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Hardware-In-The-Loop for the Design and Testing of Control Systems

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Abstract

The concept Hardware in the Loop (HIL) has a large field of applications as simulation, analysis of performance, and dynamic control of systems, among others, owing to its operation in real time. In this work, is shown a control system for a hydraulic pump driven by an electric motor, which supplies with fluid a tank arranged for the product. The pump and the motor correspond to a second order system, which when is joined to the tank makes a system of third order. This system is discretized by means of the technique of zero-order hold ZOH representing the mathematical model in the Z plane, later differential equations and solved using the simulation technique was implemented for HIL. The plant is implemented on an ARM STM32F407VG, its response to a step input through the physical signal generator was tested, and its operation is displayed on the screen of an oscilloscope. This experience allows conclude that the technique of HIL is established as an effective, fast and inexpensive way to simulate a plant and develop control dynamics, optimizing time and resources for completing a project..

***Keywords**: Discretization, mathematical model, Differential Equations, Simulation, Hardware in the loop, Analog Digital Converter (ADC), Digital Analog Converter (DAC)*

1. Introduction

HIL concept has a wide range of applications such as simulation, control, monitoring and analyzing performance of different types of systems. This technique is commonly directed toward reducing costs and production time [1]. HIL implementation in different types of development allows the simulation of different electrical elements of nature, such as sensors and actuators under development structure in real time.

HIL acquired considerable importance in the implementation of control systems, and simulation techniques using embedded devices. Thus facilitates the development of hardware cycles, creating reliable models plants [2]. Taking as an object of study this type of dynamic models by HIL an approach to the performance of the real system would be achieved, allowing an analysis of an ideal model, which is commonly not taken into account, disturbances and uncertainties that could arise from the physical world [1].

In the field of systems performance simulation, there are developments such as [3], where the concept of HIL is implemented, for flight tests on a UAV model within a virtual environment. Besides the above in [4], the simulation of a climate driver on the interior of a car is developed, based on the models of the heating, ventilation and air conditioning. Furthermore, in [5] is developed a mechatronic system, for monitoring the vibration of a mechanical part, during a milling process by predicting the behavior of the device, showing the importance of HIL, in applications where is essential the implementation of real-time systems.

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By HIL it is possible to develop interfaces, which allow analyze different types of variables, in the case of [6], where this technique is used, in order to make an approach to the braking tests, of a platform motion from a train. Also using the characteristic of real-time operating, oriented to the control of dynamic systems, as in [7] where HIL is used, in order to make a traction control of a vehicle in a test bank, using a fuzzy control algorithm, which controls the speed of the wheels, by a TargetTM xPC.

This work is intended to apply mathematical models derived from a third order plant in an embedded ARM STM32F407VG card, using as input some types of signals such as step and sinusoidal produced by a waveform generator, showing the behavior of the control developed in the computer, using a digital output displayed on the oscilloscope. In this paper, the development of the mathematical model of a first order system is shown, discretizing the transfer function of the system, thus achieving the analytical solution. The results are validated through of a numerical simulation.

At the beginning of the work, an introduction is performed to the concept of HIL, enunciating some of its main features as well as some works that demonstrate some of their uses. In the second section, is presented the plant under study, along with its application in industry and its utility. Later is performed the mathematical development of the entire system by exposing each of the dynamic models of the subsets that conform it. There is evidenced the implementation of a discrete PID control, developed in the LabView® software. In the following section, are shown the results obtained from the control, and the behavior of the plant. These results also will be analyzed to show the effectiveness of the proposed solution, by analyzing the data and graphs obtained. Finally, some conclusions are presented during the course of this work, also raising some prospects for future development, which allow give depth to the subject matter.

2. Methodology

A. Development Structure

Using the Figure 1 it is exposed the structure of the solution in the system, where are shown the variables in the present algorithm. An embedded ARM board is used to program the dynamic model of the plant under study. This card allows implementing an analog output, which is fed into it by using an ADC conversion module, which also obtains the Set-Point of the system, in order to get the system error.

