Digital Twin of a Servo Driver of a Servo Motor as a First Step towards a Digital Twin of a Robot Mechanism

Sefa Furkan Küçükoğlu[1(✉)][0000-0001-8083-2306], Giuseppe Carbone[2][0000-0003-0831-8358], and Mehmet İsmet Can Dede[1][0000-0001-6220-6678]

[1] Izmir Institute of Technology, Urla, Izmir, Turkey
{sefakucukoglu , candede} @iyte.edu.tr
[2] University of Calabria, Cosenza, Italy
giuseppe.carbone@unical.it

Abstract. Digital Twin (DT) offers us to acquire actual system's critical information and hence, it may be possible to develop and produce more suitable systems in terms of low energy consumption and effectiveness. In this way, responsible consumption and production systems can be designed and the system's parameters can be tuned via DT. In this study, the model of a servomotor system that is used for industrial purposes is experimentally obtained. This study consists of two steps. In the first step, within the embedded control of the system, position and velocity control loops are deactivated. Then through the servo driver, currents with sinusoidal waveforms at various frequencies are applied to the servomotor. The resultant angular velocity of the motor is monitored and recorded. The amplitude of the current is kept constant during this study. The frequency of the current, however, is increased logarithmically. By using these data, a first-order transfer function (TF) is identified for the motor model. In the second step, all control loops are activated. Consequently, the total servomotor system could be represented in a digital environment. Furthermore, the static friction issue is overcome by using a Coulomb friction model with stiction effect. Finally, several experiments are conducted and then results are compared with the digital model of the servomotor system. The results clearly show that digital model can fairly represent the physical system.

Keywords: Responsible Consumption and Production, Transfer Function, Servo System, Static Friction, Coulomb Friction Model, Stiction Effect.

1 Introduction

Over the last few decades, there has been remarkable attention to automation systems. More recently, Industry 4.0 has changed our daily life and so it makes us develop various point of view about technology. With the aid of this, a good deal of product has been produced in a short time, with low-cost and low manpower. Consequently, there have been numerous researches on systems' control, flexibility, efficiency etc.

Since servo motor systems yield satisfactory results in position and velocity control applications, they are one of the highly preferred actuation systems in industrial applications. For example, in [1] a macro – micro mechanism for laser cutting process has been designed with servo motor system so that the end – effector of the mechanism can follow a desired trajectory with wondrous precision under high acceleration. An ultra-precision positioning technique has been developed with the combination of a global stage and micro stage in [2] in order to achieve sub-micrometer accuracy.

When it comes to control and model of the servo motors, modeling, and identification of the parameters of a servo motor have been investigated in [3-5]. A Genetic Algorithm (GA) method is used in order to improve the transient response of the system and define the optimal parameters of the PID controller for the desired control system design specifications in [6]. Other than the traditional control approaches, there are studies with fuzzy neural network controller [7], a cascade controller with feedforward robust adaptive fuzzy compensator [8], and a robust internal model control (IMC) based on sliding mode control (SMC) [9] in literature, in order to compensate the modeling uncertainties. When we look at the current studies related to control and model of the servo motors, it is seen that several methods are implemented. Generally, there is a tendency to identify the parameters of the servo motors by conducting simulations and/or experiments.

As a first step to create a DT of a robotic mechanism presented in [1], the servo motor system of this mechanism is considered in this work. Two servo motors are used in this planar parallel mechanism. The aim of this machine is to shorten the task completion by reaching 5g acceleration while it preserves the positioning accuracy at less than ± 0,100 mm/m, and repeatability at less than ± 0,050 mm. To achieve this aim, trajectory planning algorithms are improved with the inclusion of stiffness model of the mechanism. Nevertheless, another critical factor in precise control of the mechanism under high accelerations is the servomotor control, which is main focus of this paper.

