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Research Article

SLIDING MODE CONTROLLER FOR MAGNETIC LEVITATION SYSTEM COMPARATIVES STUDIES

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ABSTRACT

The objective of this paper is to synthesize a regulator based on sliding modes for the control of a magnetic levitation system and to compare the performances of this type of regulator with other regulators namely: PID, fuzzy regulator.

The simulation results show the merits of the sliding mode technique since it is robust against disturbances and parameter changes in the model. The advantages and disadvantages of each regulator are outlined in the form of a simulation curves.

Keywords: magnetic levitation, robustness, PID, fuzzy logic, sliding mode.

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1. INTRODUCTION

During these last years, the efforts of many research centers in the world, were concentrated to control magnetic levitation systems (Maglev), and to adapt it to the most recent applications: (High speed train, heart pump,…) and to meet the requirements for integration into the architecture of the various industrial process control equipment [1, 2]. Magnetic levitation systems are inherently unstable and uncertain nonlinear dynamical systems. Therefore, it is always a challenging task to construct a high performance feedback controller to fix the position of the magnetic levitation system rapidly and exactly. In recent years, many proposals have been presented in literatures based on linear and nonlinear system models for controlling this system [3-5]. It is therefore necessary to design levitation systems well suited to the requirements of their applications, with good robust and optimal control.

It is for this reason that we propose to study in this paper the control by sliding mode since it is renowned for its robustness. Our work will focus on the control of the magnetic levitation system; this system is classified among the systems which are highly unstable. The qualitative comparative study between all of the control laws synthesized using the system's linear and non-linear model. This study will be highlighted from a point of view comparison of the step response, and robustness against disturbances and changes in the mass of the ball. Comparative studies will be done in this paper in order to validate the technique used (sliding modes). These studies will be discussed by comparing the performance of this technique with other tuning techniques such as: PID and fuzzy logic [6]. The study conducted allows us to demonstrate the effectiveness of each technique and its impact on the control of Maglev systems, in order to make the best compromise when controlling this type of system.

This paper is organized as follows; Section 2 presents gives a brief on model representation of a magnetic levitation system. Simulation results for stabilization of the magnetic levitation system follow in Section 3. Section 4 is dedicated to comparison between different regulators such as: PID, phase advance, fuzzy logic and sliding mode. Section 5 provides the conclusion

2. MODELING OF THE MAGNETIC LEVITATION SYSTEM

2.1. Electromagnetic assembly

Figure 1 shows the block diagram of a conventional magnetic levitation system. For the optical receiver, it is possible to use phototransistor mounted in jusxtapostion and this in order to have a greater travel of the sensor.

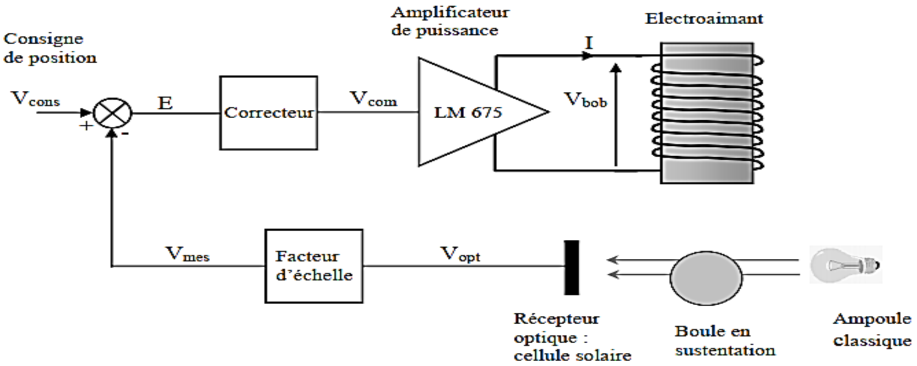

Fig.1. Schematic diagram of the device

The ball is a hollow tin sphere that originates from a gadget pen world map. Equivalents can be easily made using, for example, a polystyrene ball surrounded by strips of iron from a beverage can.

2.2. Mathematical formulation of the model

In our study, we will consider two parts to describe the system such as:

- ✓ Electrical part :

This part concerns only the coil and its internal resistance

$$u = ri + L\frac{di}{dt} \qquad (1)$$

Where

r : represents resistance of the coil in Ohm

L : inductance of the coil in H

The application of Laplace transform to the equation (1) is given as follow:

$$\frac{i}{u} = \frac{k_e}{\tau_e s+1} \qquad (2)$$

With

$k_{e=1}/_{r}$

and $\tau_{e=L}/_{r}$

- ✓ Mechanical part :

In this part, we used the second law of Newton

$$\sum \vec{F} = m\,\vec{a} \qquad (3)$$

with

F: Force

a: Acceleration

In Maglev system, we have two forces with opposite direction applied to the ball

F_1: Gravity force,

F_2: Force generated by the coil with allow to lift the ball up

$$F_1 = mg \qquad (4)$$

Where m: represents the masse of the ball and g the gravity)

$$F_2 = k\frac{i^2}{x^2} \quad [8] \qquad (5)$$

With**:**

k: Magnetic constant, i : current, x : position of the ball

Finally, substituting the equations (4) and (5) in equation (3) we obtain the equation 6:

$$m\ddot{x} = mg - F_c \quad (6)$$

$$i = k_1 * u \quad (7)$$

With:

m: mass of the ball

g: gravity

$F_c = k\frac{i^2}{x^2}$: with k is constant depends on the electromagnet (the coil) [8]

i: the current

u: the voltage

x: the position

And $M = \frac{k}{m}$

So the state representation of the system becomes: $\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = g - \frac{k{k_1}^2}{m}\frac{u^2}{x^2} = g - M\frac{i^2}{x^2} \end{cases}$ (8)

Figure 2 shows the sketch of the magnetic levitation system used in our case.

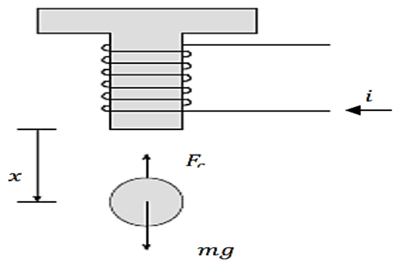

Fig.2. Sketch of the magnetic levitation system

The system parameters used in the simulation are given in Table 1.

Table 1: Parameters of the Maglev system

x	Ball Position	[0.0025, 0.025] m
i	Current in the coil	[0, 3] A
u	Voltage in coil	[0, 5] V
g	Gravity	9,81 m.s^{-2}
m	Mass of the ball	0.02 kg
k_1	constant	0.397 Ω^{-1}
k	magnetic constant	0.0000825 kg^{-1}

2.3. System stability study

If we take the current i which flows in the coil with a value included in the interval [0.5, 0.9] A, and the position of the ball x∈ [0.01, 0.025] m, we choose the function v in the following way:

$$v(x) = \frac{1}{2}{x_1}^2 + \frac{1}{2}{x_2}^2 \tag{9}$$

$v(x) > 0$ and $v(0) = 0$

So : $\dot{v}(x) = \frac{\partial v}{\partial x}\dot{x} = x_1\dot{x}_1 + x_2\dot{x}_2 = x_1x_2 + x_2\left(g - M\frac{i^2}{{x_1}^2}\right) = x_2(9.81 + x_2 - 0.0041\frac{i^2}{{x_1}^2})$ (10)

For the given intervals (of i and x), the value of g = 9.81 always remains large as the term $\left\{x_2 - 0.0041\frac{i^2}{{x_1}^2}\right\}$, then according Theorem (instability in the sense of Lyapunov [8]), If there exists x_0 such that $v(x_0) > 0$ for $||x_0||$ fairly small, so $x_e = 0$ is unstable, with $x_e = 0$ is a system equilibrium point.

Note:

- Different stability theorems have been stated by considering as origin point 0 the space of state Rn. Indeed, we can always reduce ourselves to the study of the stability of 0 by a simple change of variable [8].
- The system can have one or more balance points.

3. APPLICATION TO THE MAGNETIC LEVITATION SYSTEM

3.1. Analysis of the system in open loop (without command)

The state representation of the system is given by equation 8:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = g - \frac{k}{m}\frac{i^2}{x^2} = g - M\frac{i^2}{x^2} \end{cases} \tag{11}$$

To perform our different simulations, we used Matlab software (Simulink). Figure 3 represents the open loop simulation model without command:

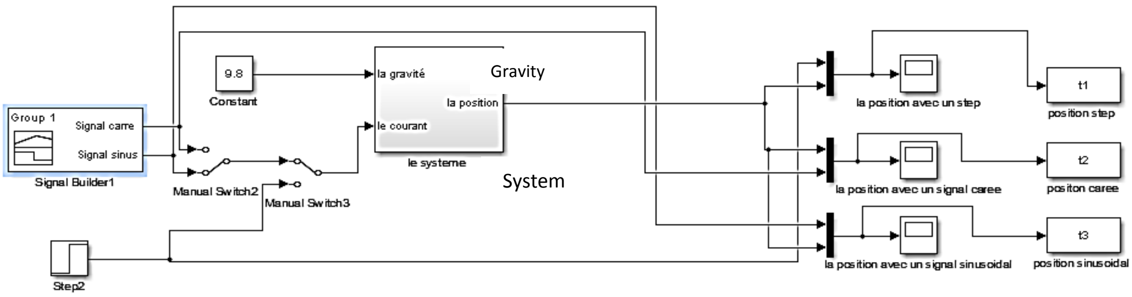

Fig.3. Open loop system simulation model

Figures 4, 5 and 6 respectively represent the system output (in our case: the position of the ball), with different signals (current in the electromagnet) such as: constant current, current in the form of a signal square and shaped like a sinusoid.

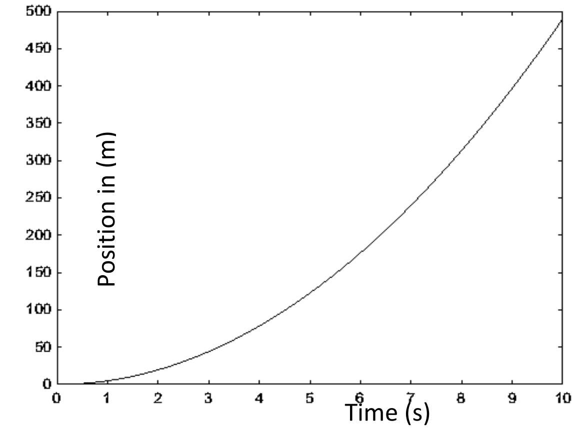

Fig.4. Position of the ball for a constant “step” current

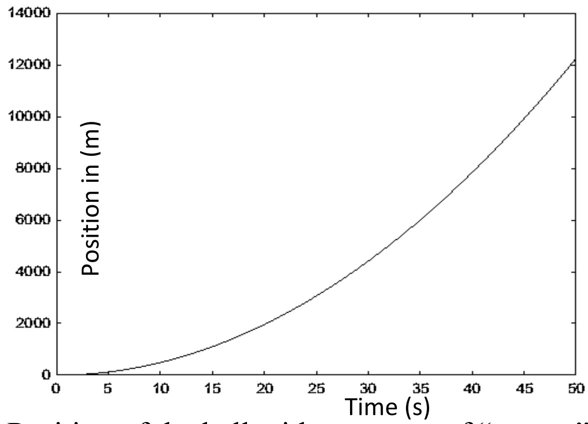

Fig.5. Position of the ball with a current of “square” shape

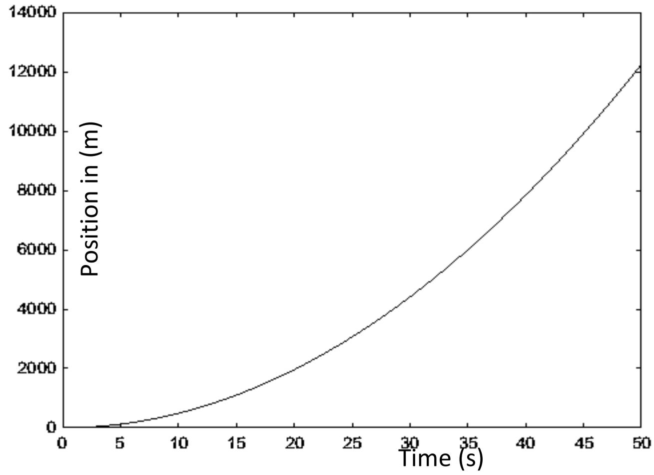

Fig.6. Position of the ball with a "sinusoid" shaped current

From the figures, it is clear that the magnetic levitation system is highly unstable in open loop.

