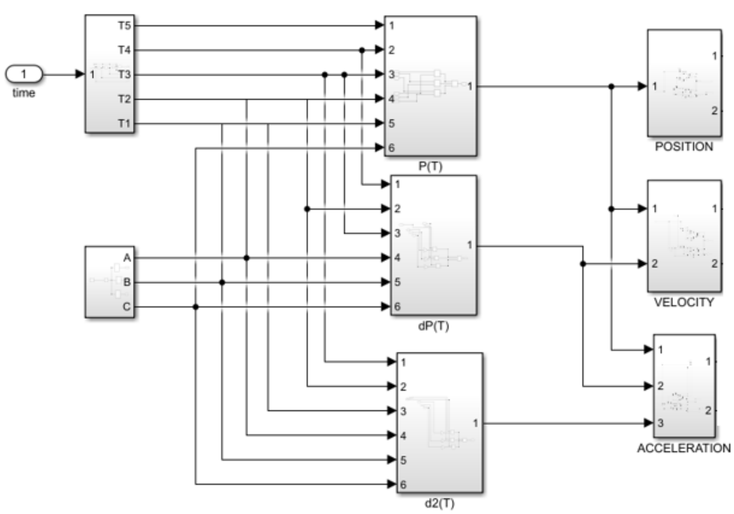


Fig 7. Normalization implemented in Simulink

3. Finally, is needed to calculate the position, velocity and acceleration and the equations used are:

   Equation for calculating the trajectory of a straight line:

   $X(\lambda) = X_i + \lambda(\sigma)X_f - X_i$

   $Y(\lambda) = Y_i + \lambda(\sigma)Y_f - Y_i$

   Equation for calculating the trajectory of a circle:

   $X(\theta) = X_c + Rcos(\theta(\lambda))$

   $Y(\theta) = Y_c + Rsen\big(\theta(\lambda)\big)$

   Equation for calculating the velocity of a straight line:

   $V_x(t) = \dot{X}\left(\lambda\big(\sigma(t)\big)\right)$

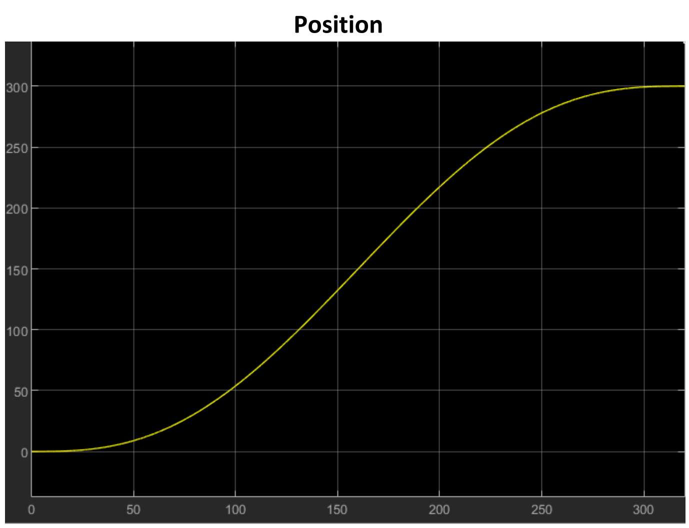
   $V_y(t) = \dot{Y}\left(\lambda\big(\sigma(t)\big)\right)$

   Equation for calculating the velocity of a straight line:

   $V_x(t) = \dot{X}\left(\theta\left(\lambda\big(\sigma(t)\big)\right)\right)$

   $V_y(t) = \dot{Y}\left(\theta\left(\lambda\big(\sigma(t)\big)\right)\right)$

The following graphs plotted using Simulink represent the behavior of a fifth-degree polynomial, in terms of position, velocity and acceleration for the first state given in Stateflow. The position is given in $[cm]$, the velocity in $\left[\frac{cm}{s}\right]$, and the acceleration in $\left[\frac{cm}{s^2}\right]$.



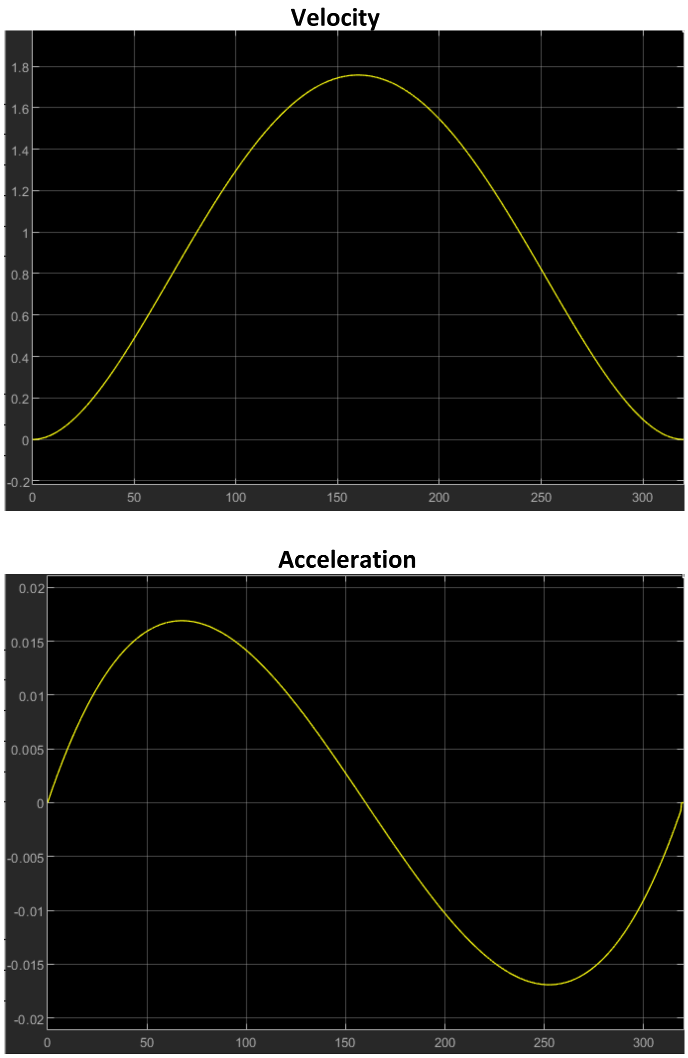


Fig 8. Graphics of position, velocity, and acceleration in a 5th order polynomial.

1.4. Control structure of a DC motor.

In order to move the cutting machine in different two-dimensional shapes, it is necessary to have two motors on each axis.

Direct current electric motors, also known as direct current (DC motor). This type of motor converts electrical energy into mechanical energy by means of a rotary movement generated because of a magnetic field.

The main characteristic of the DC motor is the possibility of regulating the speed from empty to full load. A direct current machine is mainly composed of two parts, a stator that gives mechanical support to the device and has a hole in the center, generally cylindrical in shape. In the stator there are also the poles, which can be permanent magnets or windings with copper wire on an iron core. The rotor is generally cylindrical in shape, also wound and with a core, to which the current reaches through two brushes.

This DC machine is one of the most versatile in the industry. Its easy control of position, torque and speed have made it one of the best options in process control and automation applications.

1.5. Mathematical model of the DC engine

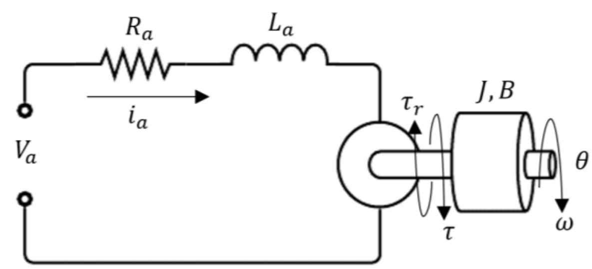


Fig 9: Direct current motor system.