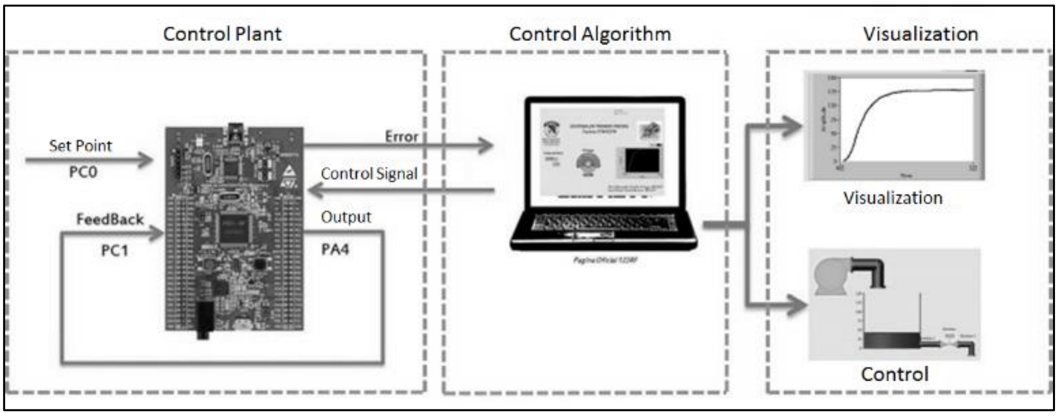

Figure 1. Development Structure

Through the communication module card, it is sent the error signal to the computer system, where is programmed the control algorithm. This is made in order to get a signal, which allows to the system follow the desired behavior for the user. Also by using the computer is disposed a visualization module for displaying the behavior of the plant, which is confirmed by the measuring instruments, as shown in III.

B. Filling System of Containers

Figure 2 allows observing the subsets of the system, electro pump and the container; all of them make the plant under study. There also variables like Q, which describes the flow of liquid pumped by the active element. Furthermore the variable H corresponds to the value of the liquid level within the container, whose output flow is limited by R corresponding to the flow resistance of liquid in the container outlet.

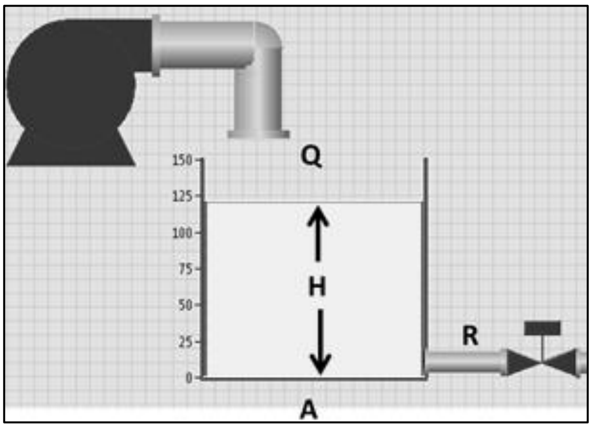

Figure 2. Filling System

The system shown in Figure 2 can be represented by a block diagram, as shown in Figure 3. There is observed, the input value V (S) of the hydraulic pump motor, whose output is the angular velocity W (s). Thereafter this variable W (s), converts hydraulic actuator capacity, in a hydraulic flow Q (s). Finally the container will get a liquid level H (s) from the flow rate Q (s) provided by the hydraulic pump.

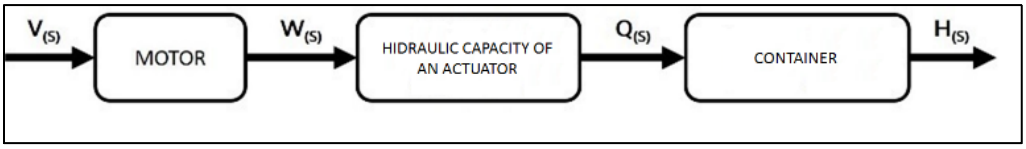

Figure 3. Block Diagram in Open Loop

A. Modeling Hydraulic Pump

The function of the hydraulic pump in the system is to provide a pressure able to move the working fluid at a rate required along a hydraulic installation of length l. This device comprises an electric motor coupled to an inertial load, which is achieved pump liquid through the increasing of pressure and speed.