3.2. Summary of the sliding mode control of a levitation system

The Model of our system can be written as follows:

$$\begin{cases} f(\dot{x},x) = g \\ b(\dot{x},x) = -M\frac{1}{x^2} \\ u = i^2 \end{cases} \tag{12}$$

According to [8], the levitation system command can be written as follows:

$$i^2 = (-M\frac{1}{x^2})^{-1}(\ddot{x_d} - \alpha\dot{e} - g) - (-M\frac{1}{x^2})^{-1}\, k * sign(s)$$

$$\text{So} : i = \sqrt{\frac{x^2}{M}((-\ddot{x}_d + \alpha\dot{e} + g) + k * sign(s))} \tag{13}$$

Thus, the equivalent command and the discontinuous command will be given by the equations:

$$u_{eq} = -\frac{x^2}{M}\,(\ddot{x_d} - \alpha\dot{e} - g) \tag{14}$$

$$u_{dis} = -\frac{x^2}{M} k * sign(s)$$

(15)

For the implementation of the command, we use the Matlab software (Figure 7):

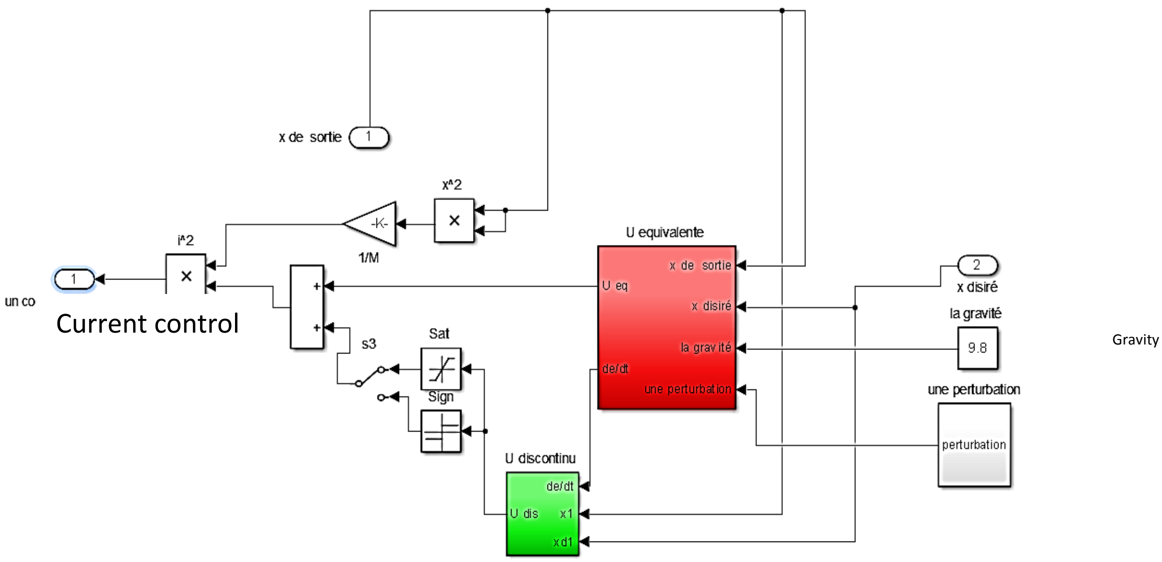

Fig.7. Block diagram of the command under Simulink

3.3. System control simulation

The simulation of the system with the command is shown in Figure 8, In this case we used the sign function (Chattering phenomenon not taken into account).

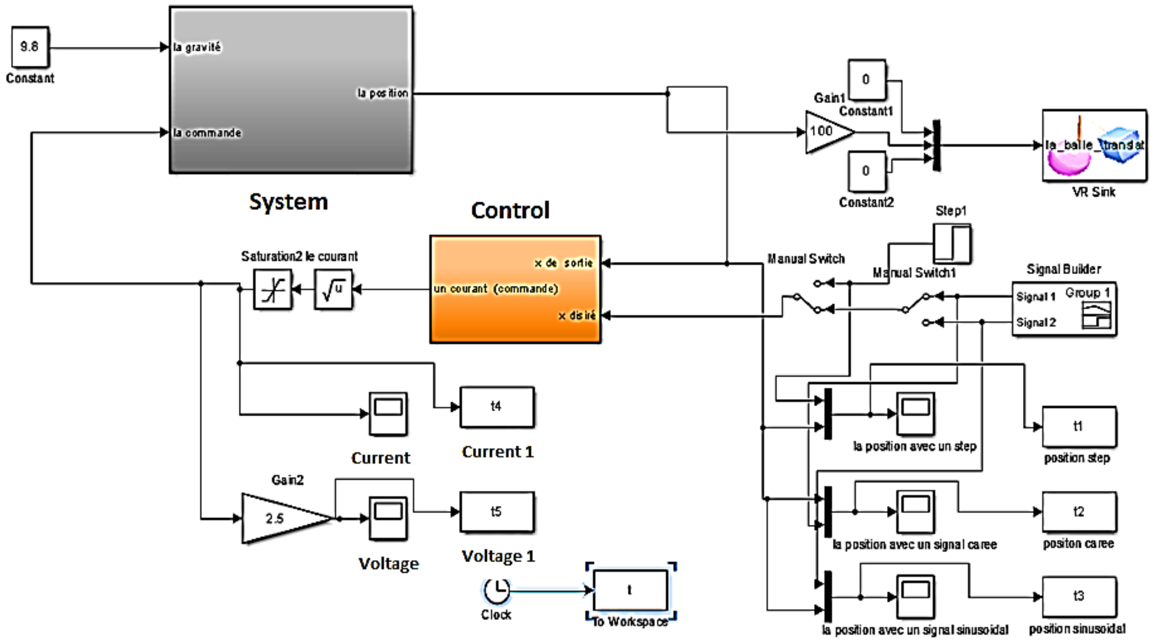

Fig.8. Block diagram of the system and control (closed loop)

3.3.1. Step response

The step response is shown schematically in Figure 9 (desired position = 0.01 m).

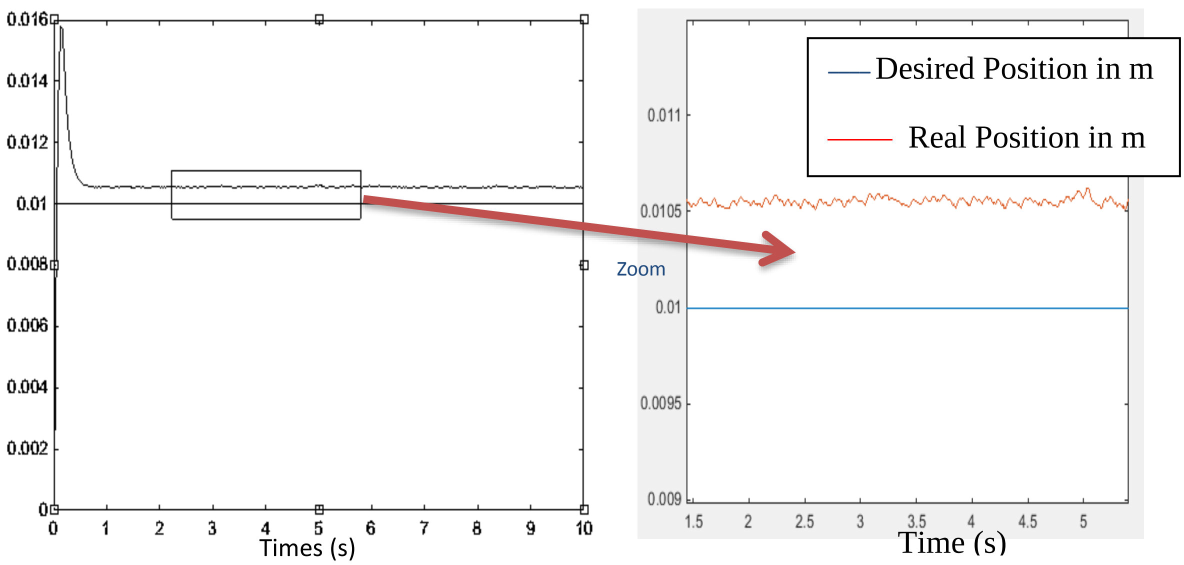

Fig.9. Step response with zoom showing the phenomenon of chattering

3.3.1.1. System performance

- **Stability** : according to the index response of the system, we deduce that the latter is stable, and has a behavior of a 2nd order system with a peak in the position of the ball at 0.016 m then stabilizes at point x = 0.0105 m after 0.6 s
- **Speed**: the system reaches 95% of the desired value after 0.6 s.

- **Precision**: A zoom on the shape of the index response shows that the error does not exceed 6%, since we imposed an interval of 2 cm allowing the movement of the ball, so the error is acceptable.
- **Chattering**: we always notice that the output signal, even after stabilization has oscillations, and this is due to the switching of the control (U_{dis}) whose frequency is very high. It is clear that the value of the current oscillates in around 0.49 and 0.54 A, as well as the voltage [1.22, 1.34] V, This is due to the phenomenon of chattering which must be taken into account to avoid damage to the electromagnet (Figures 10 and 11).

Figures 10 and 11 show the behavior of the control (current and voltage).

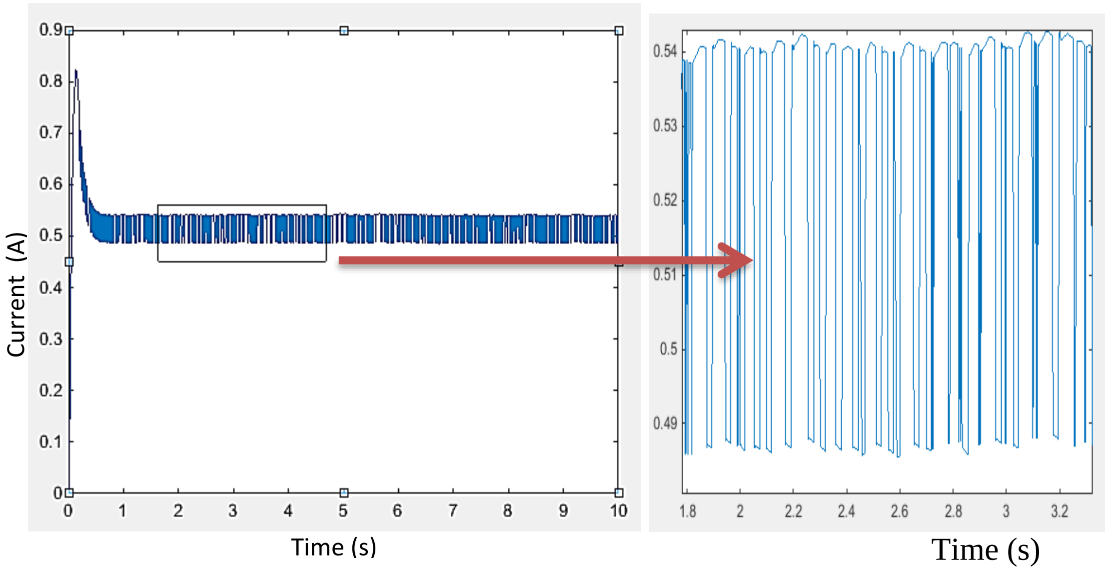

Fig.10. Current for which the ball reaches 0.01m with a zoom showing the chattering

