MODELING OF ACTUATORS FOR UAV CONTROL SURFACES

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***Abstract**: In service actuators are devices of great importance in the control of Unmanned Aerial Vehicles (UAV), where they are used to command the control surfaces of the aircraft. The performance and the stability of the vehicle depend on the adequate modeling of its performance, as well as of the experimental identification of its physical parameters. In the present work the development of an integrated environment for experimental modeling, simulation and control of flight commands for UAV is described. The software LabVIEW was used to develop an automatic system for generation of pulse width modulated (PWM) excitation signals and for reading the actuator response from position sensors of the potentiometric type. The input and output signals are used to identify possible mechanical nonlinearities of the tansmission system, as well as the time of delay in the processing of the pwm command pulses by the internal servomotor electronics. The integrated environment incorporates many options of excitation signals, using for this purpose a data acquisition board NI PCI-MIO-16E-4 DAQ. The input signal is sent to a digital processor PSOC unit that is responsible for generating the PWM servocontrol signal. The servo-actuator is connected to a potenciometric sensor whose output is read by the acquisition board. The input and output signals are analyzed both in the time and frequency domain, with algorithmd for system identitifcation and parameter estimation in the MATLAB environment.*

***Keywords**: keyword: pulse width modulator, Unmanned Aerial Vehicles, identification of its physical parameter, surfaces of control of the aircraft*

1. INTRODUCTION

Servo actuators are devices of great importance to the control of Unmanned Aerial Vehicles (UAV), since they are responsible by the deflection of the primary control surfaces of the aircraft and thence by the control of its attitude. The stability of the aircraft depends, among other factors, of the appropriate modeling of the servo actuators and the proper choice of their physical parameters. The present work presents the development of an integrated hardware/software environment specially designed for the determination of the dynamic characteristics and experimental testing of the control surface actuation system of an existing UAV system. The software LabVIEW was used to interface a data acquisition board NI PCI-MIO-16E-4 DAQ and a digital processor PSoC® to develop an automatic system capable to generate different excitation signals for two types of servo actuator systems, namely a DC servomotors and a pulse width modulation (PWM) radio controlled servomotor. In both cases a potentiometer sensor is used to read the actual control surface deflection. The input and output signals are sampled and stored for use in the identification studies of the dynamic model of the system.

The proposed system is a very efficient test platform to characterize both statically and dynamically the servo actuation system. The system provides a friendly interface to accomplishment the experimental tests in an automated and secure way. In this manner, the user has quick access to the collected data reducing the time for analysis of the results and system model identification. Related to the latter stage, a MATLAB program was created with the necessary functionalities to read the data and to return the models of a first and second order identified model as well as to draw the Bode diagram of the servo actuation system.

2. INTEGRATED SYSTEM FOR SERVOMOTOR EXPERIMENTAL CHARACTERIZATION

The system implemented is composed of basically five subsystems: (i) Servo actuator test bench; (ii) Servo actuator sensor system; (iii) Microcontroller (PSoC) signal actuation system; (iv) NI data acquisition board; and (v) Servo actuators (device under test). A brief description of each subsystem follows.

2.1. Servo actuator test bench

The mechanical test bench implemented to test the servo actuator transmission system is show in Figure 1. The experimental apparatus was built to reproduce the mechanical connection of several control surfaces of the UAV, and to test the servo system operation in load conditions similar to the real flight situation. The mechanical fixture provides support for up to six servo actuation system representing the elevator, aileron, flap, and nose wheel subsystems. As shown in the figure, the control surface and the motor lever arm mechanical assembly forms a four-bar mechanism. The servo motors are mechanically coupled to hinged control surfaces that are loaded by external spring forces. The hinge load torque can be easily modified by changing the spring mechanical compliances and by changing the load arm of the spring connection.

Figure 1. Servo actuator test bench

2.2. Servo actuator sensor system

The measurement of the angular displacement of the control surfaces can be made by 10kΩ potentiometers (*Gefran*, Model PS-11-B-0-103) connected directly to the hinged surfaces, or indirect measurements made by potentiometers connected to the actuation lever of the servomotor. The motor current is also being monitored to infer the torque delivered to the actuation system. The actual torque at the control surface is monitored by a full bridge strain gage force sensor, coupled to main bar of the transmission mechanism.

2.3. Microcontroller On-Chip PSoC®

In this project an “On-chip” microcontroller device of the PSoC® family was used to perform several functionalities of traditional analog and digital systems, including: (i) the generation of PWM pulses with adjustable width controlled by an external PCI data acquisition board; (ii) to provide to the PCI acquisition board, a measurement signal proportional to the servo actuator current. This current is measured by the voltage drop in a 0.4 Ω connected in series with the servo actuator cable; (iii) to amplify the voltage signal from the current signal, since the voltage drop on the measuring resistor is very small; (iv) to provide an analog to digital channel to receive the reference position from the external data acquisition system, and transform the converted digital signal into a PWM signal with a variable duty cycle; (v) to act as a buffer between the PCI data acquisition board and the servo actuator system, since the motherboard is not capable to supply the necessary current for running the servo system. The PSoC generates a PWM signal with the pulse width controlled by a modulating signal generated by the external PCI data acquisition board. The proposed architecture for PWM generation is very flexible, allowing the user to create specific configurations customized to the demands of each individual servo actuator application.

2.4. The Data Acquisition Board

A low-cost, general purpose data acquisition board, model NI PCI-MIO-16E-4 DAQ, was used to monitor the position control signal, the voltage difference in the current measuring resistor and the PWM signal generated by the the PSoC® microcontroller system. The PWM signal monitoring is necessary to monitor the time delay between the reception of the control signal by the actuator electronics and the actual physical response of the servo motor.