To study the control of a servo motor which is coupled with a gearbox, the initial step is to obtain its model. Firstly, frequency domain studies are carried out by generating the Bode plot of the servo motor system that is subjected to current control loop via experiments. Consequently, a transfer function is fitted to the obtained Bode plot. Thus, the motor model is obtained via experimental identification techniques. Coulomb friction model with stiction effect is used as an additional part to the obtained linear model of the motor [10]. The cascade control parameters were previously tunned with the aid of servo driver's auto-tuning capability. Then, the exact replica of this controller with its control parameters are included in the simulation model as the digital twin of the servo driver. This part is accomplished without any experimental identification procedure. Consequently, the controller and its parameters in both servo driver and the simulation model are exactly same. Thereby, the system including the servo motor and the embedded controller in the servo driver are represented in the digital environment. The sampling time of the system is kept constant as 2ms throughout the study. The final outcome of this study is considered to be satisfactory, albeit there are minuscule differences between digital and experimental system. This error is investigated by quantifying it with Mean Absolute Error (MAE) and R-Squared (R^2). As a result of this work, the first step of designing a DT of the laser - cutting mechanism is realized. Kinematic, dynamic and stiffness models of the laser - cutting mechanism have already been developed. This mechanism consists of two servo motors, and servo system model obtained will be used along with the kinematic, dynamic and stiffness models so that the whole system can be represented in the digital environment.

2 System Description and Experimental Procedure

System operation is summarized in Fig. 1. A Kollmorgen servo motor is used in this study [11]. Servo driver is connected to a computer via ethernet connection, and the parameters of the controller embedded in the servo driver is changed via Kollmorgen AKD Graphical User Interface (AKD GUI). With the help of this GUI, controller mode and enable operation can be selected. On the other hand, Quanser Q8 Data Acquisition Card (DAQ) is used in order to supply the required analog input and evaluate the related output. Then these signals are monitored and recorded in another computer via MATLAB / Simulink Software.

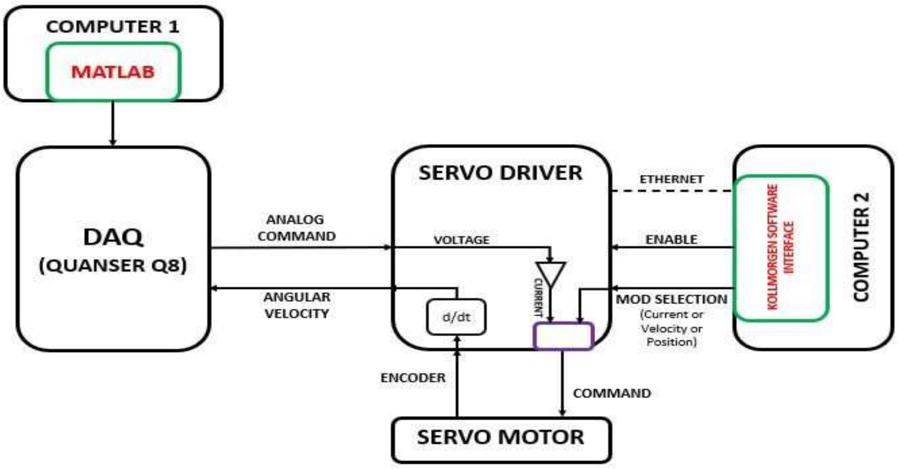

Fig. 1. System Operation

2.1 Obtaining the Transfer Function of the System with Current Controller

The whole system can be represented as a block diagram in Fig. 2 This figure is taken from the AKD GUI. The system consists of three cascade control loops, position, velocity, and current control loops, from left to right, respectively. As a first step, while the position and velocity loops are deactivated, the current loop is activated.

During the experiments, the amplitude of the sinusoidal current input is kept constant (0.2 A peak to peak). However, when this sinusoidal signal with this amplitude is suddenly applied to the motor, various problems, such as overheating problems can occur, and this might result in nonlinear behavior of the system. Therefore, the input signal's amplitude (command) is risen to the designated value with a ramp function.

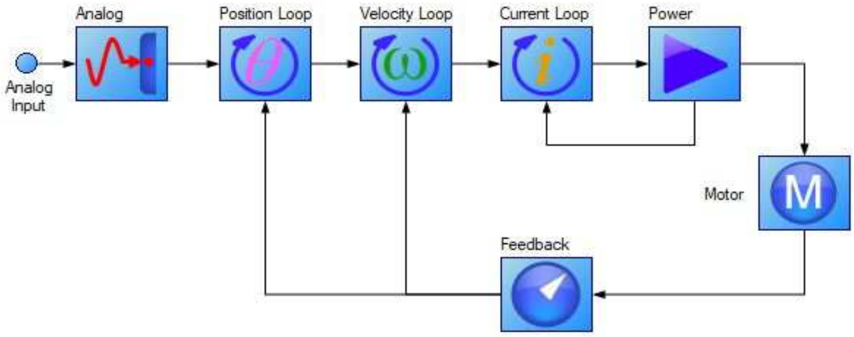

Fig. 2. System Block Diagram

The frequency of the sinusoidal current input is applied within the interval 0.2 rad/s - 60 rad/s. During the tests, for each designated frequency of the sinusoidal input, the corresponding angular velocity is recorded as an output of the servo motor system. The recording of the angular velocity is performed when the system's output reaches a steady peak value.