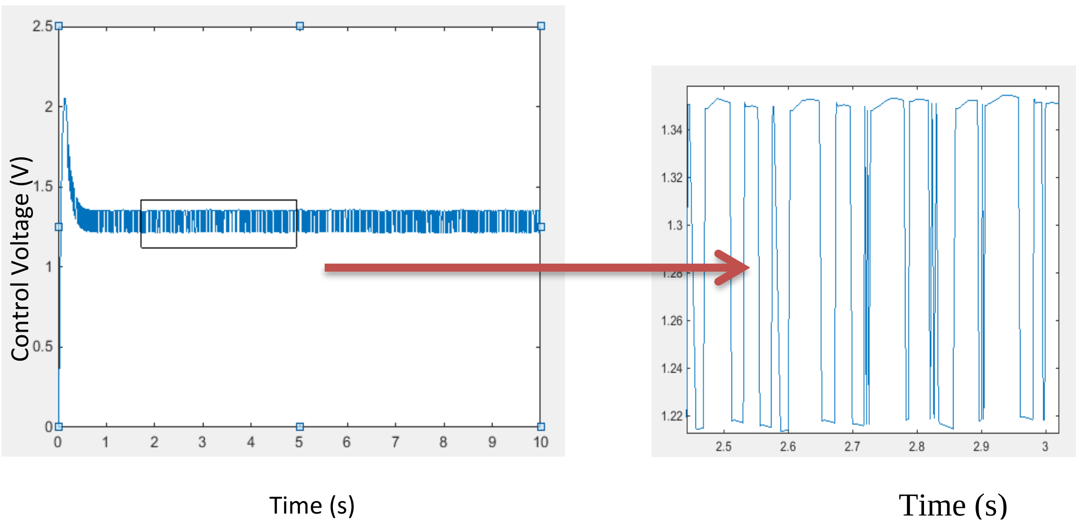

Fig.11. Control voltage for which the ball reaches 0.01m with a zoom showing the grazing

- **System security**: we note from the previous graphs, that the two quantities stabilize around acceptable values, despite the appearance of peaks (the current rises to 0.8 A, and the voltage rises to 2 V). These two values do not exceed the nominal values imposed in Table 1.

3.3.2. System response for periodic signals

In this case, we will simply impose on the setpoint periodic signals having the forms (square and sinusoidal).

• Square signal (setpoint)

Figures 12, 13 and 14 respectively represent the position of the ball, and the control (current and voltage).

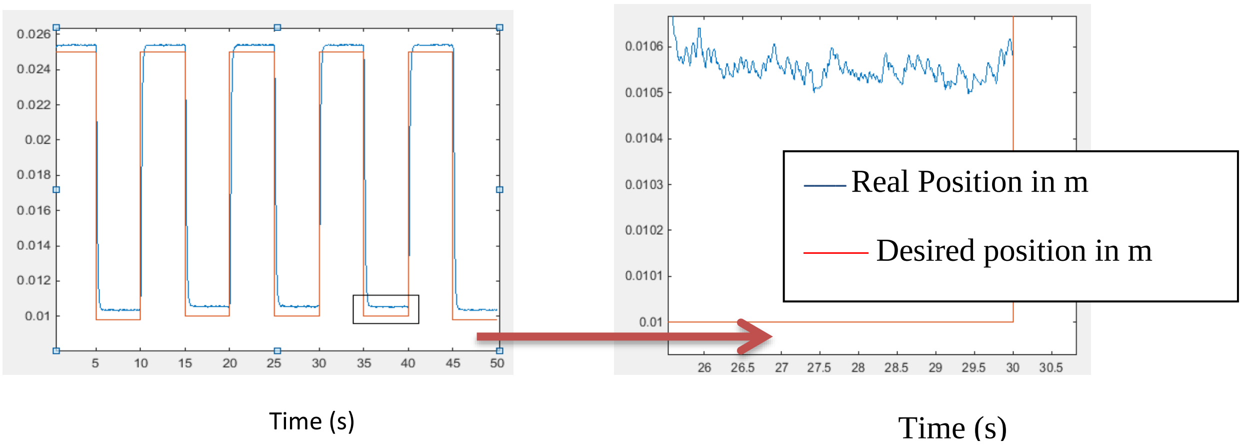

Fig.12. Position of the ball for a square signal with a zoom showing the chattering

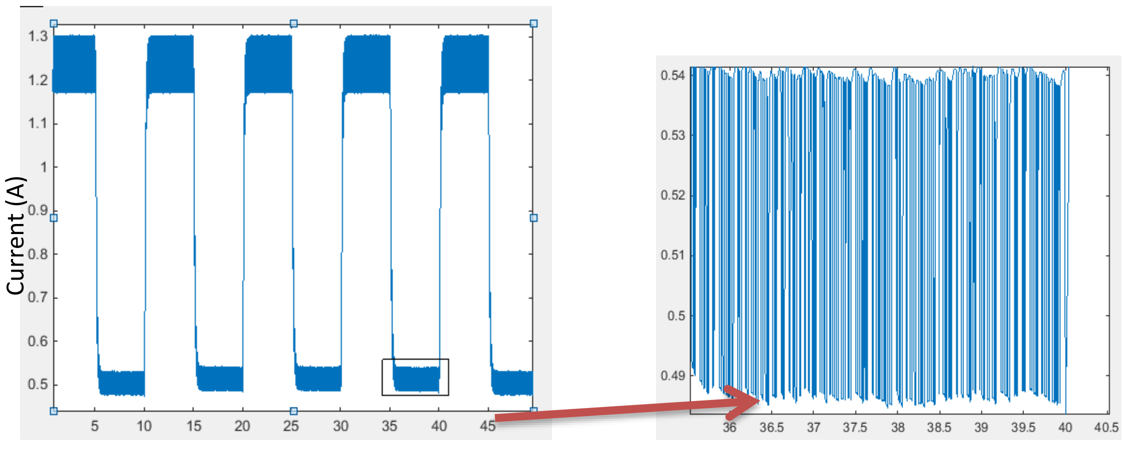

Fig.13. Current in the coil for a square signal with zoom showing chattering

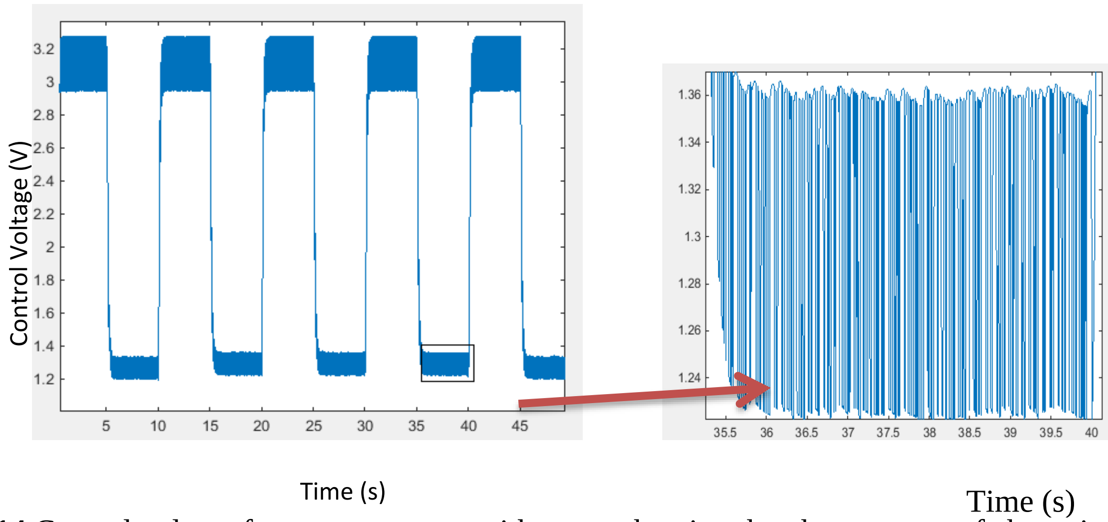

Fig.14 Control voltage for a square wave with zoom showing the phenomenon of chattering

• Sinusoidal signal (setpoint) similarly, figures. 15, 16 and 17 show the simulation results for a setpoint having the form of a sinusoid.

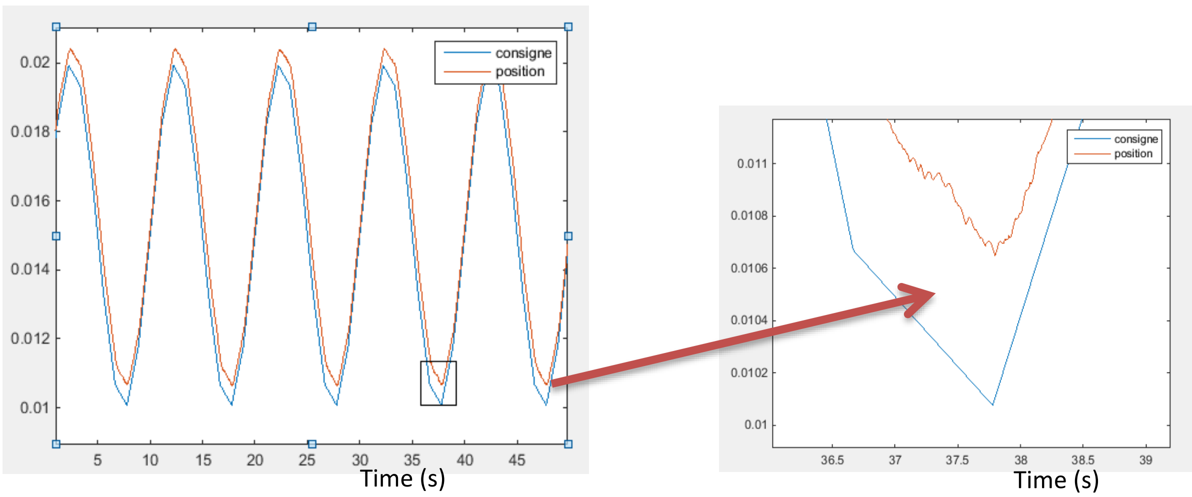

Fig.15. Position of the ball for a sinusoidal signal with a zoom showing the phenomenon of chattering

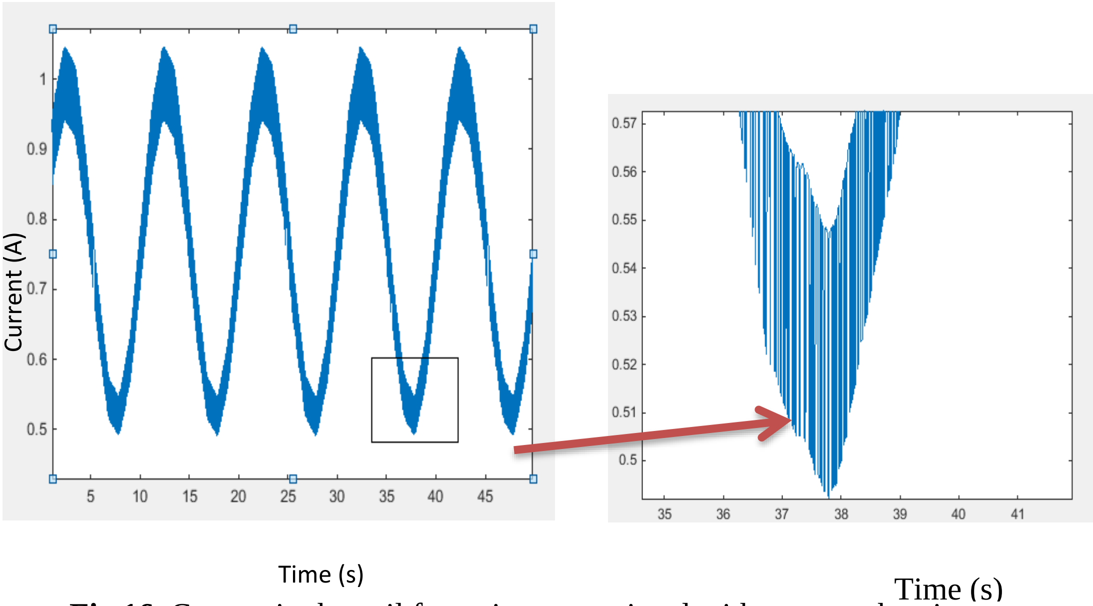

Fig.16. Current in the coil for a sine wave signal with a zoom showing the phenomenon of chattering