Electric model

$$L_a \frac{di_a}{dt} = V_a - R_a i_a - K_m \omega$$

Mechanical model

$$J \frac{d\omega}{dt} = K_m i_a - b\omega - \tau_r$$

$$\frac{d\theta}{dt} = \omega$$

Where:

L_a Armor inductance	i_a Armor current
R_a Armor Resistance	ω Rotor speed
k_m Torque coefficient and electromotive force	θ Rotor position
J Inertia	V_a Income voltage
B coefficiente di attrito	t_r Disturbance

The motor transfer function is expressed as an input-output form, that is:

$$\frac{\theta(s)}{V_a(s)} = \frac{k_m}{(L_a s + R_a)(Js + B) + k_m^2}$$

The direct current motor scheme is the following:

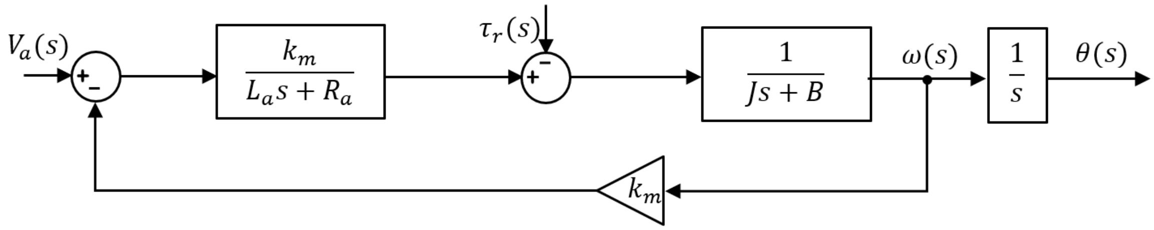


Fig 10: Block diagram of a permanent DC motor.

Any electric motor may be described in terms of two blocks, which represent:

- Electro-magnetic part, taking as input the voltage and giving as output the torque.
- Mechanical part, taking as input the torque and giving as output the velocity.

So, the electrical subsystem of the motor is therefore characterized by first order dynamics, having a real pole equal to $P_e = -\frac{R_a}{L_a}$ named electric pole and the mechanical subsystem that is of the first order too, characterized by the pole $P_m = -\frac{b}{J}$, that is called mechanical pole.

1.6. Specifications of the motors used

To cut the slabs, two equal direct current motors were used on each axis, with the following characteristics:

Ra	La	J	B	Ke, Kt
1Ω	1.0mH	0.1Kgm^2	0.029 $\frac{Nms}{rad}$	0.6

- $|V_{max}|$ = 150 Volts
- $|I_{max}|$ = 20 Ampere
- P_{max}= 3KWatts
- Coefficient transformation for both axes $\frac{1}{2000}\frac{m}{rev}$
- For each motor it is possible to measure the armature current, the rotation speed in $\frac{Rad}{sec}$ and the angle in Rad

Block diagram implemented in Simulink of a continuous current engine:

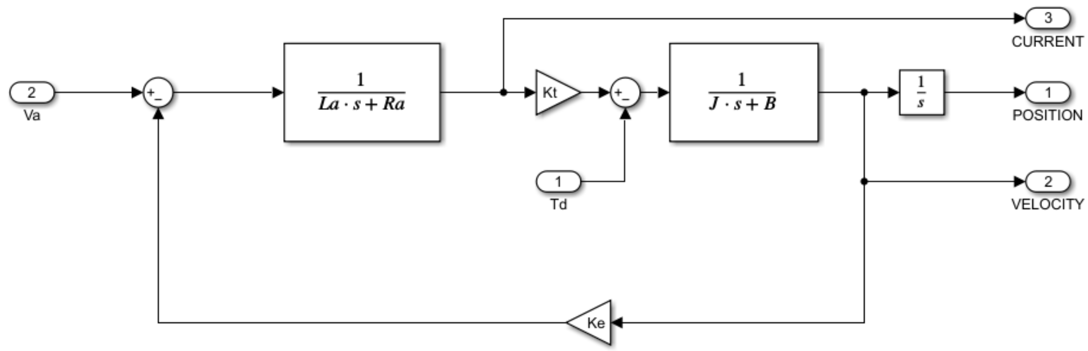


Fig 11: Block diagram of a permanent DC motor.

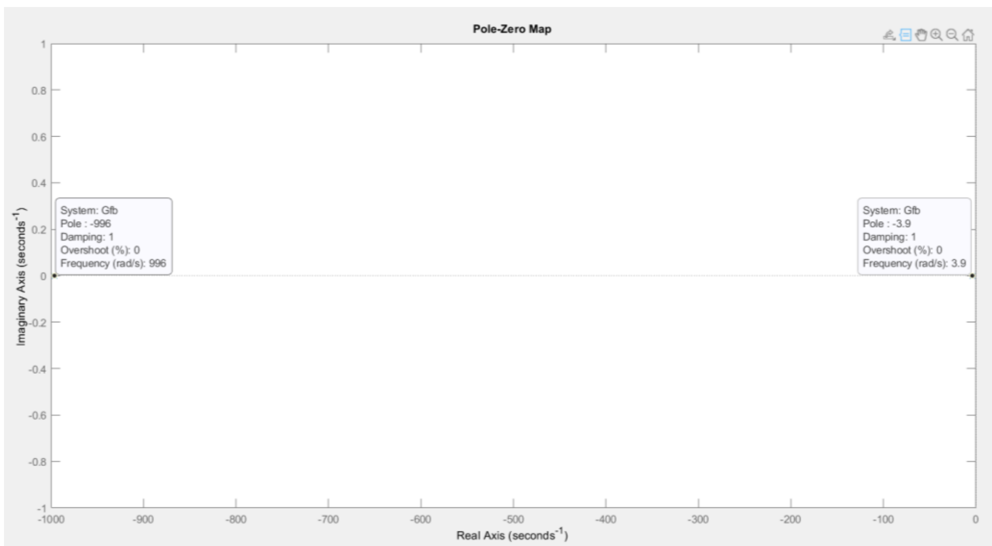


Fig 12: Pole diagram of a close-loop system

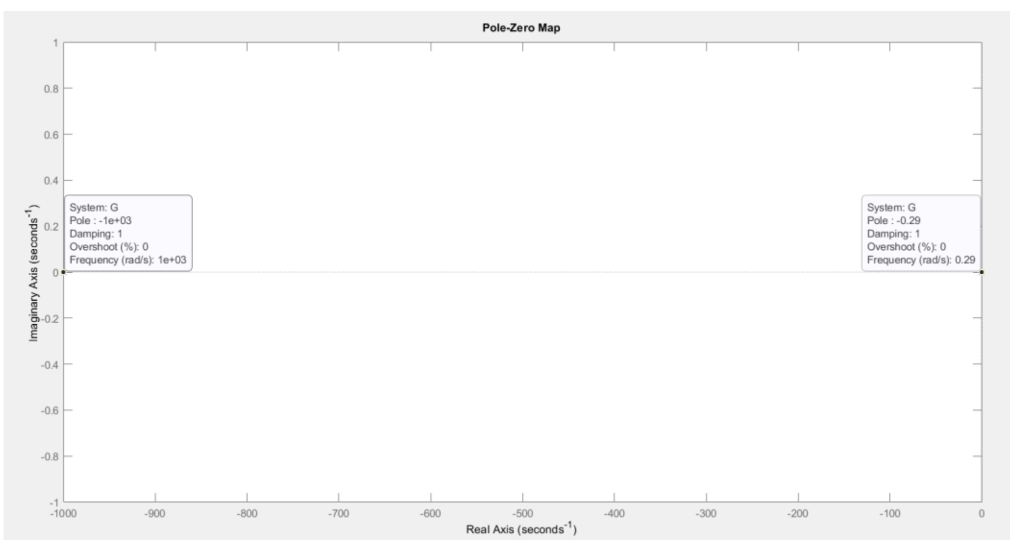


Fig 13: Pole diagram of an open-loop system

From the figure 12 and 13 it can be concluded that the poles in open-loop are: the electrical $P_e = -1000$ and the mechanical $P_m = -0.29$.
The poles of the closed-loop system are: Electric pole $P_e = -996$ and mechanical pole $P_m = -3.9$, the electric pole slows down and the mechanical pole increases its speed. The transient is governed by the mechanical pole.
It can also be concluded that the system is asymptotically stable because its poles are negative.

