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SYSTEM IDENTIFICATION VIA ARX MODEL AND CONTROL DESIGN FOR A GRANITE BENCH AT SIRIUS/LNLS *

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Abstract

Modern 4th generation synchrotron facilities demand mechatronic systems capable of fine position control, improving the performance of experiments at the Beamlines. In this context, granite benches are widely used to position systems such as optical elements and magnetos, due to its capacity of isolating interferences from the ground. This work aims to identify the transfer function that describes the motion of the granite bench at the EMA Beamline (Extreme con-ditions Methods of Analysis) and then design the control gains to reach an acceptable motion performance in the simulation environment before embedding the configuration into the real system, followed by the validation at the beamline. This improvement avoids undesired behaviour in the hardware or in the mechanism when designing the controller. The bench, weighting 1.2 tons, is responsible by carrying a coil, weighting 1.8 tons, which objective is to apply a 3 T magnetic field to the sample that receives the beam provided by the electrons accelerator. The system identification method applied in this paper is based on the auto-regressive model with exogenous inputs (ARX). The standard servo control loop of the Omron Delta Tau Power Brick controller and the identified plant were simulated in Simulink in order to find the control parameters. This paper shows the results and comparison of the simulations and the final validation of the hardware performance over the real system.

INTRODUCTION

The main theme of this work is the identification and controller design of a granite bench present in the Brazilian Synchrotron Light Laboratory (LNLS) [1], the 4th generation particles accelerator in the Brazilian Center for Research in Energy and Materials (CNPEM). The objective is to provide an effective method to identify the behavior of the granite bench responsible by positioning a coil that produces a magnetic field of extreme conditions for the scientific experiments that happen in this beamline [2]. In addition to that, the controller must be designed to move the system in a stable manner. The feedback transfer function model should be the same as the one present inside the Power Brick LV, commonly known as PBLV [3].

Figure 1 shows the coil responsible by providing the magnetic field under extreme conditions, essential for several kinds of experiments that happen inside the EMA Beamline. As mentioned in the last section, the coil weights 1.2 tons, while the bench [4], responsible by carrying the coil, weights 1.8 tons – it is the biggest of the whole laboratory, between all Beamlines in operation. The design of a good stabilizing controller is essential to guarantee the success of the experiments, as the bench must be kept stopped during the process (acquisitions during incident beams), and also move in a safe manner in order to preserve the integrity of the whole mechanism.

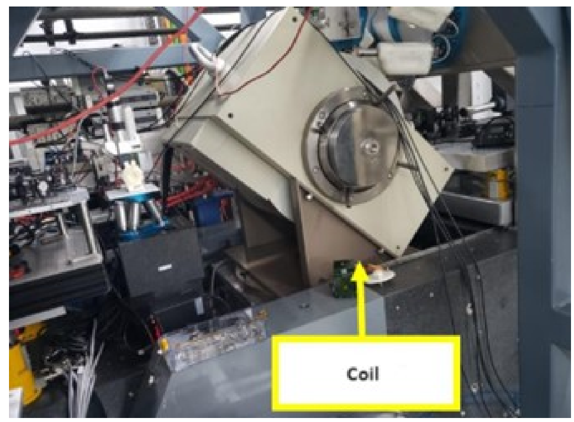

Figure 1: Coil responsible by providing the magnetic field under extreme conditions.

The plant identification was done considering the black box approach [5], and this box encompasses both electrical and mechanical systems present in the granite bench: the operational amplifier, present in the PBLV power output, and the motor coupled to a belt and pulley subassy that provides the translation of the bench and controls the position of the magnetic coil. The identification was done using the ARX model [6], and the excitation signal was a smooth ramp in reference to the controller, in closed-loop mode.

The controllers tuning – in terms of gains, such as proportional, integrative, derivative, etc. [7] – are usually done in an empirical manner. So the main contribution of this work is to identify and design the controller of the system in order to have the performance evaluated even before embedding the gains inside the PBLV. This avoids the possibility to damage the system, by bringing rough movements to the granite bench or amplifiers burnout by over-current. Also, it is possible to test and validate different controllers setups and gains configurations – due to the simulation environment that applies the identified plant –, helping to find the best performance in terms of transient and stationary stability.

EXPECTATIONS

The main expectation of this work is to provide a method to find control gains in order to stabilize critical systems,

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such as the granite bench at the EMA Beamline – one of the most critical granite benches due to the weight of the scientific equipment that it carries. Guaranteeing a stable movement in terms of transient and stationary motion is ubiquitous to preserve the integrity of the mechanism. Also, the development of a methodology to tune the controller responsible by guaranteeing such unprecedented safety applications is essential when dealing with critical scientific equipment, as the validation in the simulations environment avoids the test of gains that belong to a specific numeric range that can be dangerous to the system.