2.5 Servo Actuation System

The servo actuator used in these studies was the Hobbico Servo CS-6, in which the position control loop is accomplished with a pulse width modulation (PWM) signal with 50 Hz frequency. This servo actuator possesses an effective actuation range from 0° to approximately 202°. The zero degree position command correspond to a pulse width of 680 μs, corresponding to a duty cycle of 3.4%, and for position control of 202 ° the PWM pulse width is

2380μs, corresponding to a duty cycle of 11.9 %. The block diagram of the closed loop position control system is shown schematically in Fig. 2, where both the position and velocity signals are used to close the loop in a feedback proportional-derivative control law. The block diagram shows how the feedback signal from the potentiometer is used to generate a feedback PWM signal, whose duty cycle is proportional to the current position of the servo actuator system. Several nonlinearities are present is this internal feedback loop including the saturation effects in the pulse generator, pulse stretcher and power drive with an H-bridge system (include reference).

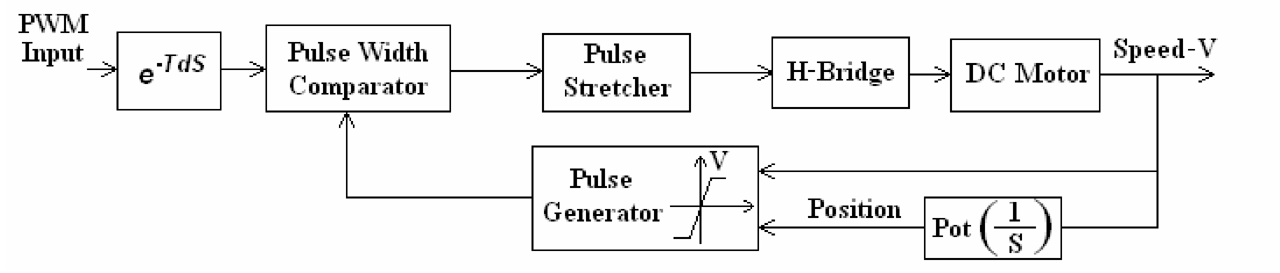

Figure 2. Servo actuator block diagram schematics

2.6 Integrated System Environment for Servo Actutor Testing

An overall view of the integrated environment for the automated testing of the servo actuator system is schematically shown in Figure 3. This figure shows: (i) the data acquisition board integrated to the PCI Bus of a host PC; (ii) the independent PSoC microcontroller and (iii) the mechanical assembly of the servo actuator system. Also shown are the logic functions implemented in the LABVIEW environment in the host PC. The National Instrument data acquisition board (NI PCI-MIO-16E-4 DAQ) sends a control signal, through D/A channel labeled "ao0", to the digital analog converter of the PSoC® microcontroller. This control signal is used to control the duty cycle of the PWM pulse generated by the PSoC®. This control signal is also re-injected into the DAQ board as a reference signal to measure the time delay between the command time and the time to start the PWM pulse. The generated PWM signal is sent directly to the servo actuator system to control the angular deflection of the control surface. A potentiometer coupled to the same axis of the servo actuator generates a voltage proportional to the angular deflection of the control surface. A current measurement in the servo actuator system was accomplished with a low valued measuring resistor (0.4 Ohms), in series with the servomotor. The PWM control signal, the measured position and motor current, are all collected by the NI PCI DAQ board using LabVIEW program. These signals are pre-processed and recorded for further application in the identification algorithm in MATLAB environment.

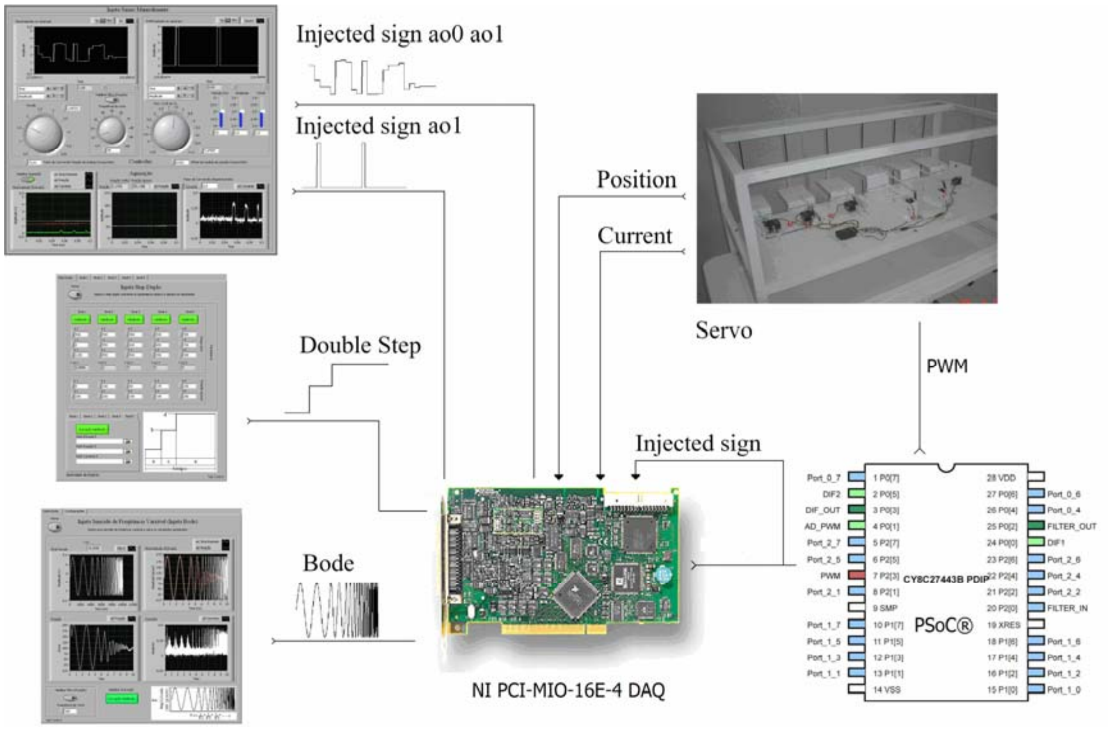

Figure 3. Schematic diagram of the integrated environment for servo actuator testing