1.7. Control scheme for the DC engine.

The strategy adopted for motor control consists in compensate the back electromotive force and implementing a cascade structure, composed of:

- The current control loop, which is the internal loop, represents the control of electrical dynamics with feedback from the armature current.
- The speed control loop, which is the central loop, consists of the control of the mechanical dynamics with feedback of the angular speed of the motor.
- Position control loop, or external loop, which is the control of the integral dynamics with feedback of the angular position of the motor.

In this way it's possible to divide the assigned control problem into three subproblems that are simpler than the first.

Current control: Due to the parameters of the electrical part of the motor are sensitives to the change of temperature (especially the resistance), is necessary a current control. The said control try maintains the pole of this part of the motor if the parameters change. To do this is used a PI control that eliminate the changed pole. The mechanical part of the motor is not considered.

$$C_i(s) = \frac{L_a s + R_a}{s} * k_i$$

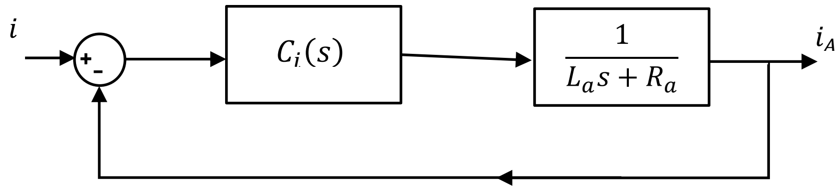


Fig 14: Current control

$$W(s) = \frac{1}{\frac{1}{k_i}s + 1}$$

$$k_i = \frac{R_a}{L_a}$$

$$C_i(s) = L_a k_i + \frac{R_a}{s} k_i$$

Speed control: For start the speed control we assume that the electrical part of the motor is a constant because it is extremely greater than the mechanical part, so its dynamics does not affect it. Again, we use a PI control but this time we chose a k_s in order to move one order to the right the mechanical pole.

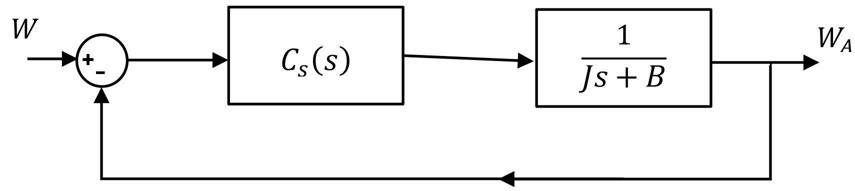


Fig 15: Speed control

$$C_s(s) = \frac{Js + B}{s} * k_s$$

$$W(s) = \frac{1}{\frac{1}{k_s}s + 1}$$

$$C_s(s) = Jk_s + \frac{B}{s} k_s$$

Position control this is a proportional control which is selected in order to move the polo at least one order to the left of the mechanical pole.

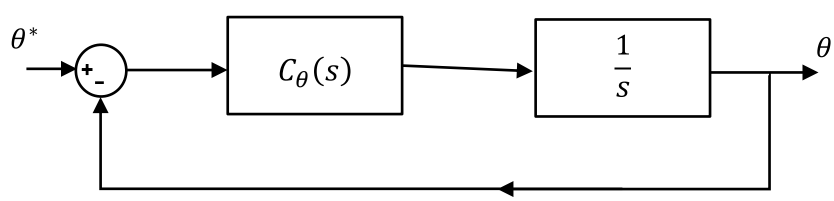


Fig 16: Position control

$$W(s) = \frac{1}{\frac{1}{k_\theta}s + 1}$$

$$C_\theta(s) = k_\theta$$

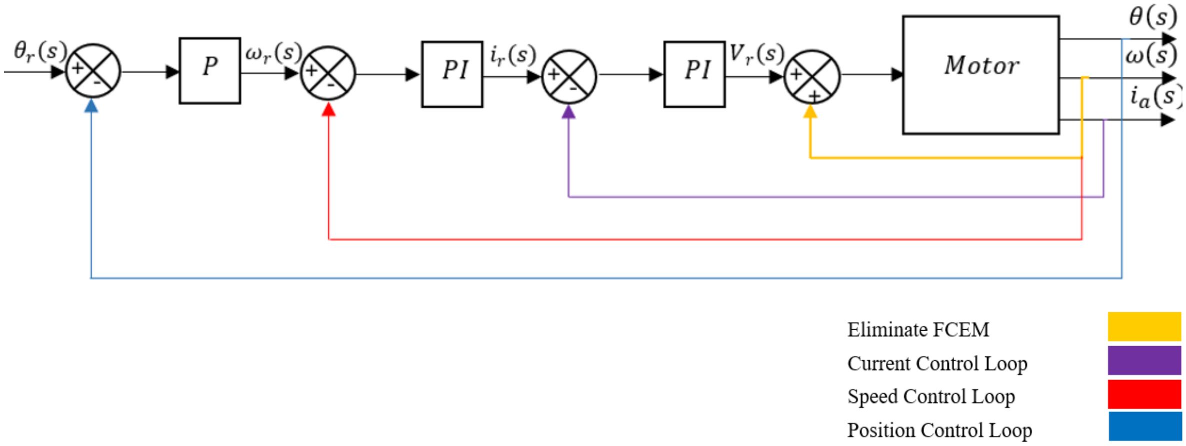


Fig 17: Complete diagram of the DC Motor with Control.

Feedforward action: To complement the control an auxiliary controller in the closed loop control is created that allows attenuating or eliminating the entrance of measured or known disturbances to the control loop that is why it is called anticipatory control, because it tries to anticipate the disturbances that go to affect the system. The scheme of the control used is shown below:

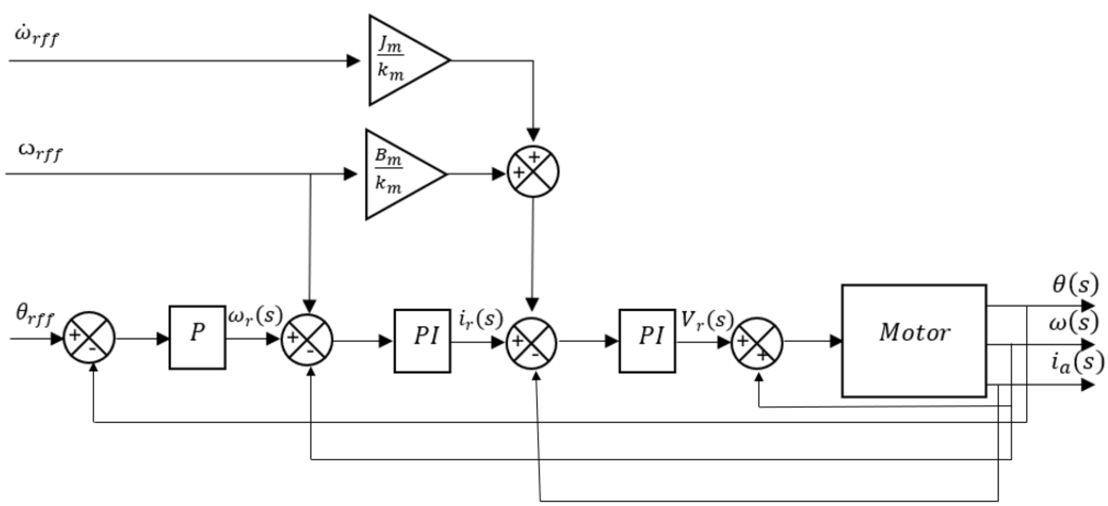


Fig 18: Feedforward Control System.

