# PREDICTIVE CONTROL DESIGN BASED ON SYSTEM IDENTIFICATION OF AN ELECTRO-HYDRAULIC ACTUATOR APPLIED TO BRAZILIAN SOUNDING ROCKETS AND MICROSATELLITE LAUNCHERS

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## ABSTRACT

*This paper presents the modeling and control design to new hydraulic actuator being developed for thrust vector assembly applied to Brazilian rockets. Traditionally PID controllers are used for this issue but based on discrete models is proposed a new digital control for best performance. It is based on models obtained from closed-loop system identification of a Brazilian electro-hydraulic actuator using Nitrogen pressure-fed system applied to Sounding Rockets and Microsatellite Launcher (VLM). The vehicles are developed at the Aeronautics and Space Institute (DCTA/IAE) and a new actuator under test is being proposed using Helium gas to the Pressure-Fed-System. Traditionally the Nitrogen gas is used in low pressure operation to feed hydraulically the actuator and a new controller is being implemented to improve the system performance. Simulations developed in AMEsim and Matlab codes show best performance using Helium gas dealing on fast movements to the high pressure hydraulic cylinder, increasing the system bandwidth. The modeling of the hydraulic actuator is presented for linear and nonlinear analysis as well as their influences on system identification algorithms. The fluid flow through the internal pipes and spool are modeled using its nonlinear flow equation while the spool linear dynamics are obtained from Newton's law and the magnet-force from Biot-Savart law. Discrete models are obtained from system identification using experimental data from the hydraulic closed-loop operation while a digital controller is designed based on that discrete models and finally implemented in the loop. A real-time electronic system with digital-to-analog and analog-to-digital converters performs the digital control, using Labview programming environment. The linear and nonlinear dynamics associated to each sub-system are discussed and simplifications hypotheses are presented in order to obtain the Low Order Equivalent System (LOES) to the entire hydraulic actuator, as well as the influences on the predictive control strategy and linear system identification. According to results in time and frequency domain the performance attends the rocket design requirements.*

*Keywords: electro-hydraulic actuator, control system, system identification*

## INTRODUCTION

The new electro-hydraulic actuator consists of a hydraulic cylinder mounted on servo-valve system presented in the Figure 1, discussed in Barbosa [7,8] and can perform high linear force, widely applied on linear servomechanisms, e. g. the well-known Thrust Vector Assembly (TVA) or nozzle as shown in the Figure1. A complete knowledge of its dynamics is of very interest for control system design [1, 12], primordially in rockets attitude control design [13] (Sounding Rockets or Launchers). The Figure 1 (left) presents the actual Brazilian hydraulic actuator being developed at DCTA-IAE. The Figure 2 shows the mechanical cylinder, the linear motion sensor and the digital controller in closed-loop operation, discussed in [8].

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**Figure 1 - (left) Actuator, (rigth) the TVA.**

The modeling process of such multi-disciplinary system is done using mechanical and electronic classical laws: Newton's laws, Fluid Dynamics, Navier-Stokes Equation, Biot-Savart law and Fluid Continuity Equation [3, 4], aided by Bond-Graphs technique [5, 11].

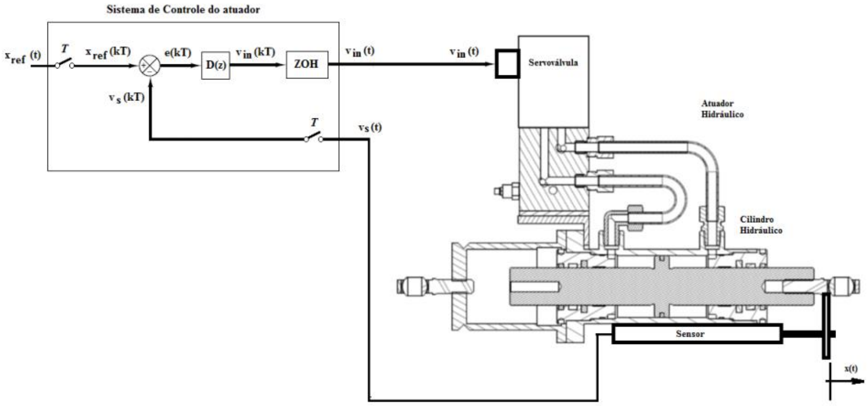

**Figure 2 - actuator in closed-loop operation.**

## SYSTEM MODELING

The TVA system consists of a nozzle or divergent and a flexible joint controlled by a hydraulic actuator, shown in the Figure 3, and the hydraulic subsystem is modeled as an equivalent Wheatstone Bridge.