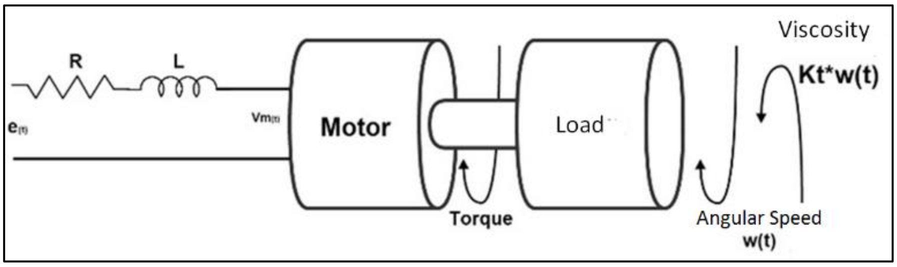

Figure 4. Motor Equivalent Model

Additionally, the motor converts electrical energy into mechanical, from an electromechanical system, comprised of a circuit armature winding [8]. Figure 4 shows the schematic of a DC motor is shown, whose output is the angular velocity W (s) related directly to an input voltage V (s).

The torque provided by the motor is used to move an initial charge with a mechanical moment J, conformed by a fluid impeller, the motor shaft and drive the working fluid. The moment of inertia of the load expressed in (1), will be equally the sum of the moments of each of the elements [9], which affect the rotation of the actuator.

$$J = J_{Eje} + J_{Impulsor} + J_{Fluido} \qquad (1)$$

For the present development is taken as a basis an electric pump with a closed radial impeller [10], which resembles the geometry of a disc, allowing simplify obtaining the moment of inertia expressed in (2), which is given by mass MI, and the radio RI of the impeller [9].

$$J_{Impulsor} = \frac{M_I R_{Impulsor}^2}{2} \qquad (2)$$

Furthermore, the inertial moment of a liquid in a hydraulic line length l, is defined by the fluid density ρ work, and its cross-sectional area [11], related as shown in (3):

$$J_{fluido} = \frac{\rho l}{A} \qquad (3)$$

Once having the motor parameters configured to feed pump, it is analyzed the relationship between the torque developed, the armature current. The input voltage and the output speed for a given load is analyzed by mass represented inertia J. this parameter, for obtaining the hydraulic pump in the pattern shown in (4), which corresponds to the angular velocity output, to an input voltage [8].

$$\frac{W_{(s)}}{V_{(s)}} = \frac{K_T}{S^2 + S\left[\frac{JR + BL}{JL}\right] + \left[\frac{K_T^2 + BR}{JL}\right]} \qquad (4)$$

In the case of the model is taken as a reference of rotary positive displacement pump [10], which together with its electri9c motor generates an output flow Q (s) under input voltage V(s) electric motor and Cv of volumetric capacity, as presented in (5).

$$Q_{(s)} = C_v W_{(s)} \qquad (5)$$

Finally, the expression shown in (5), allows to find the transfer function of the propulsion system of the working fluid, establishing a relationship between the inlet flow Q(s) to the tank A, and the input voltage to the system V(s), which can be expressed as set forth in (6).

$$\frac{Q_{(s)}}{V_{(s)}} = \frac{C_v K}{S^2 + S\left[\frac{JR + BL}{JL}\right] + \left[\frac{K_T^2 + BR}{JL}\right]} \qquad (6)$$

B. Container Model

A container liquid level rises inside H, according to the amount of fluid entering per second Q. By Figure 5, is expressed the arrangement of the plant referred to this development.

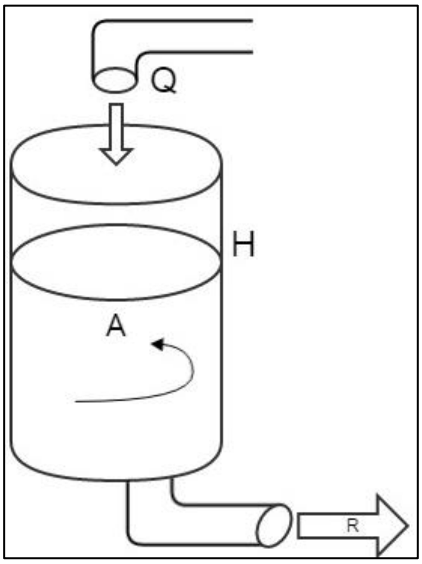

Figure 5. Equivalent Container Model

The equivalence of the dynamic model of a container [12], expressed in terms of the complex variable results (7). There, is shown the transfer function of the system, whose input is the flow of caudal Q, from which a liquid level H is obtained on the container A.