HARDWARE AND SIGNALS

Before going to the system identification method and the mathematical studies, it is essential to understand the hardware and the signals involved in the granite bench motion. As mentioned before, the system involves several dynamic components and non-linearities – such as the friction, the pneumatic system responsible by floating the granite block, the belt elasticity and backlashes on the gears coupling –, turning the identification even more challenging. The mechanism is the one shown in Fig. 2. Note the main function of the motor, controlled by PBLV, is to provide a pure translation over the X kinematic axis – in the coordinate system of the laboratory [8] –, which is perpendicular to the beam direction (parallel with the Z axis).

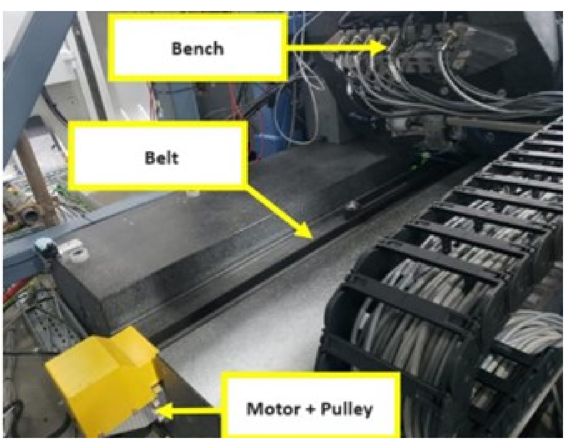

Figure 2: General assembly: bench, belt, motor and pulley.

The identification is based on the discrete time, due to two principal factors:

- The PBLV controller performs the calculations and data extraction in a discrete manner, under a frequency configured by the user [9]. In this work, the acquisition rate is equal to the loop rate, fixed in 16 kHz.
- The model is the auto-regressive of exogenous inputs (ARX), which theoretical basement is described in the next section.

As mentioned before, there are more elements to be identified in the system than only the behavior of the granite block. There is the electrical plant of current conversion, the cabling behavior and the mechanical system of the motor. Aiming to simplify the problem and the approach, all these elements – including their non-linearities, approximated to a linear system – will be identified in two black boxes, as it is assumed that there is no information available about the dynamic that rules the behavior of each subsystem of the general assembly.

First of all, the PBLV has a standardized mesh that returns a value – that will be called in this work as servo out, which is similar to the name of the register of this output, to be acquired in the PBLV. The mesh has a lot of gains and filters, but in this work the following ones will be implemented:

- Proportional gain (Kp).
- Integral gain (Ki).
- Feedback velocity gain (Kvfb).
- Feedback acceleration gain (Kafb).
- Feedforward velocity gain (Kvff).
- Feedforward acceleration gain (Kaff).

In a summarized way, the block diagram that represents the system is the one present in Fig. 3.

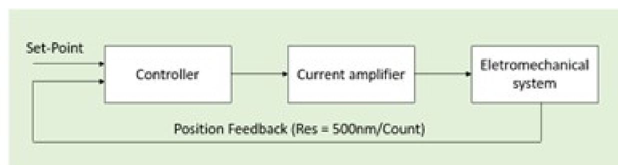

Figure 3: Resumed block diagram of the system.

In this approach, the element responsible for generating the control effort is the servo out, which is the output of the controller shown in Fig. 3. This variable was interpreted, in this analysis, as a non-dimensional one. The servo out feeds the current amplifier, responsible by generating two currents ($I_a[k]$ and ($I_b[k]$). Both currents can be acquired inside PBLV using specific registers in the k-th instant. This is the first transfer function that is identified, turning the servo out into the two currents. Despite the current controller is available in the PBLV user manual, it will be interpreted in this work as a black box as well, as the electronic components inside the amplifier and their oscillations are unknown. It is important to note that the ARX model is a SISO one – so it converts a single input to a single output. In order to meet this model, the currents $I_a[k]$ and ($I_b[k]$ must be reduced to a single variable that can represent both.