1.8. Controller parameter calculation

Calculation of current control:

- To calculate the proportional action, choose:

$$K_p = L_a k_i$$

$$k_i = \frac{R_a}{L_a}$$

$$K_p = 1000 * L_a$$

- To calculate the integral action, choose:

$$K_{in} = k_i R_a$$

$$K_{in} = 1000 * R_a$$

k_i is chosen for to maintain the electrical pole as it was in nominal conditions so $k_i \approx |P_e| = 1000$.

Calculation of speed control:

- To calculate the proportional action, choose:

$$K_p = k_s J$$

$$K_p = 10 * J$$

- To calculate the integral action, choose:

$$K_i = k_s B$$

$$K_i = 10 * B$$

k_s is chosen to allow the mechanical pole to be given a little speed, of at least a decade, In this case $k_s = 10$. With this type of feedback, errors with respect to the nominal values of J and B are compensated.

Calculation of position control:

- Only a proportional action is chosen, setting the value of $K_p = k_\theta$ at least 1 decade to the right of the velocity pole, In This case $K_p = 1$.

The motor and its control were implemented on Simulink, the model is shown in the scheme on the figure 19:

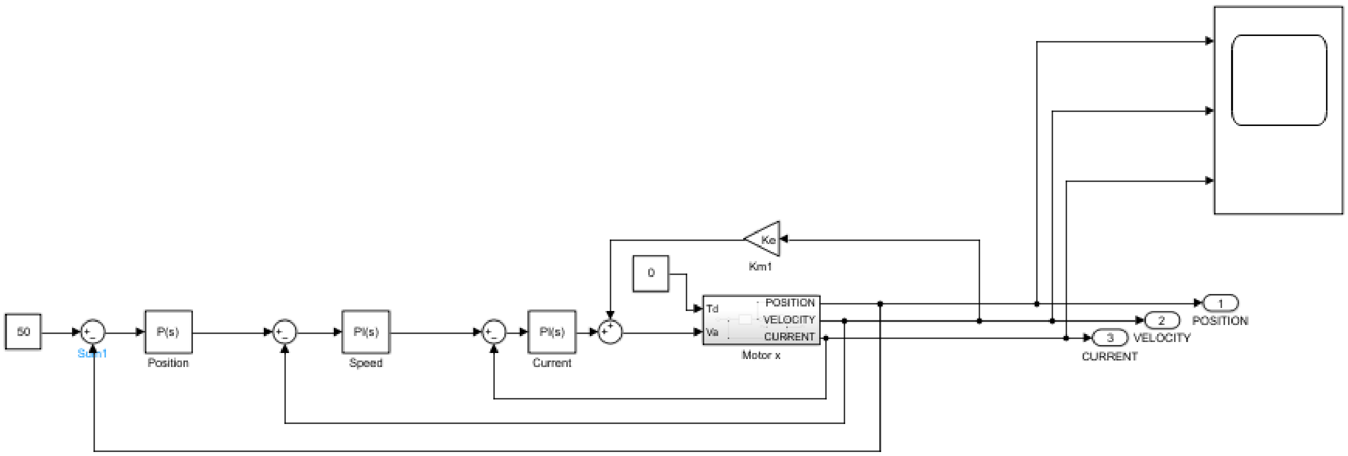


Fig 19: Implemented motor control scheme.

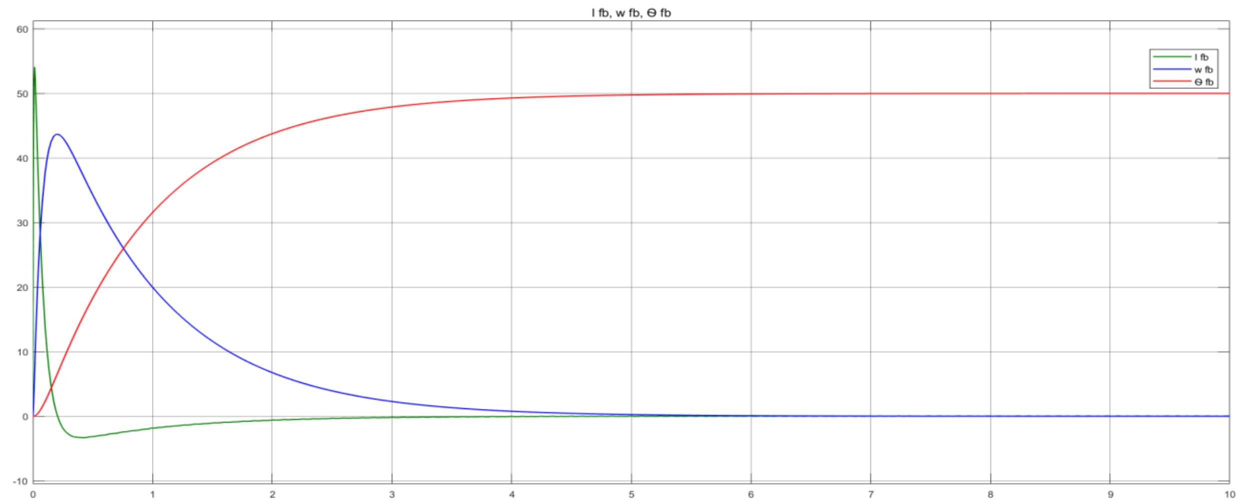


Fig 20: System stability analysis.

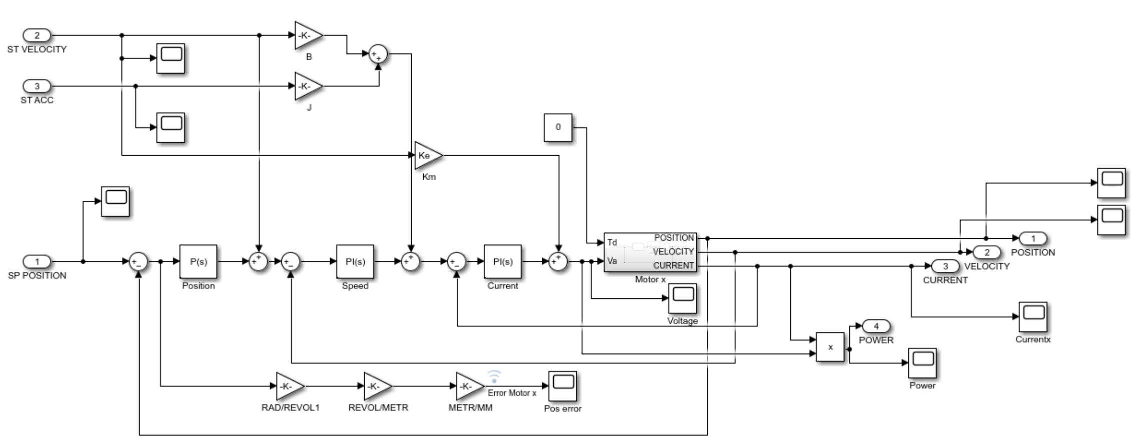


Fig 21: DC motor controller block diagram.