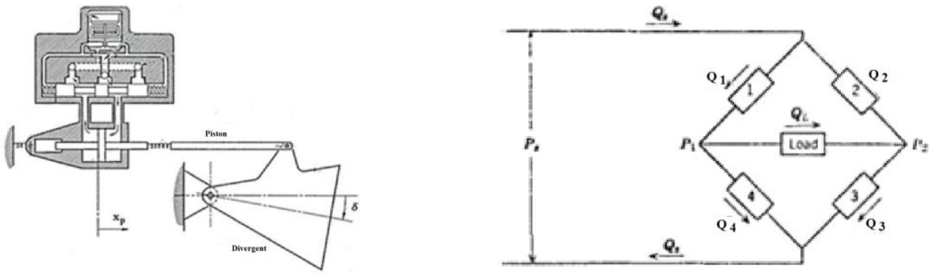

**Figure 3 - (left) The servo-valve and nozzle diagram and (right) the equivalent Wheatstone Bridge to the hydraulic system.**

Fluid flow through the internal pipes and spool are modeled using the nonlinear flow equation

$$Q_L = C_d A_1 \sqrt{\frac{1}{\rho}(P_s - P_L)} - C_d A_2 \sqrt{\frac{1}{\rho}(P_s + P_L)} \tag{1}$$

and the linearized flow equations are

$$Q_L = K_q \Delta x_v - K_c \Delta P_L \tag{2}$$

$$K_q = \partial Q_L / \partial x_v \qquad K_c = -Q_L / \partial P_L \tag{3}$$

while applying the Newton's law to the piston we get

$$F = Ma = \rho L A_v \frac{d\left(\frac{Q}{A_v}\right)}{dt} = \rho L \frac{dQ}{dt} \tag{5}$$

$$F = AP_L = M_t \frac{d^2 x_p}{dt^2} + B_p \frac{dx_p}{dt} + K x_p \tag{6}$$

and the magnet-force using the Biot-Savart law becomes

$$dB = \frac{\mu N i}{4\pi L}\left(\frac{L - x_0}{\sqrt{(L - x_0)^2 + d^2}} + \frac{x_0}{\sqrt{x_0^2 + d^2}}\right) d\theta \tag{7}$$

The input voltage to force acting to the spool transfer function is

$$F = \frac{2}{L} \frac{\left(\left(K_p + sK_d + \frac{K_i}{s}\right)(V_{ref} - V_s) - V_T\right)}{\left(s + \frac{2}{L}\left(\sqrt[4]{\frac{4K_F}{\beta^2}} + R\right)\right)} \tag{8}$$

A linear state space model is obtained from the modeling process as follows. The state space model, Eq. (9), is used for open and closed-loop system identification and after that, the discrete controller design is based on these plant discrete models.

$$\frac{d}{dt}\begin{pmatrix} x_p \\ v_p \\ P_L \\ x_{vint} \\ x_v \\ I_s \\ V_{int2} \\ V_{int} \end{pmatrix} = A \begin{pmatrix} x_p \\ v_p \\ P_L \\ x_{vint} \\ x_v \\ I_s \\ V_{int2} \\ V_{int} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{2K_d}{L} \\ 0 \\ 1 \end{pmatrix} V_{ref} \quad \begin{cases} a_{12} = 1 \\ a_{21} = -K/M_t \\ a_{22} = -B_p/M_t \\ a_{23} = A/M_t \\ a_{32} = -2\beta A/V_0 \\ a_{33} = -\dfrac{2\beta}{V_0}\left(C_{im} + \dfrac{\pi w r_c^2}{32\mu}\right) \\ a_{35} = C_d w \sqrt{P_s/\rho} \\ a_{45} = 1 \\ a_{54} = -\dfrac{K_s + 2C_d C_v w \cos(\theta) P_s}{M_s} \\ a_{56} = 1/M_s \\ a_{66} = -\dfrac{2}{L}\left(\sqrt[4]{\dfrac{4K_F}{\beta^2}} + R\right) \\ a_{67} = 2K_i/L \\ a_{68} = 2K_p/L \\ a_{78} = 1 \end{cases} \tag{9}$$