Inside the PBLV and the motor, the two currents have 90º between each other. The general amplitude is configurable by the user using the native PBLV code, and this relation is inserted inside the current loop. The general amplitude – which will be called as I_g – keeps the following relation the same during all motion:

$$\sqrt{I_a[k]^2 + I_b[k]^2} = I_g \quad (1)$$

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By acquiring the two currents, it is possible to build an complex current $I[k]$ – in which j is the imaginary unit – that has the following format in the k-th instant:

$$I[k] = I_a[k] + j \cdot I_b[k] \tag{2}$$

Note the modulus of $I[k]$ is equal to I_g, $\forall k > 0$. In the k-th instant, it is possible to build an extra variable – which will be called in this work as electric angle –, which can be represented by the following relation:

$$\varphi[k] = tan^{-1}\frac{I_b[k]}{I_a[k]} \tag{3}$$

It is possible to identify the first transfer function from the servo out to the electric angle (which is a representation of the two currents, as their modulus is always the same). Also, it is possible to identify the second transfer function from the electric angle to the position of the granite bench (reported by a encoder with resolution of 500 nm).

IDENTIFICATION MODEL

In this section, a brief bibliographic review of the ARX model [10] will be presented in order to simplify the analysis and identification using acquired data in the PBLV – as Matlab already has functions that automatically perform the identification using this model [11]. Remember that two transfer functions are meant to be identified: the current amplifier and the bench mechanism.

Model Format

The auto-regressive model with exogenous inputs can be expressed by the following generic transfer function: (assuming the noise and external disturbances are nule and have no influence on the output)

$$y[k] = \frac{B(q)}{A(q)}u[k] \tag{4}$$

In this format, $A(q)$ and $B(q)$ are functions in the domain of the delay operator q. This operator has the following property:

$$u[k]q^{-n} = u[k-n] \tag{5}$$

The functions $A(q)$ and $B(q)$ are, respectively, the denominator and the numerator of the transfer function that is meant to be identified. Indeed, they have the following format:

$$A(q) = 1 - a_1q^{-1} - a_2q^{-2} - ... - a_mq^{-m} \tag{6}$$

$$B_q = b_1q^{-1} + b_2q^{-2} + ... + b_nq^{-n} \tag{7}$$

Note the functions $A(q)$ and $B(q)$ have orders m and n, respectively. Their coefficients are meant to be calculated during the system identification process.

Parameters Estimation

To cover a calculation example of the parameters estimation, Let it be assumed that $m = 2$ and $n = 1$). Then:

$$A(q) = 1 - a_1q^{-1} - a_2q^{-2} \tag{8}$$

$$b_q = b_1q^{-1} \tag{9}$$

Bringing the delay operator to the discrete time, the relations turn into:

$$y[k] = a_1y[k-1] + a_2y[k-2] + b_1u[k-1] \tag{10}$$

In a practical way, this equation represents a causality between the input and the output, as it depends only on past values. For example: in the instants $k = 3$ and $k = 4$, the relation is, respectively:

$$y[3] = a_1y[2] + a_2y[1] + b_1u[2] \tag{11}$$

$$y[4] = a_1y[3] + a_2y[2] + b_1u[3] \tag{12}$$

The identification by the application of the ARX model must find the coefficients a_1, a_2 and b_2 that represent as good as possible the behavior of the plant. If the last relation is extrapolated to a set of N samples, starting by $k = 3$, it can be written in a matrix form:

$$y[3,4,...,N] = \begin{bmatrix} y[2] & y[1] & u[2] \\ y[3] & y[2] & u[3] \\ \vdots & \vdots & \vdots \\ y[N-2] & y[N-1] & u[N-2] \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ b_1 \end{bmatrix} \tag{13}$$

In which y and u are data acquired by the controller. The relation can be expressed by:

$$y = \Psi\Theta \tag{14}$$

In which Ψ is called regressors matrix and Θ is the vector of coefficients to be determined. Note this relation represents a linear system of equations. If the regressors matrix was square, it would be easy to find the coefficients vector by the following inversion:

$$\Theta = \Psi^{-1}y \tag{15}$$

But, as this work deals with a large set of data, the regressors matrix is not square and not invertible. To properly find the coefficients vector, the pseudo-inverse matrix is necessary: (in which Ψ' is the transpose of the matrix Ψ)

$$\Theta = [(\Psi'\Psi)]^{-1}\Psi'y \tag{16}$$

Otherwise, it is not possible to apply the chosen model to represent the transfer functions of this work. The calculation of the vector Θ returns the estimated parameters a_1, a_2 and b_1 that represent the behavior of the system as close as possible to its real dynamics. That is because the

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calculation using the pseudo-inverse is a linear approximation using minimum squares, a statistic conception based on mathematical optimization that finds the best adjustment for a set of data by minimizing the sum of the squares of the differences between the estimated and real values.

EXPERIMENTAL METHODOLOGY

The system identification using the ARX model, as explained before, is based on collecting a set of excitation and response data – using the acquisition panel of the PBLV integrated development environment (IDE) –, saving in a readable format, bring into Matlab and use its native commands to find the transfer functions. Note the experiment demands a movement to be applied in the system in order to collect the data to be post-processed in Matlab. The typical movement applied in the experimental hutch is a S-curve, and as specified by the mechanical design, the curve must have the configurations listed in Table 1.