The obtained data are plotted in Fig. 3a. The frequency axis of this plot is in logarithmic scale. Red asterisks denote the measured data for the designated frequency. In this graph, the gain (magnitude ratio) is calculated by dividing the peak of the measured output velocity by the peak of the measured input current. The initial gain (75.8959 dB) and the gain value where the line intersects the cut-off frequency are important to find the TF of the investigated system. These values are encircled and emphasized in Fig. 3a.

The expectation is to receive a first-order delay transfer function due to the relation between the input current and the output velocity. Since the input, current is directly related to the input torque by the help of the torque constant of the motor, this relationship is an obvious one by neglecting the faster dynamics of the system such as the servo driver's circuitry. The necessary equations to determine the TF of the system are presented in Eqs. (1), (2), (3), and (4).

$$T(s) = \frac{a}{s+b} = \frac{\left(\frac{a}{b}\right)}{\left(\frac{s}{b}+1\right)} \tag{1}$$

These two parameters, a, b, are to be determined from the measured data's response. In Eq. (1), the "b" value represents the cut–off frequency of the first-order TF, i.e., b = 1.6 rad/s. The remaining part of the TF is calculated as follows by considering the initial gain value.

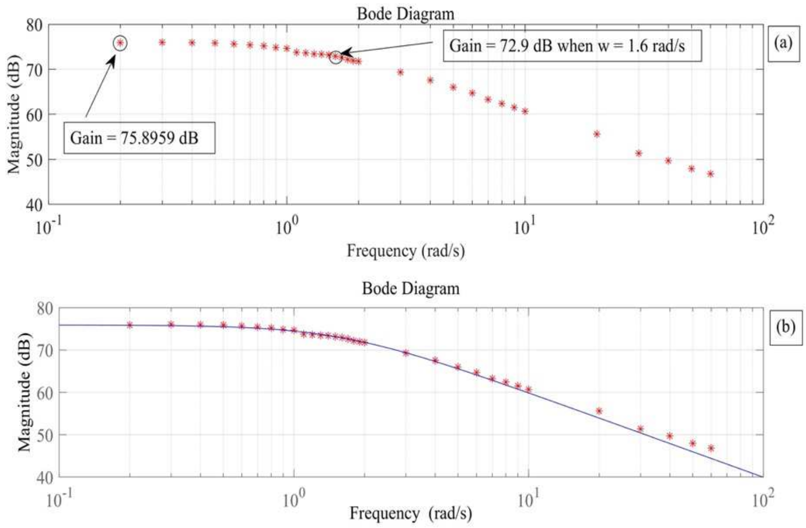

Fig. 3. Experimental results for identifying the current-controlled servo motor system (a) Measured Data (red) (b) Bode Diagram of the fitted TF (blue) and measured data (red).

$$75.8959 = 20\log_{10}\left(\frac{a}{b}\right) = 20\log_{10}\left(\frac{a}{1.6}\right) \tag{2}$$

$$3.7948 = \log_{10}\left(\frac{\mathrm{a}}{1.6}\right) \Rightarrow \mathrm{a} = \left(10^{3.7948}\right)(1.6) = 9975 \tag{3}$$

Therefore, TF of the current controlled servo motor system is identified to be,

$$\mathrm{T(s)} = \frac{9975}{\mathrm{s}+1.6} \tag{4}$$

The frequency response of this identified TF and measured data are illustrated together in Fig. 3b. It is seen that the response of the TF is to a great extent in harmony with measured data.

In addition to multiple experiments, random signals are generated and supplied to the inputs of both the identified TF and the actual servo motor system, simultaneously. In doing so, the behavior of the identified TF and the response of the servo motor system are observed and evaluated at various frequencies and amplitudes. An example is illustrated in Fig. 4a. Fig. 4b.