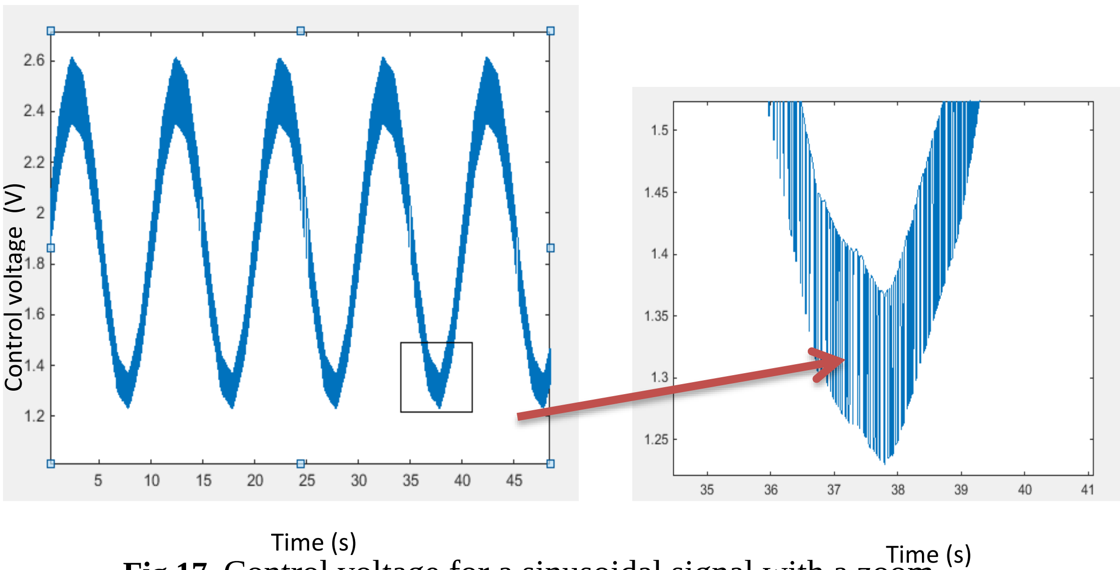

Fig.17. Control voltage for a sinusoidal signal with a zoom showing the phenomenon of chattering

As we can see from the previous figures, the system is quasi-stable. However, the chattering phenomena appear and this is due the sign function used in the simulation.

3.4. System simulation with elimination of chattering phenomenon

In this step, we try to replace the sign function used in the command with the saturation function and this to alleviate the phenomenon of chattering. We repeat the same steps as before while imposing a constant setpoint, then having the form of a square signal and finally a setpoint of sinusoidal shape.

• Constant setpoint

In this case, a set point of 1 cm is imposed (Figure 18).

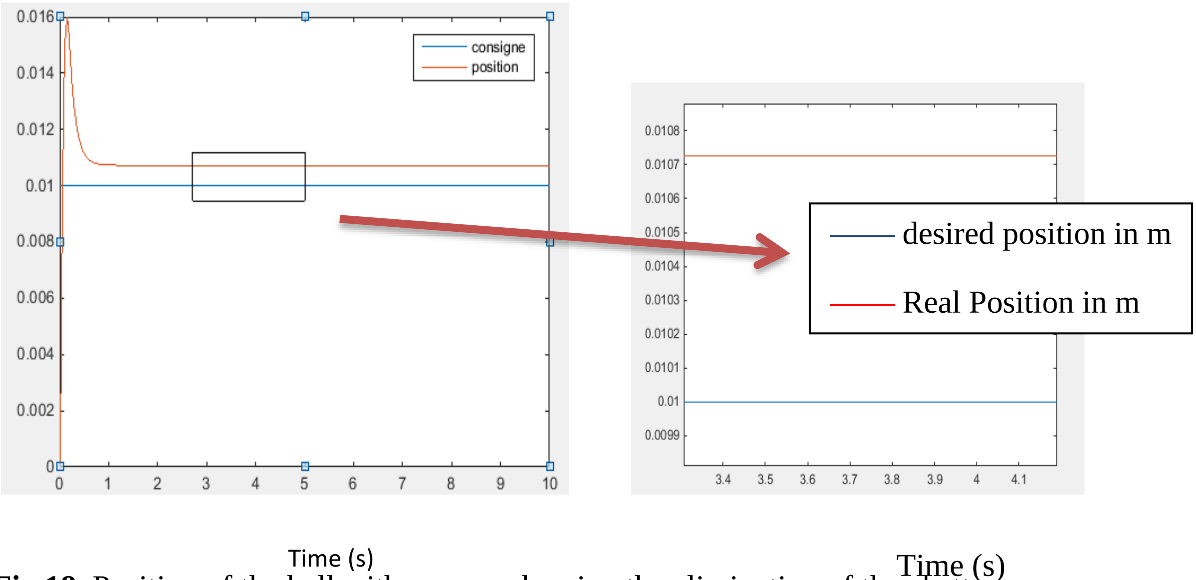

Fig.18. Position of the ball with a zoom showing the elimination of the chatter

3.4.1. System performance

- **Stability:** according to the index response of the system, we deduce that it is stable, it has a behavior of a 2nd order system with a peak of 0.016 m at t = 0.16 s, then it stabilizes at point x = 0.0107m.
- **Speed:** the system reaches 95% of the desired value after 0.6 s.
- **Precision:** the zoom on the figure allows us to have an idea on the precision. It does not exceed 7%, which is acceptable given that we did not exceed the interval imposed at the start.
- **Chattering:** it is clear in figure 18, that the output signal (the position) is smooth, and is superimposed almost perfectly with the setpoint imposed. It is clear that the current value stabilizes at 0.52 A, the voltage value stabilizes at 1.3V, and we notice the cancellation of the chatter phenomenon.

Figures 19 and 20 show the control behavior (current and voltage).

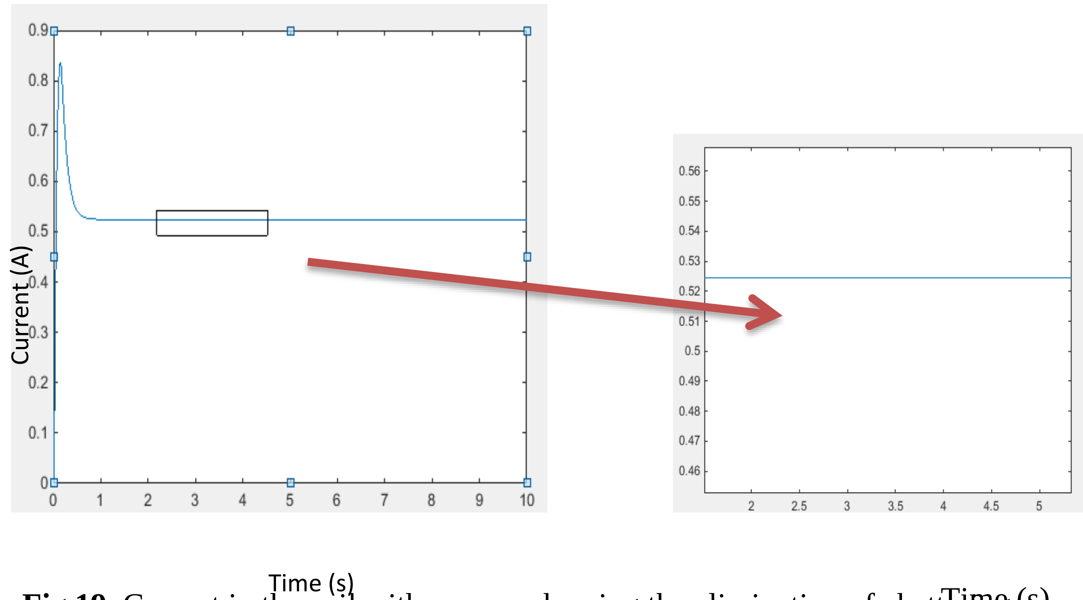

Fig.19. Current in the coil with a zoom showing the elimination of chattering

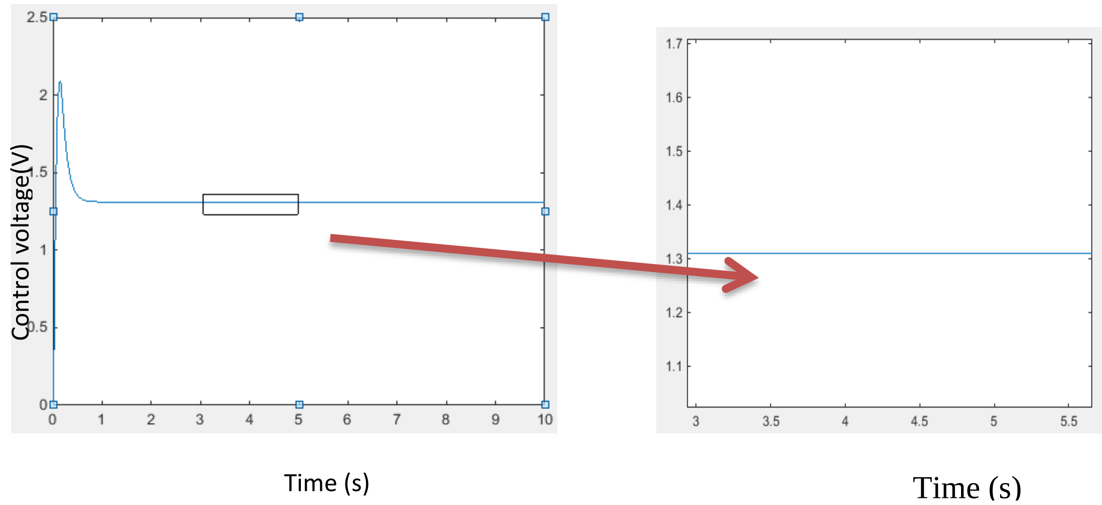

Fig.20. Control voltage with a zoom showing the elimination of chattering

- **System security:** we note here that the two quantities stabilize around acceptable values despite the appearance of a peak (the current rises to 0.8 A, and the voltage rises to 2 V), but does not exceeding the range imposed in table 1.

3.4.2. System responses for shape setpoints: square and sinusoidal

In what follows, we sketch the simulation results while imposing on the input of the set points of shape: square and sinusoidal.

Square signal

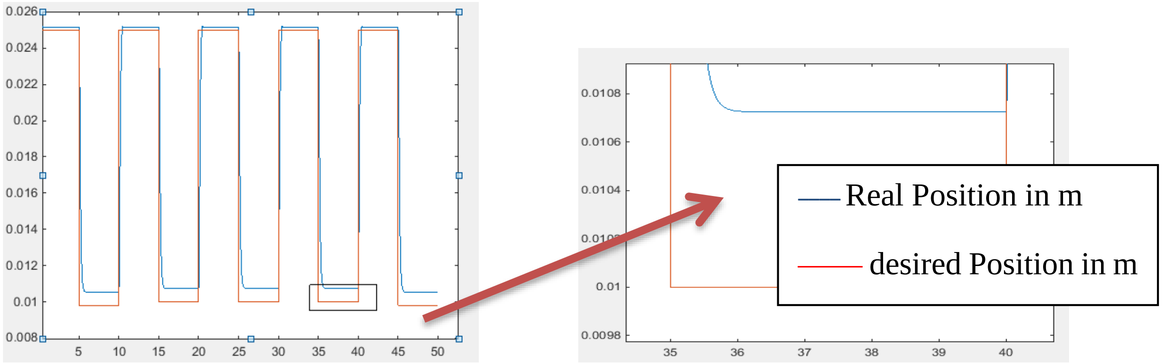

Fig.21. Position of the ball with a zoom showing the elimination of the chattering