3. SYSTEM DESCRIPTION AND USAGE

Basically, the developed LABVIEW program possesses three main functions: (i) to generate a manual excitation of the system; (ii) to generate an excitation signal in the form of a step signal and a doublet signals, and (iii) to generate a swept sine signal for frequency response determination. The first function has as objective to manually control the width of the PWM pulses. In this way, the user can position the control surface manually and can calibrate the null position for the tests. This is especially important when one needs to test different servo units, which may have different limiting and null positions. Besides making possible to configure each servo unit independently, this function also makes possible to send a PWM signal without the use of the PSoC® processor. This option is desirable to allow different PWM frequencies, which may vary among different servo motor models.

Figure 4 shows a screen shot of the displays available in this function. The bottom left of the screen contains a graph of the signals read by the PCI DAQ board, namely the PWM control signal, the potentiometer signal and the current signal. The other graphs, in the second and third window, show a zoom in the position and current signals, respectively. The left control knobs seen in this figure are used to control the dc level of the PWM control signal injected in the PSoC A/D channel, as well as to define the filter bandwidth used to filter the position and current measurements. The control knob on the right allows manipulation of the PWM parameters that are sent directly to the servo actuator units.

The program developed to inject a doublet allows configuring the time and position parameters of the individual pulses, and is capable to make up to five tests automatically. This is the main functionality implemented in the main program that beside the described capabilities to generate and record the position, current and control signals cans also digitaly filter the data and save it for further processing in the MATLAB environment. Typical results of the doublet excitation and collected response is shown in Figure 5. The results are presented in four windows, as shown in Fig. 5, containing the input doublet signal, the output signal and the motor current. The last graph show a superposition of the input and output position in a single graph.

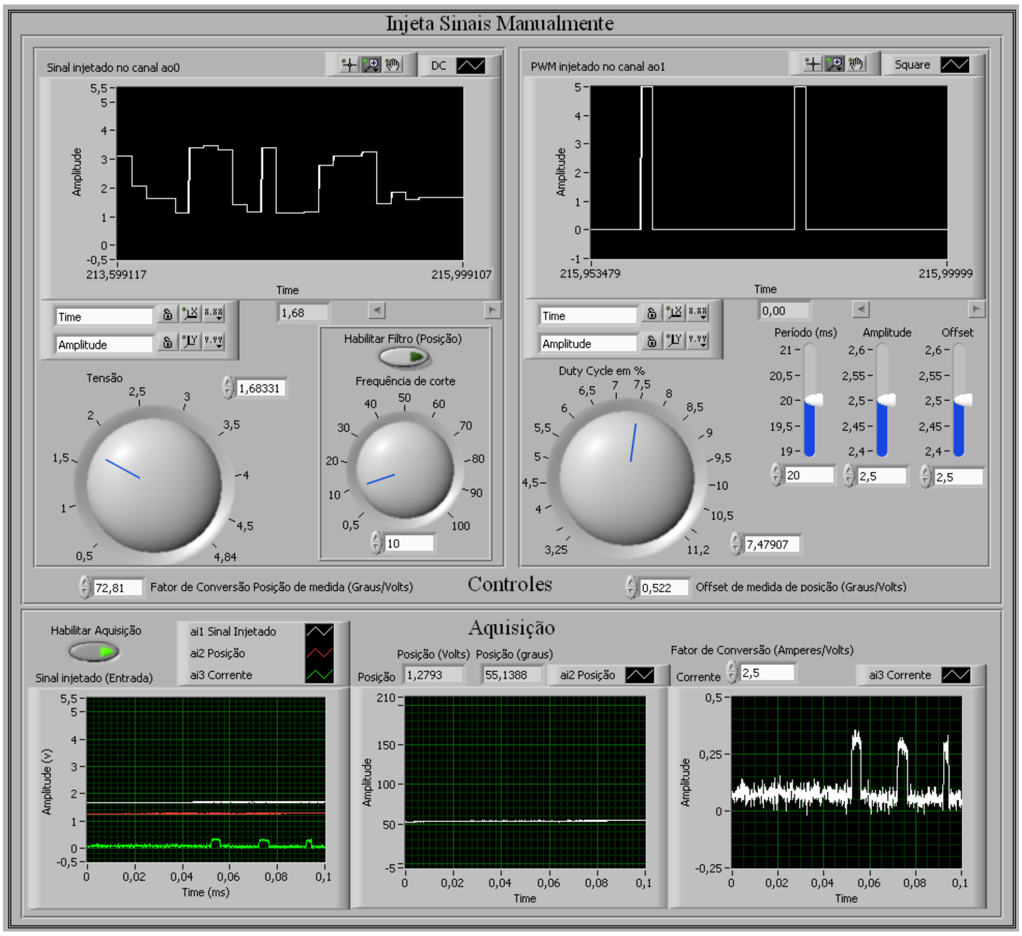

Figure 4. Screen view of GUI to manually generate excitation signals

By last, it was implemented a function to generate a sine wave with variable frequency with the objective to determine the Bode Response of the servo actuator system. The frequencies were defined a priory to be 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 Hz. As in the previous case, besides injecting the sinusoidal signal, the program also allows the recording of the surface position and motor current for subsequent analysis. As before, the analog channels are operated at a sample rate of 20 kHz.