Table 1: Margin Specifications

Motion Configuration	Value
Acceleration time	8000 ms
Final velocity	2 counts/ms

By zeroing all gains of the motor – except the proportional gain, kept in a low value $K_p = 5 \cdot 10^{-4}$ – and configuring the reference to follow the mentioned curve, it is possible to acquire the set of data (excitation and feedback). Note this represents a smooth movement and can be interpreted as an acquisition specifically for system identification.

SYSTEM IDENTIFICATION: RESULTS

As mentioned before, a smooth movement under weak controller conditions is necessary to run the system identification method. A set of acquired data at these conditions is expressed in Fig. 4. It is important to note that this acquisition was done using the gather window of the PBLV integrated development environment (IDE) at the same rate of the servo controller (fixed in 16 kHz). The gathered data then can be exported to a .txt format, which can be read and interpreted by another post-processing application – such as Matlab and Simulink, the chosen ones to run the system identification procedures of the auto-regressive models.

Bringing the data to Matlab, it is possible to calculate the electric angle between A and B phases of the motor, using the relation based on the tangent inverse shown before. The result is expressed in Fig. 5.

By having the acquired data imported into Matlab, it is possible to run the native calculations of the ARX model in order to obtain the estimated transfer functions and, then, run the simulations using Simulink. For the next sections, let $G(z)$ be the transfer function that turns the servo out into electric angle. Also, let $V(z)$ be the transfer function that turns the electric angle into position.

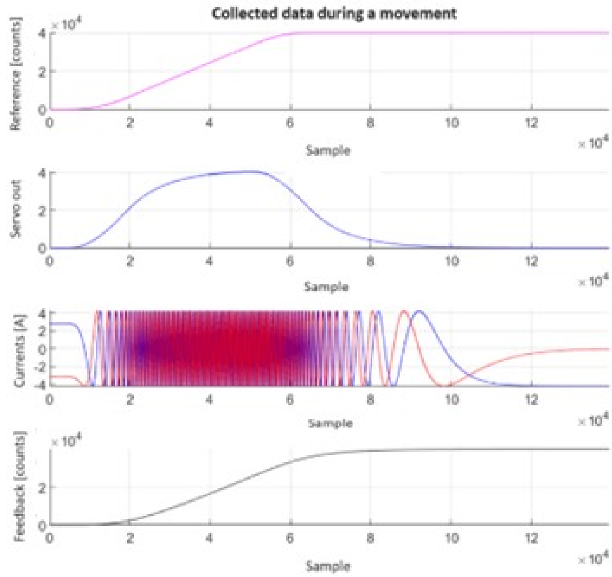

Figure 4: Collected data for granite bench system identification.

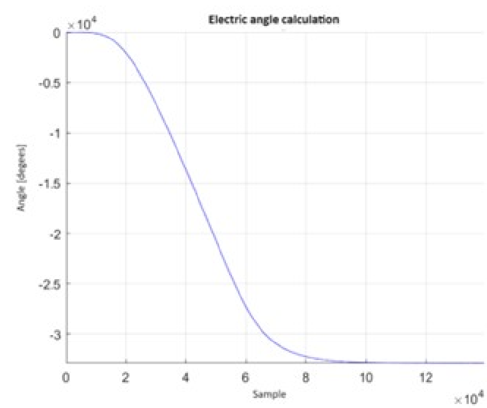

Figure 5: Electric angle calculation, from currents acquired.

CONTROLLER DESIGN

By having the discrete transfer functions $G(z)$ and $V(z)$ that represent the closest behavior to the real dynamic of the system, it is possible to embed them into a Simulink model – together with the standard controller structure that is natively implemented inside the PBLV – and, then, simulate the expected performance when configuring determined control gains.

The model to be inserted into a Simulink structure is the one present in the Fig. 6. Note the identified transfer functions using the ARX model appear right after the controller main structure. This simulation must be done in discrete time – always having on mind the configured servo loop rate, in this specific case, was set up to 16 kHz, and the resolution is 500 nm per encoder count.