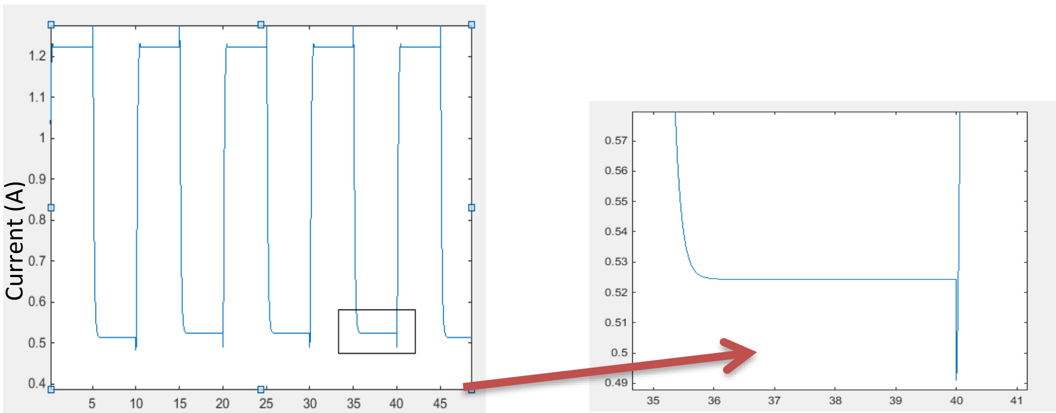

Fig.22. Current in the electromagnet with a zoom showing the elimination of chattering

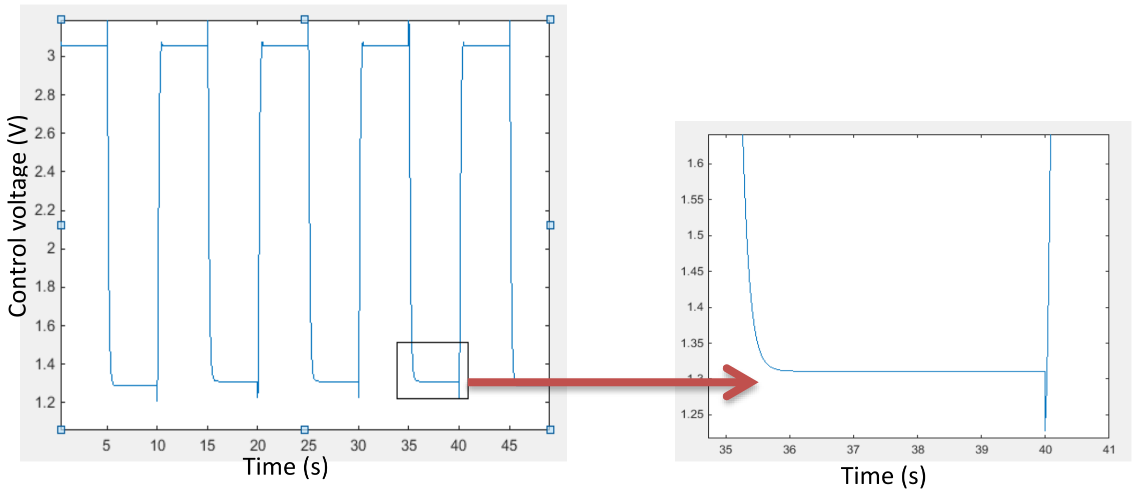

Fig.23. Control voltage with a zoom showing the elimination of chattering

• **Sinusoidal signal**

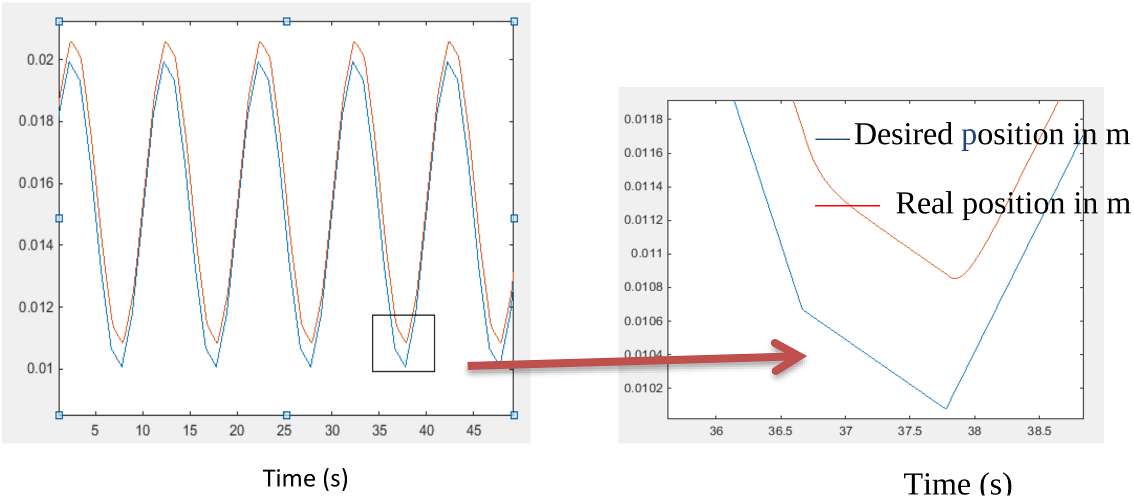

Fig.24. Position of the ball with a zoom showing the elimination of the chattering

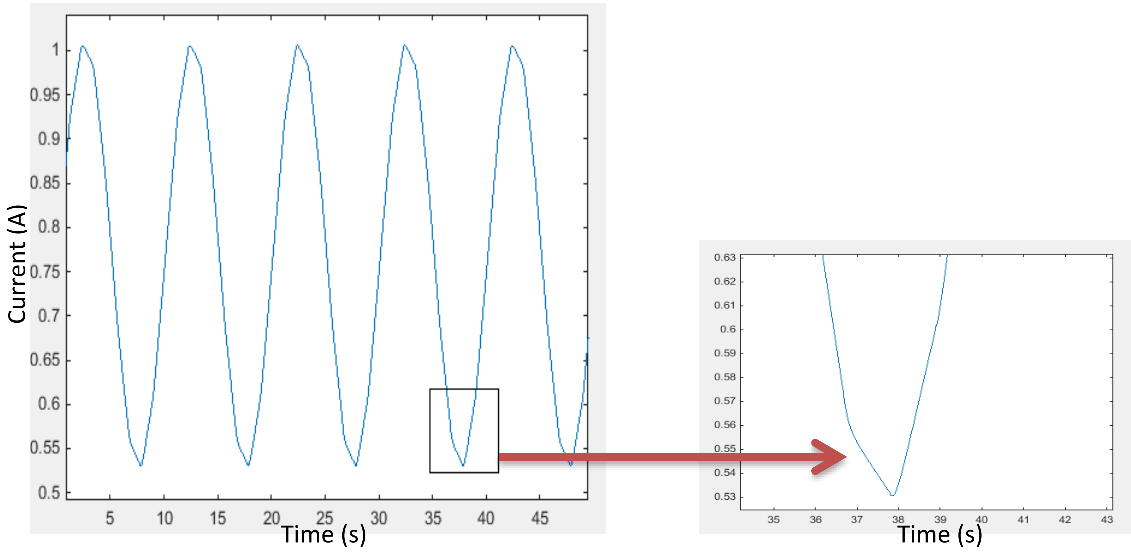

Fig.25. Current in the coil with a zoom showing the elimination of chattering

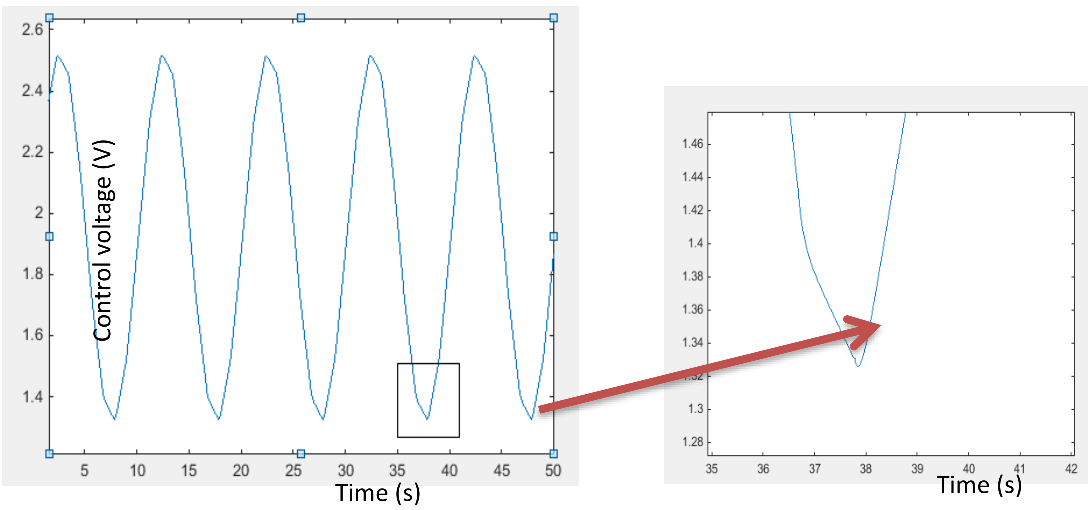

Fig.26. Control voltage with a zoom showing the elimination of chattering

As we can see from the previous figures, the system is more stable with the elimination of chaettering phenomena.

3.5. Control Robustness Test

3.5.1. Robustness of the control against disturbances

In order to show the effectiveness of the developed command, we are going to set a 2cm setpoint, while introducing impulse train on the position of the ball (pushing on the ball) considered as disturbances (figure 27).

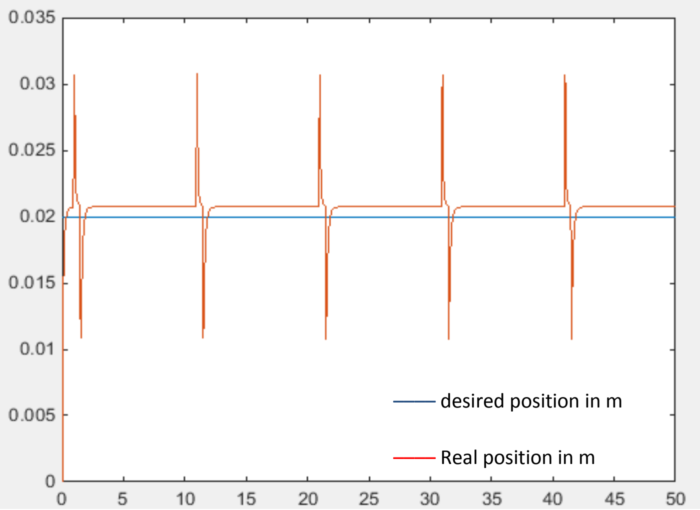

Fig.27. Position of the ball with disturbances

The train of pulses present on the ball at a period of 10s (imposed on the ball). Note that the ball deviates from its position on each impulse and then returns, but with an error of 7%.

Figures 28.a and 28.b show the behavior of the control (current and voltage) in the presence of disturbances.

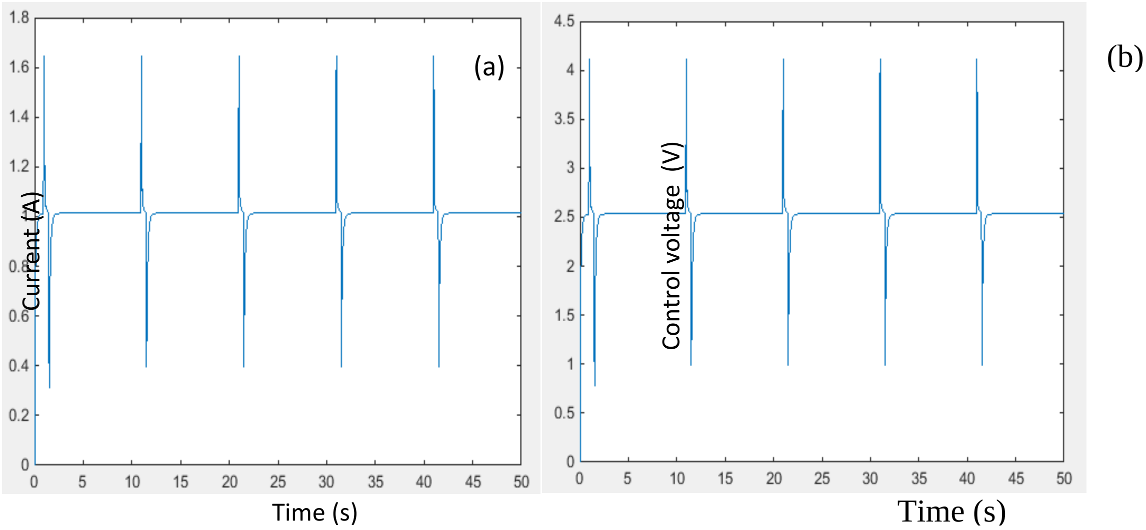

Fig.28. Control with disturbances

(a) Current in the coil

(b) Control voltage

From the two signals obtained from the control, it is clear that the disturbance has an influence on the two quantities such that the voltage drops to 0.75 v and the current to 0.3 A, then they return to their stable values (i = 1A, u = 2.5v).