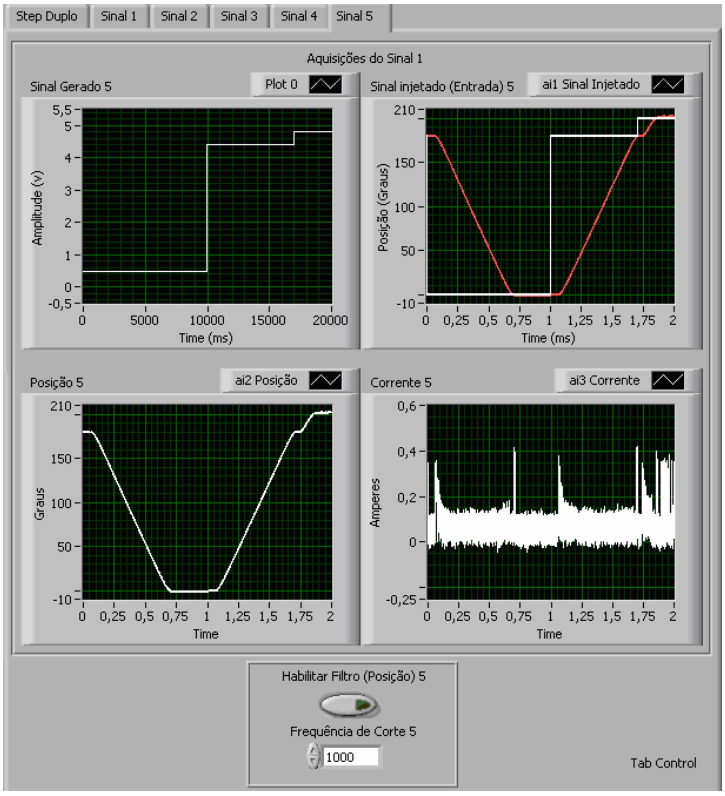

Figure 5. Doublet excitation using VI Express and MATLAB Script

3.1 Experimental Results.

Figure 6 shows the experimental results obtained with a step input corresponding to a 200º angular deflection. The reference signal is shown in blue and the actual angular position in green. Notice that, before the input signal is applied, the measurement system automatically positions the servo unit in a reference position corresponding to 0º. Also shown, in red, is the PWM signal used to control the servo actuation system.

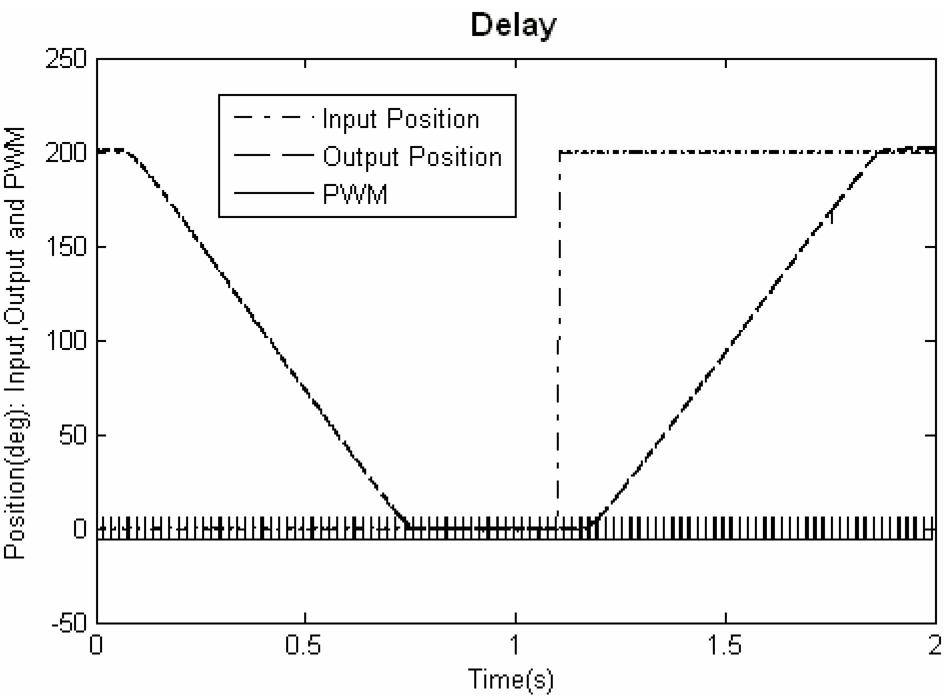

Figure 6. Servo actuator step response

Figure 7 below show an expanded time scale corresponding to initial response shown in Figure 6 above, emphasizing the time delay between the command signal and the time required to change the width of the PWM pulses, and the actual motor response.