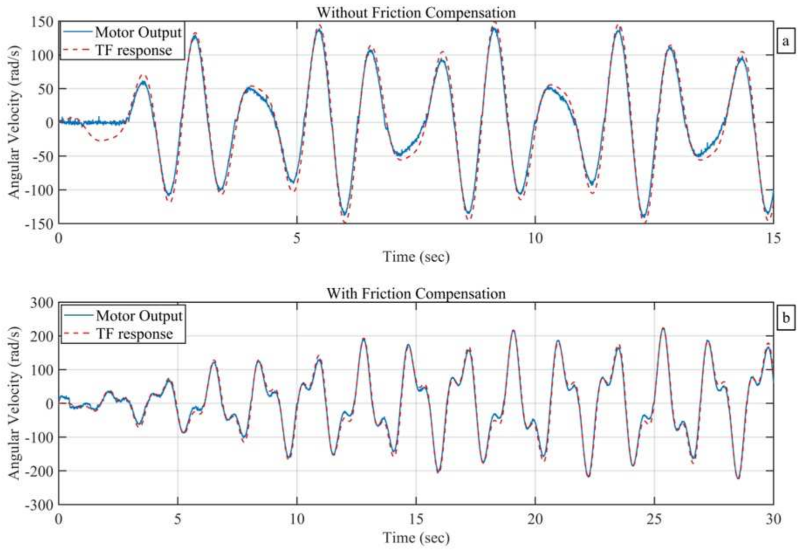

Fig. 4. TF (red) and servo motor's measured (blue) outputs when (a) there is no friction compensation. (b) there is friction compensation.

In the first few seconds, because of the static friction, the motor could not initiate its motion. Since the identified TF is a linear model of the system, it does not contain the nonlinearity feature that the static friction brings to the actual system. Consequently, a coulomb friction model with stiction effect is implemented on the system's model. The result of the system with the static friction model is given in Fig. 4b.

3 Position Control of the Servo Motor System

As a next step for generating the DT of the servo motor system, the embedded controller of the servo driver is studied. Initially, the position and velocity control loop parameters are tuned and adjusted automatically by the servo driver's software. The same control loops with the same parameters that is embedded in the servo driver are used in the simulation model of the servo motor system. Consequently, the DT of the total servo driver with all the control loops is generated. Proportional (P) and Proportional and Integral (PI) controllers are implemented for position and velocity loops, respectively. To validate the accuracy of the DT, same random inputs are supplied to both the DT and the actual servo motor system. The results of an experimental study against the results obtained from the DT of the system are given in Fig. 5.