As can be seen, the System is stable before a chosen random reference of 50 rad, so it can be concluded that the selected parameters of the controller are correct. Then, the complete control scheme (including the feedforward control) was implemented on each motor as it is shown on figure 21. Finally, all the necessary tools reviewed before were joint to get the model of the cutting machine (figure 22)

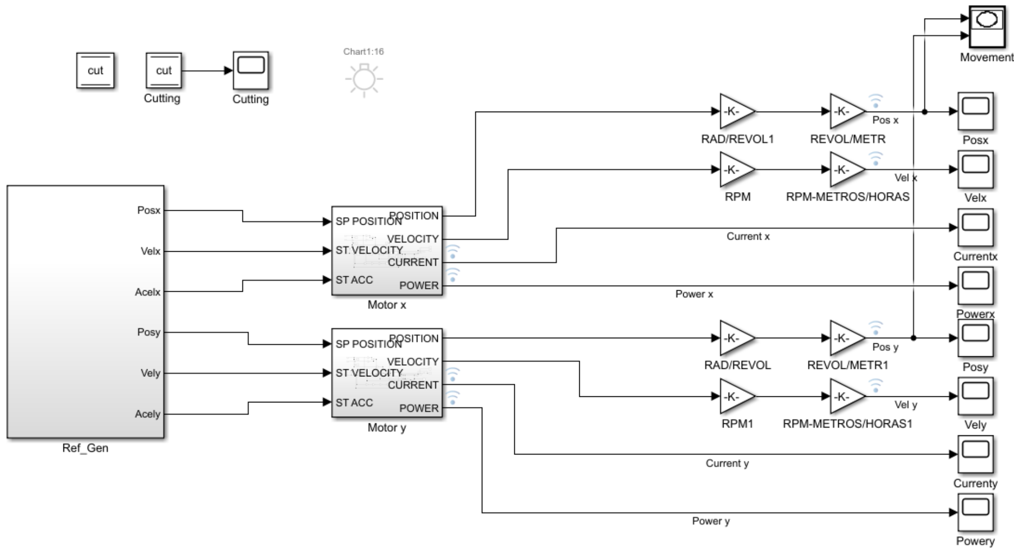


Fig 22: General diagram of the cutting machine

Chapter 2

2.1. Results

Signals obtained by the reference generator

The figures 23, 24, and 25 show the signals generated by the reference generator, they fulfill the purpose of used a fifth-grade polynomial they are continues and smooth curves.

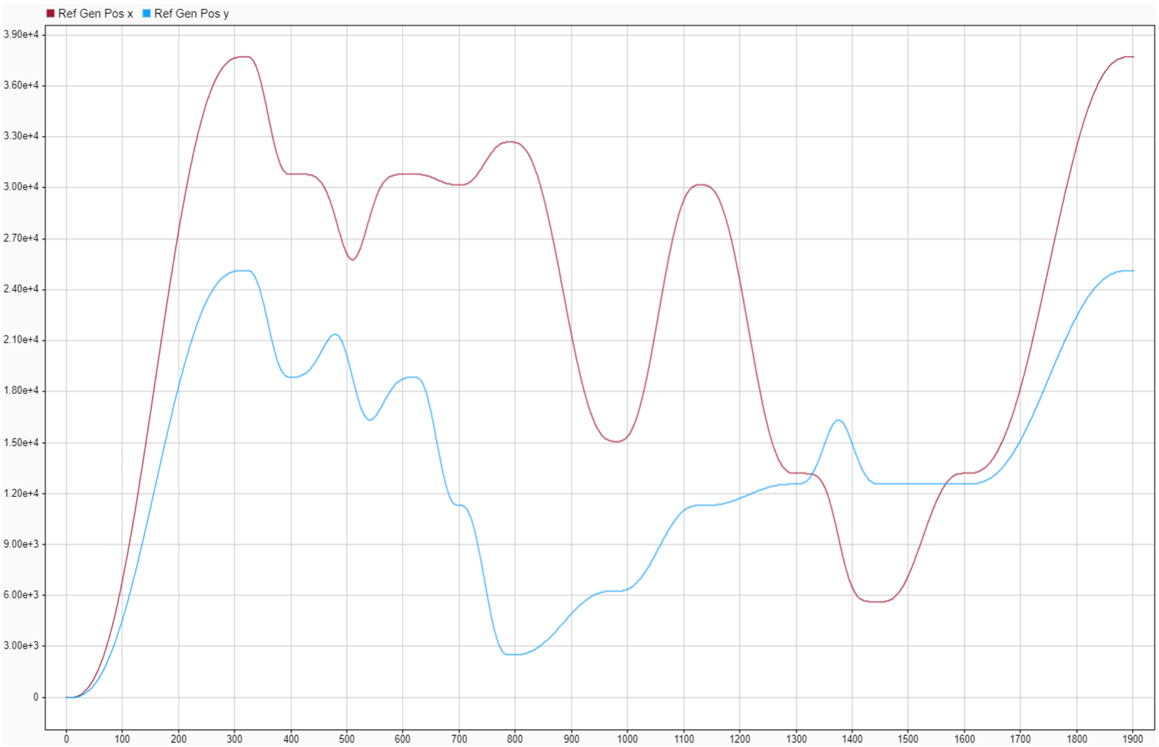


Fig 23: Position of axes X and Y of reference generator

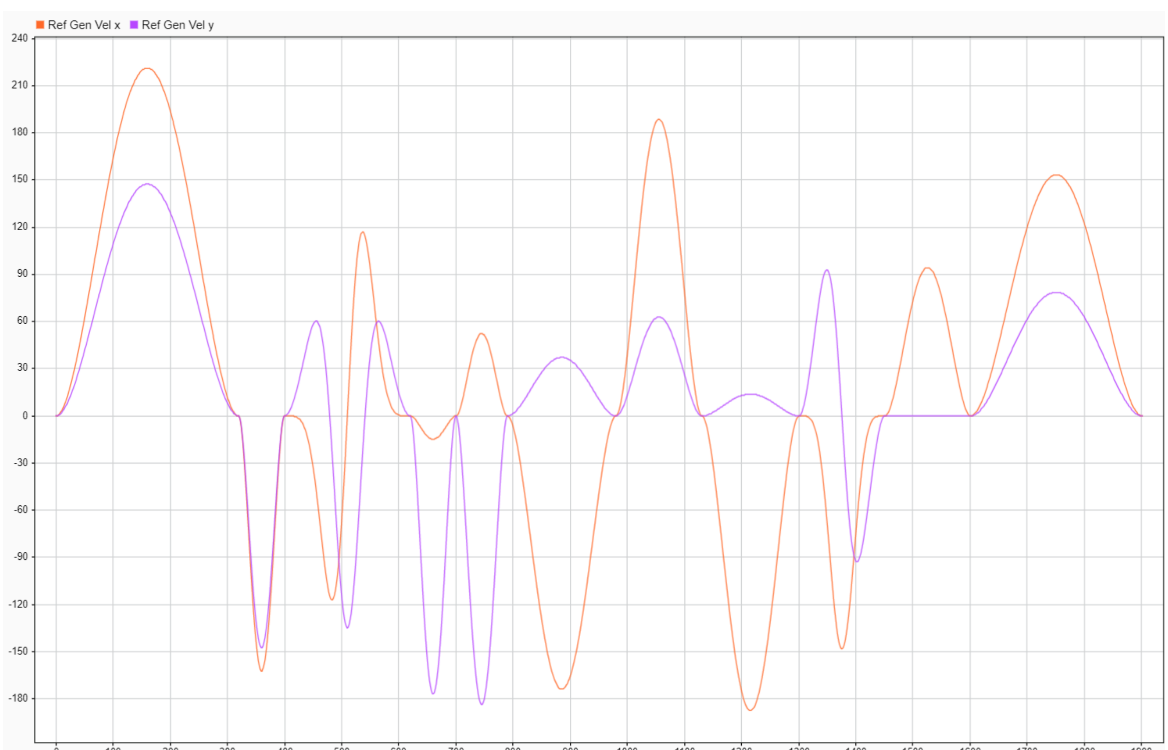


Fig 24: Velocity of axes X and Y of reference generator

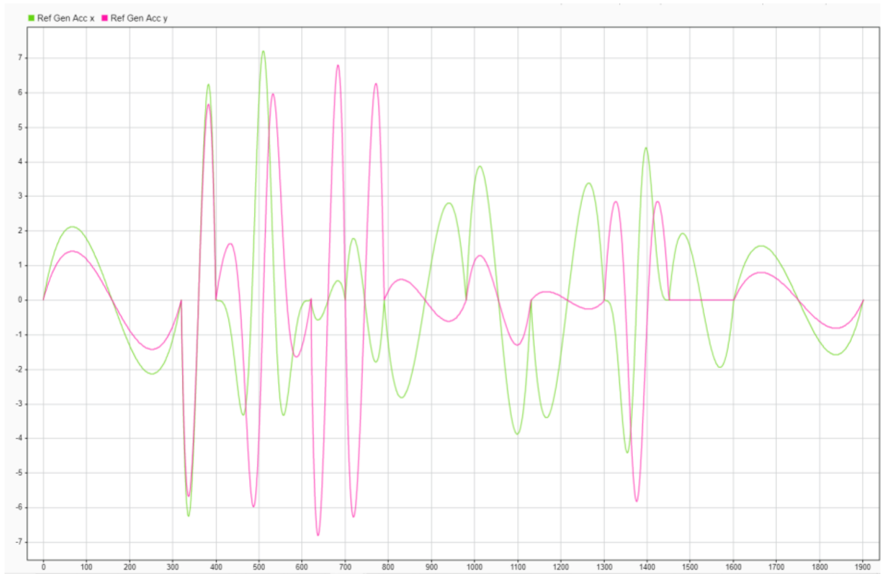


Fig 25: Acceleration of axes X and Y of reference generator

Signals measured in each motor after the control and during the cutting.