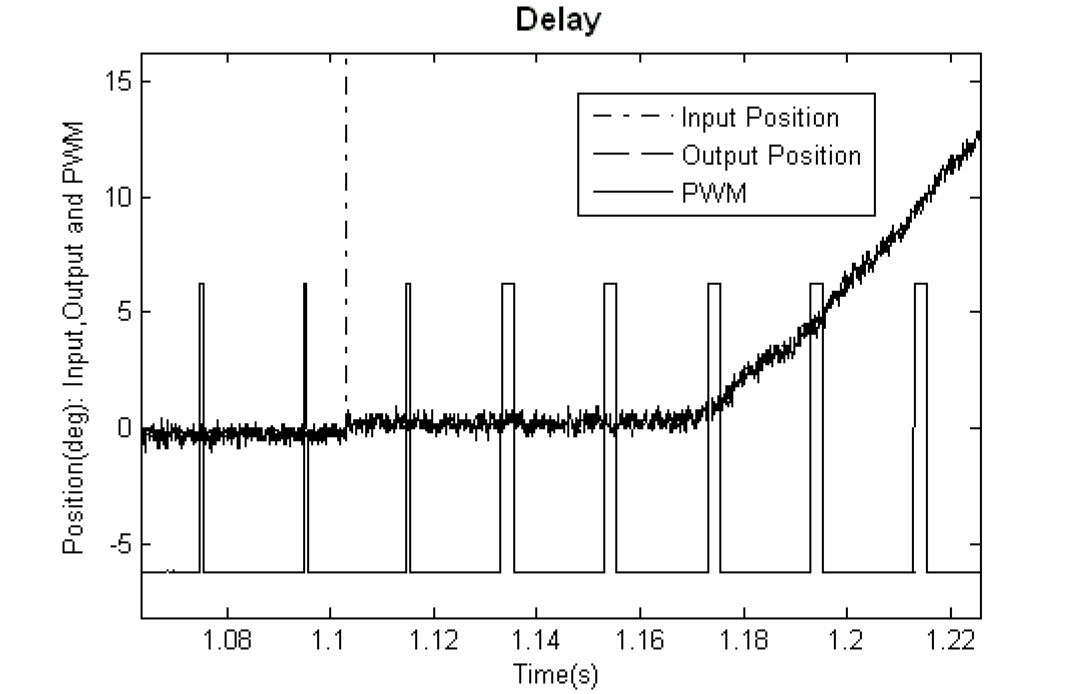

Figure 7. Time delay measurements between the servo command and the PWM pulse generation

Figure 6 and 7 also show the effect of the saturation non-linearity in the displacement response of the servomotor, related to the maximum slew rate of the actuator response, on the order of 285 degrees/sec. presents the input signs and output (position) of the Servo now with the current sign.

Finally, Figure 8 show the input and output signals obtained with a swept sine wave excitation, corresponding to a sinusoidal oscillation with 200° maximum amplitude. For each frequency at least two periods were supplied. The output response decreases rapidly as the input frequency is increased. These signals will be used to determine the experimental transfer function of the servo motor, through the calculation of its Bode diagram.

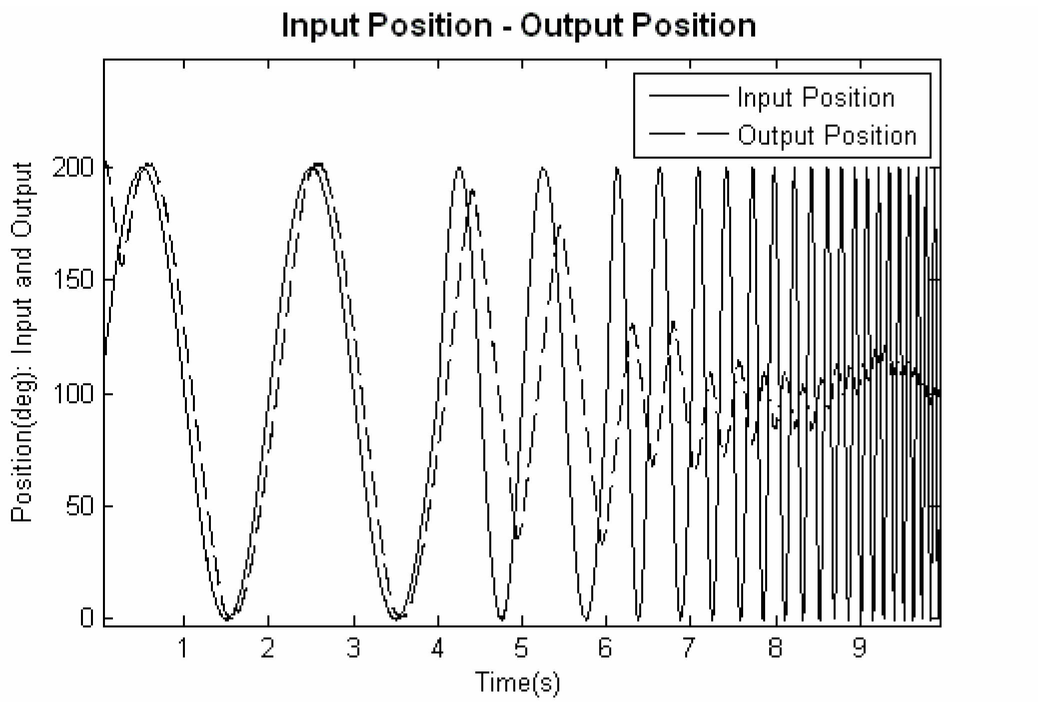

Figure 8. Frequency response obtained with a swept sine wave excitation.

4. SYSTEM IDENTIFICATION

Once the input and output data signals have been captured with the LabVIEW program, one can then begin the identification studies of the servo actuation system. The grey box methodology for linear system identification consists of modeling its physical properties from first principles and then adjusts the physical parameters of the model by minimizing the difference between the model output and the real observed output. However, in the case at hand it is not possible to obtain a reliable model for the servo actuator, based only on the study of its components, because it operate in a closed loop fashion and because the hardware system is tightly sealed for protection purposes. It is also known, that an electronic circuit for internal position control exists, with added nonlinearities to the system.