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$$y = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_p \\ v_p \\ P_L \\ x_{vint} \\ x_v \\ I_s \\ V_{int2} \\ V_{int} \end{pmatrix}$$

## DIGITAL CONTROLLER DESIGN

The predictive control strategy was applied to obtain a digital closed-loop control based on the discrete models obtained from the linear system identification using experimental data. The predictive controller assumes a 40 step prediction and step of *1 ms* of time duration. The predictive control implementation is based on a matrix predictor as the following equation

$$\hat{y} = Gu + H\hat{u} + Fc \tag{10}$$

where the size of $\hat{y}$-vedtor is the prediction window. In this work the predictor adopted is an adaptation of Eq (10), in the following equation

$$\hat{y} = Gu + Fc \tag{11}$$

The $\hat{y}$ and $\hat{u}$-vectors are as follows

$$\hat{y} = \left[\hat{y}(k + \hat{d} + 1), \ldots, \hat{y}(k + Hp)\right]^T \qquad u = \left[u(k), \ldots, u(k + Hp - \hat{d} - 1)\right]^T$$

$$\hat{u} = \left[\frac{u(k-1)}{\hat{A}}, \frac{u(k-2)}{\hat{A}}, \ldots\right]^T \qquad c = [c(k), c(k-1), \ldots]^T \tag{12}$$

The predictive control implementation can be stated as a simultaneous design of F, C and H blocks, in the block structure represented in the Figure (4).

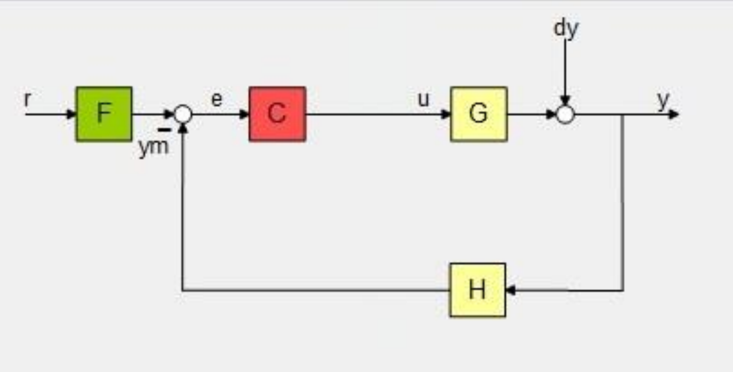


**Figure 4 - Block diagram of the predictive control structure.**

A cost function is described in the matrix equation and the problem turns on analogous to the Least Squared Problem (LS), so that do exist an optimum solution – and unique – to the parameters.

## SYSTEM IDENTIFICATION AND TEST RESULTS

Experimental test was performed using input signal as the Pseudo-Random Binary Signal (PRBS) and Random Gaussian Signal (RGS). The Fig. 5 (left) and (right) show the input time histories as well as the measured piston linear displacement.

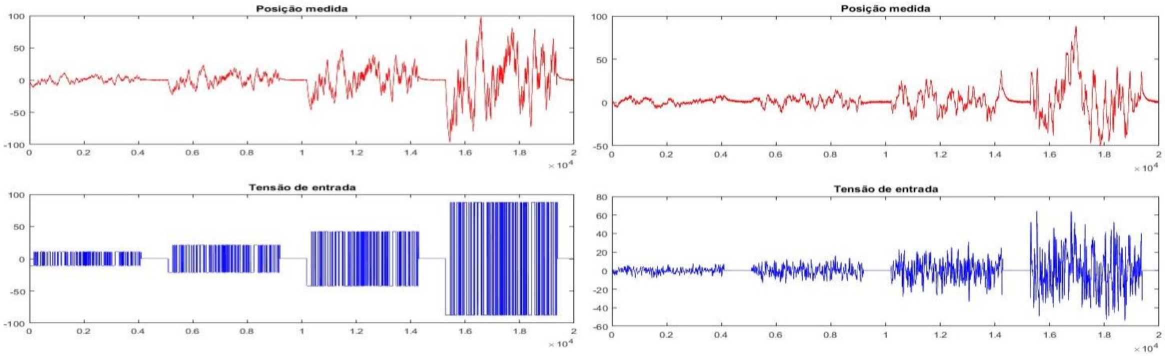
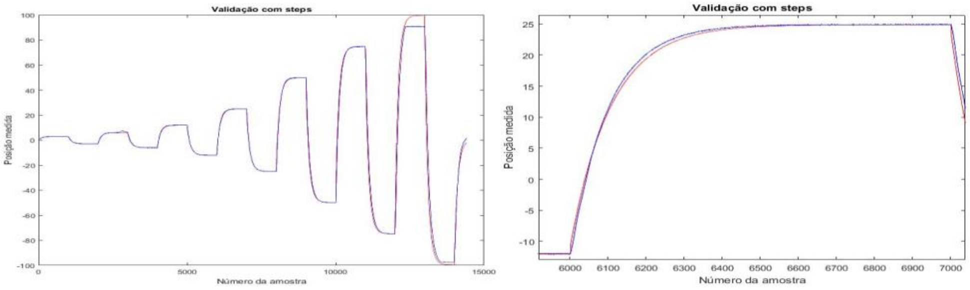