The configuration presented in Table 2 shall be tested. This configuration was found after several tests with different combinations of gains. The comparison brings the

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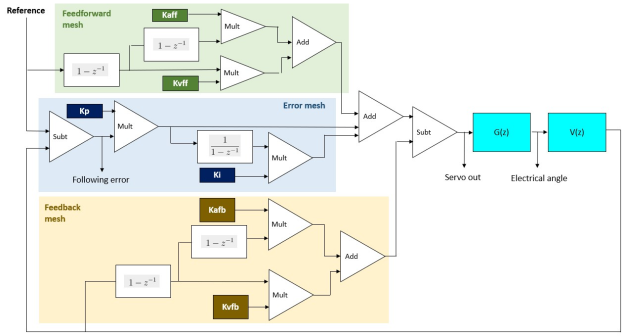

Figure 6: Controller standard structure inside PBLV to be simulated in Simulink.

conclusion that this is the best solution – although there may be other untested solutions. Also, the integral gain was not added because it does not matter if the error during the stationary velocity is brought to zero – it can be controlled in the neighbors of a value. The main objective here is to bring the mechanism from one point to another in a smooth way, and the error in the final destination must be set to zero.

Table 2: Configuration of Controller to Be Embedded Into PBLV (Gains and Respective Registers and Values)

Gain	**Value**
Proportional	0.0008
Integral	0
Velocity feedback	0
Acceleration feedback	0
Velocity feedforward	4.8
Acceleration feedforward	0

By simulating the configuration present in Table 1 and Table 2, together with the block diagram present in Fig. 6 using Simulink, and plotting some key variables, the expected performance is the one shown in Fig. 7.

Note the expected performance, as mentioned before, is smooth, as the following error does not seem to have rough movements during the motion from one point to another.

RESULTS

The next step, after fully designing the controller and verifying its expected performance, is to embed the gains to PBLV and verifying the real behavior. The acquisition in closed-loop is the one present in Fig. 8, after commanding the motor under the same reference setup of the Table 1 and the Table 2. It is possible to realize that the observed behavior is close to the simulated one.

CONCLUSION

This work presented a mathematical model and a methodology that describes the behavior of a granite bench of the new Brazilian Synchrotron Light source. The model was obtained through the parametrical identification that applies

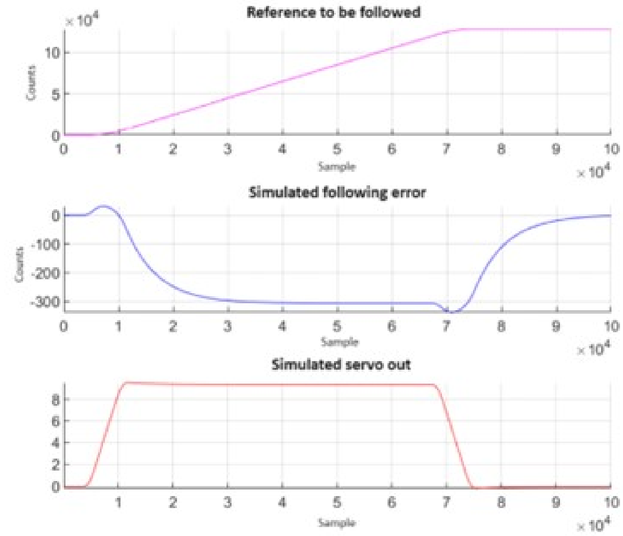

Figure 7: Expected results after controller design. Simulation done using Simulink.

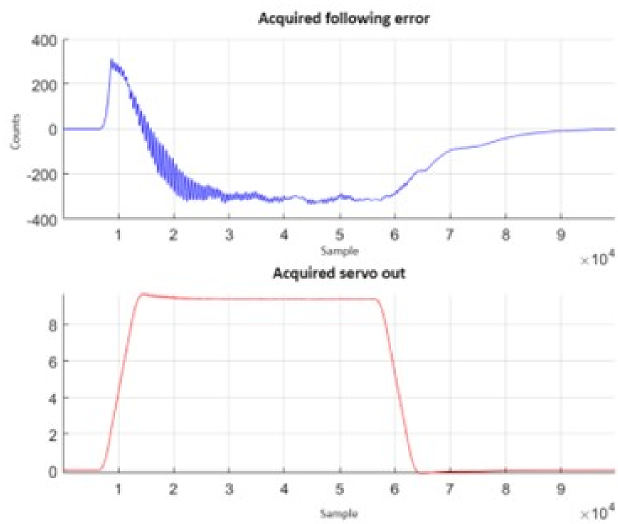

Figure 8: Acquired results after embedding controller into PBLV and commanding the motor.

auto-regressive models with exogenous inputs, and it was important to anticipate possible components of the real system, even before embedding the controller gains into the hardware. This procedure allowed the team to test the control system in a wider way, avoiding the application of determined gains that could damage or overcharging the system. The comparison between the experimental model and the observed practical results has put on evidence the efficacy and the importance of the proposed methodology.

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