So we can conclude that the command is robust, and rejects external interventions.

• Signals (square and sinusoidal) with presence of disturbances

Still in the same perspective of robustness tests, we impose on the setpoint, signals of square and sinusoidal shape with introduction of disturbances in the form of an impulse train on the position of the ball. The simulations are shown in Figures 29, 30 and 31.

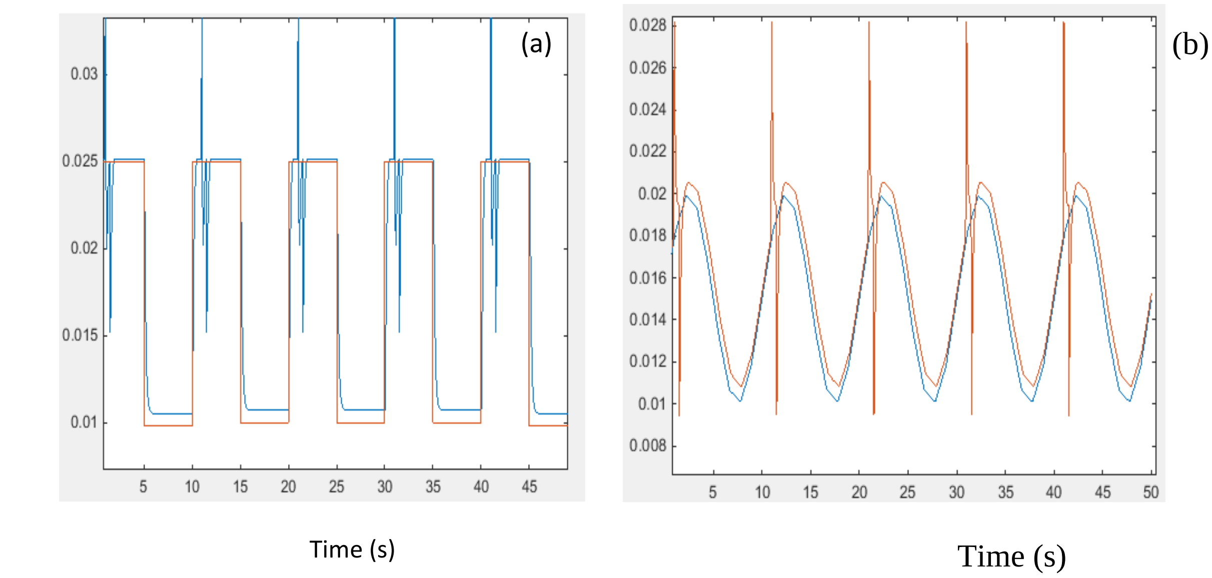

Fig.29. Position of the ball with introduction of disturbances

(a): Square signal

(b) Sinusoidal signal

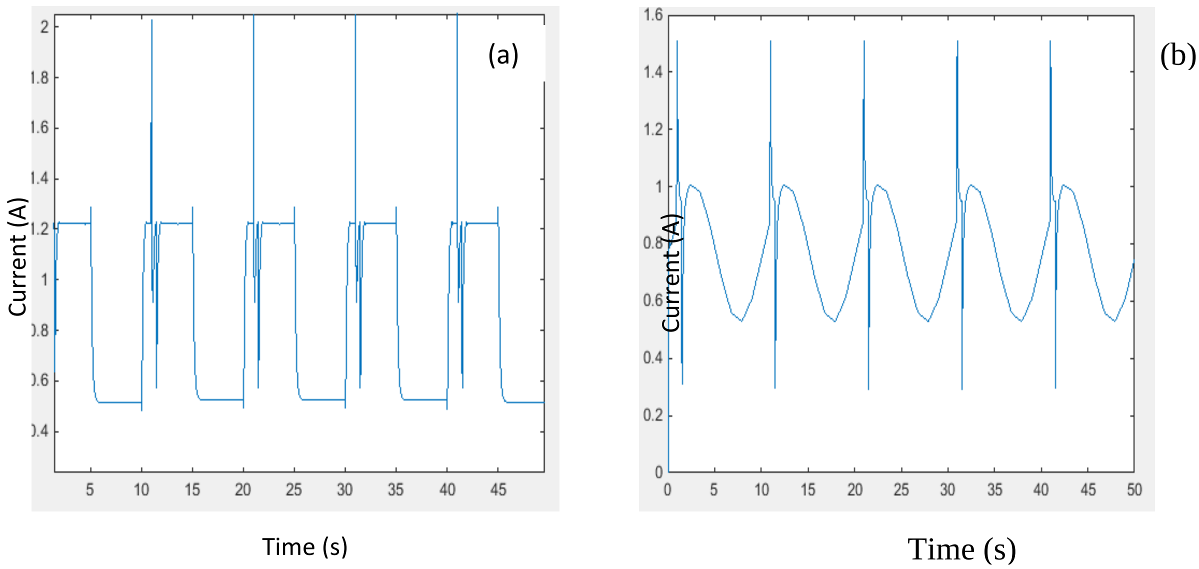

Fig.30. Current in the coil with introduction of disturbances

(a): Square signal

(b): Sinusoidal signal

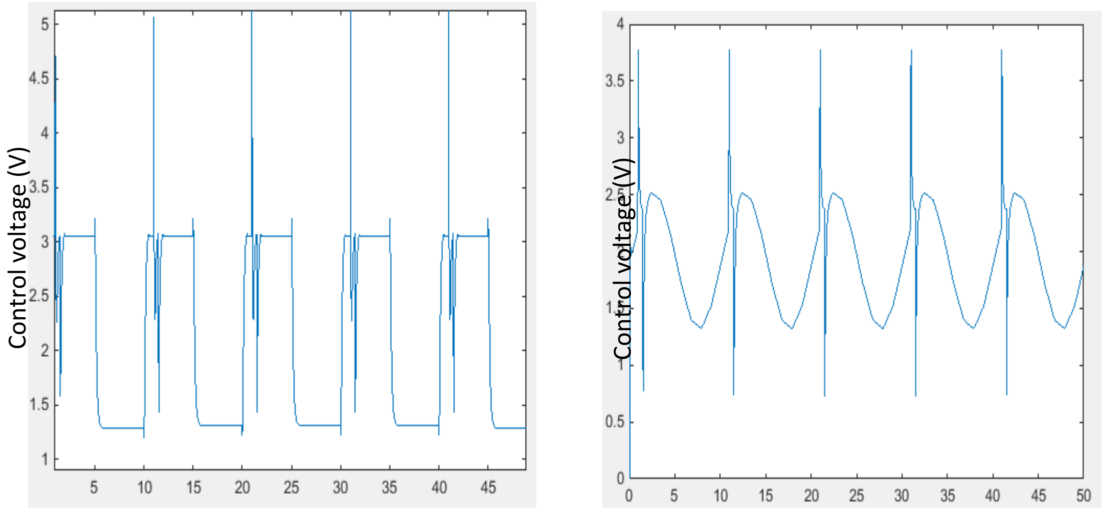

Fig.31. Control voltage with introduction of disturbances

(a): Square signal

(b): Sinusoidal signal

3.5.2. Robustness test of the control for different mass values

Finally, we end up testing the robustness of the control against changes in the mass of the bale. We sketch here in Figures 32, 33, 34 and 35, the position of the ball for the different masses.