$$\frac{H}{Q} = \frac{1/A}{S + \frac{\rho g}{RA}} \tag{7}$$

C. Plant Model

Finally, in order to reduce the complexity of the transfer function of the system (11), the variables are defined a (8) b (9) and c (10), which form part of the model of open-loop system shown in Figure 3.

$$a = \frac{\rho g}{RA} \tag{8}$$

$$b = \frac{JR + BL}{JL} \tag{9}$$

$$c = \frac{K_T^2 + BR}{JL} \tag{10}$$

The transfer function of the open-loop system is the product between the transfer functions of the electric motor, the pump and its volumetric capacity, together with the model of the container. Finally, the relationship between the supply voltage V of the hydraulic pump V(s), and the liquid level H(s) is obtained, forming the plant under study for the present development.

$$Gp_{(s)} = \frac{H_{(s)}}{V_{(s)}} = \frac{(C_v\, K)/A}{S^3 + S^2[a + b] + S[c + ab] + ac} \tag{11}$$

D. Plant Discretization

Once it is obtained the transfer function of the plant under study, then it is proceed to bring this equation in continues time to discrete time. During this development, is used the method of discretizing Zoh zero order retainer [13], the general expression is shown in (12).

$$G_{(s)} = Gzoh_{(s)} * Gp_{(s)} = \frac{1 - e^{-Ts}}{s} * Gp_{(s)} \tag{12}$$

$$Gp_{(z)} = (1 - z^{-1}) * \mathcal{Z}\left[\frac{Gp_{(s)}}{s}\right] \tag{13}$$

After applying this technique of discretization, is obtained the mathematical model of the plant in the Z domain [12], presented in (14) using the n coefficients arranged in Table 1.

$$\frac{H_z}{V_z} = \frac{n_1 Z^{-1} + n_2 Z^{-2} + n_3 Z^{-3}}{1 + d_1 Z^{-1} + d_2 Z^{-2} + d_3 Z^{-3}} \tag{14}$$

By the Table 1, are shown the values of n coefficients found in the discretization process of the plant.

Table 1. Coefficients of the Differences Equations

COEFFICIENTS	
$d_1 = -0.78$	$n_1 = 0.21$
$d_2 = -2.4x10^{-9}$	$n_2 = 0.013$
$d_3 = -3.3x10^{-18}$	$n_3 = -2.4x10^{-11}$

Applying the properties of the Z transform [14], the displacement and proportionality to the equation presented in (14), are obtained the relationship in differences shown in (12).

$$H_k = n_1 V_{k-1} + n_2 V_{k-2} + n_3 V_{k-3} + d_1 H_{k-1} + d_2 H_{k-2} + d_3 H_{k-3} \tag{15}$$

Then it will be (15), the difference equation of the plant will ultimately be implemented in the embedded system, which is a function of k iterations in this case. Thus, is proposed an approximation of the dynamic behavior of the real plant, in the discrete time.

E. PID Controller.

For this development, it is proposed to implement the strategy of PID control in equation (16), due to the integral action eliminates the error in stable, which is stabilized by adding an action of proportionality [15] . Besides the above, by adding a derivative effect on the plant, is achieved anticipate changes in the control process, achieving stabilization of the fluid level in the tank in less time [12]. Moreover, since the plant has order 3, with the addition of this action of order 2, is provided the definition of the behavior of the plant, based on the response time [8].

$$\frac{C_{(s)}}{E_{(s)}} = \frac{K_d S^2 + K_d S + K_i}{S} \tag{16}$$

It is recommend using the same technique of discretization in both the controller and the plant, in order to avoid delays related to the sampling times T and its interference on math. In this order of ideas by Zoh discretization strategy [12], the PID controller is taken to the Z domain as is shown in (16), achieving an expression dependent of Kp, Ki and Kd factors, shown in (14).

$$\frac{C_{(Z)}}{E_{(Z)}} = \frac{K_d + Z^{-1}\left[K_p + K_i T - K_d\right] + Z^{-2}\left[K_d - K_p\right]}{1 - Z^{-1}} \quad (17)$$