The identification process proposed here is of the black box type. This identification method is an alternative to the gray box model based on first physical principles of the investigated process, and thus obtained based only on relevant data description of the system response to known observed data input. The interesting feature of this methodology is that at the end we have a dynamic model of the system without necessarily know the physical characteristics of its internal devices. It is common in these cases that a group of candidate models are available and be tested, before the identification of their parameters actually starts. In the case at hand, the dynamic models were limited to linear models with time invariant properties, and with one or two poles.

The parameter estimation of a system usually needs a recursive algorithm, which needs computational resources for this identification. Besides, the sampled input and output data, the input-output model need be discrete in time. This is obtained from the continuous system model in the state space by, such that:

$$\dot{x}(t) = Ax(t) + Bu(t) + Ke(t) \tag{1}$$

$$y(t) = Cx(t) + Du(t) + e(t) \tag{2}$$

which, after discretization is rewritten as:

$$x(kT + T) = Ax(kT) + Bu(kT) + Ke(kT) \tag{3}$$

$$y(kT) = Cx(kT) + Du(kT) + e(kT) \tag{4}$$

Here, A, B, C and D are the state, input, output and forward matrices, respectively. In this model we are considering that uncertainties exist in system modeling and noise properties. The disturbance effect in the state description is represented in the output equation by the vector, *e*. The matrix gain, K in the state equation model represents the Kalman gain, that models disturbances in the system. Initially, the proposed identification will be based in a first order system characterized by the following transfer function:

$$T(s) = \frac{1}{\tau s + 1} \tag{5}$$

The representation in state space is written in terms of the matrix $A=[\theta_1]$, $B=[\theta_2]$, $C=[\theta_3]$, $D=[0]$. For the identification of this system it is necessary to begin the process supposing initial values. For this case, the matrix *A, B* and *C* received both value 1, while the matrix *D* received the value 0.

For the case of a second order system, we will consider a system description with the following characteristics:

$$T(s) = \frac{\omega_n^2}{s + 2\xi\omega_n s + \omega_n^2} \tag{6}$$

As in the previous case, its representation in the state space is given as:

$$A = \begin{bmatrix} 0 & 1 \\ \theta_1 & \theta_2 \end{bmatrix} \quad B = \begin{bmatrix} 1 \\ \theta_3 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 \end{bmatrix} \tag{7}$$

5. EXPERIMENTAL RESULTS

For a more practical and fast use of the available MATLAB functions, a graphic interface was created, as shown in the Fig. 9. The developed interface allows the selection of input and output data that will be used for identification purposes, and display the results in a graphical way and in transfer function format for both the first and second order models. In graphic form, the input and the output values for the two cases, as well as the measured value, are shown together so that they can be compared by the user. Another function was added to perform the system identification in the frequency domain by implementation of the command "Bode". This function uses the data generated through the swept sine excitation and it calculates the real Bode diagram, showing the results in a graphic way.

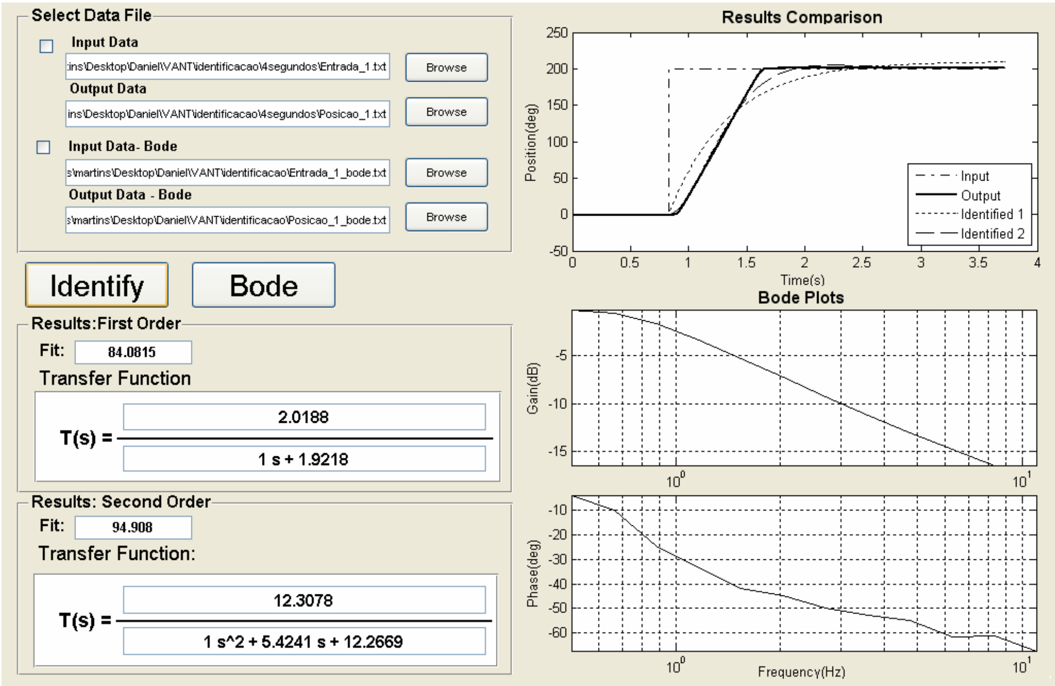

Figure 9. Graphic interface

5.1. Servomotor Parameter Estimation

Applying the obtained data of the servo actuation system, it was possible to execute a MATLAB for system identification. The results can be observed in Figures 10 and 11. In the first approach a first order system was considered, resulting a fit with 84.1 % for correlation coefficient. Despite the fitting coefficient, it is observed a considerable difference deviation between the real data and the estimated one. The identified model has slow time constant of the order of τ=0,520 sec., when compares with the measured sign. These observations make the model of first order system inappropriate to represent the servo actuator system.