• m = 40g

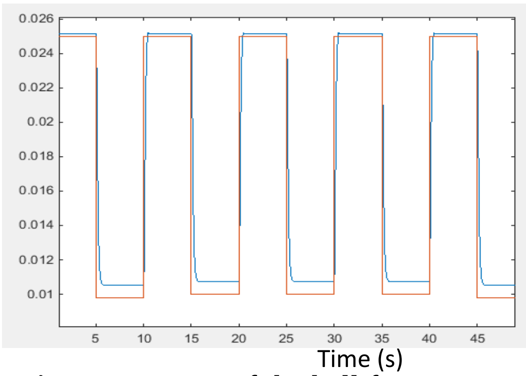

Fig.32. Position of the ball for m = 40g

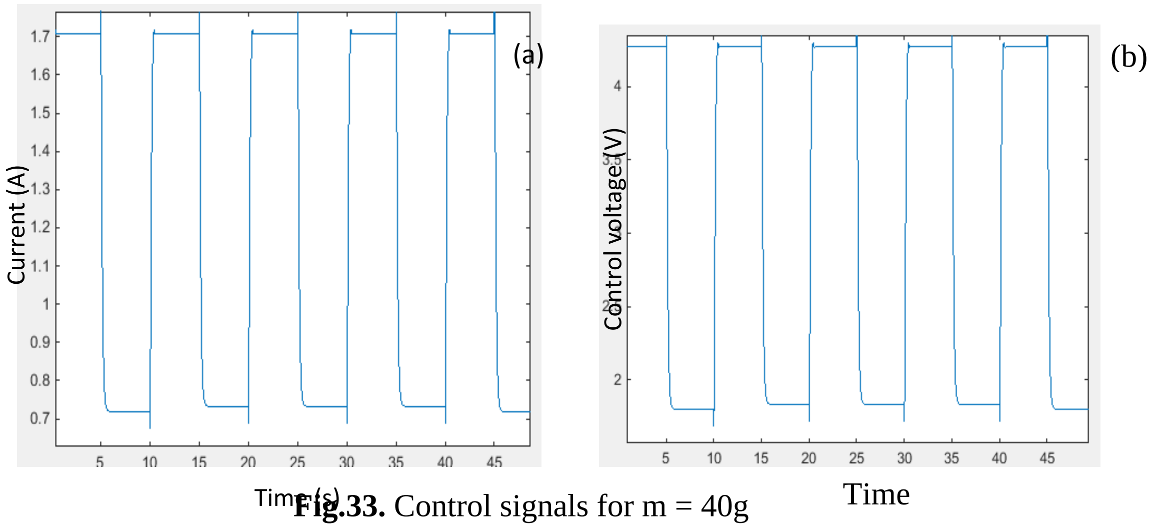

Fig.33. Control signals for m = 40g

(a) Current

(b) Control voltage

- **m=60g**

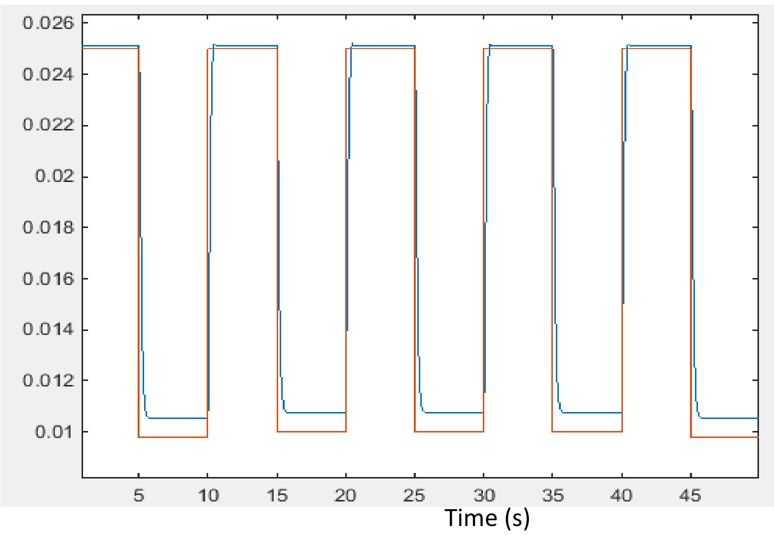

Fig.34. Position of the ball for m = 60g

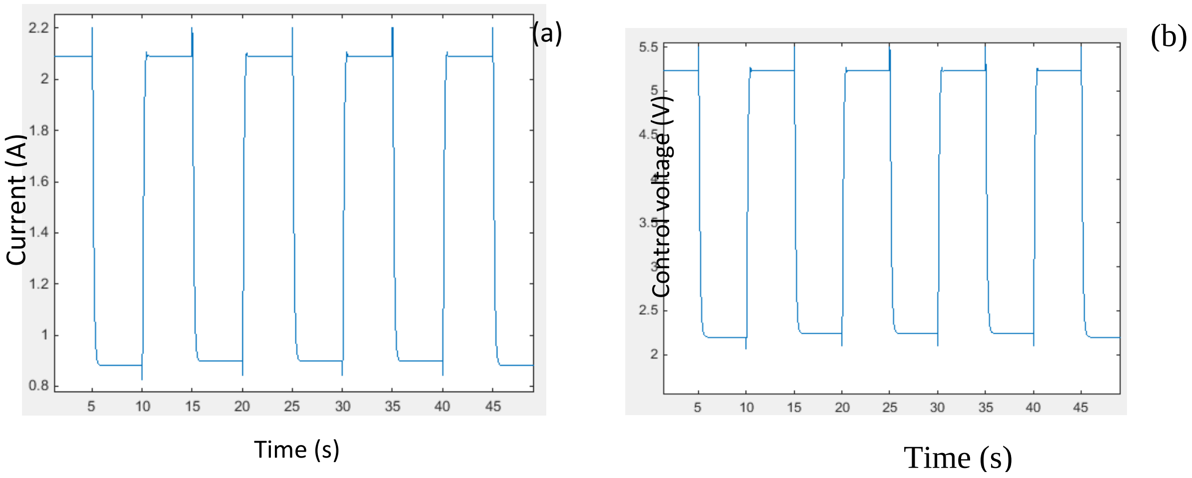

Fig.35. Control signals for m = 60g

(a) Current

(b) Control voltage

- **m=100g**

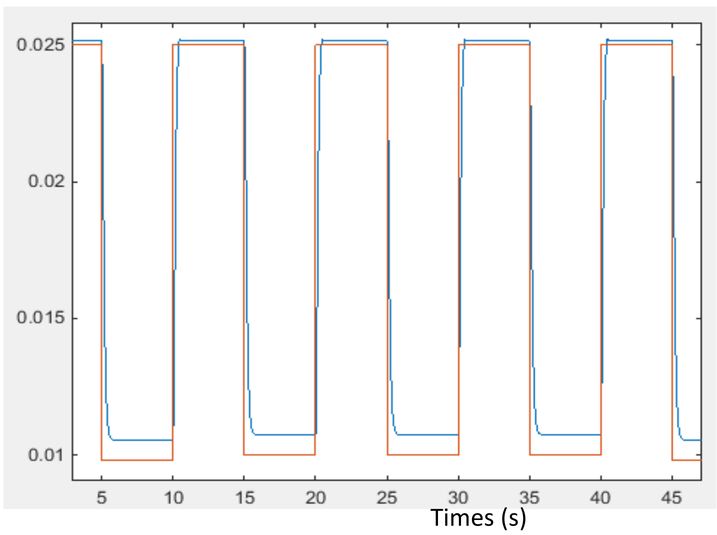

Fig.36. Position of the ball for m = 100g

- **m=130g**

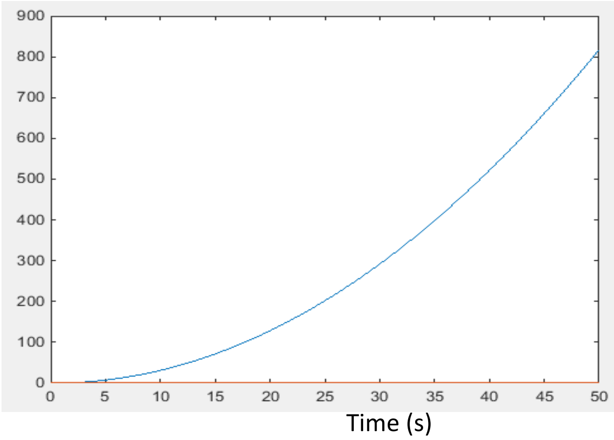

Fig.37. Position of the ball for m = 130g

We can see from the figures that our system remains robust for a mass reaching 100g. However, for m = 130g, the electromagnet fails to suspend the ball (Figure 37). In addition, we noted that for m = 60g, the tension exceeds by 0.6 v the imposed threshold. For all these reasons and as such.

3.5.3. Comparison of step responses

In order to analyze the system responses, we will plot on the same graph all the responses using the regulators (phase advance, PID, fuzzy logic) [6] and sliding modes. The simulation results are sketched in figure 38.

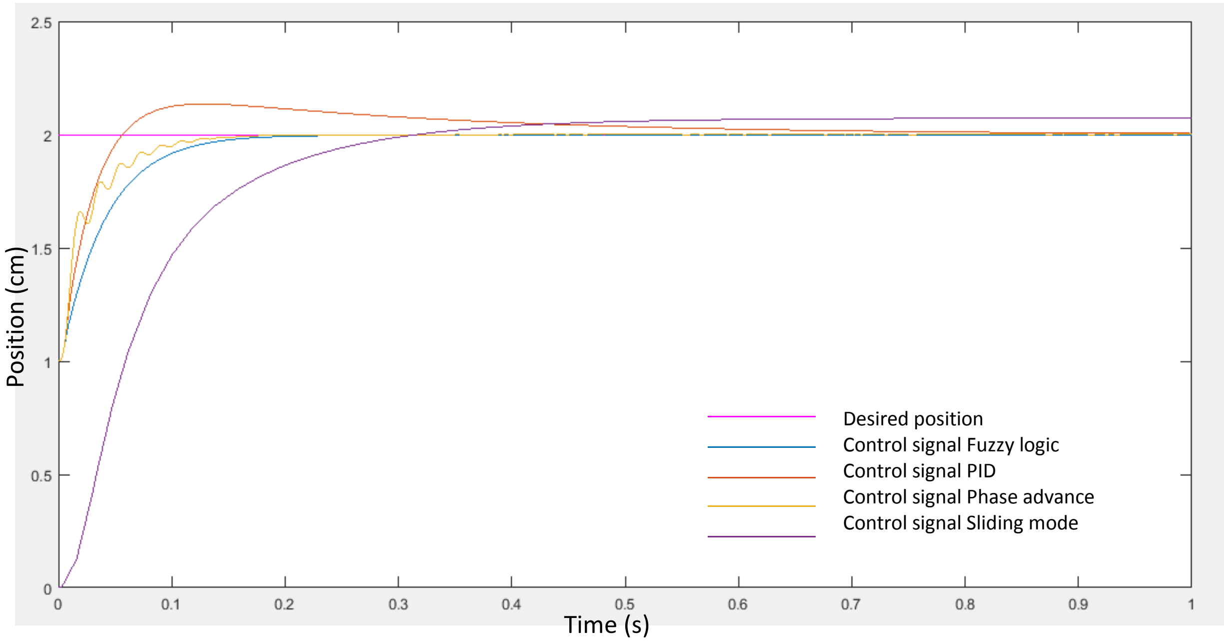

Fig.38. System step responses

We note from a speed point of view, the fuzzy regulator and the phase advance have a low response time compared to the other regulators. However, the static error remains low for a PID and phase advance. This error is around 5% for a slip mode regulator.

4. COMPARISON BETWEEN REGULATOR CONTROL SIGNALS

This step is very important, since we will analyze the behavior of the control signals.

According to Figures 39, 40 and 41, and at the transient level all the control signals have sudden oscillations and variations in the control, except for the control by sliding mode the behavior is different, the regulator output varies gradually until stabilization in the steady state.