With the system represented in delays, it can be used of the properties of the Z transform [14], in order to obtain the spatial representation of iterations k shown in (18). This mathematical model of the controller, dependent on previous control action C (k-1) and E and error iterations, given by the difference between the fluid level and the desired obtained.

$$C_k = C_{k-1} + E_k[K_d] + E_{k-1}\left[K_p + K_i T - K_d\right] + E_{k-2}\left[K_d - K_p\right]) \quad (18)$$

It is disposed of difference equations of the controller (18) in the computer, which takes as an input the error signal from the ARM and responds to a step input, entered by hardware type via a wave generator using the ARM. Once it is obtained the result of the algorithm from the controller, is sent the control signal to the plant implemented in hardware (15). The result of the plant controlled, is shown by the oscilloscope to the output of the plant.

3. Results

As a result it was developed a simulation and visualization platform to control a dynamic system based on the concept of HIL. In the Figure No 6 is exposed the UI, which can displays the error signal of the system and the control action using a digital voltmeter. In the user interface, also it can be altered the constants of the control algorithm.

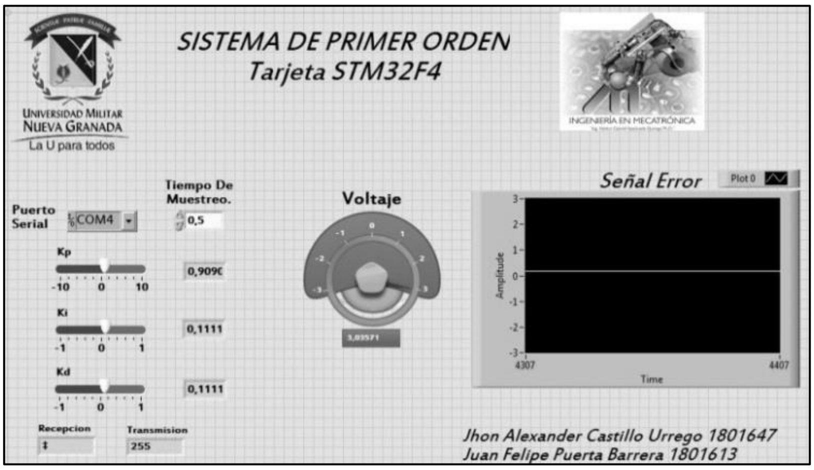

Figure 6. User Interface

Figure 7 shows the system response due to the control constants Kp = 1; Ki = 0.5; Kd = 0.1; which provides a under-damped signal with a settling time of 15 seconds, taking into account the sampling time of 0.5 seconds.

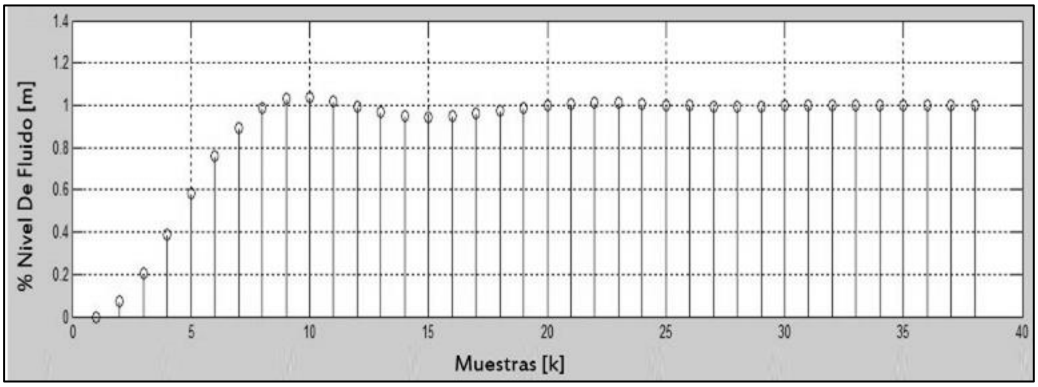

Figure 7. Output of the Control System

When is made a comparison of the expected system response that is obtained, against the one shown in Figure 8, is observed a sensible change in the type of response, this is due to the accumulation of arithmetic errors.