**Figure 5 - (Left) Input PRBS (red) and output (red) time histories; and (right) RGS input signal (blue) time history and output linear position (red).**

The Akaike information criterion (AIC) is a fined technique based on in-sample fit to estimate the likelihood of a model to predict and to estimate the future values. It uses the information theory and entropy to determine the best regression. The experimental data used for the AIC, and several discrete models were tested regarding to the numerator and denominator order, and the best discrete model obtained consists of one discrete zero and one discrete pole. Assuming the low order equivalent system (LOES) as a typical discrete model, Equation 13

$$\frac{a_2z^2+a_1z+a_0}{b_2z^2+b_1z+b_0} \tag{13}$$

The cost function used for model parameters determination becomes $I(\theta) = 0.5e^TQe$, where the e-vector is the error vector, Q is the inverse of the error covariance matrix, I is the cost and $\theta$ is the parameters vector. The discrete model validation was performed using another different signal time history, e.g. a unit-step was used. The predictions to the discrete model are shown in the Figures 6 and 7.



(a) (b)

**Figure 6 - (a) Predicted output: Input step for validation – experimental (blue) and output prediction from model simulation, (b) detail of step response.**

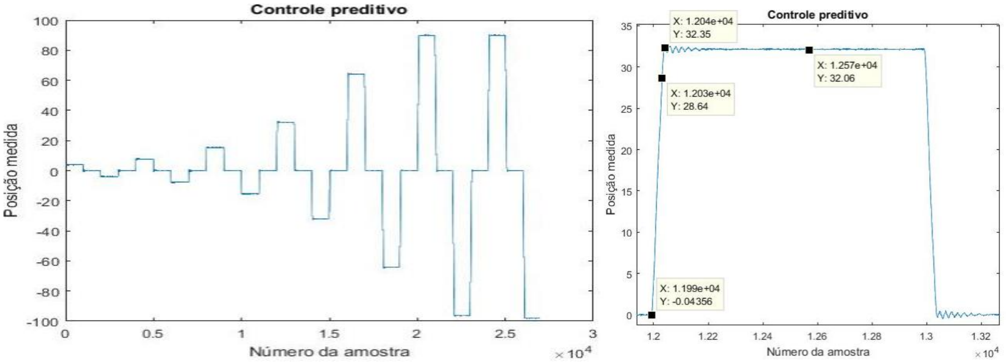


**Figure.7 - (left) multi amplitude step input and output response, (right) details in the unit-step response from experimental tests.**

The experimental tests were performed using a real-time system named CompactRIO based on the FPGA architecture. The Figures 7 show the results obtained using a step as excitation.

## CONCLUSIONS

Step-unit response requirements were obtained from the implementation of the predictive controller, validating the control design. The low order equivalent system discrete model obtained from linear system identification can represent the dynamics of the hydraulic actuator (electronics, servo-valve, cylinder and LVDT linear position sensor) and many control strategies can be accessed to improve time performance due to unit-step of excitation in order to obtain the best closed-loop bandwidth. The linear models were obtained from system linearization, in some cases assuming simplification hypothesis to the nonlinear dynamics, e. g., the electro-magnetic force and fluid flow equation.

This work has shown reliability on model identification procedures that are common in the literature, as the Akaike Information Criterion (to obtain the best model order) and minimization of cost functions (to obtain the best model for a given order). As exposed above, the identification of a low order plant and the development of a controller were obtained very successfully with the presented theory.

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