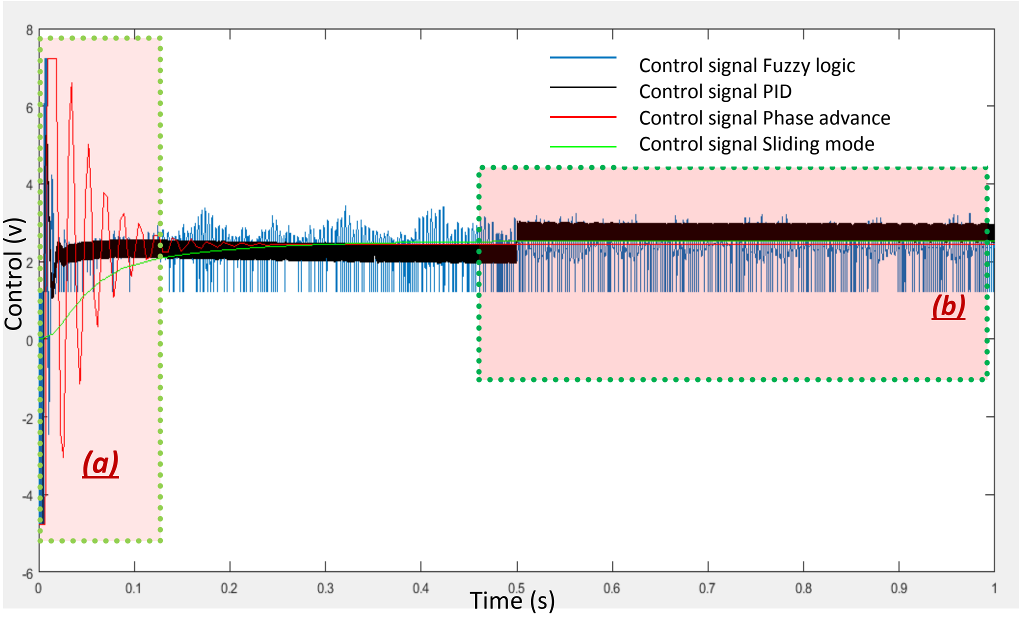

Fig.39. Different control signals

(a) Transitional order regime

(b) Permanent order regime

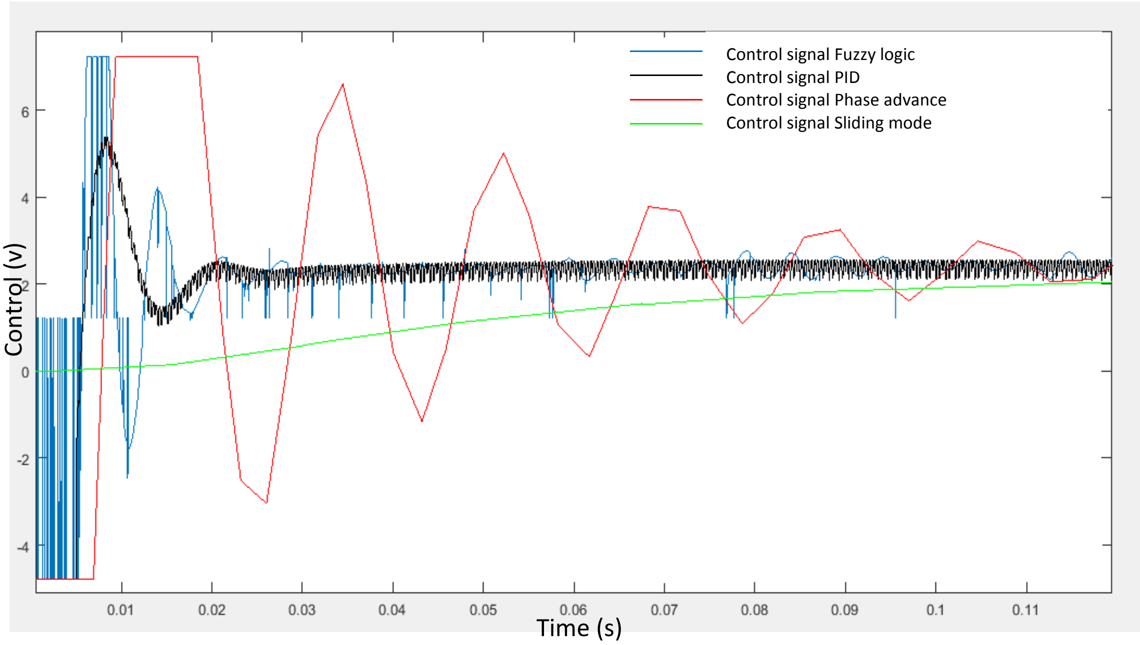

Fig.40. Zoom on part (a) of the control signals

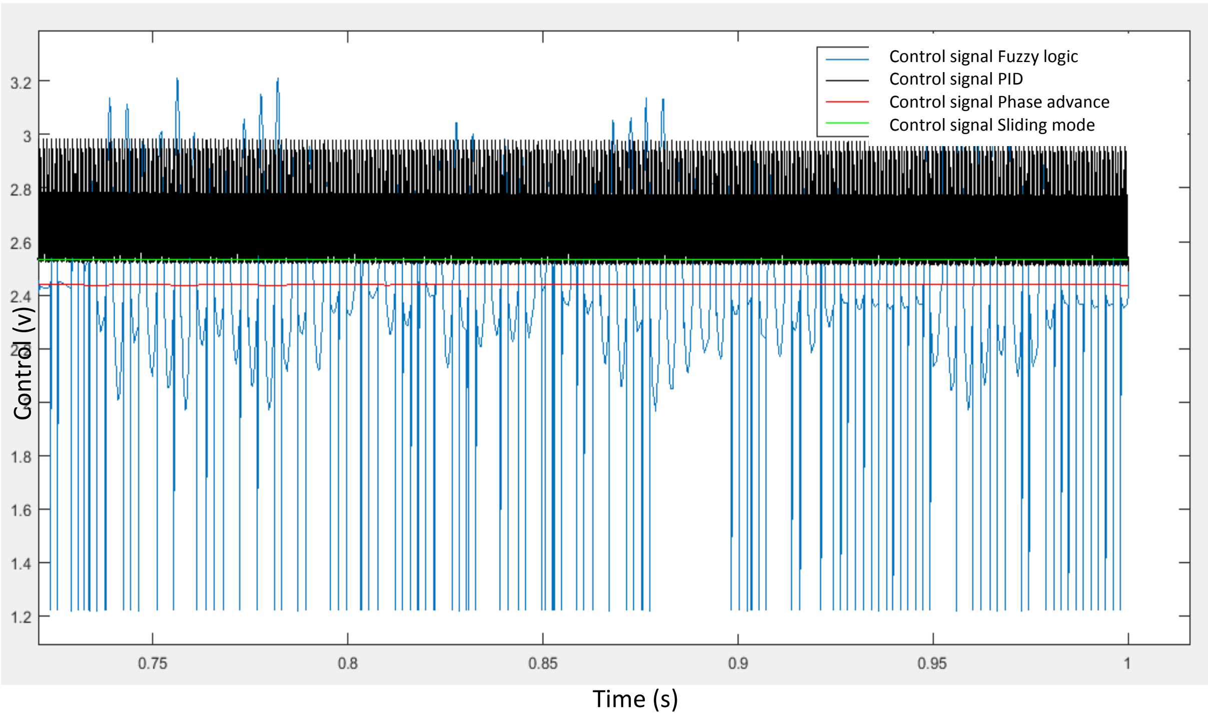

Fig.41. Zoom on part (b) of the control signal

4.1. Comparison of the step response with the introduction of **disturbances**

Figure 42 represents the responses of the corrected system using the different regulators with the introduction of disturbances on the position of the ball.

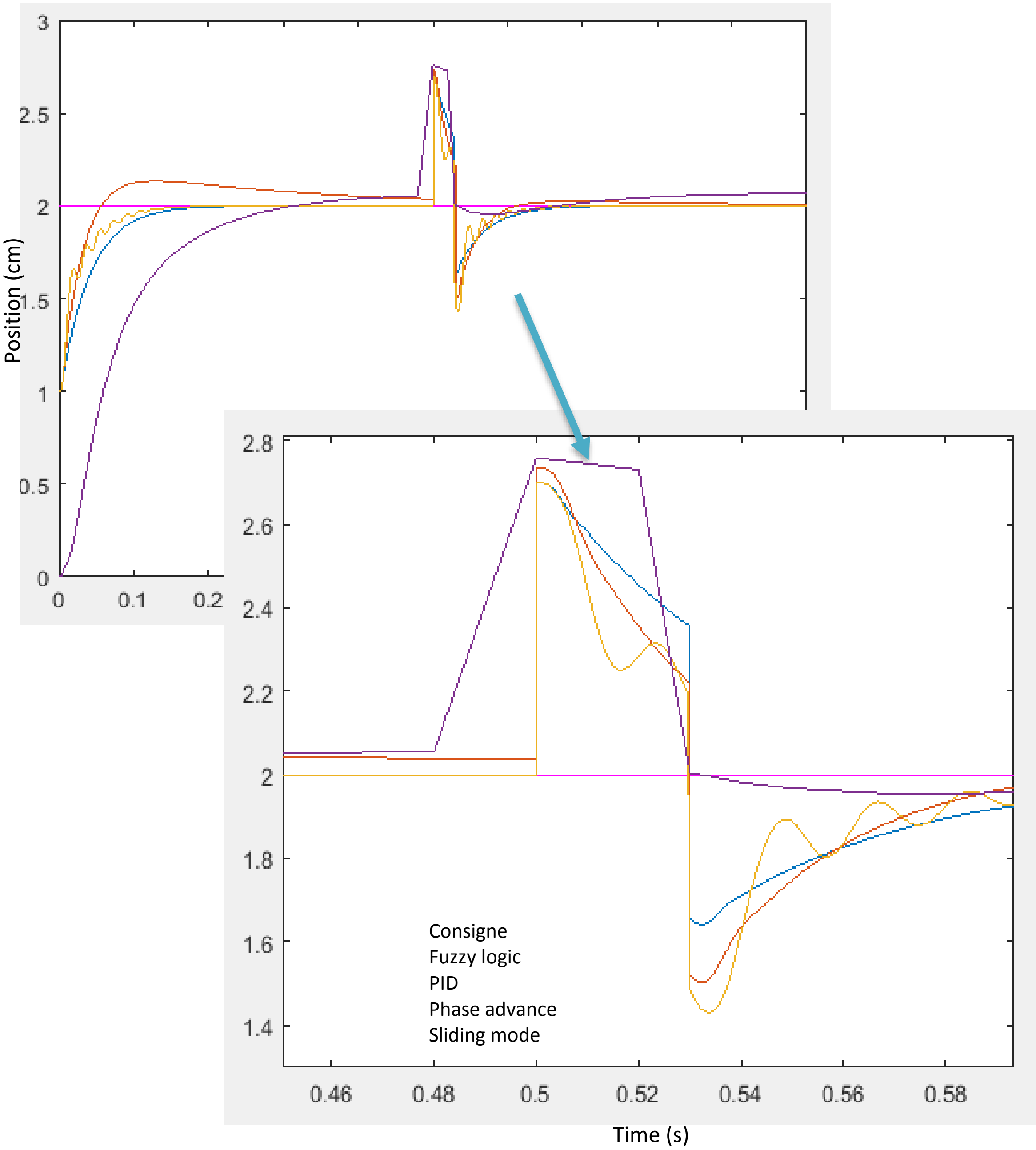

Fig.42. Step response with disturbances

It can be seen that the control by sliding mode remains robust with regard to disturbances. We can conclude that the sliding mode and fuzzy logic commands are robust, which confirms the validity of this type of command.

4.2 Comparison of the step response with changes in mass

Figure 43 shows the response of the system by replacing the 20g bullet with another 60g bullet. Correction by slip mode remains robust against changes as well as PID. However, the fuzzy regulator has too low a static error and this is quite remarkable for the phase advance.

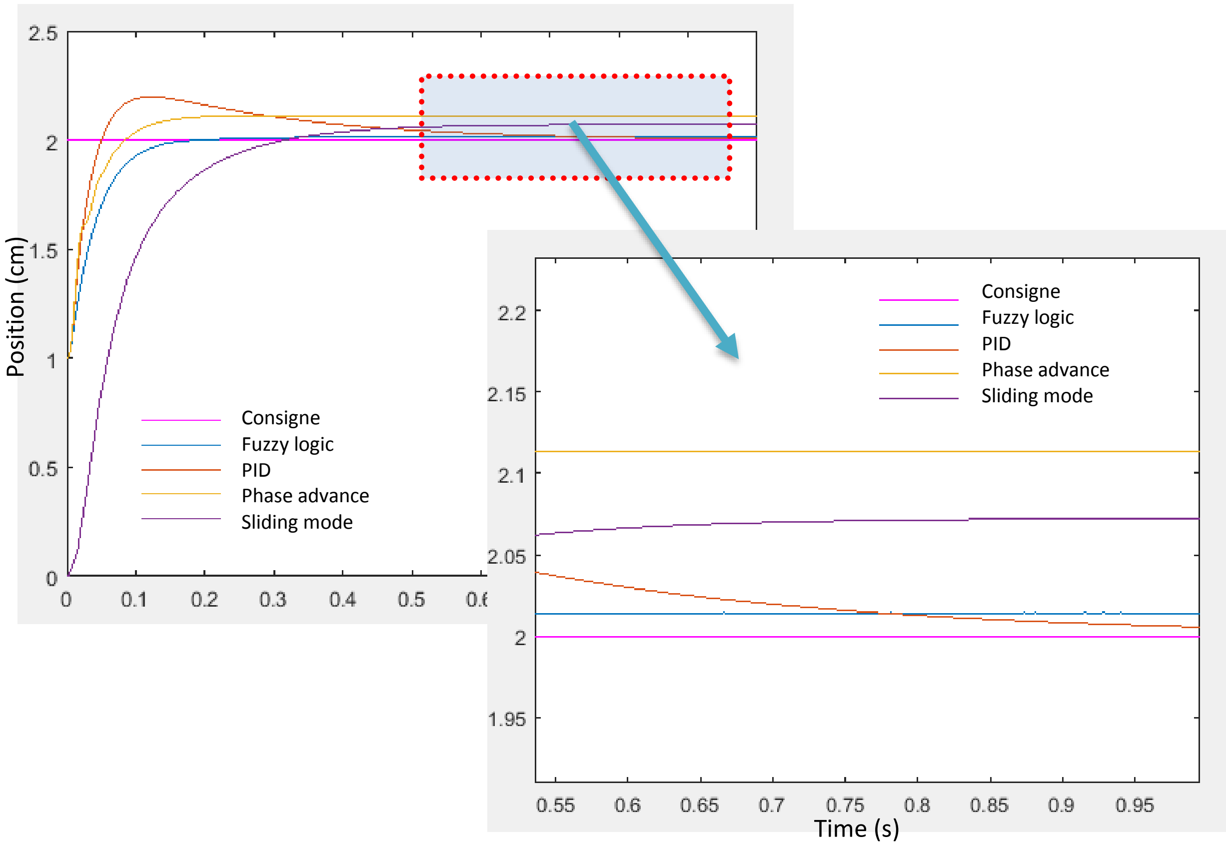

Fig.43. Step response for m = 60g

5. CONCLUSION

In our study, we examined the performance of synthesized regulators. The results obtained by simulation are encouraging.

Our comparative study was developed with the aim of showing the advantages and disadvantages of each type of control.

In this work, we have examined the operation of the magnetic levitation system using the sliding mode setting. The objective of this work was to find a robust command for the control of a highly unstable open loop system.

First, we were interested in the sliding mode technique to synthesize the regulator using the nonlinear model of the system, the simulation results show the merits of this technique. The suppression of the chattering phenomenon was achieved by replacing the sign function with the Saturation function.

This study opens up new perspectives in a very important field of research and development which is the control of nonlinear systems. We can consider using the neural or neuro-fuzzy approach for control. The neural approach allows not only to establish important analytical relationships for the control phase, but also great flexibility since there are no restrictions as to the number of parameters of the system in input and output.

6. REFERENCES

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