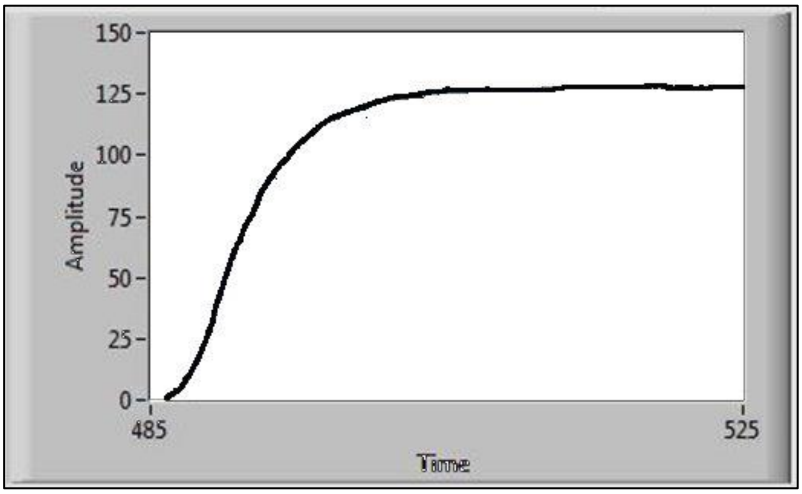

Figure 8. System Response

Figure 9 shows the behavior of the error through a number of samples. Where it can be observed that the input signal to the computer can be negative, that means the need of a signal conditioning, for the purpose of ensure that the system has the ability to detect negative errors due to the overlap of this, which could cause problems in the control algorithm.

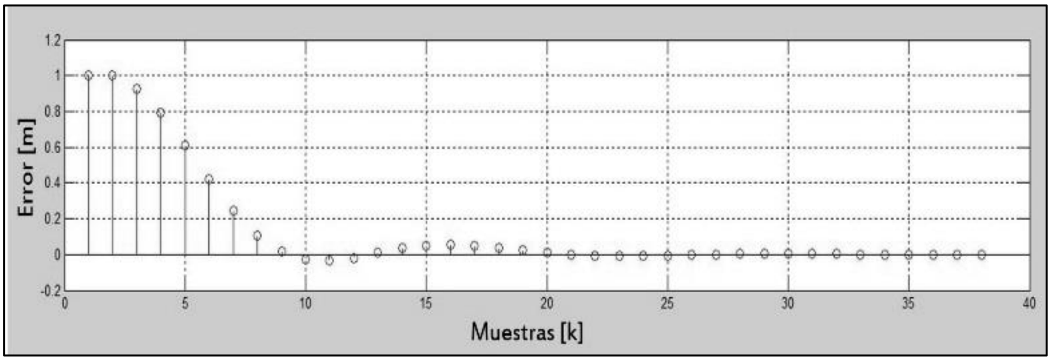

Figure 9. Expected Error

In Figure 10 is show the error signal decreasing almost to zero where it stays stable, however, it can be appreciated that the steady-state error is not zero. This occurs due to the ARM used was configured to read the password in a buffer of 12 bits, but it was necessary to condition the signal in an 8-bit for sending it. Moreover, it should be proposed a regression for handling the limit of the negative error, which affects the display of it.

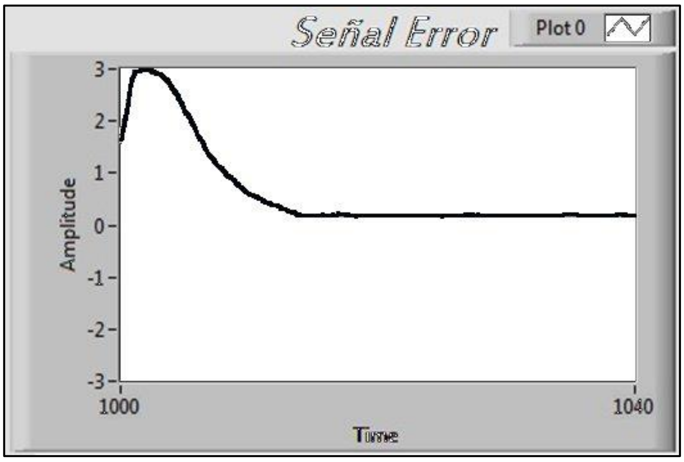

Figure 10. Obtained Error in Steady State

It was performed a system validation with a step input from a generator with a frequency of 50mHz, Obtaining the behavior shown in Figure 11, where it can be appreciated, the system responding in an appropriate way. Also it was observed a signal delay, close to three units due to the nature of the system, which depends on three backward variables in space time.