The figures 26, 27, 28, 29, and 30 show the behavior of signals of position, velocity, current, voltage, and power of the motor during the cutting and after the control. Measured in meters, meters/hours, amperes, volts, and watts respectability. As it is shown the values are not greater than the maxims parameters of the motor. Due to the current is always lower than 20 amperes, the voltage is smaller than 150 volts, and the power does not overstep 3000 watts, the motors can complete the cutting without suffering any damage.

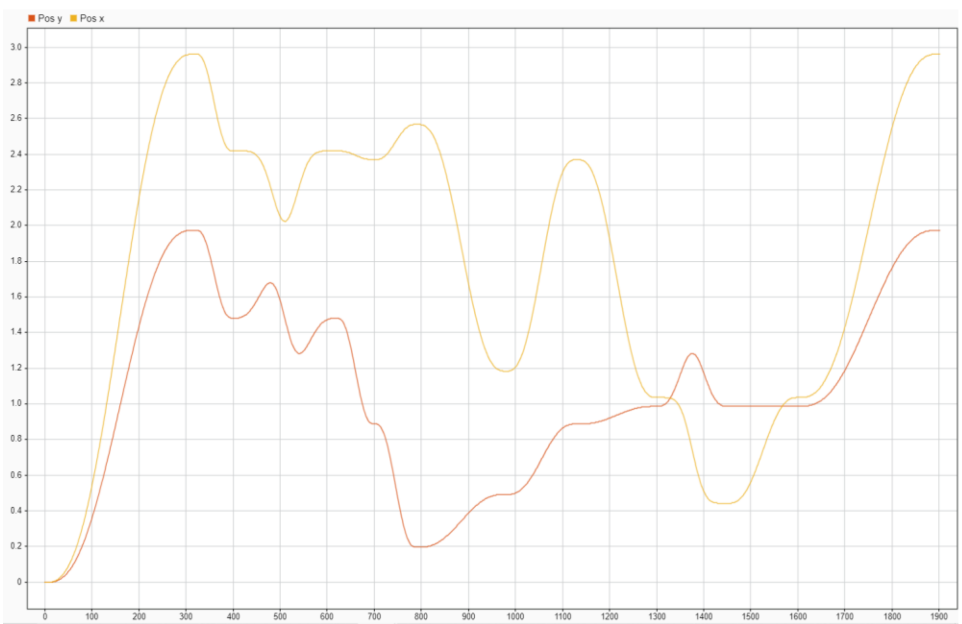


Fig 26: Position of motor X and Y during the cutting

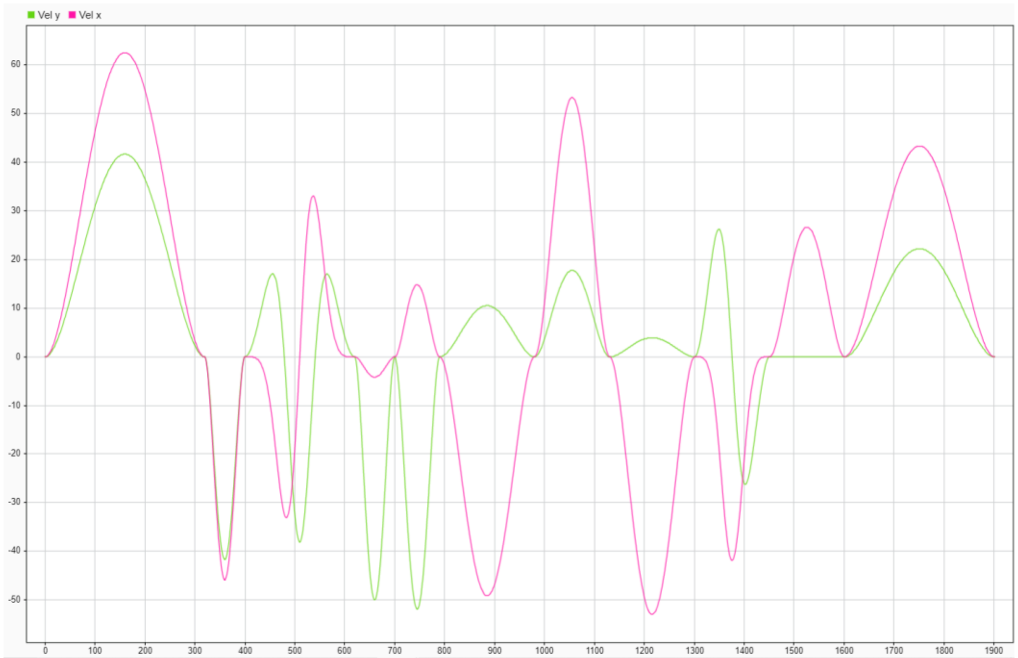


Fig 27: Velocity of motor X and Y during the cutting

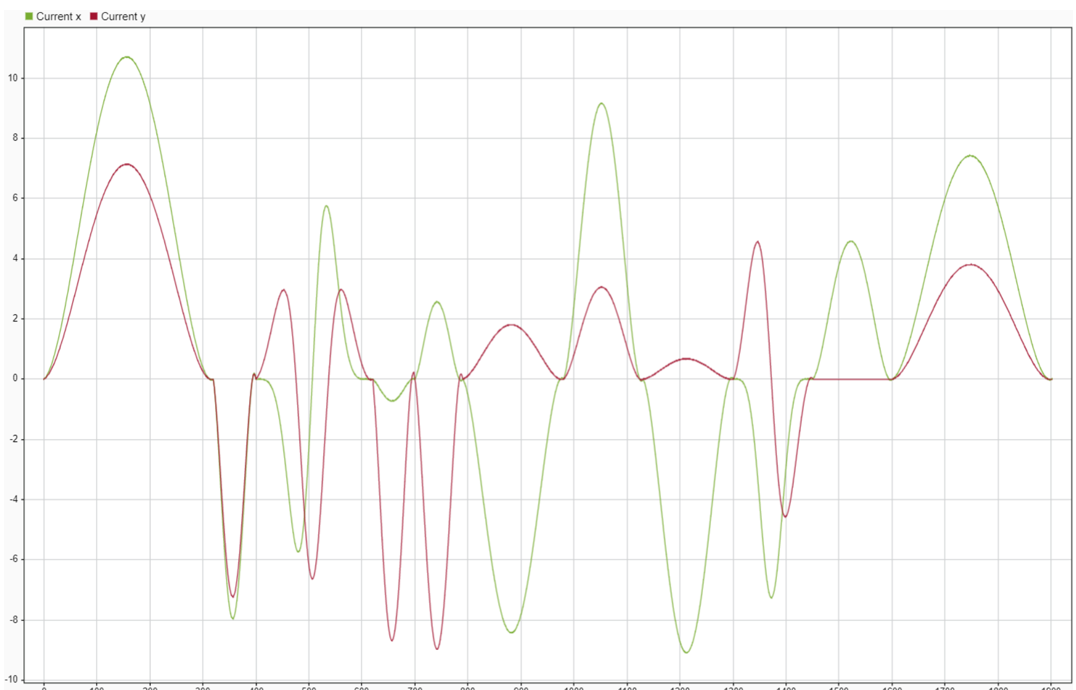