Considering now a second order model, the fit coefficient, shown in Figure 10, presents a value of 94.91 %, which is much more reasonable than the first order system. Besides, the obtained transfer function is also capable to reproduce the measured signal. One can still notice significant difference in the system rise time, because the studied servo has strong nonlinear characteristics not modeled by the identified system. It is also noticed that an overdamped system was identified in this case. On the other hand the steady state value obtained is very close to the real one.

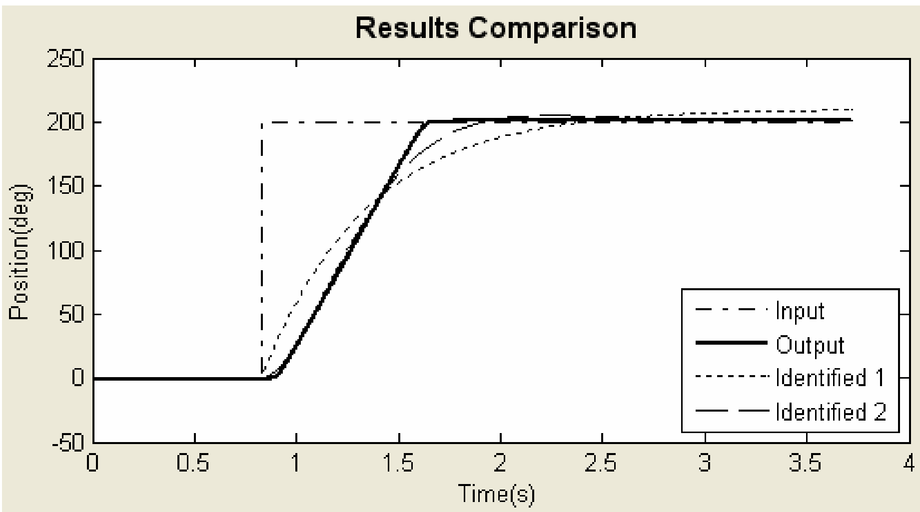

Figure 10. Result graph of the Servo identification

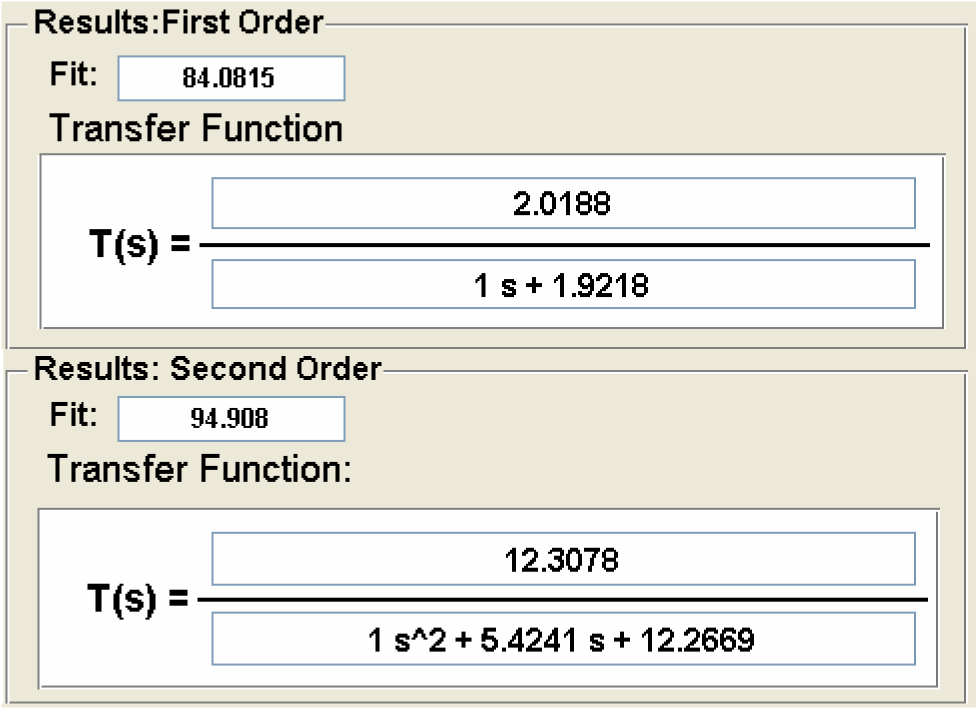

Figure 11. Results for transfer function identification

Figure 11 display the results for the estimated Bode Diagram obtained with sine wave excitation with frequencies between 0,5 and 11 Hz. It is notices that the servo behaves as a lowpass with a very small bandwidth, as it was already expected because of the large servomotor inertia. It was observed that the phase diagram obtained it shows a great variation between 0.5 and 2 Hz. Figure 12 presents the input and output response, and the time variation of the motor current for the case of sinusoidal excitation. The current waveform is pulsed and it possesses its largest value when it departs from rest, at the servo position of 0º or 200°.