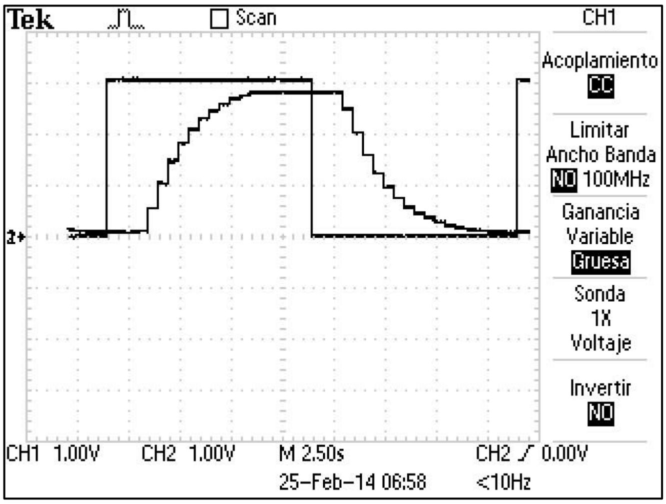

Figure 11. Response of the System to a Step Input

In Figure 12 is observed the system behavior, with a sinusoidal input, where it can be illustrated both the delay and the loss in the gain, discarding by this way the signal type, as the main cause of these problems.

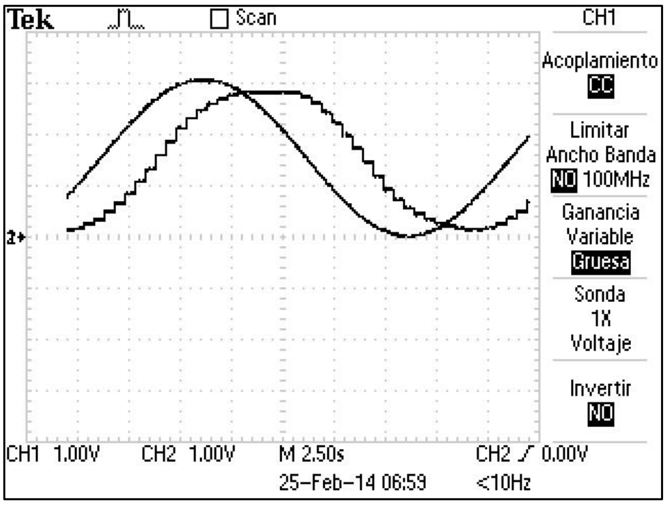

Figure 12. Response of the System to a Sinusoidal Input

After making a review and summary of the results it is obtained that the imperfections of delays and gains, are not differing significantly from the behaviors found in physical models, such as those studied in [16] and [17], suggesting that imperfections in these models, have not a great implication in the final results

4. Conclusions

The implementation of dynamic systems within the HIL architecture, it allows to find a close approximation to the behavior of a real system, also speed up the search for the optimum performance of the system.

The quality of the approximation of real systems, compared to dynamic systems embedded, it is dependent directly of the sampling capacity of the devices and the quality of discretization strategy.

In the development of control platforms, based on the concept of HIL is important to use the same discretization technique for both the dynamic system and the control. This avoids problems different problems in the sampling time, in different types of discretization techniques.

It is important to have in count, the setting of the size data, according to the smallest buffer available in transmission operations, reading and writing ADC - DAC. This in order to avoid problems with the proceeds of the system, as it is explained in section III. These problems may produce a loss of data and as a consequence a loss of accuracy in the process.

It is recommended to realize a physical model in order to make the comparison between the response of the actual dynamic behavior of the system and the embedded system from the control algorithm.

It is proposed developing a diffuse control as shown in [18], with the aim of studying possible changes in the efficiency and the performance of the types of control algorithms using embedded systems such as ARM's. Thus it could be concluded, some limitations and advantages of the HIL concept

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