Fig 28: Current of motor X and Y during the cutting

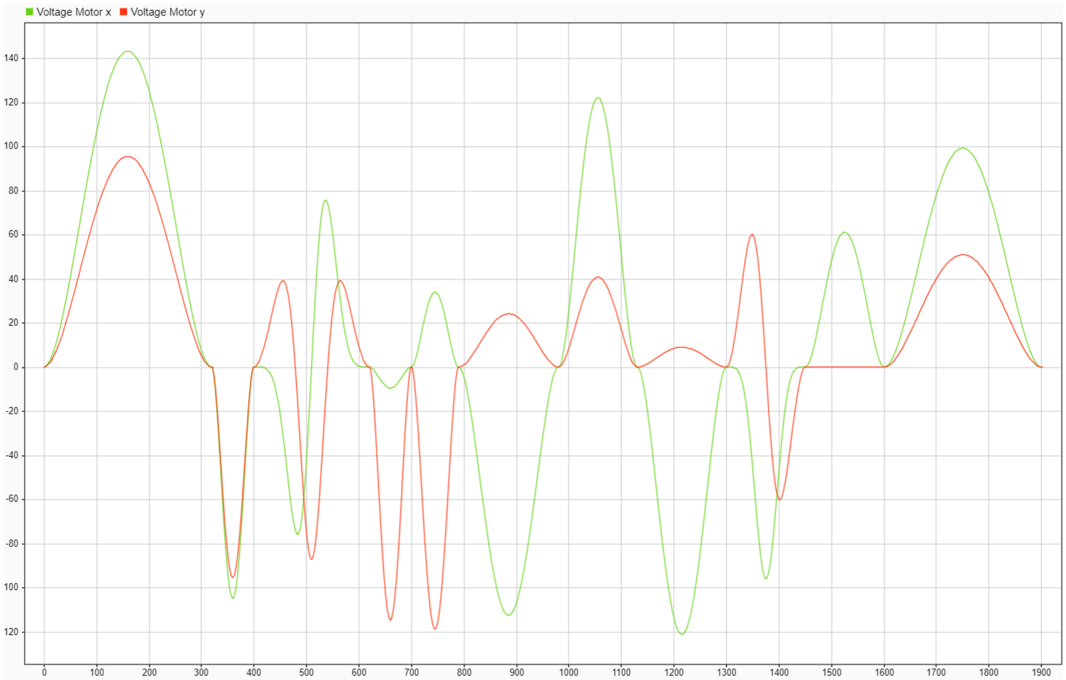


Fig 29: Voltage of motor X and Y during the cutting

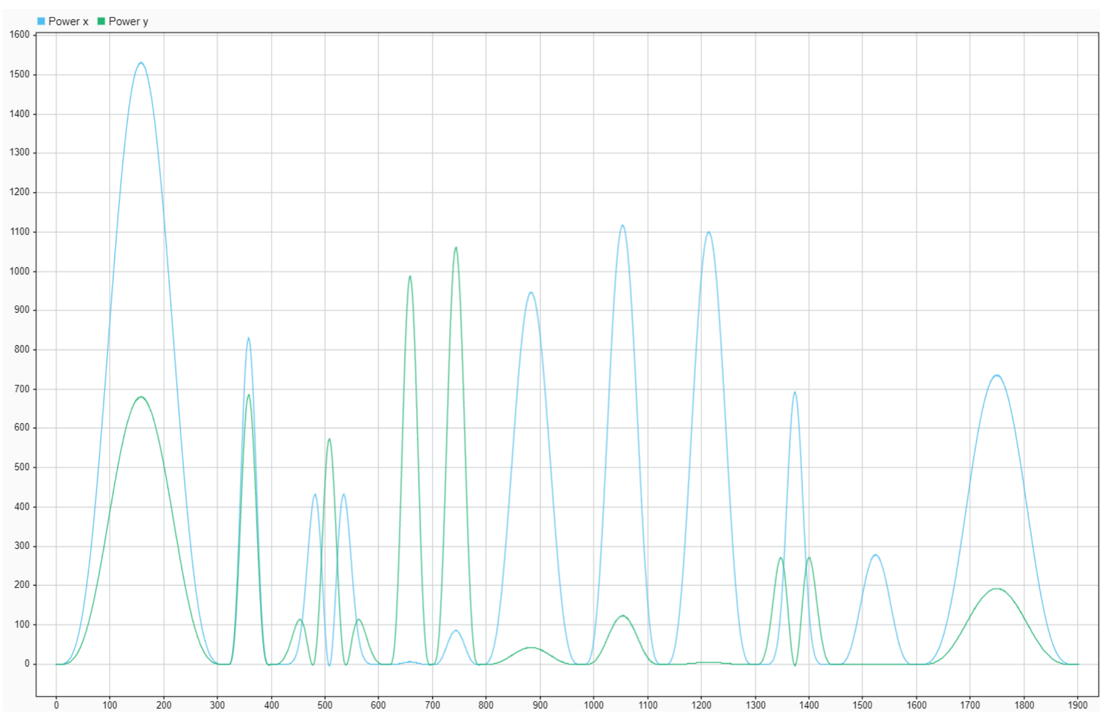


Fig 30: Power of motor X and Y during the cutting

Signal of error.

The feedback controller for each motor must guarantee maximum position error of less than 2 milimeters even when there is an uncertainty of parameters J and B of 10% with respect to the nominal ones. Thus, the figures 31, 32, and 33 show the error signal in millimeters of both motors when J and B are nominal values, then when a 10% from the nominal value is added, and finally when 10% from the nominal value is subtracted.

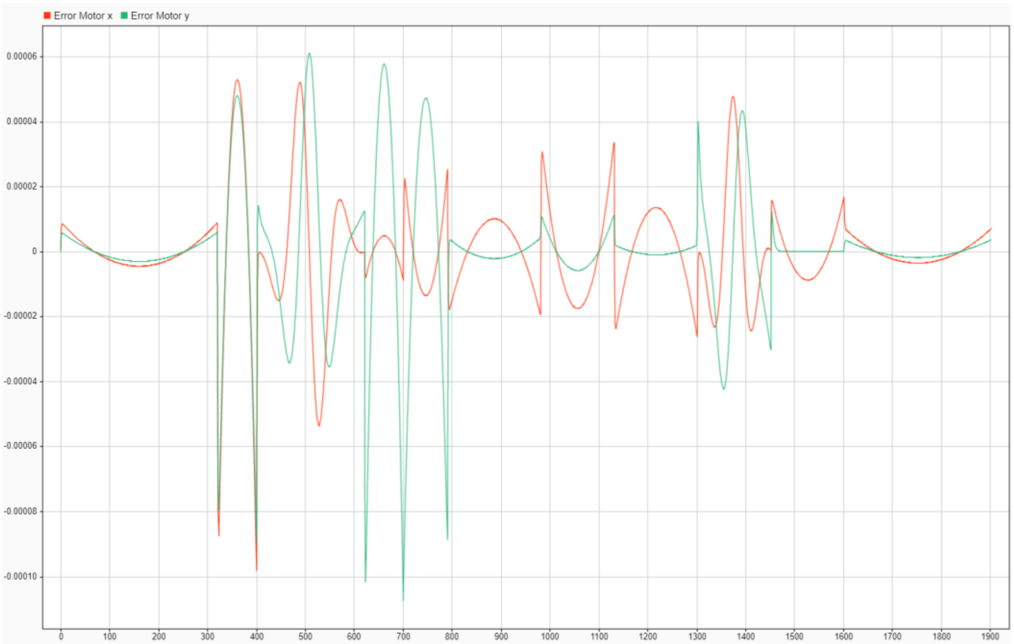


Fig 31: Signal error in motor X and Y with nominal values.