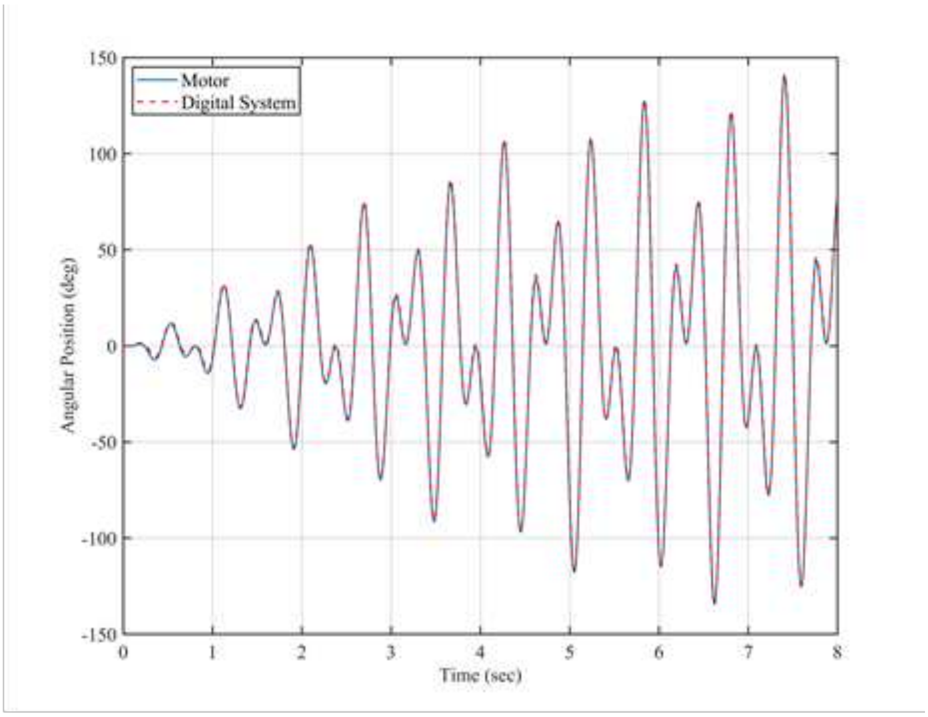

Fig. 5 Response of both the actual system and its DT for a random input

4 Conclusion and Discussion

As it is observed from Fig. 5, the DT of the actual servo motor system produces similar results with the actual system. Multiple experiments with different amplitudes and frequencies are performed which could not be presented in this paper due to space limitations. The performance of the DT is evaluated quantitatively with two performance metrics, Mean Absolute Error (MAE) and R-Squared (R^2). The evaluations based on these metrics are presented in Table 1. The input signal presented in this Table is in radians and t variable is in seconds.

Table 1. Performance of the obtained system.

Input Signal	MAE	R^2
4sin (t)	0.3002°	1
7sin (5t)	0.3624°	1
7sin (t)	0.395°	1
7sin (3t)	0.3283°	1
3sin (t)	0.2725°	1
3sin (10t)	0.2441°	0.9998
[3sin (6t+2.2864) + 3sin (10t)]	0.2707°	0.9998

As a result of this study, the DT of the servo motor system of a mechanism is generated. After implementing the kinematics, dynamics and stiffness model of the mechanism, the controller parameters of the system can be tuned without the need of using the actual system.

Acknowledgments. This study is founded by The Scientific and Technological Research Council of Turkey (grant number 116M272). Also, we would like to thank Dr. Emre Uzunoğlu, İbrahimcan Görgülü and Assoc. Prof. Dr. Gökhan Kiper.

References

1. Dede, M.İ.C., Kiper, G., Uzunoğlu, E.: A macro-micro mechanism design for laser cutting process. The 17th International Conference on Machine Design and Production, UMTIK, Bursa (2016).
2. Pahk, H. J., Lee, D.S., Park J.H.: Ultra precision positioning system for servo motor-piezo actuator using the servo loop and digital filter implementation. International Journal of Machine Tools and Manufacture, vol. 41, pp 51-63. (2001).
3. Garrido, R., Miranda R.: DC Servomechanism parameter identification: A closed loop input error approach. ISA Transactions, vol. 51, pp 42-49. (2012).
4. Ishak, N., Abdullah, N.I., Rahiman, M.H.F., Samad, A.M., Adnan, R.: Model identification and controller design for servomotor. 2010 6th International Colloquium on Signal Processing & its Applications, pp. 1-4, (2010). doi: 10.1109/CSPA.2010.5545294.
5. Wu, Y., Wang, Z., Li, Y., Chen, W., Du R., Chen Q.: Characteristic Modeling and Control of Servo Systems with Backlash and Friction. Mathematical Problems in Engineering, (2014). Article ID: 328450.
6. Bindu, R., Namboothiripad, M.K.: Tuning of PID Controller for DC Servo Motor using Genetic Algorithm. International Journal of Emerging Technology and Advanced Engineering, vol. 2, issue. 3. (2012).
7. Lin, F.J., Wai, R.J., Chen H.P.: A PM synchronous servo motor drive with an on-line trained fuzzy neural network controller. In IEEE Transactions on Energy Conversion, vol.13, no.4, pp. 319-325, (1998). doi: 10.1109/60.736317.
8. Liu, Y., Wang, Z.Z., Wang, Y.F., Wang, D.H., Xu, J.F.: Cascade tracking control of servo motor with robust adaptive fuzzy compensation. Information Science, vol.569, pp. 450-468, (2021).
9. Li, P., Zhu, G.: Robust internal model control of servo motor based on sliding mode control approach. ISA Transactions, vol.93, pp. 199-208. (2019).
10. Niranjan, P., Karinka, S., Sairam, K.V.S.S.S.S., Upadhya, A., Shetty, S.: Friction modeling in servo machines: a review, International Journal of Dynamics and Control 6, pp. 893-906, (2018).
11. AKM Series Servo Motor Specifications, https://www.kollmorgen.com/en-us/products/motors/servo/akm-series/akm-series-ac-synchronous-motors/ac-synchronous-servo-motors/