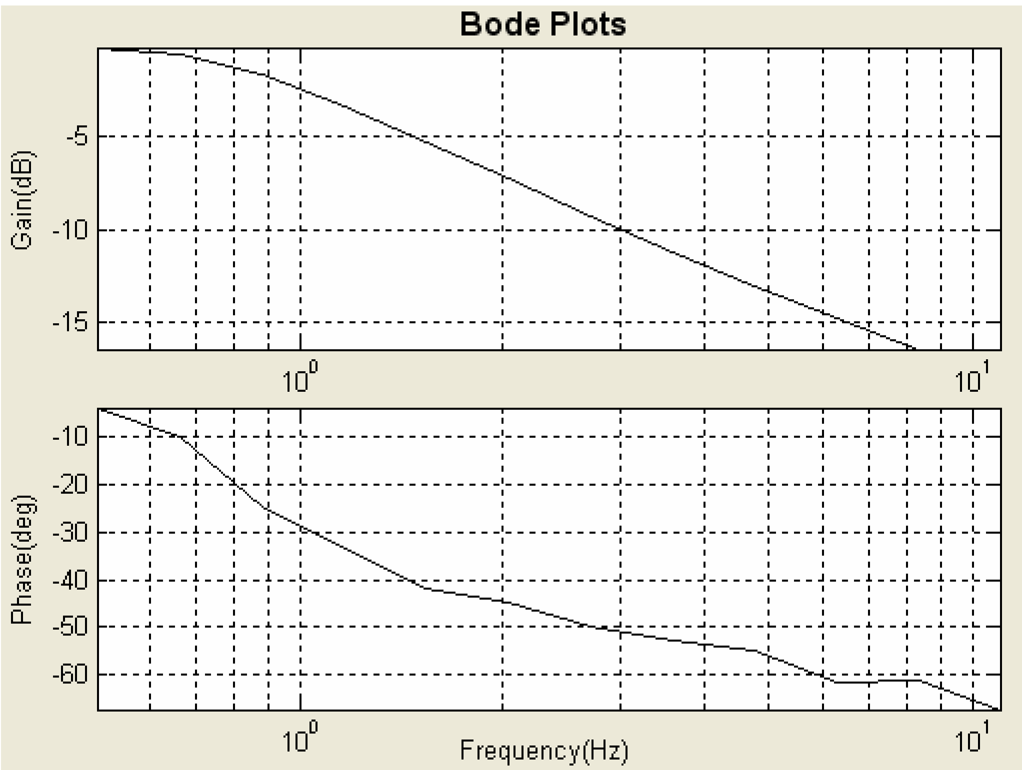

Figure 12. Estimated Bode diagram obtained with swept sine wave excitation

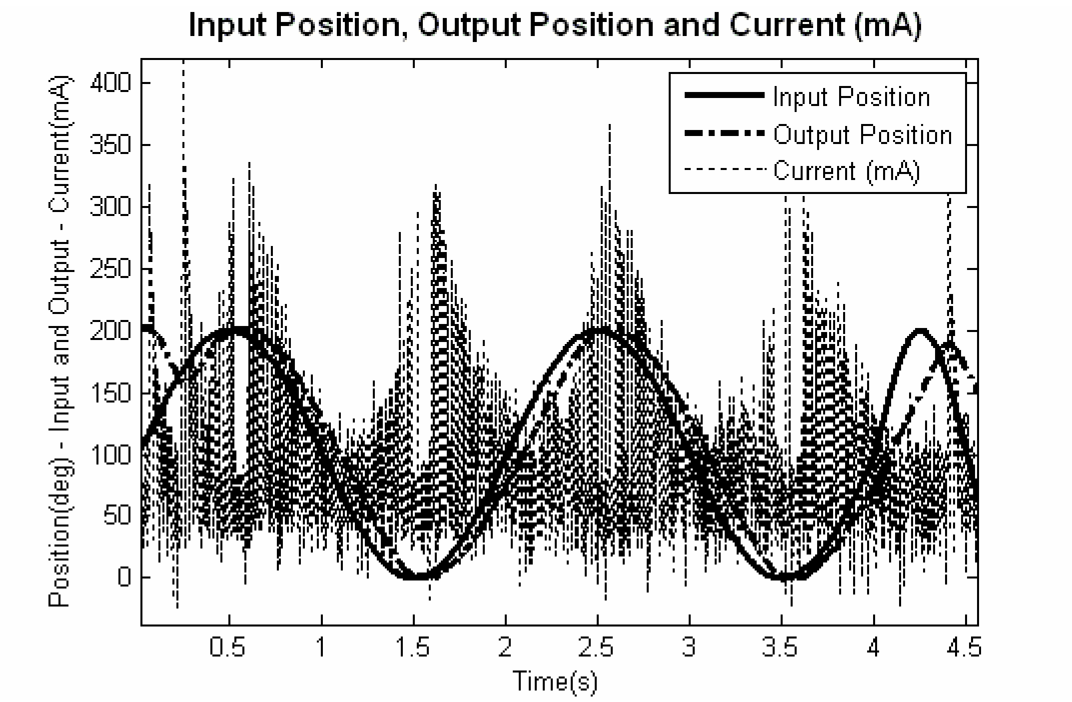

Figure 13. Form of motor current wave for the case of sine wave excitation

5. CONCLUSIONS

In this work, an integrated system was presented for automatic testing a servo actuation system used in UAV system. The software LabVIEW and MATLAB where integrated to develop an integrated environment for data collection and data processing leading to system identification and parameter estimation of the servomotor. The developed program was used to generate excitation signals and to collect system response for further processing, using both LabVIEW and MATLAB. Although this interface was created to test servo actuator systems for UAV, it can be used as a general purpose test environment that can be excited with time steps or sinusoidal input signals. The systems showed very efficient to excite the real system, collect its response and process the data according to known a priori models for gray or black box identification, and in this way, it can be used in several types of system studies.

The procedures regarding the system identification showed reasonable results, even considering that the identified model does not take in account existent nonlinearities of the plant. In preliminary tests, the system was tested in a much reduced time, and the obtained result was not as satisfactory, because of the small amount of samples. In that situation, it was not possible to obtain a good model for the first order system approach. An alternative to improve the model is to insert a time delay between the PWM signal and the servomotor response.

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