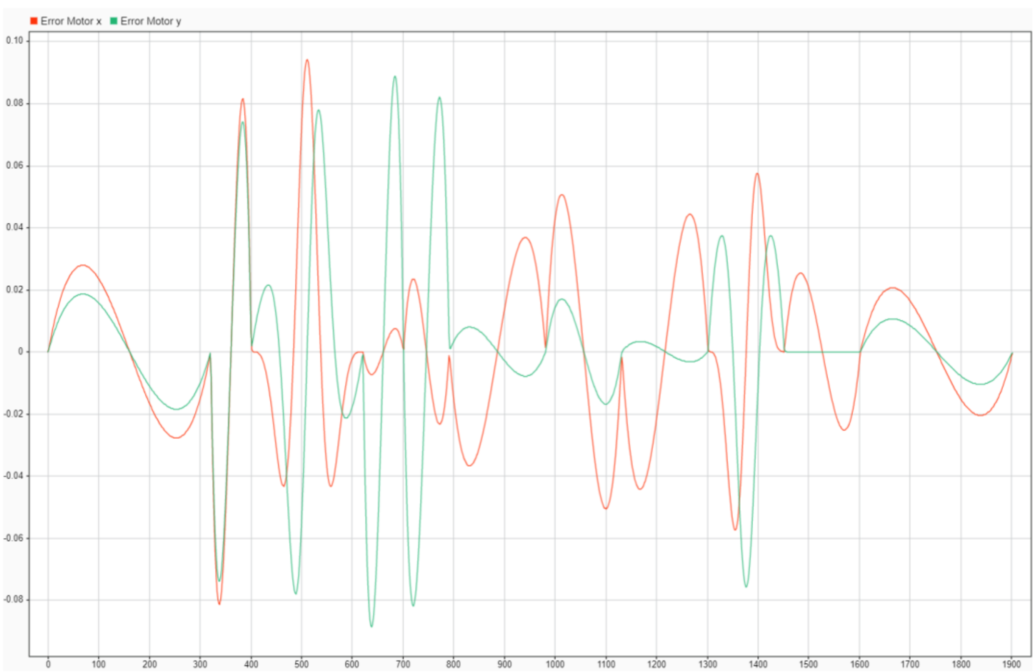


Fig 32: Signal error in motor X and Y with 10% on J and B added.

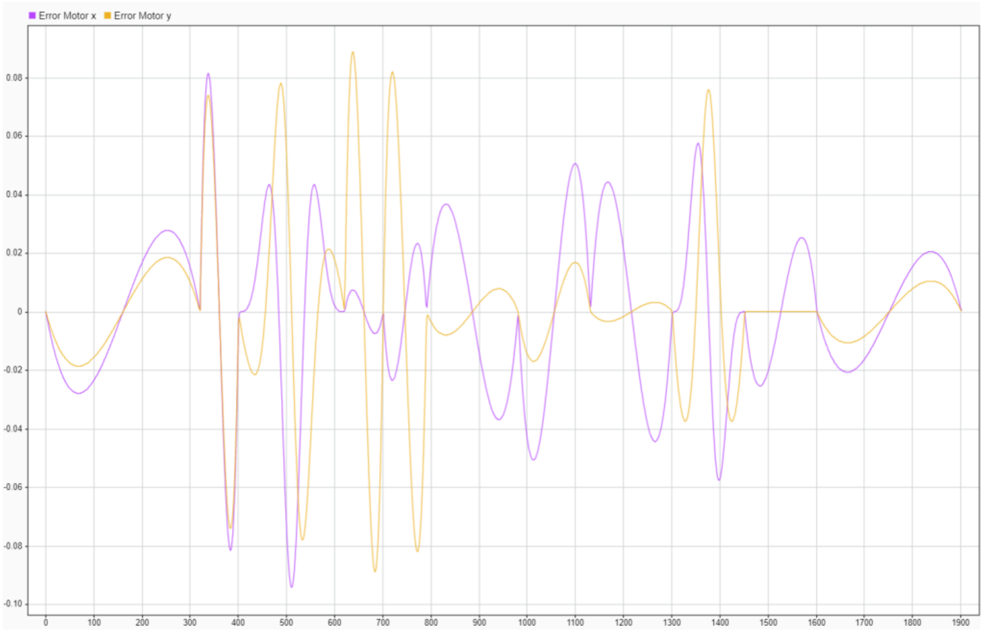


Fig 33: Signal error in motor X and Y with 10% on J and B subtracted.

Final cutting result.

The result after the work of cutting machine is observed in the following figure. Where the continues blue line represent the cut shapes and the broken blue line is the movement of the laser head without making any cut.

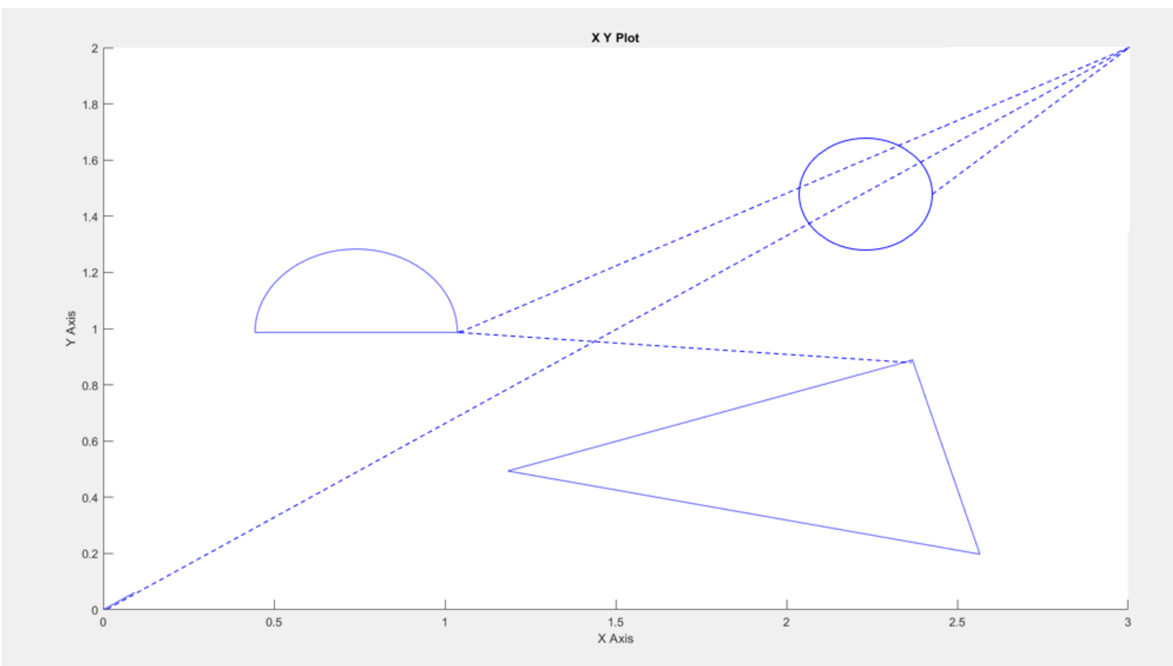


Fig 34: Signal error in motor X and Y with 10% on J and B subtracted.

CONCLUSIONS

This work has focused on planning the trajectory of a cutting machine to carry out the cut of a specific shapes assigned from a rectangular piece, in this case the trajectory was given through a fifth-order polynomial function. Due to the mechanism of the cutting machine, are needed two identical motors which moves the laser head along the x and y axis. To develop a good behavior of the motors a control action was implemented.

The reference generator and control action has been implemented using Simulink which is a MatLab's environment. The final results were successful, it was obtaining a small error between the output and the signals given by the reference generator. This error was sent to the controller which helps to the cutting machine to have a good performance during the cutting.

BIBLIOGRAPHY

1. Prof Pietro M. Muraca, Notes from the Industrial Automation Course.
2. K.Ogata. Modern Control Engineering, 5ta Edition.